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Soil Farming Techniques for Climate Resilient Agriculture

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PREFACE

Agriculture has always been at the forefront of human development, providing us with food, fiber, and other essential resources. With the growing population and changing climate, there is an urgent need to produce more food while minimizing the impact on the environment. Soil is the foundation of agriculture, and its health and fertility are essential for sustainable food production.

This book, "Soil Farming Techniques for Climate Resilient Agriculture," aims to provide an in-depth understanding of the soil and its relationship with climate change, as well as the latest techniques and best practices for soil management. The book is intended for farmers, agronomists, extension workers, policymakers, and anyone interested in sustainable agriculture.

The book is divided into several chapters, each focusing on a different aspect of soil management. This book is the result of the collective effort of experts in the field of agriculture and soil science. Their contributions have been invaluable in making this book a comprehensive guide to soil management for sustainable agriculture. We hope that this book will serve as a valuable resource for anyone interested in sustainable agriculture and help to promote climate resilient farming practices.

Editors
Dr. Ankit Gill
Aashu Rajput
Alkajyoti Sharma
Okram Ricky Devi
Anshu

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I owe entire responsibility for all the errors and omissions.

Editors

Dr. Ankit Gill

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CONTENT

IMPACT OF CONVENTIONAL TILLAGE PRACTICES ON THE SOIL PHYSICAL PROPERTIES

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Abstract:

Moderation of soil habitat by various cultivation practices can affect crop growth and productivity. Tillage, one of the basic components of cultivation practices, has an impact on the sustainability of agriculture by altering the vertical distribution of soil organic material and nutrient supplies to plants. It may also have an impact on the physical, chemical and biological properties of the soil, which in turn has an impact on the transformation and recycling of soil organic matter and nutrients. Moreover, conventional tillage practices in combination with monoculture and restricted recycling of crop residues along with increased pressure from livestock and tractors have led to the degradation of soil and water resources. Therefore, it is important to choose a tillage method that maintains the soil's physicochemical properties, which are necessary for effective growth of agricultural crops. Several studies have shown that crops grown with conservation tillage produce yields that are comparable to or even superior to crops grown with conventional tillage. However, some researchers have found that conventional tillage increases crop yields and other researchers have found no change in crop yields regardless of the tillage method. This chapter discusses how conventional tillage practices influencing the soils physical properties thereby affecting the crop productivity.

Keywords: Conventional, conservation, recycling, organic matter and soil properties

Introduction:

The integrated management of arable soil plays an important role in sustaining the agricultural production. In arable soil, the main aim of seedbed preparation is to create favourable soil conditions required for germination, seedling establishment, optimum plant population and crop growth and yield. The soil management practices used for altering the composite soil mass may result in beneficial or harmful outcomes (Derpsch *et al.*, 2010; Wolfarth *et al.*, 2011), by depletion of soil organic matter and nutrients which in turn causes a decline of agricultural productivity (Ramos *et al.*, 2011).

Recently, a number of reports have been released to emphasize the significance of soil quality in promoting sustainable agricultural systems, which aim to establish an equilibrium between output, profitability and environmental protection. The world's biggest challenge in future was to feed the ever-rising population, which would likely to rise 8.9 billion in 2050 (Khurshid *et al.*, 2019). When we consider per capita arable land, the situation is made worse because of the urbanisation and industrialization. Arable land per person has decreased due to the intensification of global agricultural systems, going from 0.44 ha in 1960 to 0.18 ha in 2005 and is expected to drop to 0.1 ha by 2050 (FAO, 2013; Waage *et al.*, 2010). The rapidly rising global population exerts pressure on the limited amount of arable land available for crop production, so maintaining soil quality is important not only for sustainability of agriculture but also for protection of environment. In many regions of the world where there aren't the basics of effective agricultural practices, problems with land erosion, diminishing soil fertility and quickly dropping output levels are common, these issues could be mitigated by maintaining soil quality. Tillage is energy intensive in large scale mechanized farming and labour intensive in low recourse agriculture (Lal, 1991). Conventional tillage involves the repeated operations for preparation of suitable seedbed, which causes breakdown of soil structure as a result decreases the permeability of soil (Kribaa *et al.,* 2001). Conventional tillage practices cause the destruction of soil's physical, chemical and biological properties which plays an important role in increasing crop productivity and water and nutrient use efficiency. So, it is important to determine the influence of conventional tillage practices on soil properties, so that soil quality can be maintained.

Tillage

Soil tillage is one of the important key elements influencing the soil properties and crop productivity (Linn and Doran, 1984a; 1984b). Tillage is required to create an ideal seedbed, which mainly depends on type of soil, nature of previous crop and crop residue management systems. Tillage influences the sustainable use of soil resource through its impact on soil properties (Lal and Stewart, 2013) and it contributes to the 20 per cent among the crop production factors (Khurshid *et al.,* 2006). Tillage is a technique used for a broad range of purposes, including: (a) suitable seedbed preparation for the plants to germinate (Reddy and Reddy, 2018); (b) to destroy weeds; (c) soil and water conservation; and (d) to bury or remove crop residues and incorporation of manure into the soil, etc (Khan, 2019). The injudicious use of tillage practices causes destruction of soil structure, accelerated soil erosion, depletion of soil organic matter and nutrients and disruption of water, organic carbon and nutrients cycles (Lal, 1993).

The word tillage has been derived from the Anglo-Saxon words *tilian* and *teolian,* which means to prepare the soil for sowing of seed, cultivation and raising crops. Tillage is the physical manipulation of soil with tools and implements to prepare seedbeds conducive for field crop production (Reddy and Reddy, 2018). Various implements for cultivation practices were emerged according to the need of the farmers. Jethro Tull who is considered as the father of tillage, emphasized the need of tillage to improve soil productivity as it causes break down of larger soil aggregates into finer ones, thereby increasing the surface area from which plant roots obtain their food. He also introduced the concept of “Horse Hoeing Husbandry” in which crops are planted and “Horse-hoeing” is done in between.

Types of tillage

Tillage methods are generally classified into conventional and conservation tillage (Fig. 1). The conventional tillage system involves the inversion of soil, whereas no soil inversion is involved in conservational tillage system, rather it retained the crop residue from the last year’s standing crops.

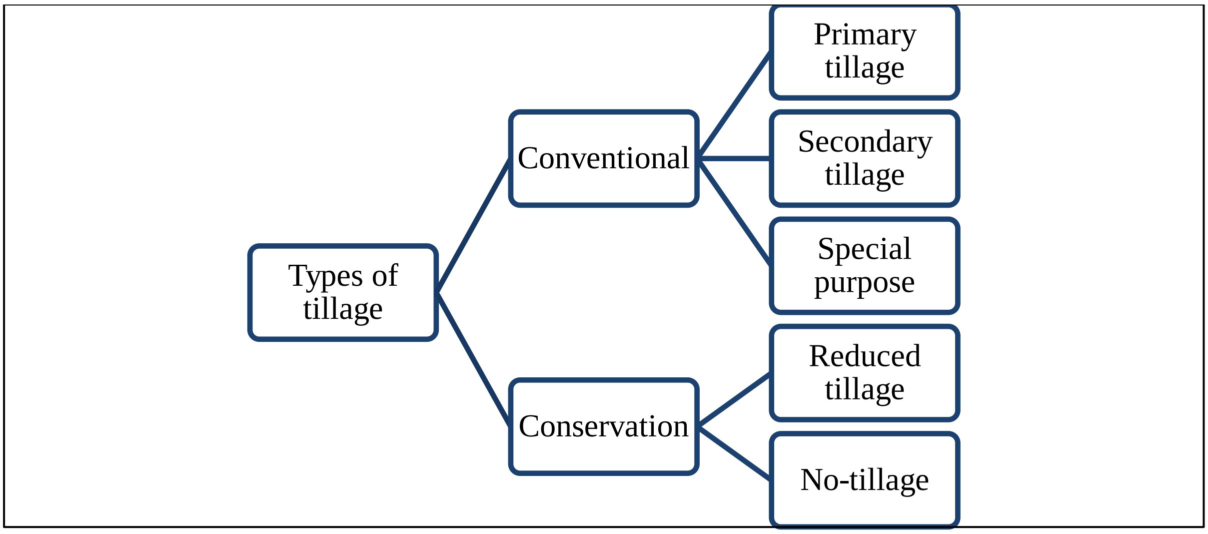

Figure 1: Schematic presentation of types of tillage

Conventional tillage

In conventional tillage, primary and secondary tillage activities are combined to prepare the seed bed using an animal or a machine. This causes the subsoil to become hard, which reduces rainwater infiltration and makes the soil more vulnerable to runoff and soil erosion. In addition, the conventional tillage method included primary, secondary and special purpose tillage.

1. **Primary tillage:** The first soil tillage after the previous crop is known as primary tillage. It is done when the ground is firm enough to provide adequate traction and moist enough to permit ploughing. The objectives of primary tillage are to aerate the soil, eliminate weeds, obtain an adequate layer of soft soil and incorporate crop residue. In primary tillage country plough, mould board plough, tractor and power tiller are used. Primary tillage is further classified into deep tillage, subsoiling and year around tillage depending on the purpose.
   i. **Deep tillage -** Deep tillage is the practise of performing tillage activities below the normal ploughing level in order to modify the physical or chemical properties of a soil. Deep-rooted crops like pigeon pea require deep tillage of 25–30 cm, whereas maize only needs moderate deep tillage of 15-20 cm. Additionally, deep tillage increases soil water content.
   ii. **Subsoiling -** The soil may contain hard pans, which would restrict the development of crop roots. Examples include pans made of silt, iron or aluminium, clay, or man-made materials. Subsoiling is the process of removing the hard pan without inversion and with the least amount of surface soil disturbance. Chisel ploughs are also used up to the depths of 60-70cm to break up hard pans.
   iii. **Year-round tillage -** Year-round tillage is the term used to describe year-round tillage activities. In dry agricultural areas, summer showers assist with field preparation. Tillage activities are repeated, until crop is planted.
2. **Secondary tillage:** The tillage operations done on the land to improve the soil tilth after primary tillage are referred to as secondary tillage. Secondary tillage is used to split up clods,

aerate the soil and integrate fertilizers and manure. To achieve these ends, planking and harrowing are used.

3. **Special purpose tillage:** Special purpose tillage is performed for specified purposes. It is carried out to prepare the soil for the upcoming main season crop. Below are a few examples of special purpose tillage:
   i. **Clean Tillage** – In clean tillage the soil is turned over and most of the residue is buried. These techniques manage pests, soil-borne pathogens and weeds. It is advised to perform clean tillage in the field once every five years.
   ii. **Blind Tillage -** It is weed-uprooting tillage carried out after crop sowing, either during the pre-emergence period or the early phases of crop development. It is carried out to eradicate weeds and thin out the crop population.
   iii. **Contour Tillage -** Contour tillage is the tillage practice applied to the contour field to reduce the rate of runoff and erosion.
   iv. **Dry Tillage -** It is performed in dryland areas for raising crops where the soil has 21-23% moisture content that makes soil soft, porous and aerated thereby increasing the water-holding capacity of the soil.
   v. **Wet Tillage -** Wet tillage is also known as puddling where tillage is carried out in standing water. Puddling reduces the deep percolation and allows water to remain for extended periods by forming an impermeable layer below the soil surface. Wet tillage is used to prevent weed infestation and to incorporate manure. It is advised to use this kind of tillage on semi-aquatic plants like rice.

Effect on soil physical properties

Deep ploughing, whether conventional or conservation, improves overall soil properties by increasing porosity and aeration, which in turn increases soil moisture content and nutrient absorption capacity and decreases bulk density. Conventional tillage, however, also had some negative impacts on the soil's properties, which lowers agricultural production.

1. Soil temperature

Soil temperature refers to the temperature of the soil at a particular depth below the surface. It is an essential parameter for understanding the processes that occur in the soil, such as plant growth, nutrient cycling, and microbial activity. The temperature of the soil affects the rate of plant growth and development, as well as the rate of nutrient uptake by the plants.

The temperature of the soil is influenced by various factors such as air temperature, solar radiation, soil moisture, soil type, vegetation cover and cultivation practices (Singh *et al.*, 2018). Conventional tillage can affect soil temperature in several ways. However, the effects of conventional tillage on soil temperature depends on a variety of factors, including soil type, climate, and management practices. Soil exposure: Conventional tillage involves loosening and turning over the soil with plows, disks, or other tools. This can expose the soil to more sunlight and air, which can increase the temperature of the soil. Overall, the effects of conventional tillage on soil temperature can vary depending on factors such as the timing and intensity of the tillage, the type of equipment used, and the soil type and moisture content. In general, however, conventional tillage can lead to higher soil temperatures, which can affect plant growth and soil quality over time. Green and Lafond (1999) observed that at 5 cm depth, soil temperature decreased by 0.29 ºC under conventionally tilled fields during winter season, while during summer, the soil temperature increased by 0.89 ºC. This shows that conventionally tilled fields have no heat advantage as intensive tillage does not help in the regulation of soil temperature.

2. Soil texture

Soil texture refers to the relative proportions of different-sized mineral particles (sand, silt, and clay) in a soil. These particles vary in size, with sand being the largest, followed by silt, and then clay being the smallest. The proportion of each particle size in the soil determines its texture. Soil texture has a significant impact on soil properties such as water-holding capacity, drainage, and nutrient availability (Singh *et al.*, 2018).

Conventional tillage practices involve the use of intensive mechanical manipulation of the soil to prepare it for planting crops. These practices can have both positive and negative effects on soil texture.

On the positive side, conventional tillage can help to loosen compacted soil and improve soil aeration, which can improve soil texture by increasing the amount of pore space in the soil (Bouma, 1991). Additionally, tillage can incorporate organic matter into the soil, which can improve soil structure and texture over time.

However, there are also negative effects of conventional tillage on soil texture. Tillage can cause soil erosion, which can lead to a loss of topsoil and a decrease in soil quality. Additionally, frequent tillage can break down soil aggregates and cause soil compaction, which can decrease soil porosity and negatively impact soil texture (Lal and Shukla, 2004).

3. Soil structure

Soil structure refers to the way that soil particles are arranged into larger clumps or aggregates. Soil structure is one of the most crucial factors impacting crop development because it controls how deeply roots can grow, how much water can be stored in the soil, and how air, water, and soil fauna may travel through the soil (Langmaack, 1999). The structure of soil is determined by a variety of factors, including the size and shape of soil particles, the amount of organic matter present, and the soil's history of physical disturbances.

The soil quality and soil structure are inextricably linked and degradation of the latter is the primary cause of many environmental problems in intensively farmed areas, including erosion, desertification, and compaction susceptibility (Lal and Shukla, 2004). Also, the structure of the soil plays a significant role in how well it performs its many tasks, with the soil's ideal structure being one that allows for a variety of purposes (Dexter *et al.*, 2002). Use of mechanical equipment such as plows, disks, and cultivators in conventional tillage practices have both beneficial and harmful effects on soil structure.

One of the positive effects of conventional tillage is that it loosens the compacted soil, allowing for better root growth and increased water infiltration which results in the enhancement of soil aeration, reduction of soil erosion and increase in the crop yields (Singh et al. 2018). However, the repeated use of conventional tillage can also have negative effects on soil structure. According to Pagliai *et al.* (2004) traditional plowing caused more significant changes to the physical characteristics of the soil, which harmed the soil's structure. Surface crusts and ploughpan formation were two drawbacks of conventional tillage practices (Dexter *et al.,* 2002). In addition to reducing the amount of water that can travel through the surface layers of traditionally tilled soil, the development of the ploughpan and the decline in porosity, especially the continuous elongated pores, may further impede root growth.

In general, adoption of conventional tillage for long term cultivation results in soil structure degradation, which further reduces the impact of chemical fertilizers (Pagliai et al. 2004). Furthermore, conventional tillage also leads to the loss of topsoil, as soil particles are loosened and then carried away by wind and water erosion which results in reduced soil quality and productivity, as well as increased sedimentation in nearby waterways (Langmaack, 1999).

4. Aggregate stability

The stability of soil structure is the resistance to the structural reorganization of particles as well as pores when subjected to various pressures, such as trampling, cultivation techniques, and irrigation (Krull *et al.,* 2004).

These aggregates play a crucial role in soil structure and fertility, as they provide pore spaces for air and water movement, support plant growth, and protect against erosion. Aggregation is a significant aspect of soil physical properties because it influences soil porosity and bulk density, which in turn affect water infiltration, wind and water erosion, water usage effectiveness as well as crop production (Singh *et al.,* 2018).

Several elements, including texture and organic matter content of soil have an impact on aggregation. Conventional tillage practices have a significant impact on soil aggregate stability. As soil aggregates are groups of soil particles that are bound together by organic matter, clay, and other substances, and their stability is important for soil structure, water infiltration, and nutrient cycling (Schlüter *et al.,* 2018).

Annual tillage and cultivation techniques destroy soil aggregates and speed up the degradation of the organic material in the soil that serves as the cementing agent (Esmeraldo, 2017). Conventional tillage can disrupt soil aggregates and cause them to break apart, reducing soil structure and pore space, and increasing soil erosion. The mechanical action of tillage can also reduce organic matter content and disrupt soil microbial communities, which can further decrease soil aggregate stability (Schlüter *et al.,* 2018). Over time, repeated tillage can lead to a decline in soil aggregate stability, making the soil more susceptible to compaction, erosion, and reduced water holding capacity.

5. Water holding capacity

The water holding capacity of soil refers to the amount of water that a particular soil can hold and retain for plant growth. It is an important soil characteristic that determines how much water is available to plants, and also affects nutrient availability and soil structure.

The water holding capacity of soil is influenced by several factors, including soil texture, organic matter content, and soil structure. Soils with a high proportion of clay particles generally have a higher water holding capacity than those with more sand or silt. Organic matter can also increase the water holding capacity of soil by improving soil structure and porosity (Singh *et al.,* 2018).

Conventional tillage significantly affects the soil water holding capacity, depending on various factors such as the type of soil, climate, and type of tillage equipment.

On one hand, conventional tillage can increase soil water holding capacity by improving soil structure and increasing soil organic matter content. Tilling can break up compacted soil, allowing water to penetrate deeper into the soil profile and reducing runoff. The addition of organic matter through tillage also increases the soil's ability to hold water by improving soil structure and promoting the formation of soil aggregates (Krull *et al.,* 2004).

On the other hand, conventional tillage can also decrease soil water holding capacity by increasing soil erosion and reducing soil organic matter content. Tilling can disturb the soil structure, exposing it to erosion by wind and water, which can lead to the loss of topsoil and reduce the soil's ability to hold water. Tilling also accelerates the breakdown of soil organic matter, which is critical for maintaining soil structure and improving water holding capacity (Esmeraldo, 2017). Cultivation practices including conventional tillage can alter the distribution of pore sizes. Further, the impact of raindrops as well as wetting and drying cycles leads to either collapse or sealing of pore spaces during the growth season of crops (Topaloglu, 1999).

6. Infiltration rate

The rate of entry of water into the soil per unit of time is known as the infiltration rate. Raindrops that fall directly on a surface clog pores and seal the surface, reduces penetration and promotes runoff, which leads to water erosion (Singh *et al.,* 2018).

The physical qualities of the soil, such as porosity, bulk density, aggregation and water sorptivity impact how well the soil infiltrates water (Singh et al. 2018). Pore size distribution, continuity of pores, and soil structure all affect the entry of water into the soil surface and its movement through the soil profile (Reynolds and Elrick, 2002). The rate of infiltration in soil is also impacted by tillage techniques. Due to the presence of small number of macropores along with reduced microbial activity, infiltration is said to be lower in tilled soils (McGarry *et al.,* 2000).

On the one hand, conventional tillage can help to break up compacted soils and improve the soil's ability to absorb water. By creating more space between soil particles, tillage can increase the pore space within the soil, allowing water to infiltrate more easily. This can be particularly beneficial in areas with heavy clay soils that tend to be more prone to compaction and runoff. Ferreras *et al.* (2000) recorded higher soil infiltration rate as well as hydraulic conductivity under conventional tillage because of lower bulk density and enhanced porosity produced by adoption of tillage practices.

On the other hand, conventional tillage can also have negative effects on soil infiltration rate. For example, tillage can disrupt the natural structure of the soil and destroy soil aggregates, which can decrease the soil's ability to absorb and retain water. Tripathi *et al.* (2003) found that conventional tillage practices led to compaction of subsurface and degradation of soil aggregates in puddled conditions which ultimately led to lower rate of infiltration in rice season. Similar findings were reported by Shukla *et al.* (2003) where reduction in the soil organic carbon under conventional tillage resulted in lower infiltration rates.

Long term intensive tillage practices reportedly disrupted the macropore continuity and led to reduction in infiltration rate of soil along with hydraulic conductivity (Logsdon *et al.*, 1990). Overall, the effect of conventional tillage on soil infiltration rate depends on a variety of factors, including the type of soil, the intensity and frequency of tillage, and the presence of other soil management practices such as cover cropping or reduced tillage (Topaloglu, 1999).

7. Porosity and Density of soil

Tillage affects both bulk density and porosity, but it has no effect on particle density because tillage and other short-term modifications do not influence the overall quantity of the soil mineral particles. Soil bulk density is inversely proportional to the soil porosity. Tilled soils under continuous cultivation had generally high soil porosity as reported by Mohammadi *et al.* (2009) that the amount of soil porosity in mouldboard plow + rotavator is higher than no tillage system owing to excessive pulverization of soil by mouldboard plow and rotary tillage which alters the soil structure by converting soil to lower aggregates and therefore altering the pore space in between the soil particles.

Soil bulk density (BD) is often used in soil quality studies as an index of the soil's mechanical resistance to root growth (Reynolds *et al.,* 2007). The implementation of conventional tillage and no tillage for seven years in durum winter wheat under mediterranean climate of France showed higher reduction in soil bulk density with conventional tillage practice in comparison to no tillage (Khaledian *et al.,* 2007). The bulk density of tilled soils (using mouldboard plough) can be significantly affected by the activity of mouldboard plough (cuts, lifts, breaks up, and loosens soil) leads to the creation of large pores in the plough layer(15cm), thereby, reduced soil bulk density (MousaviBougar *et al.,* 2012 ; Gholami *et al.,* 2013 ; Boloor *et al.,* 2013). Osunbitan *et al.* (2005) reported reduction in soil bulk density due to four tillage practices. The highest reduction in bulk density was found in plough-harrow tillage practice followed by plough-plough tillage, manual tillage, while no-tillage showed lowest reduction. Ordoñez-Morales *et al.* (2019), investigated the effect of different tillage practices on soil physical properties of Mexico. The results showed that reduction in soil bulk density and hydraulic conductivity in the order conventional tillage (maximum reduction in bulk density)> no-tillage> vertical tillage (least reduction in bulk density). Chen *et al.* (2014) associated soil bulk density under different tillage systems (no tillage, mouldboard plow and ridge tillage) to the soil porosity and reported increment in soil bulk density with no tillage and ridge tillage compared to mouldboard plow at 0-20 cm soil depth owing to less soil disturbance in no tillage and ridge tillage leads to reduction in soil porosity and escalation of soil bulk density.

8. Hydraulic conductivity

As per darcy's law, Hydraulic Conductivity" (K) is the capacity of a porous medium (soil) to transmit water. It has been found that soil tillage generally increases porosity and reduces soil bulk density due to loosening of surface soil (Green *et al.*, 2003). Tillage also affects hydraulic conductivity of soil but studies on the effects of cultivation practises on changes in the hydraulic conductivity (K) are inconsistent and do not follow a clear pattern as some findings reported increase in K with tillage (Kribaa *et al.,* 2001; Moret and Arrue, 2007), while, some findings indicated decrease in K with tillage (Benjamin, 1993; Mahboudi *et al.*, 1993; Mapa *et* *al.*, 1986). The inconsistent results of soil hydraulic properties under tilled and no-till systems may be attributed to the factors viz., temporary nature of the soil structure, initial and final soil water content, site history, time of sampling and structural integrity of the soil pores (Azooz *et al.*, 1996).

In the case of no-till system, because of improved soil structure, increased soil organic matter, better maintenance of soil micropore and macropore continuity and presence of preferential flow paths due to macrofauna activities compared to conventional tillage, highest saturated hydraulic conductivity was reported (Six *et al.* (1998); Kodesova *et al.* (2009); Kargas *et al.* (2012). Mechanical breakdown or disintegration of soil aggregates due to conventional tillage practices, leads to soil dispersion by slaking of macro aggregates, thereby clogging soil pores and reducing equilibrium water infiltration rate and hydraulic conductivity (Fuentes, (2004) and Hu *et al.* (2009).

9. Soil friability

Soil friability *is* the tendency of a mass of unconfined soil to break down and crumble under applied stress into a particular size range of smaller fragments (Utomo and Dexter, 1981). It is a desirable characteristic when preparing a medium for sowing and a method for its measurement is *originated from* the concept of brittle fracture of soil aggregates (Hatibu and Hettiaratchi, 1993). Various studies investigated the vulnerability of topsoil structure to stress exerted by intensive tillage indicated that friability of uncultivated soils (forests, pasturelands) are higher than soils under continuous cultivation owing to good soil structural stability, preservation of soil organic matter in uncultivated soils (Braunack *et al.,* 1979). Chan, (1989) and Macks *et al.* (1996) in their studies found that continuing operations of soil tillage leads to significant reduction in friability in comparison with no-tillage. One possible indicator of soil friability is the distribution of tensile strength (Utomo and Dexter, 1981). The force per unit area needed to cause aggregate disruption is known as the tensile strength of aggregates. (Dexter and Kroesbergen, 1985). Blanco-Canqui *et al.* (2005) in Ohio reported that mould board ploughing and chisel ploughing increased soil tensile strength at 0–10 cm depth compared to no-tillage management. The lower tensile strength for no-till system might be attributed to the higher soil organic carbon concentration, better macro pore flow and reduced surface sealing under the mulch, whereas conventional tillage can increase soil compaction below the plough layer by disrupting the pores continuity and increase susceptibility to surface sealing which ultimately increased tensile strength and reduced soil friability. Munkholm *et al.* (2001) established the need to convert conventional tillage practices to zero tillage as tensile strength of soil aggregates especially in wet soil increased due to intensive secondary tillage practices which ultimately reduced soil friability.

Conclusion:

Soils are one of the world's most precious commodities. Millions of agricultural families around the globe are facing risk of food security and losing their means of subsistence due to ongoing soil degradation. Farmers of India generally following conventional tillage practices which no doubt has significant effect on soil health only for short period of time, but in long run it degraded the soil's physico-chemical and biological properties, thus, invites the need to go for conservative tillage practices.

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PROBLEMATIC SOILS: ORIGIN, TYPES AND MANAGEMENT

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Introduction:

Problematic soils are those soil which are unfavourable for crop production due to excess amounts of salts, water logging, exchangeable sodium percentage (ESP) and soil aeration etc, which adversely affect the soil productivity. In the world, India is the second most populous country faces severe problems in agriculture sector. According to estimates, 173.65 M hectare area of India is degraded out of the 328.8 m ha of the total geographical area, producing less than 20% of its potential yield.

Major problematic soils of India

Sr. No.	Problematic Soils	Key Diagnosis	Major constraints
1	Clay soils	Dominated by clay particles	Compaction, water logging, poor aeration, difficult to cultivate
2	Sandy soils	Dominated by Coarse sand particles	Poor fertility, low SOM, low water holding capacity, erosion
3	Acid soils	Soil pH is less than 6.5	Fe, Al toxicity (Strong acid soil)
4	Saline soils	ECe is greater than 4.0 dS/m	High osmotic potential, nutrient imbalance,
5	Sodic soils	ESP is greater than 15	Deteriorated physical condition, nutrient imbalance, Na toxicity
6	Saline sodic soils	ECe is greater than 4.0 dS/m and ESP is greater than 15	High osmotic potential, deteriorated physical condition, nutrient imbalance
7	Calcareous soils	$CaCO_3$ is greater than 5.0 %	P, Fe deficiency
8	Water logged soils	Low infiltration rate, Water Stagnation,	Poor aeration

Acid soil

Soil acidity is more common in humid regions with rainfall high enough to leach appreciable quantities of exchangeable base forming cations (Ca^{++}, Mg^{++}, K^{+} and Na^{+}) from surface soil layers. The pH of soil is used to determine the acidity or alkalinity of the solution. The pH of a soil solution is the negative logarithm of hydrogen ion activity. These soils are less productive due to lack of some plant macro and micro nutrients like as P, B, Ca, Mg, Mo as well as poor micro- organism activity (bacteria, fungi etc). The pH of acidic soil is less than 6.5.

The pH range of soil and degree of soil acidity

pH range	**Acidity of soil**
<4.5	extremely acidic
4.5- 5.0	very strongly acidic
5.1- 5.5	strongly acidic
5.6 - 6.0	moderately acidic
6.1- 6.5	slightly acidic
6.6 - 7.3	neutral

In India, acid soils comprise about 28% of the geographical area, out of which 9.3% are strong to moderately acidic (pH<5.5), while 18.9% are slightly acidic (5.5 to 6.5).

Source of soil acidity

i. Carbon dioxide (CO_2)

If soil has a high concentration of CO_2, the pH value will be low, causing the soil acidic. The metabolism roots activity may also operate as a source of CO_2 which further increases to the soil acidification.

ii. Leaching caused by Heavy rainfall

When there is a lot of precipitation and rainfall, exchangeable base are significantly removed from the surface soil, and an insoluble compound of Al and Fe remains in the soil , although base elements naturally contain acid, when their oxides and hydroxides interact with water, it release H^{+} ions in to soil solution and producing the soil acidic.

iii. Acidic parent material

Some soils may be somewhat more acidic since they were originated from acid parent material such as granite.

iv. Acid forming fertilizers

The application of acid-forming fertilizers such as ammonium nitrate and ammonium sulphate increase the soil acidity.

Type of soil acidity

There are three major kinds of soil acidity namely, active acidity, exchangeable acidity and reserve acidity.

(a) Active acidity

Active acidity is the acidity that results from the concentration of hydrogen and aluminum ions in the soil solution. The acidity strength is limited. This pool is very small, compared to the exchangeable and residual pools. Active acidity is very essential because it influences the solubility of many substances and generate the soil solution environment to which plant roots and microorganism are exposed.

(b) Exchangeable acidity

Exchangeable acidity is known as salt replaceable acidity. The soil colloids absorbed hydrogen and aluminium ions caused to develop the soil acidity. This exchangeable acidity has extremely high magnitudes. In soils with moderate to strong acidity, exchangeable acidity is quite high and difficult to neutralize. Exchangeable acidity is typically highest for montmorillonite, intermediate for vermiculite and lowest for kaolinite at a given pH.

(c) Residual acidity

This acidity is essentially connected to hydrogen and aluminum ions including Al-hydroxyl ions such as $Al(OH)_2^+$ and $Al(OH)^+$ that are attached to non-exchangeable form by clay and organic matter in the soil). As pH rise, the bound hydrogen dissociated and the bound aluminum ions are released and precipitate as amorphous $Al(OH)_3$. These modifications enhance the CEC and release the negative cation exchange sites.

Thus, the total acidity = active acidity + exchangeable acidity + residual acidity

Problems of soil acidity

Problems of soil acidity may be classified in to three categories which are as follows**:**

1. Toxic effects

(I) Toxicity of acid

The higher hydrogen ion concentration is toxic to plants under strong acid conditions of soil. The acid toxicity includes possible toxicities of acid anions as well as H^+ ions.

(II) Toxicity of various nutrients elements

The concentration of these ions (Fe^{2+}, Mn^{2+} and Al^{3+}) in soil rises to an extremely high level and there toxicity developed.

(III) Exchangeable bases:

The availability of exchangeable bases included two components: the ion uptake process and release of base from the exchangeable form, both of which may be adversely impacted by soil acidity. Acidic soils have deficits in bases like Ca^{2+} and Mg^{2+}.

2. Nutrients imbalances

It is established that moderate to strongly acid soil usually comprises larger quantities of soluble iron, aluminium and manganese. Plant cannot use Phosphorus because of the reaction between phosphorus and these ions, which result in insoluble phosphatic compounds. In addition to these, the availability of phosphorus is reduced by the fixation of phosphorus by the hydrous oxides of iron and aluminium or by adsorption. Iron, manganese, copper and zinc are all plentiful in acidic soils but molybdenum is scarce and unavailable to plants. The availability of boron may also be reduced in acidic soil with very low pH level due to adsorption on sesquioxide's, iron and aluminium hydroxyl compounds. In an acidic soil with a pH below 5.5, nitrogen, potassium and sulphur become less readily available.

3. Microbial activity

It is general knowledge that changes in the soil reactivity have an impact on soil organisms. Actinomycetes and Bacteria perform much better in soils with moderate to high pH levels. When the pH of the soil falls below 5.5, they are not able to exhibit activity and reducing azotobacter sp. activity significantly affects nitrogen fixation by influencing Rhizobium sp. activity. In extremely acidic, fungi can grow and produce a range of illnesses, inducing potato blights and tobacco root rot.

Reclamation of acidic soils

Principles of liming reactions

By adding liming material such as calcite limestone ($CaCO_3$), acidic soils can be resorted. The Shoemaker *et al.* (1961) method is used in the lab to calculate the rate of lime required. The rate of the neutralizing reaction is influenced by the liming materials particle size. In pure water, both of these lime tones are very soluble but they become soluble in water that contains CO_2. The lime stone is more soluble as the higher the partial pressure of CO_2 in the system. Calcite is more soluble than dolomite, although only slightly. The reaction of limestone ($CaCO_3$) can be written as:

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca(HCO_3)_2$$

$$Ca\,(HCO_3)_2 \rightarrow Ca^{2+} \downarrow + 2HCO_3^-$$

(Takes part in cation exchange reactions)

$$H^+ + CO_3^{2-} \rightarrow H_2CO_3^- \leftrightarrow H_2O + CO_2$$

(From soil solution) (From lime)

In this way hydrogen ions (H^+) in the soil solution react to form weakly dissociated water and the calcium (Ca^{2+}) ion from lime stones is left to undergo cation exchange reactions. The acidity of the soil is, therefore, neutralized and the per cent base saturation of the colloidal material is increased.

Soil salinity and sodicity:

Globally according to FAO 2008, globally more than 800 million hectors of land are estimated to be salt affected soil. An area of 6.74 Mha in India suffer from salt accumulation out of which 3.78 Mha are sodic while 2.96 Mha are saline soil (Mandal *et al*. 2013). Salt affected soils are those where the salt concentration is so high that one negatively impacts plant growth and agricultural productivity. Salts are always present in the soil in some quantity. These salts are not toxic to plant growth when their concentration is low. But as a result, salt concentration of the soil rises to high level, plant growth is negatively impacted, which in turn lowers crop output. However, a number of parameters including type and amount of salt components, soil texture the distribution of salt in the soil profile, the species of plant planted, the degree of soil-water- crop management, and climate condition, affect how much growth and productivity are reduced.

Classification of salt affected soils

For the purpose of creating specific management systems for particular kinds of purpose and limitations in the production of crop, the salt affected soils needs to classify in to various groups. Based on how salts behaved in the soil the US Salinity Laboratory Staff grouped salt affected soils in to three distinct classes based on the behavior of salts in the soils viz. (i) Saline soils, (ii) Alkali soils and (iii) Saline- alkali soils.

Characteristics	Saline soil	Non saline alkali soil	Saline-alkaline soil	Degraded alkaline soil
Content in soil	Excess soluble salts of sodium	Absence of soluble soil and presence of exchangeable Na on the soil complex	These soils are both saline and non saline alkali soil.	-
Exchangeable ions	Calcium	Sodium	-	-
SAR	Less than 13	More than 13	More than 13	Less than 13 in surface layer more than 13 is lower horizon
ESP	Less than 15	More than 15	More than 15	More than 15
pH	Less than 8.5	8.5 to 10	More than 8.5	
Electrical conductivity of the saturation	>4 dSm^{-1}	<4 dSm^{-1}	>4 dSm^{-1}	<4 dSm^{-1}

(A) Saline soils Solonchak (Russian term), Saline non sodic, White alkali

Saline soils considered as a soil having an exchangeable sodium percentage (ESP) less than 15 as well as conductivity of the saturation extract greater than 4 dSm^{-1} (0.4 Sm^{-1} or 4 mmhos cm^{-1}) at 25 ^{0}C and. The pH of saline is less than 8.5. Saline soils contains sufficient concentration of soluble salts in the root zone soil which are adversely affects the crop productivity or simply, the accumulation of water-soluble salts in the soil which restrict the crop production is called saline soil. The amount of soluble salts present in the soil is determined by the electrical conductivity or individual analysis of salts present in the soil. Among the salts present in the soil Ca^{+2}, Mg^{+2}, Na^+ and K^+ are the dominant cations whereas CO_2, CO_3^{-2}, Cl^-, SO_4^{-2} are the dominant anions in arid and semi-arid region of the world. The process of accumulation of soluble salts in the soils is known as salinization.

Causes of soil salinity

(i) Primary minerals: It is primary and essential direct source of every salt component. Various elements including Ca, Mg and Na are gradually released and produced solubility during the weathering process which including hydrolysis, hydration, solution, oxidation and carbonation. Dolomite [Ca Mg $(CO_3)_2$], Calcite ($CaCO_3$) and Halite (NaCl) are a few examples.

(ii) Arid and semi-arid climate: The most salt affected soil is produced in arid and semi-arid climate where high evaporation and low rainfall are the norm. Due to lack of adequate rainfall in this area to properly leach out the solubility weathered compounds; salt builds up in the soils. Additionally, due to capillary rise of salt with evaporating water from the lower zone in certain places, excessive evaporation causes salt to deposit in the root zone with increase climate aridity, salinization become more intense.

(iii) Sea as a source of salts: As a soil where the parent materials are marine deposited that were laid down during earlier geological phase and have been reclaimed, the ocean may be source of salt. The salt is low laying area near seacoast are also derived from the ocean. Salts that are transported inland by wind boron spray are sometimes referred to as "cyclic salts." Salt affected soils are seen in the ***bhal*** reason in Gujarat.

(iv) Restricted leaching and transportation: In comparison to humid areas, arid regions do not undergo as complete a leaching and transfer of dissolved salts to the ocean. In dry areas, leaching often occurs regionally and soluble salts may not be transported much further. It occurs not always due to the reduced rainfall available to absorb and transfer the salt, in addition to increased evaporation rates, which tend to concentrate the salt in the soils and in surface water.

(v) Low permeability of the soil: Because preventing the water from flowing downward, this leads to poor drainage. Due to inadequate permeability, the ground water table may rise or there may be persistent deposition of soluble salts in the soils which can be caused by unfavorable hard pans, soil structure or texture or clay pans.

(vi) Ground water: When the water table and evapo-transpiration rate is high, salts along with water move upward through capillary activity and salts accumulation on the soil surface. Ground water contains large amounts of water-soluble salts that depend on the nature and properties of the geological material with which water remains in contact.

(vii) Irrigation water: The water table and surface salt content in the soils rise when irrigation water is applied improperly (i.e. lack of drainage and leaching facilities).

(viii) Poor drainage of soil: The salts are leached from the upper layer during times of heavy rainfall and if drainage is prevented, they accumulate in the lower layer. Salts are left in the soils after water evaporation. These types of soils typically grow in low-lying areas.

(ix) High water table: A lot of soluble salts are typically present in the ground water of arid areas. Large amounts of water flow to the surface through capillary action and evaporate when the water table is high, leaving soluble salts on the surface.

(x) Canal as a source of salinization: Even through canal water does not actually contain much soluble salt, use so much of it in the initial stage speed up the rise of the ground water table. Ground water moves upward in to the root zone and to the soil surface as the water table rise to within 5 or 6 feet from the soil surface. In such a situation, both irrigation water and ground water contribute to the salinization of soils.

(B) Alkali or sodic soil, Solonetz (Russian term), Non saline sodic, Black alkali

These soils contain sodium salts capable of causing alkaline hydrolysis, mainly Na_2CO_3. Such soils were termed as the alkali soils. The sodic soils have ECe less than 4 at 25^0C, ESP more than 15 and SAR more than 13. Alkali soils have sufficient sodium saturation on the exchange complex and alkalinity to adversely affect plant growth and crop productivity. Carbonates (CO_3^{-2} + HCO_3^-) of sodium are dominant salts. The concentration of natural salts (Cl^- and SO_4^{-2}) is much lower.

Alkalinity or Alkaline: It indicate the reaction of soil, means soils contains excess alkalinity (pH more than 7.0).

Alkali: It indicates condition of soil where alkali ion (sodium) is dominant on exchange complex of the soil.

Alkalization: It is the process of accumulation of sodium ion on soil exchange complex is known as alkalization.

Causes of Alkalinity:

Process where exchangeable Na content in soil increased due to precipitation of Ca and Mg as carbonate (Na_2CO_3 or $NaHCO_3$) by low of mass action, Ca and Mg replaced by Na on exchange complex.

(i) Hydrolysis of sodium silicate or weathering of minerals.

$$Na\,\mathbf{X} + H_2O \xrightarrow{\text{hydrolysis}} NaOH + H\,\mathbf{X}$$

$$NaOH + CO_2 \xrightarrow{\text{hydrolysis}} NaHCO_3$$

$$2NaHCO_3 \xrightarrow{\text{decomposition}} Na_2CO_3 + CO_2 + H_2O$$

Na_2SiO_3 → Sodium silicate → highly sodic

NaOH → also highly sodic

(ii) Replace Na_2SO_4 or NaCl by $CaCO_3$

$$Na_2SO_4 + CaCO_3 \rightarrow Na_2CO_3 + CaSO_4$$

$$2NaCl + CaCO_3 \rightarrow Na_2CO_3 + CaCl_2$$

(iii) Hydrolysis of exchangeable Na

$$Na\,X\,Na + H_2O + CO_2 \rightarrow H\,X\,H + Na_2CO_3$$

$$Na\,X\,Na + CaCO_3 \rightarrow Ca\,X\,Ca + Na_2CO_3$$

$$Na\,X\,Na + Ca(HCO_3)_2 \rightarrow Ca\,X\,Ca + NaHCO_3$$

(iv) Reduction of Na_2SO_4 through microorganisms

$$Na_2SO_4 + 2C + CO_2 \rightarrow Na_2S + 2CO_2$$

$$Na_2S + CO_2 + H_2O \rightarrow H_2S + Na_2CO_3$$

(v) Decomposition of organic matter

$$Na_2SO_4 \rightarrow Na_2S + 2O_2$$

$$Na_2S + 2H_2O \rightarrow H_2S + 2NaOH$$

$$NaOH + CO_2 \rightarrow NaHCO_3$$

(vi) Use of alkali or sodic water for irrigation

(vii) Excessive use of basic fertilizers: Use of basic fertilizers like Na_2NO_3, basic slag etc. may develop alkalinity in the soils.

(viii) Humid and semi-humid regions: Alkaline soils can also grow in other place such as semi-humid and temperate regions especially in depressions where drainage is defective and where the underground water table is high or close to the surface.

(C) Saline - Sodic soil

These soils have high concentration of neutral salts and appreciable sodium on the exchangeable complex. The saline sodic soils having a conductivity of the saturation extract greater than 4 at 25^0C, exchangeable sodium percentage (ESP) more than 15 and sodium adsorption ration (SAR) more than 13 in this soil, both free salt and exchangeable sodium are present.

(D) Degraded alkali or sodic soil

If a saline-sodic soil is extensively leached in the absence of any calcium or magnesium sources, some of the exchangeable sodium is eventually replaced by hydrogen. The resulting soil may have an unstable structure and a mild acidity. Degraded alkali or sodic soil is the term given to this type of soil.

$$\text{Clay Na} + H_2O \leftrightarrow \text{H clay} + NaOH \downarrow$$

(Acid soil on the leaching surface horizon)

$$2NaOH + CO_2 = Na_2CO_3 + H_2O$$

(From soil) (Alkali soil in the sub-surface horizon)

Management and reclamation of salt affected soil

Physical reclamation- Physical reclamation methods are including sub soiling, deep ploughing, profile inversion, marling (sanding), scarping and flushing.

I. **Sub soiling and deep ploughing-** These two methods mechanically break the impermeable layer, cemented sub soil layer or hardpan in the soil profile at some depth to increase the infiltration and transportation of salt dissolved in water to deep soil layers. Deep ploughing is very useful where the subsoil has gypsum or lime.
II. **Profile inversion-** It can be working in situations where surface soil is relatively free of salts and Na but soil below is sodic, saline or saline sodic.
III. **Marling (sanding)** – Sometimes sand is mixed in the salt- affected soil to improve permeability and air water relations in the root zone.
IV. **Flushing** – Flushing involves washing away the surface accumulated salts by flushing water over the surface. It is sometimes used to desalinize soils having surface salt crusts.
V. **Scraping** – Removal of few centimeters of salts encrustation is called scrapping.

Reclamation of saline and sodic soils

I. Leaching

The main objective in reclamation of these soils is to be leach the salts below the root zone. Leaching requirement (LR) has been defined as that fraction of water that must be leached through the root zone to control the salt at as specified level. This is achieved by flood and drainage. To make it effective, bound are raised around plots prepared and water is applied depending on their water requirement to leach salts.

LR (leaching requirement) = $EC_{IW} / EC_{DW} * 100$

EC_{IW} = EC of irrigation water

EC_{DW} = EC of drainage water

II. Chemical Process

Chemical processes involve applying materials like gypsum, sulphur, sulphuric acid and hydrochloric acid. Whereas sulphur, sulphuric acid and hydrochloric acid are only useful on calcareous saline-sodic soils, gypsum performs on both sodic and saline sodic soils. By reducing the pH of the soil, reacting with soluble carbonates and exchanging out the exchangeable sodium and calcium, these amendments remediate the soil.

Gypsum

Gypsum is by far, the most economical and commonly used chemical amendment. In India the resources of gypsum are estimated to be more than 1000 million tones. The Gypsum requirement (GR) for amelioration of alkali/sodic soil depends upon exchangeable sodium content to be replaced, exchange efficiency and the depth of soil to be reclaimed. The Laboratory estimation of GR (US Salinity Laboratory staff, 1954) is carried out by equilibrating a sodic soil with gypsum solution of known calcium concentration and then estimating the calcium deficit (as a result of exchange of sodium with calcium) in the extract Solution. This determination includes Ca^{+2} required to replace the exchangeable Na^{+} ions plus that required to neutralize alkalinity. The quantity of gypsum required to replace an initial l level of exchangeable sodium (ENa_i) and achieve its reduction to a desired level of exchangeable sodium (ENa_f) per unit area and per unit depth of the soil, can also be calculated using Equation:

GR (in cmol/kg soil) = (ENa_i - ENa_f) CEC

Where, ENa and CEC are in cmol (P^{+}) /kg soil Science one cmol. Gypsum/kg soil is equal to 860 kg gypsum/106 kg soil, for one hectare to a depth of 0-15 cm (2×106kg soil), the GR can be calculated by Equation:

GR (kg/ha) =1720× (ENa_i - ENa_f) CEC

Application of gypsum

Gypsum must be distributed and mixed into the top 0–10 cm of soil using a cultivator or dicing. Gypsum is less effective when mixed into deeper soil because some of the applied gypsum may interact with soluble carbonates to precipitate calcium as $CaCO_3$. Based on the desired effectiveness of reclamation, cost of grinding, and simplicity of application, the ideal size of gypsum particles is chosen. Gypsum that has been mined and crushed to pass through a 2-mm filter has been found to react more quickly and can effectively reclaim alkali soil.

III. Biological process

The biological activity in the soil is improved by organic materials and plant roots. By dissolving calcium molecules, CO_2 and organic acids that are present in soil due to material decomposition are able to help mobilize calcium. Green manuring, the integration of crop leftovers, the use of FYM, press mud and other organic materials can all help with this. Due to its strong resistance to soil sodicity, rice is preferred to be grown during the restoration of alkali soils. The lack of water for ideal rice growth encourages the partial pressure of CO_2 to build up and the leaching of salts from the sodium through calcium exchange.

Waterlogged soil:

A waterlogged or flooded soil is described as having moisture levels above the threshold at which water will stagnate. Another way to put it is that water-logged soils are those that have been saturated with water for long period in a year to cause the following different gley layers to form in the soil as a result of the oxidation-reduction process.

Properties of waterlogged soils

a. Physical properties

Diffusion of molecular oxygen and development of aerobic to anaerobic layer: When a soil is submerged, water replaces the air in the pore spaces. Except in a thin layer at the soil surface, and sometimes a layer below the plough sole, most soil layers are virtually oxygen free within a few hours after submergence and promote anaerobic layer.

b. Aeration status of a submerged soil

Immediately after submergence the entry of O_2 and other atmospheric gases in the soil is severely restricted. The escape of soil gases by diffusion is also affected to the same degree. The net result of submergence is the concentration of O_2 in the soil is reduced to a very low value, while that of soil gases, notably CO_2 is increased especially if conditions are favorable for biological activity.

c. Accumulation of carbon dioxide

Soil gases like CO_2 and methane accumulate due to submergence and also may escape as bubbles if pressure builds up. It has been recorded that during the first three weeks of submergence some soils may generate CO_2 up to 25-ton ha^{-1}.

Management of waterlogged soils

Improvement of drainage: Drainage is the most important problem of waterlogged areas. No shortcut method can solve all drainage problems. For bringing about improvement in drainage following studies and survey work should be done thoroughly.

i. Field reconnaissance - To find out the number and location of natural waterways and possible location of drainage outlets.

ii. Topographic survey - To identify the slope, undulation, to find out the potential drainage outlet.

iii. Soil Survey - To find out the characteristics of underlying soil layers of waterlogged area and each layer should be analyzed in the laboratory to determine their drainabilty.

iv. Water table survey - The position and fluctuation of water table can be determined by installing observation wells.

Calcareous soils:

Calcareous soils naturally occur in subtropical and semi-arid reason because there is very less leaching. If the parent material is high in $CaCO_3$, such as limestone, shells or calcareous glacial tills and the parent material is relatively fresh and has undergone little weathering, they can also be found in humid and semiarid regions. Certain soils with calcareous parent materials may also have calcareous soil across their entire profile. This will typically occur in arid areas with little precipitation. In other soils, $CaCO_3$ has been accumulated in horizons B or C after being leached from the upper layers. After extensive soil cultivation, these lower $CaCO_3$ layers can be raised to the surface. The $CaCO_3$ deposits are concentrated in thicknesses that in some soils may be exceedingly hard and water-impermeable. Rainfall leaches the salts to a specific depth in the soil where the water content is so low that carbonates precipitate resulting in the formation of these caliche layers. Long-term irrigation with water that contains dissolved $CaCO_3$ can also cause soil to be become calcareous.

Conclusions:

Problematic soils have a varied range of issues including high salinity, alkalinity, acidity, poor drainage, low fertility or contamination by pollutants, heavy metals or pathogens. Improving soil fertility and structure, adding organic matter, adjusting pH levels and using soil amendments or treatments like lime, gypsum or compost are typical methods for dealing with problematic soils. Problematic soils have a significant impact on human health, environmental quality and agricultural productivity. It is possible to rectify or mitigate these problems to restore the productivity and health of the soil, though with the careful assessment and management practices.

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NITROGEN MANAGEMENT IN RICE WHEAT CROPPING SYSTEM

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Introduction:

Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) play a pivotal role in food security in the Indo-Gangetic flood plains and most of South Asia. These two crops are usually grown as a double-crop annual (R–W) rotation in this region. Rice–wheat cropping sequence (RWCS) is the world's largest agricultural production system occupying around 13.5 Mha in the Indo-Gangetic plains (IGP) region, of which 10 Mha are in India, majorly comprising western parts of the country i.e.- Punjab, Haryana, Uttarakhand & western UP&it accounts for >80% of the total cereal production and about 50% of the total calorie intake.

Recently this system is facing various types of issues, one of thembeing the low concentration of soil organic matter (SOM) and low nutrient use efficiency. As the crop residues are also removed from the system for use as fuel rather than fertilizer, nutrient-supplying capacity is also reducing.

Nitrogen is the one of most limiting nutrients for the rice-wheat production system. Out of the total nitrogen applied, 60-70% of it is lost from the rice ecosystem in the various forms of N species such as ammonia (NH_3), nitrous oxide (N_2O), nitric oxide (NO), nitrogen dioxide (NO_2) and leached as nitrate (NO_3^-) through various processes. Low N-fertilizer use efficiency is a major limitation in the R–W system, especially in transplanted rice. Hence there is aprime importance to enhance N use efficiency through improved N management for ensuring food security and environmental sustainability. An efficient N management strategylies in takingthe right decisionson the optimum level, time, form, and method of N application.

The urgent requirement for efficient nutrient management in the context of the growing population is very well illustrated from an observation of rice.

- To obtain the projected grain yield of 8.0 t ha^{-1} in irrigated rice by the year 2025, it is necessary to apply 280 kg N ha^{-1} at 33% fertilizer N recovery efficiency (Cassman and Pingali, 1995). This means that urea fertilizer applied to irrigated rice in Asia would increase from 15.5 to 43.6 million tons--nearly a 300% increase in N use for a 63% increase in yield.
- By increasing fertilizer N recovery efficiency by 50%, it is possible to reduce the N application rate from 280 to 187 kg ha^{-1} and urea fertilizer need from 43.6 to 29.1 million, which is still a 200% increase in fertilizer N application for a 63% increase in yield (Cassman and Pingali, 1995).

Blanket fertilizer recommendations and soil test-based fertilizer recommendations are some methods commonly adopted by farmers. Deep placement of urea super granules (USG) in the reduced zone, and subsurface incorporation of urea are some of the low-cost&farmer-friendly

methods that could be recommended to the farmers. Recently several advancements have been made in N management practices for rice crops such as site-specific N management (SSNM), real-time N management using leaf colour chart (LCC) and customized LCC, SPAD/ Chlorophyll meter and GIS and remote sensing (RS) - based N application technologies.

In this chapter, we willdiscuss the established and emerging N management alternatives for enhancing productivity, N use efficiency, and environmental sustainability of the rice-wheat cropping system.

Available N status of Indian soils

A soil test summary based on analysis of 9.2 million soil samples collected from allover the country revealed that out of 365 districts, only 18 districts of north-eastern and north-western hill regions have high available soil N, and the rest have either medium or low available N status (Ghosh and Hasan, 1980). Hence, a good response to N fertilizer application can be seen for both rice and wheat crops in almost all Indian soil.

Nitrogen requirement and removal by the rice-wheat system

Rice and wheat responded significantly to the applied nitrogen up to 200 kg ha^{-1}. Rice yielded about 17 % more in applying over 120 kg N ha^{-1} and 5% more when applying over 160 kg ha^{-1}. In the case of the wheat crop, this increase was 16 and 4% respectively. Beyond 160 kg N the response becomes very low ranging from 4-5% in both crops. The total productivity of the system was highest at 9.5 t ha^{-1} while applying 200 kg N ha^{-1} followed by 9.15 t ha^{-1} at 160 ka ha^{-1} which was 15% higher than recommended N 120 kg ha^{-1}. Thus, the farm trails indicate that in the Rice-Wheat cropping sequence, the optimum dose of N for both Rice and Wheat was about 160 kg N ha^{-1} (A K bhardwaj, 2002).

The Rice-wheat cropping system removes 270-680 kg ha^{-1} of N, P, and Kannually. Nutrient removal depends upon various factors like the production level, soil type, and whether crop residues are removed or recycled into the soil. When crop residues are left in the soil, large amounts of nutrients are recycled. Average N, P, and K uptake per tonne of grain are about 24.5, 3.8, and 27.3 kg for wheat and 20.1, 4.9, and 25.0 kg for rice, respectively (Tandon and Sekhon, 1988).

Nitrogen cycle in rice-wheat environment

The atmosphere is the single most important source of nitrogen which contains about 78% N_2 on a volume basis. Atmospheric N_2 is added to soil due to the formation of its oxides during thunderstorms, lightening and rainfall (natural N_2 fixation), biological N_2 fixation by autotrophs (blue-green algae), heterotrophs (Azotobacter and Azospirillum), and associative/symbiotic N_2, fixers (Azolla and legumes) and through the addition of fertilizers (industrial N_2 fixation). Besides, the application of organics such as farmyard manure, compost, green manures, crop residues, irrigation water, and direct absorption of ammonia from the atmosphere also add a significant amount of N to this system. On the other hand, N is removed from the system through crop uptake, microbial immobilization, run-off, soil erosion, leaching (Rice soil), ammonia volatilization (Rice soil), denitrification (Rice soil), and weed removal. The first two processes are not actually losses in the absolute sense but desirable from the crop production point of view, the rest of other processes cause loss of N from the soil system and hence are undesirable and detrimental tothe environment and economy. Since ammonia volatilization and nitrification-denitrification processes occur in wetland rice soil, nitrogen in the form of NH_3, N_2O, and N_2 gas escape back to the atmosphere in the nitrogen cycle. An appropriate N management practice should be adopted for adequate addition of N to the soil, maximum N utilization by rice plant, and minimizing losses of N thus, preventing its adverse impacts on the environment.

Transformations and losses of nitrogen from the soil-plant system

In any given ecosystem, various forms of N become substrates for other N transformations. As N supply, transformations, and transfers are linked, a thorough understanding of the N economy in a rice-wheat system and its surroundings is necessary to have better know-how about the rate-limiting steps of different N turnover processes. The maximum amount of N that could be utilized by the crop even after adopting best management practices is not more than two third of the N added as a fertilizer or as biologically fixed N_2. The amount of losses is about one-half of the total nitrogen applied or fixed. The major contributions of Nitrogen losses from rice-wheat systems could be accounted for by ammonia volatilization, denitrification, and leaching. Since the major portion of total fertilizer N used in the rice-wheat cropping system in the Indo-Gangetic Plains is urea, the rate of nitrification is a primary determinant of N losses. Nitrate ions act as a substrate for denitrification. Excess rate of nitrification results in a build-up of a high concentration of NO^{3-} ions which are lost through run-off and leaching thus polluting groundwater and making it unsafe for human consumption. On the other hand, slow rates of nitrification would result in the accumulation of NH^{4+}-N, which may enhance fertilizer-use efficiency by reducing denitrification and leaching losses. However, the accumulation of NH^{4+} ions could also increase N losses via NH_3 volatilization. Thus, nitrification is a key process in determining fertilizer-use-efficiency by crops and N losses from soils.

1) Nitrification-denitrification

Nitrification is the process of conversion of ammonia to nitrite and then into nitrate in the aerobic condition mediated by Nitrosomonas and Nitrobacter, respectively. The major factors governing nitrification include soil aeration status, the concentration of NH^{4+}-N, temperature, soil pH, and soil texture. The nitrate thus formed in this process further undergoes the process of denitrification when the field gets submerged due to rainfall or over-irrigation. Besides this, the nitrate ions formed through nitrification in aerobic sites (top oxidized soil layer, rhizosphere, and flood water) of submerged rice soil diffuses to the underlying reduced layer and where it is subjected to denitrification process mediated by anaerobic heterotrophs e.g., Pseudomonas, Micrococcus, Alcaligenes, and Bacillus which use organic carbon compounds as electron donors for energy and synthesis of cellular constituents. Denitrification constitutes the major loss of N in the rice ecosystem.

Optimum soil pH (7.0-8.5), the adequate oxygen supply in soil (Eh value more than 200mV), soil moisture content equivalent to 60% of the water holding capacity, and soil temperature ranging from 25 to 35°C favour the nitrification process. Whereas pH range of 6-8, Eh less than 200 mV, water-filled pore space beyond 80%, high organic carbon content, and temperature range of 25- 35 °C, are optimum conditions for the denitrification process.

Alternate wetting and drying of rice fields create favourable conditions for increasing denitrification losses. In several regions of the Indo-Gangetic Plains, it is difficult to maintain continuous flooding for rice either due to the shortage of water or due to high water percolation rates of the soil, leading to alternating wetting and drying conditions. Therefore, nitrification occurs during ‘‘dry spells’’ and nitrates thus produced are subsequently reduced to N_2 and N_2O through denitrification when soils are re-flooded (Aulakh and Bijay Singh, 1997).

The incorporation of crop residues can also influence nitrification in flooded soils. While the incorporation of wheat residues did not influence the nitrification rate in the upland soil, its successive levels in flooded soil showed a profound effect on the nitrification rate (Aulakh, 1989).

2) Ammonia volatilization

Ammonia volatilization is a major pathway of N loss, especially in rice ecosystems that involve the transformation of ammonium ions added to the soil from ammoniacal or amide fertilizers, and the decomposition of added or native organic matter to ammonia gas which escapes to the atmosphere. Ammonia volatilization loss has been reported to range from 48 to 56% at an N level of 53-80 kg ha^{-1} when urea was broadcast-applied onto flood water 10 days after transplanting at a lowland site (De Datta *et al.*, 1989).

When factors such as pH, temperature, wind velocity, and CEC of the soil are favourable for ammonia volatilization, loss of N will be determined by the concentration of NH^{4+} in the floodwater of flooded rice soils. However, in coarse-textured soils, NH^{4+}-N in floodwater is readily transported to subsurface soil layers along with the percolating water. Ammonium-N placed at depth cannot move back up to the soil surface because of the regular downward flux of percolating water under repeatedly irrigated rice culture. Thus, in contrast to ideal rice soils, highly permeable soils under wetland rice do not favour substantial losses of N via ammonia volatilization.

3) Leaching

Leaching is the process of downward movement of nutrient ions along with percolating water. Leaching of N takes place mostly as NO_3^- ion which is a product of nitrification in soil and to some extent as unhydrolyzed urea molecules. However, the leaching of unhydrolyzed urea is comparatively less because of the rapid rate of hydrolysis into NH^{4+} ions and weak adsorption property (Nayak and Panda, 2000). The leaching of NH^{4+} in soils may not be a problem except when applied in very large quantities on coarse-textured soils having low cation exchange capacity. Leaching loss to the extent of 45-60% of applied N has been reported from upland rice soils having coarse texture, low cation exchange capacity, and a higher rate of water percolation (Pandey and Adak, 1971). However, in the case of flooded rice fields of eastern India which are characterized by low percolation rate and high ground water table, the leaching loss of N was measured to be less than 1 percent (Panda *et al.*, 1989).

In a highly percolating soil under a rice-wheat system, Katyal et al. (1987) studied the distribution of ^{15}N in soil profiles under wheat to which urea, urea-PPD, urea-DCD, and KNO_3

were either basally applied or top-dressed before or after irrigation. Despite a high percolation rate for the soil (78 mm day^{-1}), leaching of applied N was not found to be significant. In fact, the applied nitrate was fully recovered between the plant and the soil. In the case of urea-based sources, about 75% of the soil ^{15}N was in the top 15 cm, reflecting little or no leaching of N. In contrast, when applied before irrigation, ^{15}N derived from urea or urea-DCD moved down to the 15- to 30-cm layer. The most pronounced movement was observed for KNO_3 applied before irrigation with 47% of the soil ^{15}N found between 50 and 90 cm depth.

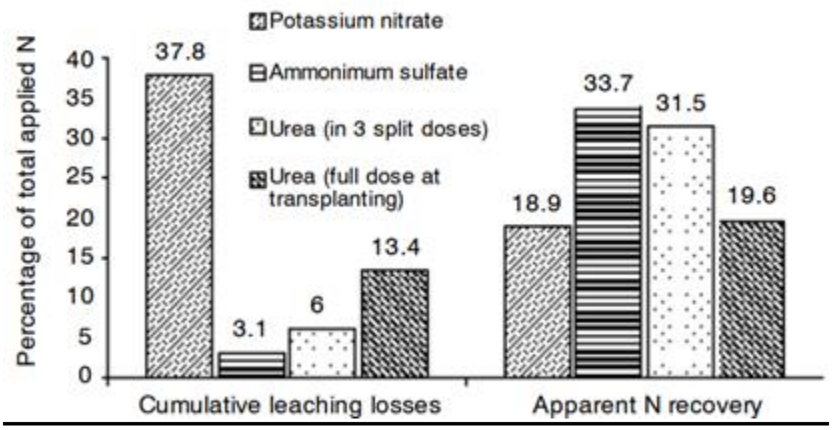

Figure 1: Cumulative leaching losses of N as urea, NH^{4+}, and NO^{3-} and apparent fertilizer N recovery by rice grown in lysimeters. In each lysimeter, a total of 848 mg N equivalent to 120 kg N ha^{-1} was applied (adapted from Bijay-Singh *et al.*, 1991)

4) Run-off

Due to the high mobility of NO_3^--N ion, it is susceptible to runoff loss, particularly in unbunded slopy land or land with an impervious layer that hinders the downward movement of water. Runoff loss of N varied from 6 to 70% of total N applied depending upon the form, rate, and method of N application and water management (Pamaja and Koshy, 1978; Panda, 1986; Nayak, 1996). In the rainfed lowland rice field with 25 cm ponding water if Prilled Urea is surface broadcasted, runoff loss of N could be as high as 78% of applied N.

Table 1: Loss of N through key loss processes following the application 120 kg N ha^{-1} to lowland rice (Pathak *et al.*, 2004)

N form and process	N loss (kg N ha^{-1})
NH_3 volatilization	15
N_2O denitrification	30
NO_3^- leaching	15
Total losses (50% of applied N)	**60**

Nitrogen fertilizer management

Amount of nitrogen

Whatever the source, the application of fertilizer N at 120 kg N ha^{-1} has been recommended in most of the rice-wheat growing regions. In the eastern parts of the Indo-Gangetic Plains, the rate of N application is relatively lower. In general, the rate of N application up to 120 kg N ha^{-1} shows a significant effect and it is also economical keeping in view the cost of the fertilizer and the value of the produce. In soils with low organic carbon, significant and economical responses of rice have been recorded up to 150 kg N ha^{-1} (Bijay-Singh, Yadvinder-Singh and Maskina, 1987) and this recommendation is widely followed by farmers. Wheat responded significantly to N application up to 120 kg N ha-1 with occasional responses observed up to 180 kg N ha-1 under intensive cropping. The optimum dose of N for wheat is in the range of 140-150 kg N ha-1 (Tandon, 1980).

Various soil characteristics such as organic carbon content, cropping intensity, length of the growing season, irrigation, and weed management practices determine response to N application. In case of wheat grown in alkali soil 25% higher dose than normal application rate is followed. The need for fertilizer use has been increasing due to the adoption and spread of this intensive rice-wheat cropping system. According to recent data, more than 150 kg N ha^{-1} is applied to rice grown after wheat in the north-western Indian states of Punjab, Haryana, and western Uttar Pradesh. The grain yields of 10 to 12 t ha^{-1} per annum are being harvested from the rice-wheat system. The response to applied N in Rice-Wheat is also influenced by soil N supply. In an experiment, it was found that Soil N-Supplying Capacities (SNSC), measured as total N accumulation from the zero-N plots, and grain yields without N additions were greater for rice than for wheat. The reason behind the higher SNSC in rice could be due to the greater mineralization of soil organic N in the warm, moist conditions in the monsoon season than in the cooler, drier wheat season. The linear relationship between grain yield and N accumulation in wheat shows that the mobilization of plant N to the grain was less affected by biotic and abiotic stresses than in rice.

Sources of nitrogen

Urea contributes a major share of fertilizer N for the rice-wheat system in the Indo-Gangetic Plains of South Asia. Calcium Ammonium Nitrate (CAN), Ammonium Chloride (AC), and Ammonium Sulphate (AS) are also used by farmers in small amounts. A review of work done on sources of N in India suggests that urea, CAN, AC, and AS are generally equally effective in wheat (Yadvinder-Singh, Meelu, and Bijay-Singh, 1990; Meelu, Yadvinder-Singh and Bijay-Singh, 1990). CAN be performed better than other sources on calcareous soils of Bihar (Gupta and Narula, 1973) and alkaline soils of Punjab (Thind, Singh and Gill, 1984) and Delhi (Prasad and Prasad, 1992). The favourable effect of CAN in wheat is due to the presence of both NO_3^- & NH_4^+ ions.

The efficiency of N sources in rice has been found to be affected by soil conditions and fertilizer management practices, especially the time and method of its application. In the majority of cases, ammonium-forming fertilizers exhibited similar efficiency in increasing the grain yield of rice. Nitrate-containing fertilizers such as CAN application in rice proved to be less efficient because nitrate is prone to be lost via denitrification and leaching under submerged soil conditions (Meelu *et al.*, 1987). Ammonium sulfate, due to its strong acidic property, has been more efficient as an N source than urea on salt-affected soils (Yadvinder-Singh, Meelu, and Bijay Singh, 1990). Nitant and Dargan (1974) have shown that as compared to CAN and urea, ammonium sulfate was abetter source of N for wheat grown in alkali soils.

Substantial efforts have been made to increase the low fertilizer N use efficiency in rice and wheat through modifications in N sources. Urea super granules (USG) and coated slow-release urea are most widely studied in this context. Urea super granules are granules each weighing 1 g and diameter of 1 cm are placed in the soil at 5-7 cm depth. This is especially suitable for rice-growing areas. Depending upon the soil and agroclimatic conditions a yield benefit of 15-20% can be obtained upon one-time application of deep-placed USG as obtained by the same amount of N applied in split doses through prilled urea. Deep-placed USG, however, did not perform better than prilled urea in coarse-textured soils with high percolation rates as are commonly found in Punjab.

Despite being various advantages of USG in fine-textured soils, it is not popular amongst farmers due to the lack of a suitable mechanical applicator. Sulfur-coated Slow-release N fertilizer has also been tested in a large number of field trials on rice in the Indo-Gangetic Plains. This material performed better over prilled urea in almost all soil types. However, due to the higher price of sulfur in South Asia (there are no S reserves in this region), the use of sulfur-coated urea is not economical. Recently, various biodegradable polymer-coated slow-release fertilizers have been introduced.

Table 2: Comparative efficiency of different sources of N in rice grown in the Indo-Gangetic Plains of India (singh, 2001)

Location	Grain yield of rice (t ha $^{-1}$)				References
	Calcium ammonium nitrate	Urea	Ammonium chloride	Ammonium sulphate	
Himachal Pradesh	3.72	3.54	3.50	3.63	Kanwar and Joshi (1964)
Punjab	6.42	7.48	7.16	-	Thind et al. (1984)
Punjab	5.10	5.31	-	-	Meelu et al. (1987)
Delhi	4.51	4.60	-	4.83	Prakasa Rao and Prasad (1980)
Haryana	4.80	5.36	-	5.51	Singh et al. (1985)

Time and method of N application

For higher N use efficiency, Fertilizer N should be applied at a time when crop needs are high which reduces N losses from the soil-plant system.

Rice

N uptake pattern of the crop decide the number and timing of split application of fertilizer. Short-duration varieties (80- 100 days) generally show a continuous N absorption pattern from transplanting to flowering whereas, in the case of medium and late-duration varieties (120-140 days), the rate of N accumulation is faster from transplanting to the maximum tillering stage after which it slows down during the vegetative lag phase and again becomes faster between panicle initiation (PI) and flowering stage. Accordingly, scheduling of N application as a basal and top dressing in splits has been worked out for short-duration and medium and late-duration varieties (Patnaik *et al.*, 1967; Samanta ray *et al.*, 1990). For hybrid rice, four equal splits of 25% N each at transplanting, Maximum Tillering, PI, and flowering stages have been recommended (Mohanty, 2005).

The texture of the soil is also an important parameter that should be considered while deciding the number of splits. In finer textured soil, it is recommended to give 50% of N as basal application followed by two splits of 25% each at maximum tillering (MT) and panicle initiation (PI) stages. However, for light texture soils splitting of N in 25:50:25 or 30:30:30 proportion is considered the best. In rainfed lowland rice, prone to waterlogging, however, application of the entire dose of 60 kg N ha^{-1} along with 30 kg P_2O_5 and 30 kg K_2O ha^{-1} in seed furrows at the time of dry sowing has been suggested (Nayak and Panda, 2002; Kabat *et al.*, 2005).

- Application of fertilizer N in three equal split doses at transplanting, tillering (21 days after transplanting [DAT]), and panicle initiation (42 DAT) is more efficient in terms of grain yield compared to its application in one or two doses irrespective of the N-source and the soil type (Meelu *et al.*, 1987).
- Application of one-third to one-half dose of N at transplanting was found to enhance overall fertilizer N use (Meelu and Bhandari, 1978). As crop needs of N during the initial days are likely to be very small, the application of N at 7 DAT proved more beneficial than the application of the first dose at transplanting.

The important principle behind the Improved and efficient fertilizer N management is that fertilization should be done when there is maximum requirement and uptake of N and is most efficiently translated into grain yield. In a field study conducted on non-traditional rice soil (Bijay Singh *et al.*, 1986), the path coefficient (it separates the direct and indirect effects of a correlation coefficient. Therefore, path analysis plays an important role in determining the degree of relationship between yield and yield components) showed that the rice grain yield response to applied N was due to higher panicle density and spikelet number. N fertilization has slightly affected the test weight (1000 grain weight) of rice. As panicle density and spikelet number are usually determined within 70 DAT of rice, so higher value of these two parameters was found to be critical for achieving maximum grain yield response to applied N.

Wheat

The efficiency of nitrogen fertilizer use for wheat can be improved by applying nitrogen at appropriate crop growth stages so that applied nitrogen is not lost from the soil-plant system. For increasing grain yield and N uptake of wheat, fertilizer N is applied in two equal split doses--half at sowing and half at crown root initiation stage (along with first irrigation).

Wheat yield differences were not significant for N-application in two or three equal split doses (Meelu *et al.*, 1987).

- Application of the first half N dose with pre-sowing irrigation resulted in significantly higher wheat yield than its application at sowing (Sidhu, Sur, and Aggrawal, 1994). It is possible that nitrogen applied during pre-seeding irrigation was transported to a lower depth in the soil and no losses due to ammonia volatilization occurred. In soils with a coarse grain composition, it is recommended to apply nitrogen in three equal splits, i.e- sowing, and along with the first and second irrigation.

- Chaudhary and Katoch (1981) observed a 14% higher grain yield of wheat when N was applied in three equal split doses rather than two. Drilling of half N at the sowing of wheat has been shown to perform better than broadcasting (Khanna and Chaudhary, 1979). Top dressing of the second dose of N after the first irrigation increased N use efficiency compared to its application before the irrigation (Verma and Srivastava, 1995).
- However, in highly percolating soils, application of N before irrigation resulted in the transportation of N to a depth, hence losses of N via ammonia volatilization were reduced. Therefore, better fertilizer N use efficiency and higher grain yields of wheat were observed (Katyal *et al.*, 1987).
- Results of several field experiments showed that 33% of total N applied as basal and the rest in two equal split doses at 21 and 42 days after sowing of wheat gave the best results in alkali soils.

Different modern approaches to N fertilizer management

1) Site Specific Nitrogen Management (SSNM)

The fundamental underlying principle of SSNM is to establish an optimum synchronization between the supply and demand of N for plant growth. Based on when and what type of decisions are made, SSNM can be grouped into two categories,

A) **Prescriptive SSNM**- Here the amount and its application time are analyzed prior to sowing based on N supplying power of the soil, expected crop N requirement for assumed yield target, and expected N utilization efficiency of fertilizer products in use.

B) **Corrective SSNM**-This strategy involves the use of diagnostic tools such as a chlorophyll meter/SPAD meter, and leaf colour chart (LCC) to assess the nitrogen status of standing crops.

The recent approach of Site-Specific Nutrient Management (SSNM) emphasizes on determining the exact amount of N required by the crop after considering climatic yield potential, yield target, and availability of N from all possible indigenous sources which generally vary from site to site.

On the basis of principles of site-specific nutrient recommendation, a web-based nutrient management tool, Rice Crop Manager (RCM) has been developed jointly by the International Rice Research Institute (IRRI) and ICAR-NRRI for rice growers of Odisha which gives region-specific NPK recommendations on the basis of cropping history.

Field experiments conducted in several parts of south Asia indicated a 30-40% increase in the N-use efficiency of irrigated rice following SSNM-based N application (Doberman *et al.*, 2002). Gill *et al.* (2009) reported that maximum N, P, and K accumulation by crop was registered in SSNM, followed by Improved State Recommendations (ISR), and it was lowest in the Farmers' Fertilization Practice (FFP). Overall fertilizer use efficiency was much higher in SSNM compared with FFP.

SSNM slightly increased the average cost of fertilizer but produced a relatively larger gross margin increase compared to FFP.

2) Chlorophyll meter-based Nitrogen Management

The nitrogen status of crops can be estimated through a chlorophyll meter since most of the plant nitrogen is found in chloroplasts hence, it is closely related to leaf chlorophyll content (Olesen *et al.*, 2004).

The principle of the chlorophyll meter-based method is that the nitrogen status of the leaf is reflected in the greenness of the leaf, which is reflected in values such as SPAD, CCI, and NDVI. Chlorophyll meters, for example, the SPAD-502 (Spectrum Technologies, Plainfield, Illinois, USA), provide a simple, quick, and non-destructive method for estimating leaf chlorophyll content. The principle of the meter is that it exposes a small portion of the leaf to abundant light and measures how much was not captured by chlorophyll in the photosynthetic process.

The SPAD reading is calculated from two transmittances: the transmittance of red light at 650 nm, which is absorbed by chlorophyll, and the transmittance of infrared light, which is 940 nm, which is not absorbed by chlorophyll. Fertilizer recommendations based on the SSNM and LCC methods are more flexible and adjusted according to the needs of the crop, resulting in yield increases of up to 0.3-0.5 t/ha and savings of up to 20-30% in fertilizer application.

The approach to using the chlorophyll meter focused on defining fixed threshold readings for rice so that farmers could easily apply them in the field. Peng et al. (1996) suggested the use of 35 as a critical chlorophyll meter reading for a recent IRRI variety, IR-72 in the dry season, when 30-kg N ha^{-1} top-dressings could be applied as SPAD readings fell below this number. This value has to be reduced to 32 during the wet season when solar radiation is relatively low. The 35 reading was based on a correspondence to 1.4-g N m^{-2} leaf area, a number that was found to be fairly stable for a high-yielding IR-72 crop during the growing season. the use of 35 as critical reading was found to result in higher Agronomic Efficiency (i.e., similar yields with less N fertilizer applied) compared to fixed split-timing schemes (Peng et al.,1996).

Wheat is also very sensitive to insufficient nitrogen and very responsive to N fertilization. The chlorophyll meter is faster and more accurate than tissue testing or other nitrogen measurement methods, thus reducing the risk of under- or over-fertilization of wheat crops. SPAD meter-based SSNM approach has been extensively demonstrated in Southwest Asia (China, India, and Bangladesh) compared to traditional local nitrogen management practices, SPAD meter-based SSNM in rice crop can increases yield, Recovery Efficiency of Nitrogen, and net return to the tune of 7, 30, and 12% respectively (Dobermann *et al.*, 2004).

Table 3: Impact of SPAD meter-based nitrogen management on rice performance and nitrogen recovery (Singh *et al.*, 2012)

Treatment	N rate (Kg/ha)	Yield (t/ha)	PFP_N
Farmers' Fertilization Practice (FFP)	120	5.6	46
SPAD based SSNM	60	5.7	62

3) Leaf Colour Chart (LCC) based N management

LCC is an economical and easy-to-use diagnostic tool that acts as a plant health indicator particularly to optimize the nitrogen supply of rice-wheat cropping systems. It recommends the time of N application by measuring the relative greenness of plant leaves which is directly correlated with its chlorophyll content. Nitrogen is a principal component of leaf chlorophyll so its measurement over various phenological stages serves as the indirect basis for nitrogen management.

Like the chlorophyll meter, the critical colour shade on the LCC needs to be determined to guide N application to rice. The critical or threshold values vary depending on the varieties and crop establishment method and it can be determined after one or two seasons of testing for local situations. The use of leaf colour shade 4 was reasonably consistent with the SPAD meter and helped in avoiding the over-application of fertilization to the rice crop, because shade 4 on the LCC represents greenness equivalent to a SPAD value between 35 and 37, it was found to be the threshold value for inbred rice varieties prevalent in the Indo-Gangetic plains in India (Bijay-Singh 2008).

Results from experiments on rice (‘PB-1’) show that grain yield and N-use efficiency under different N management practices indicated a significant improvement in yield and agronomic efficiency of N with LCC-based N application compared with fixed time N application. Application of 30 kg N ha^{-1} at LCC 4 resulted in a total N application of 90 kg N ha-1 and a grain yield statistically similar to that obtained with 120 kg N ha-1 applied in recommended splits (Bijay-Singh et al. 2002).

4) Soil Test Crop Response (STCR) approach

Soil test crop response includes the concept of targeted yield to find out fertilizer nutrient requirements to obtain a particular yield. Here the fertilizer dose is recommended for a particular crop under a particular agro-climatic zone by using mathematical equations considering the inherent soil fertility and the quantity of yield to be obtained.

Soil test values should be correlated with actual plant responses obtained in the field. A separate calibration chart is required for each crop and soil. The soil's inherent fertility and crop yield level are taken into account when recommending fertilizer doses.

Long-term fertilizer experiments provide the best possible means to study changes in soil properties, dynamics of nutrient processes, and future strategies for maintaining soil health (Swarup, 2010). Rajput *et al.* (2016) revealed that balanced fertilization based on soil tests recorded a higheryield of rice over the generally recommended dose of fertilizers. Similarly, treatment with FYM plus recommended amounts of STCR-based fertilizer also significantly improved microbial activity in terms of soil organic carbon, available NPK and fluorescein diacetate hydrolase (FDA), dehydrogenase (DHA) and phosphatase activity. Khosa et al. (2012) also reported the superiority of the target yield concept over other practices for different crops as it gave higher yields and optimal economic returns. The specific yield equation based on soil health besides ensuring sustainable crop production also steers the farmers towards economic use of costly fertilizer inputs depending on their financial status and the prevailing market price of the crop under consideration (Bera *et al.*, 2006).

5) Nutrient expert & Simulation models-based N management

Nutrient Expert is an easy-to-use, interactive, and computer-based decision support tool that can rapidly provide nutrient recommendations for an individual farmer's field in the presence or absence of soil testing data. It uses various Machine Learning algorithms to respond to a query based on some pre-fitted database.

It is an emerging N management diagnostic tool wherein the input variables such as fertilizers are applied in the right amount, at the right place, and at right time (variable rate application) as per the demand of the crop plants (Pampolino et al.,2012). It helps to improve the input use efficiency, and economy of fertilizer use and ensures sustainable use of natural resources.

Simulation models or Decision Support Systems (DSS) are sophisticated tools that mimic the actual environment and show the results that could be obtained under actual conditions. The soil N balance processes in the DSS's include root N uptake, mineralization, immobilization, nitrification, denitrification, and N leaching.

The CROPGRO-legume model is a process-oriented, mechanistic model that simulates crop development, carbon (C) balance, crop and soil N balance, and soil water balance. It can simulate N fixation in legumes and its relationship with N uptake by plants (Boote et al. 2009). Most of these decision-support programs supply information not only about the fertilizer need or value, but also consider different ways of N losses (leaching, denitrification, and Ammonia volatilization).

6) Application of GIS and Remote Sensing technology for N management

The GIS and RS-based techniques have great potential for site-specific recommendations of nutrients thereby reducing fertilizer use and environmental risks. To overcome tedious soil and tissue testing required for regional scale quantitative recommendations ground-based remote sensors, and digital, aerial, and satellite imageries can be used.

In order to obtain accurate nitrogen recommendations in a rice-growing area, a fuzzy clustering approach should be used to classify the whole area into different subsets based on homogeneous soil and plant characteristics to create homogeneous management areas in order to obtain accurate nitrogen recommendations.

Recently, various remote sensing devices used in agriculture have been limited to developing vegetation indices based on red and near-infrared reflectance. One widely used and accepted vegetation index is the Normalized Difference Vegetation Index (NDVI).

The N requirement of crops can be estimated by calculating early season N uptake and potential yield by measuring the reflectance in the red (defined by chlorophyll content) and near-infrared (defined by living vegetation) region of the electromagnetic spectrum. Normalized Difference Vegetation Index (NDVI) based on the in-season sensor reading can predict biomass, plant N concentration, and plant N uptake (Gupta 2006). The higher the NDVI value higher will be the leaf greenness and green leaf area, and this can be used as a guide for in-season N applications.

The major reasons for variations in crop yield are Spatial and temporal variability in the nutrient supply, which can be managed by dividing a heterogeneous field into more or less uniform management zones. The creation of Management zones requires information about the crop yield, soil data, or crop conditions by adopting remote sensing techniques. The data obtained are superimposed on a base map to create management zones using GIS. These management zone maps serve as a basis for site-specific input management rather than applying a uniform dose of fertilizer N over the entire field.

The use of a green seeker, which is also a hand-held instrument for measuring the NDVI at various critical growth stages, generates data for crop conditions (Gupta 2006; Singh et al. 2006). Then the N requirement is calculated by comparing these NDVI data from a standard plot, which has been sufficiently fertilized with N, with a reference plot for which the N requirement is to be determined.

7) Controlled/Slow-Release Fertilizers (CRF/SRFs)

An important route for improving NUE is the use of mineral fertilizers, particularly N fertilizers, which release nutrients according to the plants' requirements, so-called 'intelligent fertilizers', i.e. by the application of slow and controlled release, or by 'stabilized' N fertilizers, which preserve the nutrients until plants really require them (Trenkel 2007). Slow-release fertilizers can be used to save fertilizer consumption and minimize environmental pollution.

The basic difference between Slow release and controlled release is that in the former one, some coating/barrier is provided, which restricts the nutrient release at one time e.g. sulfur-coated urea, polymer-coated urea, gypsum/rock phosphate coated urea, lac-coated urea, neem (*Azadirachta indica*) slurry-coated urea (NCU) and in the controlled release the nutrient is inherently less soluble e.g. Isobutylidene di-urea (IBDU), urea form, urea Z.

Controlled or slow-release nitrogenous fertilizers (SRNFs) having a coating of hydrophobic organic polymers are supposed to provide the best control over the nutrient release from applied fertilizers. Thind *et al.* (2010) also noted that NCU gave 9.4, 5.6, and 2.5% higher grain yield over urea with an application of 48, 96, and 120 kg N ha-1, respectively, at Ludhiana, India.

8) Integrated management of organic and inorganic sources in rice-wheat

Integrated Nitrogen Management (INM) refers to the combined use of fertilizer N and organic N, which includes N fixed by legumes and other organisms (Azotobacter, Azospirillum, blue–green algae, Azolla, etc.) and N supplied by organic manures such as farmyard manure, compost, vermicompost, crop residues, and animal refuse. INM in the rice-wheat production system is a sustainable way towards attaining food security and soil health improvement. In a holistic approach, the INM practices improve the quality and quantity of crop produce, decrease nutrient losses, increase N use efficiency, economizes on fertilizer use, and minimize energy consumption in agriculture.

In long-term fertilizer experiments conducted at several locations in India, combined application of NPK fertilizers at optimum level and farmyard manure @ 5- 10 t/ha/year increased rice grain yield by 0.4-0.7 t/ha over NPK fertilizers. It also resulted in favourable balance of nutrients in the soil and sustained rice yield at higher levels. Continuous rice-wheat cropping system had variable effects on soil fertility depending on soil types, nutrient application, and productivity levels.

- The improvement in mean grain yield of wheat (4.0 t ha^{-1}) and straw (6.3 t ha^{-1}) was recorded due to the use of organic manure (FYM+Sesbania) to proceeding rice as compared to the control (Singh *et al.,* 2001).
- Integrated use of 75% NPK and FYM @ 5 t ha^{-1} or poultry manure @ 1.5 mg ha^{-1} or phosphor-compost @5 mg ha^{-1} to rainy season crops and 75% NPK to wheat significantly improved the yield of wheat over application of 100% NPK in both the season (Bandyopadhyay *et al.,* 2009).
- Singh *et al.* (2001) indicated that FYM can substitute a part fertilizer N needs of monsoon crops without any adverse effect on the total productivity of cereal-based cropping system. It was also noted that by replacing 25% of the nutrient demand of ongoing monsoon crops through FYM, winter wheat fertilizer requirements could be reduced by 25%.

The integrated use of fertilizers gives several positive effects, which can be seen in the increase in the yield of grain and straw, the growth of plants and the accumulation of wheat biomass, and the increase in biological parameters, i.e. Soil microbial biomass carbon (SMBC), soil microbial biomass nitrogen (SMBN) and dehydrogenase activity (DHA). The bio-fertilizer application significantly improved grain yield and straw yield of wheat over uninoculated plots and enhanced the concentration of micronutrients like Fe, Zn, Cu, and Mn (Malik *et al.,* 2009). An increase in nitrogen content has also been seen due to inoculation with Azotobacter.

Conclusion:

Low NUE is one of several major factors contributing to huge yield variances in most crops. In addition to economic loss due to low NUE and wastage, N leakages into the environment are the major causes of concern. More precise and versatile nitrogen management strategies are required to maintain and improve nitrogen use efficiency. Improved N management agenda include decisions on optimum level, time, form, and method of N application. Nitrogen management using SSNM, SPAD meter, and LCC resulting in higher grain yields and higher NUE than blanket nitrogen recommendations. Efficient nitrogen management plays a key role in improving long-term sustainability in modern crop production systems. Integrated nitrogen management and balanced fertilizer not only improve plant performance, but also improve NUE in the production system.

Three critical growth stages tillering, panicle initiation, and flowering of rice, and maximum tillering, booting, and flowering stage of wheat should be targeted for making N management decisions to obtain economically optimum grain yields. The use of organic and green manures along with fertilizers has been shown to be effective in improving and maintaining soil fertility, increasing nutrient use efficiency and maximizing productivity in a variety of cropping systems. Therefore, an integrated approach of management based on the most important natural resources is of great importance, ensuring efficient use of farm-generated organic manure in combination with mineral fertilizers to ensure sustainable crop production.

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TECHNIQUES FOR IMPROVING NUTRIENT USE EFFICIENCY (NUE)

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Abstract:

The idea of nutrient usage efficiency (NUE) is crucial to agricultural production systems. In order to receive the best results, fertilizers must respond to application and be used effectively. Many factors, including surface runoff, leaching, volatilization, denitrification and the fixation of micronutrients in the soil, contribute to the low nutrient usage efficiency. The lowest portions of the yield response curve are always where the maximum nutrient usage efficiency is found, however efficacy of fertilizers in boosting crop yields and maximising farmer profitability should not be compromised for efficiency's sake. Fertilizer best management methods should be utilised to apply nutrients at the proper rate, timing and location, together with the appropriate agronomic procedures, in order to maximise nutrient usage efficiency. A technique has been created to clarify the idea of nutrient use efficiency and the treatments that may be utilised to improve nutrient use efficiency.

Introduction:

One of the main forces behind the increased worldwide agricultural production needed to feed the expanding human population is the usage of mineral fertilizers. The world's use of fertilizers is rather uneven: Environmental pollution results from over-fertilization in North America, Western Europe, China, and India, while soil mining results from under-fertilization in Africa, Eurasia, and some parts of Latin America (National Geographic 2013). According to estimates, the 11.8 Mt of excess nitrogen fertilizer used in China could possibly treble crop yields on the 174 million acres of agriculture in sub-Saharan Africa (Ju *et al.*, 2009; Twomlow *et al.*, 2011).

Moreover, the ratio of nutrients is frequently out of balance. According to Peuelas *et al.* (2012) and (2013), Africa's N and P consumption is predicted to be 2.8 Mt and 96 Kt, respectively, representing increases of 150 and 16% between 1975 and 2005. Contrast this with industrialised nations where soil P capital has grown over time to balance out any undersupply or where both N and P supplies are balanced (van der Velde *et al.*, 2014; Withers *et al.*, 2014). In Africa, utilisation of secondary and micronutrients in agricultural cultivation is essentially nonexistent (Vanlauwe *et al.*, 2014).

According to Stoorvogel *et al.* (1993) and Bindraban *et al.* (2012), decades of applying solely NPK may have caused micronutrient shortage and soil degradation. Applying secondary and micronutrients might enhance yields by 20–70% depending on the crop (Zingore *et al.*, 2008; Voortman and Bindraban 2015).

N is a crucial nutrient for agricultural production as well as for the safety and security of the world's food supply, and nitrogen is crucial for meeting global food demand. The price of nitrogenous fertilizers is very high (Cassman *et al.,* 2002). The fundamental goal of marginal farmers is to maximise agricultural production from the smallest amount of land possible while utilising good nutrient efficiency, particularly nitrogen fertilizer. The efficiency of crop management and environmental conditions directly affect nitrogen fertilizer recovery. For the small-scale farmers, it is incredibly expensive. Due to possible nitrogen fertilizer losses from leaching, evapo-transpiration, ammonification and crop, fertilizers are applied in double the recommended amount to meet the need for nitrogen.

The efficiency of crop management and environmental conditions directly affect nitrogen fertilizer recovery. For the small-scale farmers, it is incredibly expensive. Due to possible nitrogen fertilizer losses via leaching, evapo-transpiration, ammonification and crop, twice as much fertilizer must be administered to meet the crop's nutrient needs. Enhancing and maintaining soil fertility will be made possible by the idea of nutrient usage efficiency. The majority of farmers use urea in excessive amounts. Inorganic or synthetic fertilizer known as urea helps increase crop and cereal output by providing immediate results. For better nitrogen utilisation efficiency, microorganisms (such as plant growth encouraging ones) are responsible for fixing nitrogen from the free environment in the soil. the use of fertilizers especially nitrogen is most important.

We must use the precise application technique, the correct fertilizer dosage, and the fertilizer is always applied at the appropriate time to increase the effectiveness of fertilizers. Recently, slow-release fertilizers such as prilled urea, sulphur-coated urea, polymer-coated urea, and neem-coated urea have been utilised to improve the efficiency of nitrogen utilisation. There are two types of fertilizers present in the soil: total nitrogen and accessible nitrogen. These modified fertilizers are producing the best results for increasing soil fertility by gradually releasing the nutrients in the soil. Although plants don't use total nitrogen directly, they do use accessible nitrogen fertilizer more frequently. The available nitrogen fertilizers increase the effectiveness of using nitrogen.

The first nutrient limitation that is having an impact on both the overall food supply and the protein content of meals is the lack of nitrogen. Raun and Johnson, (1999) and Godfrey *et al*. (2010). The development of photosynthetic activity and photosynthetic capacity are basic physiological processes that are impacted by the uptake and translocation of nitrogen. Formation and maintenance of sink and source capacity, which are connected to biomass production and grain output of cereal crops (Bange *et al.,* 1997; Dreccer *et al.,* 2000); (Kaizzi *et al.,* 2012). It has been determined that nitrogen fertilizer has four main roles in the biomass production of crops and cereal grains.

However due to the increasing use of nitrogen fertilizer for the particular crop, fertilizer use today is completely out of balance. These negative effects have been seen not only in India but also in China, the United States, and other countries in Europe. Due to overfertilization, it results in effects such as water pollution, soil pollution, erosion, environmental pollution and occasionally under-utilization in some regions of Africa and a few regions of Latin America, where soil mining is taking place and causing fertile soil losses (Austin *et al.,* 2013). Whereas maize cropping exhibited a negative balance, wheat cropping is neutral (Alvarez and Grigera, 2005).

Use of balancing fertilizers in Switzerland and the United States (Spiess, 2011) is the ideal example of improving the efficiency of nitrogen usage by maize cropping. With correct nitrogen utilisation and efficiency, the impact of unbalanced fertilizers must be lessened while also providing enough food to insure a larger population due to increased food security. Because nitrogen helps crops develop vegetatively. These fundamental objectives are upheld by modern technology and attached current knowledge data to curb negative environmental effects and ensure optimal nitrogen fertilizer use.

Techniques for improving Fertilizer Use Efficiency (FUE)

Model of generator for fertilizer

Every fertilizer nowadays is essential to the agricultural sector, but sometimes fertilizers that are imbalanced have a negative impact on the soil. The mixture of two separate nitrogen fertilizers makes ammonium nitrate (NH_4NO_3), according to the agronomy department, an outstanding fertilizer. It was previously stated that the usage of this fertilizer improved the quality of wheat's baking fermentation. However, due to its low nitrogen concentration when compared to other generators, nitrogen-related costs for transportation, storage, and application are higher.

The ammonium sulphate ($(NH_4)_2SO_4$) is the ideal fertilizer for soils with high pH levels because it supplies the crop with both nitrogen and sulphur. However, it has the drawback of having a very low nitrogen content (21%) compared to other sources. On the other hand, ammonium sulphate fertilizer is widely used throughout the world, especially in areas where rice is grown. Both urea and diammonium phosphate are significant sources of both nitrogen and phosphorus. For sensitive crops (like cereal crops), ammonium chloride fertilizer offers two separate fertilizers-nitrogen and chloride (Cl^-) as a dual-purpose fertilizer, however "N" content is quite low in ammonium chloride, which is mostly utilised in Japan, China, India, and Southeast rice crops.

Few crops can endure an acidic environment, and ammonium chloride and sulphate fertilizer will increase the amount of acid in the soil (Kaag and Krishnamurthy, 2010). Urea ($CO(NH_2)_2$) is a highly significant fertilizer that is applied globally to apply nitrogen or carbon. Fertilizer is now more dependable than ever for handling, storing, transporting, importing, and exporting. The downside of urea is that it has very phototoxic effects on sensitive crops and is easily volatile (Ni *et al.*, 2015). (Citrus, pine apple, apple and mango). At the emerging stage, free NH_3 released harmful effects from hydrolysis. It also has an impact on seed germination (Patten and Glick, 2002).

Controlled and maintained release fertilizers' nitrogen

Fertilizers with controlled and gradual release, such as prilled urea, polymer urea and sulfur-coated urea. These are extremely valuable and effective fertilizers for farms. That fertilizers' primary function is to gradually distribute fertilizer, particularly nitrogen, to the crops. Due to coated fertilizer, the losses of fertilizer are also readily reduced in this manner. Farmers that apply coated fertilizer to the soil will see a slower rate of volatilization and a greater yield of nutrients or fertilizer. It is also beneficial to lessen the impacts of fertilizer leaching. Rimski-Korsakov *et al.* (2012). This is where applied nitrogen fertilizer recovery comes from as well (Shaviv, 2001).

These fertilizers work by increasing nitrogen and accessible nitrogen, which is needed by crops to complete their life cycles, by dispersing soluble nitrogen in the form of NH_4 or NO_3 in the soil for many weeks or months. Fertilizers with slow releases of nitrogen release nutrients by chemical and biological processes, such as aldehydes (Chien *et al.*, 2009 and Du *et al.*, 2008). Moreover, urea triazone is employed as a longer-lasting slow-release nitrogen fertilizer. If given in safe or necessary proportions, a foliar application that is well absorbed by plants without being poisonous can be used. Otherwise, the toxicity of urea fertilizer would burn the leaves and too much nitrogen fertilizer will harm the plant.

Nitrification inhibitors

Because of their level of success, urease inhibitors have only been utilised commercially in a few nations (Upadhyay, 2012). Neem- and polymer-coated urea were utilised by Ambus and Jensen (2001) and as a result, potato tube yields increased and nitrogen utilisation efficiency rose from 17.8% to 58%. According to Delgado *et al.* (1996), urea dicyandiamide (DCD) greatly reduces the rate of N_2O emissions and nitrogen loss to the environment.

Microorganism inoculation to enhance nitrogen

These days, a great deal of microorganisms are used to create rich soil for the agricultural sector and their effectiveness will only rise as time goes on. Microorganisms will have a very favourable impact on future events. Microorganisms are also utilised in the integration (combined operation) to lower the amount of fertilizer input in the soil. The nodules found in the roots of pulse and green manure crops are utilised to fix nitrogen that is present in the free atmosphere but that plants cannot directly absorb or ingest. Hence, the microorganisms perform a crucial role in fixing the unavailable nitrogen into a usable form (Bindraban *et al.*, 2015).

Rhizobium: Rhizobium species are now exploited as microorganisms by leguminous plants, particularly soybean and dhaincha, to increase crop yield, economic yield, and biological yield. They fix the free atmosphere nitrogen concentration in soil Collino *et al*. (2015). The availability of nitrogen in the soil and the inoculant bacteria, which are also present in the soil but at larger concentrations and have a better capacity to accomplish their task than the native population, are always important factors in a successful response. The best mix of nitrogen and phosphorous between rhizobium species caused the nitrogen absorption to occasionally rise (Harris *et al.*, 1985 and Fan *et al.*, 2007).

Azospirilluim: Immunization increases the yield rate in a few different grain crops (Pereg *et al.*, 2016). because the soil's free nitrogen was adequately fixed, and because the roots actively used or absorbed more water and soluble minerals to develop. The yield is increased with a low input method or source with the assistance of azospirillum in integrated nutrient managements. (El-Sirafy *et al.*, 2006)

Bacillus spp.: Bacillus spp. were utilised in the wheat crop, and it was seen that the yield improved consistently with the correct effectiveness of fertilizer applied at their recommended levels (Barneix *et al.,* 2005).

Cultural practices:

The government spends a significant portion of its budget just on the manufacturing of fertilizers in order to fulfil its objectives and meet the nation's food needs. Hence, agronomic treatments are essential in this situation to lower the need for fertilizers and increase food production from a given area of land while also assisting in the improvement of the nutrient use efficiency index (Coque *et al.,* 2008).

Cultivation operations: Soil cultivation is a vital activity for losing the top soil for building a healthy seed bed by deep ploughing and superficial harrowing for forming the soil appropriately and keeping soil fertility levels. Yet, after properly mixing the soil during the cultivation operation, the nutrient usage efficiency and fertility index are in harmony. In order to create a suitable seed bed by deep ploughing and shallow harrowing, soil cultivation is one of the most crucial operations. This ensures that the soil is properly created and that the fertility level of the soil is maintained. Nonetheless, the nutrient utilisation efficiency is well maintained and the fertility index is in equilibrium after proper soil mixing during the cultivation operation (Bouwman *et al.,* 2002).

Cover crop: A cover crop is a crop that is primarily cultivated to control weeds, pests, insects, diseases, soil erosion, soil fertility and soil quality. Biological, environmental, social, cultural and economic aspects of the food system in which they function influence the factors' decisions about which cover crop kinds to produce and manage (Fan *et al.,* 2007). With the aid of cover crops, soil particles are held in place while moisture loss and weed growth are reduced.

Deep and shallow root system: Both deep and superficial root systems are important for maintaining the soil's fertility and production for "NUE." For proper nutrient consumption, the roots must be sown at different depths depending on the season. For example, in the kharif season, plant shallow-rooted crops, and in the *rabi* season, sow deep-rooted crops. Most nutrients are found in the top layer of soil, where crop roots may easily access them. Nevertheless, due to leaching and ploughing, nutrients are also found deeper in the soil. Deep-rooted plants are highly beneficial for proper nutrient absorption and for quickly raising the "NUE" score.

Crop rotation: The productivity and organic matter content of the irrigated semi-arid subtropical soil of south Asia have been negatively impacted by the continued rotation of cereal-based crops such as rice, wheat, intensive cultivation and complete removal of post-harvest crop residue (CR) for animal consumption and fuel or its burning. Developing efficient tillage and CR management techniques could promote ecologically friendly and sustainable agriculture systems. The fertility of the soil was boosted by introducing legume crops to the cropping scheme or by rotating crops from various families.

Methods of applying fertilizer:

The most common approach to apply fertilizer is via broad casting, fertilising, foliar application, drip irrigation, sprinkling, dusting, etc., but the most important method is how to apply? When do I apply? How much should I use? Right rate, right time, right source and right place are the four R Approaches.

Right rate: Since most crops are location- and season-specific, depending on cultivar management techniques, climate, etc., it is essential to set realistic yield goals and apply nutrients to achieve the target yield. Failure to do so will reduce nutrient use efficiency or worsen crop quality and yield. One of the most effective methods for assessing the soil's ability to give nutrients is still soil testing (Balasubramanian *et al.*, 2004).

Right time: A closer match between crop demand and nutrient supply is required to increase the effectiveness of nutrient utilisation, particularly for 'N.' (Aulakh and Malhi, 2004) Splitting up N applications during the growing season instead of making one large application before planting is known to increase N use efficiency (Cassman *et al.*, 2002). Leaf colour charts have been extremely helpful in guiding split N application in Asia's rice and now maize production, and chlorophyll metres have been useful in managing season N. (Havlin, 2004).

Right sources: Choosing the correct sources guarantees that the fertilizer used corresponds to the requirements of the crop by applying nutrients that are available to plants or in a form that transforms into a plant-available form while in the soil. The correct source of nutrients can help balance the amount of necessary nutrients for plants, giving them the nutrient they need in the optimal form possible for absorption.

While choosing the best fertilizer supply for a particular area, the physical and chemical characteristics of the soil are also taken into account. Using the correct source principle, for instance, would prevent the application of nitrates to flooded soils and the surface application of urea to soils with high pH levels. The synergistic interactions between various nutritional components and sources, such as the interaction between zinc and phosphorus and the increased availability of phosphorus from nitrogen, must also be understood.

Right place: The manner fertilizer is applied has always been important for ensuring that nutrients are utilised effectively. Almost as crucial as figuring out the precise application rate is choosing the appropriate spot. There are various fertilizer placement techniques, both surface and subsurface deployments are crucial (Arshdeep *et al.*, 2018). Fertilizers can be broadcast, or evenly spread across the soil's surface, or they can be applied as a band, typically 5 to 20 cm deep. The crop and soil conditions, which affect nutrient uptake and availability, play a role in placement decisions. One of the most popular methods for enhancing fertilizer effectiveness is the appropriate and balanced application of fertilizer.

Fertigation:

The plants and crops benefit more when fertilizer, particularly urea for nitrogen, is mixed with water. The fertilisation will use as much fertilizer as possible. the direct application of fertilizer in liquid form at close proximity to the root zone. Plants' roots absorb more liquid through their hairs than through their roots. Nitrogen fertilizer losses and excessive usage will both be decreased and properly utilised. The absence of nitrogen fertilizer from the field also lowered crop weed competition (Arshdeep *et al.*, 2018). Compared to other approaches, fertigation will boost the efficiency of nutrients.

Chlorophyll meter:

The majority of the nitrogen (N) in plants is contained in their chloroplasts, so using a chlorophyll metre to measure the amount of chlorophyll in the leaves can assist determine the crop's overall N content. It has the capacity to self-calibrate for various soil types, climatic conditions, and crop types. It is also advised to evaluate whether late nitrogen application to standing crops may boost grain production and protein content (Chardon *et al.,* 2010).

Leaf colour chart:

Simple leaf colour chart (LCC) is a straightforward instrument that serves as a stand-in for leaf N and is used to determine leaf colour (Abalos *et al.*, 2014) LCC is a diagnostic tool that can assist farmers in making suitable decisions on the requirement for nitrogen fertilizer treatments in standing crops. It measures leaf colour intensity, leaf N status, and the ideal time for N application. Conceptually, it is based on the relative greenness of plant leaves, which is directly related to the amount of chlorophyll in those leaves. As nitrogen is a key component of leaf chlorophyll, phonological stage measurements provide an indirect basis for nitrogen control in rice.

Green manuring:

Legumes are preferable than non-legumes in crops used as green manures because they can fix atmospheric nitrogen in the soil. Legumes grown for green manuring must have a few qualities, including quick growth, short duration, higher biomass production, atmospheric nitrogen fixation, and most crucially, the least number of cultural practises. The range of annual nitrogen storage by legumes is 20 to 300 kg/hectare (Vitousek *et al.*, 2009).

Residue incorporation:

Crop residues are the leftovers from harvesting crops that remain on the field (Brauer and Shelp 2010). Agricultural residue is important for the growth and development of plants because it affects the amount of nutrients that are accessible to crops. The main source and sink for the carbon and nitrogen cycles are plant leftovers (Burgess *et al.*, 2002). Crop leftovers provide nitrogen to plants for a longer period of time by first converting it to an inorganic form and then mineralizing it later on in the crop cycle when the crop has a significant need for N.

Precision farming:

To identify, analyse, and manage spatial and temporal variability associated with all aspects of agricultural productions with in fields for maximum profitability, sustainability, improving crop performance, safeguarding land resources, and maintaining or improving the environment quality, precision farming is an information and technology-based farm input management system (Abrol *et al.*, 2007).

Conclusion:

The fertilizer business, as well as agriculture in general, faces the fundamental challenge of improving nutrient efficiency. Modern crop production systems require nutrient management to increase long-term sustainability. Farmers, society, and the environment will gain from the careful application of fertilizer at the proper rate, time, location, and agronomic practise aiming at both high yields and nutrient efficiency. In comparison to a general N suggestion, N management employing SSNM, a chlorophyll metre, and an LCC results in higher grain yield and NUE. The NUE of the production system is improved by integrated nutrient management and balanced fertilisation in addition to plant performance. Using more advanced scientific interventions along with locally accessible technologies improves NUE. NUE could also be increased by choosing the best timing, rate, application technique, and fertilizer formulation, including the use of nitrification and urease inhibitors. To increase the effectiveness of applied nutrients, there are opportunities and resources available. We must take care, though, to ensure that efficiency gains do not come at the expense of the environment or the financial survival of farmers.

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IMPACTS OF INORGANIC FERTILIZER USE ON ENVIRONMENT AND MITIGATION STRATEGIES

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Introduction:

To meet the growing demand for food due to an increasing population and dwindling resources, there is a pressing need to increase agricultural production. The challenge of agriculture today is to increase crop production while avoiding any adverse impact on the environment, with the continuously growing global human population[1]. One way farmers trying to achieve increased crop production is by using fertilizers, whether natural or synthetic, to enrich the soil with vital nutrients for plant growth and to enhance crop yields[2,3]. A report from the early 1970s showed that only 27 kilograms of NPK fertilizer per hectare were needed to produce one ton of grain, while in 2008, this amount increased to 109 kilograms per hectare. According to the International Fertilizer Industry Association (IFIA), there has been a significant increase in the demand for fertilizer, with a projected consumption of 192.8 million tons in 2016-2017[4]. Plants need an adequate and balanced supply of nutrients to grow optimally. Although soil contains natural reserves of these nutrients, most of them are not immediately accessible to plants, with only a small portion being made available each year through biological activity or chemical processes. This rate is not sufficient to replace the nutrients lost through agriculture and meet the demands of crops. So, fertilizers are used to supplement the soil's nutrient supply[5]. The use of fertilizers has become a crucial aspect of increasing crop yield and improving product quality in agriculture. Fertilizers, either inorganic or organic in nature, serve as a source of essential nutrients for plant growth and development [6]. Non-organic fertilizers, typically containing nitrates, ammonium, potassium and phosphate salts, are effective in this regard, although having negative environmental impacts. The fertilizer industry has been identified as a source of natural radionuclides and heavy metals, such as mercury, cadmium, lead, and uranium, which can accumulate in the soil, water, air and even the food chain. With the exponential increase in fertilizer consumption worldwide, it has become a growing concern for environmental pollution[7]. Overdosing of chemical fertilizers in runoff can lead to eutrophication in aquatic ecosystems, causing an overgrowth of algae due to the enrichment of nutrients in the water, which blocks the supply of oxygen to aquatic life. However, the efficiency of using mineral fertilizers or applied chemicals is typically below 30%[8].

As inorganic fertilizers are expensive and can have negative environmental impacts if not properly managed, leading to soil degradation and nutrient imbalances that reduce crop yields.

Soil fertility is primarily based on organic matter, and microbial fertilizers are environmentally friendly which can play a significant role in plant nutrition. Also, organic fertilizers are cost-effective and readily available from local sources, making them a popular choice over chemical fertilizers. Farmers often use a combination of organic and inorganic fertilizers based on climate, locality, natural conditions, and soil variations. Leafy vegetables, fruits, and cereal crops are efficient sources of basic nutrients, secondary nutrients, and micronutrients [9]. Thus, to reduce the adverse effects of synthetic fertilizers on human health and the environment, organic, sustainable, or ecological agriculture has become a popular practice[10].

Fertilizer fundamentals

The use of fertilizers dates back to ancient times, when farmers used animal waste and compost to improve soil fertility. The modern history of fertilizers began in the mid-19th century and the use of inorganic fertilizers in agriculture can be traced back to the early 20th century. In the early 1900s, German chemist Fritz Haber discovered the process of converting atmospheric nitrogen into ammonia, which could be used as a fertilizer. The production of synthetic fertilizers increased significantly after World War II, as the demand for food rose and the global population grew[11]. Fertilizers play an important role in supplying plants with the necessary minerals and elements for growth and productivity in agriculture. The use of these agricultural fertilizers improves the nutrient content of the soil, leading to an increase in crop yield. The fertilizer acts as a source of nourishment for plants, providing them with the essential nutrients they require, while the soil acts as a conduit between the crops and the fertilizers[1]. Therefore, a material that comprises of at least 5% of one or more of the primary nutrients nitrogen (N), phosphorous (P), or potassium (K) can be referred to as a fertilizer, regardless of whether it is of natural or synthetic origin. Plants require over 70 elements for growth, development, and formation of tissue. The three most crucial elements, accounting for 90 percent of the dry mass, are carbon(C), oxygen(O), and hydrogen(H). Nitrogen(N), phosphorus(P), potassium(K), magnesium (Mg), sulfur (S), sodium (Na), and calcium (Ca), collectively known as macro-elements, make up 8-9 percent of the plant's total mass. The remaining 1-2 percent is comprised of microelements such as iron (Fe), copper (Cu), manganese (Mg), zinc (Zn), molybdenum (Mo), and cobalt (Co), which plants only require in trace amounts (0.001-0.0001**%)** **[12].** Different type of nutrients present in fertilizers are given in table 1.

Table 1: Classification of Nutrients

Nutrients supplied by water and air	Nutrients supplied by the soil			
Nonmineral	Primary macronutrient	Secondary macronutrient	Micronutrients	
Carbon (C)	Nitrogen (N)	Calcium (Ca)	Zinc (Zn)	Cobalt (Co)
Hydrogen (H)	Phosphorous(P)	Magnesium (Mg)	Chlorine (Cl)	Nickel (Ni)
Oxygen (O)	Potassium(K)	Sulfur (S)	Boron (B)	Iron (Fe)
			Molybdenum (Mo)	Manganese (Mg)

Classification of fertilizers

Fertilizers play a crucial role in modern agriculture by providing essential nutrients to crops and boosting their productivity. The use of fertilizers has allowed farmers to increase their yields and meet the growing demand for food. There various types of fertilizers that can be classified based on their origin, state and composition as shown in figure 1. Organic and inorganic (also known as synthetic) fertilizers are one of the most common categories. Fertilizers can also be classified as liquid or solid, and as complex or straight, depending on their composition. Each type of fertilizer has its own unique properties, advantages and limitations in terms of promoting plant growth and soil fertility. Additionally, fertilizers can also be classified as slow-release or fast-release, depending on how quickly they release their nutrients to plants. Slow-release fertilizers deliver nutrients gradually over time, while fast-release fertilizers provide nutrients quickly and are typically used to address acute nutrient deficiencies in plants. Understanding the different types of fertilizers available can help farmers and gardeners choose the most appropriate and effective product for their crops[6,13].

1. Based on Origin, fertilizers can be classified as Organic and Inorganic fertilizers:

Inorganic fertilizer	➢ Inorganic fertilizers are made from chemical substances and are often referred to as artificial or synthetic fertilizers. ➢ Unlike organic fertilizers, these are not biodegradable and are produced in factories using advanced technology. They are typically more durable and effective than organic fertilizers and are classified into different categories based on their composition and preparation methods. ➢ Examples of these fertilizers include granular triple superphosphate, potassium chloride, urea, and anhydrous ammonia.
Organic fertilizers	➢ Organic fertilizers are made from naturally occurring, biodegradable substances that help improve soil fertility. Anything that is found in nature and decomposes easily can be considered organic, and if it provides nutrients to the soil, it is classified as an organic fertilizer. ➢ It is widely accepted that using organic fertilization techniques is more environmentally friendly and provides slow but stable results. ➢ Examples of naturally occurring organic fertilizers include manure, slurry, worm castings, peat, seaweed, and guano. Meanwhile, manufactured organic fertilizers include green manure and compost, blood meal, bone meal, and seaweed extracts.

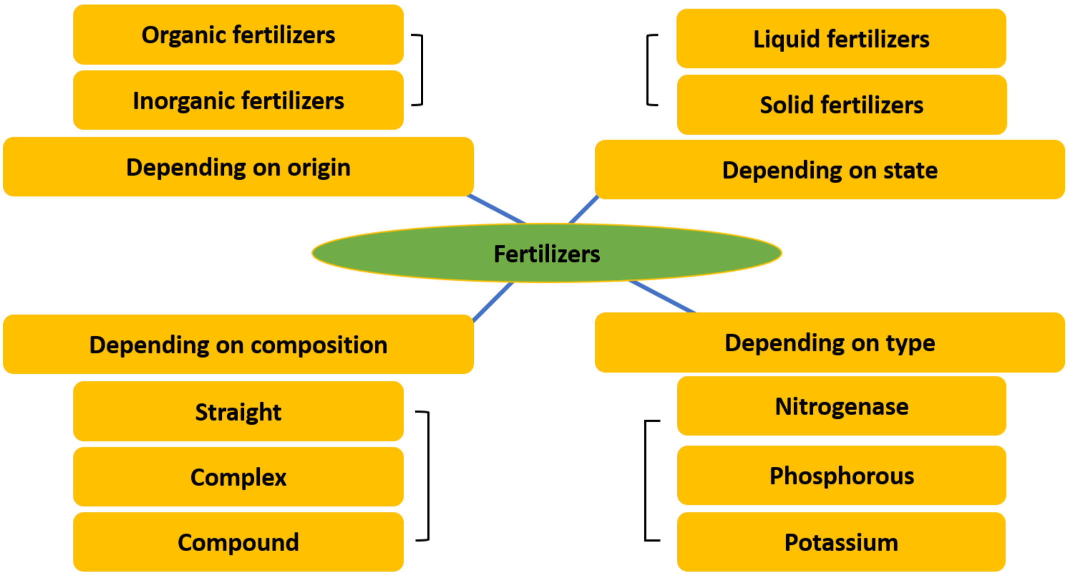

Figure 1: Classification of fertilizers

2. Based on composition, fertilizers can be classified as:

Straight fertilizers	➢ These fertilizers contain only one primary nutrient, such as nitrogen, phosphorus, or potassium. ➢ Examples of these fertilizers are urea, ammonium sulfate, potassium chloride and potassium sulfate.
Compound fertilizers	➢ These fertilizers have content of at least two primary nutrients, which can be obtained through chemical processes, blending, or a combination of both.
Complex fertilizers	➢ These fertilizers are produced through chemical reactions, solution, or granulation and must have a declared content of at least two of the primary nutrients ➢ Examples of these fertilizers are Diammonium phosphate (DAP), nitro-phosphates and ammonium phosphate.

3. Based on state, fertilizers can be classified as:

Fertilizers come in various solid forms with different presentations based on their production process, solubility, and application method.

Powder or non-granular form	➢ These fertilizers have small particle diameter of up to 3mm. ➢ This form of fertilizers are not commonly used due to handling difficulties.
Crystalline form	➢ These fertilizers are highly soluble fertilizers and used for preparing solutions for fertigation or foliar spray. ➢ This form is not suitable for use with mechanical spreaders.
Granules	➢ These are designed for improved uniformity in mechanical distribution and are spherical in shape.

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	➢ The distinction between granular and prilled is related to their production method.
Pelletized/ pelleted	➢ These are granular fertilizers with uniform size and spherical shape, resulting in improved distribution uniformity.
Macrogranules	➢ These are granules of 1-3cm to provide a slower release of nutrients.
Fluid fertilizers	➢ These fertilizers are available in suspension or solution, or both. ➢ Fertilizers with dispersed particles are called "suspension fertilizers," while those without solid particles are called "solution fertilizers." ➢ Pressure solutions refer to those with a higher concentration of anhydrous ammonia than can be maintained in equilibrium with the atmosphere.
Gaseous fertilizers	➢ With only one type in this category, anhydrous ammonia, which must be injected into the soil.

4. Based on its type, fertilizers can be classified as:

Nitrogenous fertilizers			
Ammonical Fertilizers	Nitrate Fertilizers	Ammonical and nitrate Fertilizers	Amide Fertilizers
Ammonium Sulphate [20.6% N and 24.0 % S.]	Sodium Nitrate [15.6 %N]	Ammonium Nitrate [35 %N]	Urea [46% N]
Ammonium chloride [26 % N]	Calcium Nitrate [15.5% N and 19.5% Ca]	Calcium Ammonium Nitrate [26% N]	Calcium Cynamide [20.6% N]
Anhydrous ammonia [82.0 % N]	Potassium Nitrate	Ammonium Sulphate Nitrate [26 %N, 12.1 % N]	
Phosphatic fertilizers			
Super phosphate [Ca $(H_2PO_4)_2$]	16 % P_2O_5		
Triple super phosphate:	46 % P_2O_5		
Potassic fertilizers			
Potassium chloride (KCI)	60 % K_2O		
Potassium sulphate (K_2S0_4)	*48 % K_2O*		

Impact of inorganic fertilizer on environment

The use of chemical fertilizers has been shown to have negative effects on the environment. These effects can be attributed to their composition and method of application. Chemical fertilizers contain high levels of nitrogen, phosphorus, and potassium, which are essential for plant growth, but when they are over-applied or not properly managed, they can lead to environmental problems. The excessive use of chemical fertilizers may lead to leaching and contamination of water resources, destruction of helpful microorganisms and insects, increased vulnerability of crops to disease, changes in soil pH and soil fertility degradation, which can cause permanent damage to the ecosystem. In addition, excessive nitrogen levels can cause plants to become soft and more susceptible to diseases and pests. Chemical fertilizers also reduce the presence of beneficial mycorrhizae and hinder symbiotic nitrogen fixation by rhizobia, due to high levels of nitrogen. Excessive fertilization can speed up the decomposition of soil organic matter, leading to soil degradation and reduced soil structure. Additionally, nutrients can easily escape from the soil through fixation, leaching, or gas emission, reducing the overall efficiency of the fertilizer [5]. The use of high levels of nitrogen and phosphorus fertilizers can lead to an increase in the amount of nitrates and phosphates in drinking water and rivers. These nutrients are carried by surface flow and may contaminate these sources of water. Fertilizer use in agriculture can also contribute to environmental losses, with 20-70% of the fertilizer being released into the environment as pollutants like dissolved nutrients and greenhouse gases. Nitrogenous fertilizers are often only partially absorbed by plants, with the rest being lost to the environment through various pathways, including agricultural runoff. This runoff can be a significant source of environmental pollution, with 50-70% of nitrogen compounds in the environment coming from agricultural runoff. Inorganic fertilizers, especially phosphate fertilizers, contain heavy metals like Arsenic, Cadmium, Chromium, Copper, Palladium, and Zinc which can accumulate in the soil and pose health risks to plants and humans. Fertilizer use in agriculture can also contribute to environmental losses, with 20-70% of the fertilizer being released into the environment as pollutants like dissolved nutrients and greenhouse gases [1].

Impact of inorganic fertilizers on water pollution

Agricultural intensification and population growth have led to increased fertilizer use and a higher leakage of N and P into the environment, causing degradation of freshwater, estuarine, and marine ecosystems. Of these, freshwater systems are particularly susceptible due to widespread exploitation. The enrichment of inland and coastal waters with nitrogen (N) and phosphorus (P) due to human activities, known as eutrophication, is a significant contributor to various societal problems. The effects of eutrophication vary across different water bodies, but excessive growth of aquatic weeds and phytoplankton, harmful algae blooms, and impacts on fish populations are the main concerns for the public. The growth of nuisance algae, particularly in freshwater, is mainly due to an increase in P availability, but it is widely acknowledged that reducing inputs of both nutrients is necessary for effective control [8].

The use of inorganic fertilizers in crop production results in a portion of the applied fertilizer being unused by the crops, leading to its presence in the soil and potential leaching into ground and surface water. The exact amount of nitrogen that leaches depends on various factors including soil, climate, and management practices. While optimization of fertilizer use can help reduce nitrate leaching, the current trend of nitrate pollution in freshwater is also a result of decades of past and current fertilizer and manure applications [14]. The high concentration of nitrate in the groundwater in states such as Punjab and Haryana may result from the excessive use of nitrogen-based fertilizers, which was found to be the highest in India. This has led to a consistent increase in nitrate content in the groundwater since the first samples were analyzed in 1975. Based on data from the reconnaissance of nitrate levels in shallow groundwater, the Central Ground Water Board of India has designated the region as a high-risk zone for nitrate pollution. The estimated average loss of nitrate-N through leaching in Punjab is over 50 kg per hectare per year [15,16,17]. While nitrates themselves are not harmful, they can become problematic when converted to nitrite in the body and cause illnesses such as blue baby syndrome and gastric cancer. The nitrates can also lead to the formation of nitrosamines and nitrosamides in the stomach, which are carcinogenic. Additionally, there are reports linking high nitrate consumption to an increase in goitre, although this has not yet been definitively proven [18,19,20].

Impact of inorganic fertilizers on air pollution

The use of chemical fertilizers is crucial for feeding the rapidly growing population that is projected to reach 10 billion by 2050. However, the production and utilization of these fertilizers also pose significant environmental challenges, including the need for decarbonization and improved nitrogen cycling. The production and use of nitrogen fertilizers contribute to 2.1% of total greenhouse gas emissions, with the majority (59%) of these emissions taking place during utilization and the rest arising from production (39%) and transportation[21].

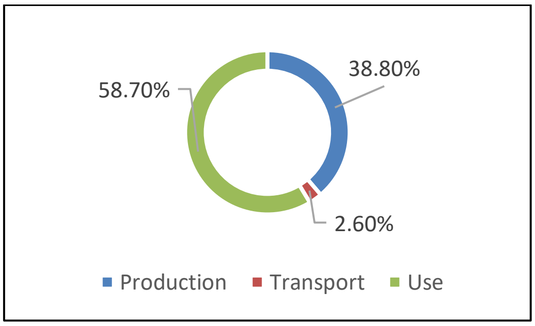

Figure 2: Greenhouse gas emission from Inorganic fertilizers

The overuse or underuse of inorganic fertilizers in agriculture is a major problem, with either situation leading to negative consequences. Insufficient use can result in lower yields and lower quality crops, while excessive use contributes to air pollution from nitrogen oxide emissions and the growth of greenhouse gases. The concentration of nitrous oxide (N_2O) in the atmosphere is growing by 0.2 to 0.3% each year, and the excess use of nitrogen-based fertilizers can lead to high nitrate levels in leafy greens, which is a threat to human health. In soils that are alkaline or have a lot of calcium, the addition of ammonium fertilizers and urea can result in the evaporation of ammonia, which is dependent on various environmental and soil factors. The emission of ammonia from treated lands can harm nearby ecosystems and vegetation. Ammonia can also be oxidized and transformed into nitric or sulfuric acid, contributing to acid rain and further damaging vegetation and organisms in lakes and reservoirs. Agriculture is responsible for 60% of the N_2O emissions caused by human activity, with agricultural soils being the main source of these emissions. The use of chemical fertilizers to improve crop production has had several negative impacts on the environment. The production and excessive use of nitrogen-based fertilizers results in emissions of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrogen oxides (NO, N_2O, NO_2), which contribute to air pollution. Nitrous oxide(N_2O), also known as laughing gas is a significant contributor to the destruction of ozone in the atmosphere, which creates "holes" and exposes humans and animals to excessive ultraviolet radiation. The emission of N_2O is particularly concerning, as it is the third most potent greenhouse gas after CO_2 and methane, with a global warming potential 310 times greater than CO_2. Additionally, the use of ammonium-based fertilizers can increase methane emissions from paddy fields, which is a potent greenhouse gas that contributes to global climate change [22,23,24].

Impact of inorganic fertilizers on soil pollution

The soil plays a crucial role as the natural growing medium for plants and the habitat of various soil organisms. It is responsible for recycling nutrients, providing various ecosystem services, and maintaining soil health. However, excessive use of chemical fertilizers can have adverse effects on soil quality and the environment. Improper use of fertilizer can harm soil quality by causing nutrient imbalances and damaging soil structure, which can increase bulk density and lead to soil compaction. The use of certain fertilizers such as sodium nitrate ($NaNo_3$), ammonium nitrate (NH_4NO_3), potassium chloride (KCI), potassium sulphate (K_2SO_4), and ammonium chloride (NH_4Cl) can destroy soil structure, which makes it challenging to produce crops of high quality and efficiency. Excessive application of fertilizer can also result in the build-up of mineral salts, leading to long-term degradation of the soil. These negative effects are significant and often irreversible. The long-term use of fertilizers can cause toxic substances to accumulate in crops, posing a risk to human and animal health. Excessive use of chemical fertilizers can result in soil acidification, leading to a decline in the organic matter and humus content and reducing the soil's capacity to retain nutrients, eventually hampering plant growth. Sandy soils are more susceptible to acidification than clay soils, which can better resist the impacts of chemical fertilizers. Fertilizers that contain high levels of sodium and potassium can worsen soil acidity and further damage soil structure, ultimately affecting crop yield and quality. Repeated applications of chemical fertilizers can result in the build-up of toxic heavy metals such as arsenic, cadmium, and uranium in the soil, which can contaminate food crops and harm human health. Overuse of chemical fertilizers can also contribute to the release of greenhouse gases and alter the balance between the macronutrients (N, P, K) required for plant growth. Excessive use of nitrogen fertilizers can negatively impact symbiotic nitrogen-fixing microorganisms and limit the activities of nitrifying bacteria, resulting in damage to the second nitrogen source. The use of large amounts of potassium fertilizers can also disrupt the balance of nutrients in plants, preventing them from receiving essential elements like Ca, Fe, and Zn. Furthermore, chemical fertilizers have a devastating and lethal effect on soil organisms such as worms and soil mites[25,26,27].

Mitigation strategies

The use of inorganic fertilizers has increased crop production over past decades but due to negative effects of these fertilizers there is a need to reduce the use of chemical fertilizers on our ecosystem and for that there are several alternative strategies that can be implemented such as use of biofertilizers, integrated nutrient management, slow-release fertilizers and various others.

1. **Biofertilizers**

Biofertilizers are substances containing living microorganisms that can promote root growth and seed germination. They differ from chemical and organic fertilizers in that they do not directly provide nutrients to crops but instead consist of cultures of beneficial bacteria and fungi. These microorganisms play a crucial role in regulating the dynamics of organic matter decomposition and the availability of plant nutrients such as nitrogen, phosphorus, and sulfur. Examples of microorganisms used as biofertilizers include Rhizobia, Azotobacters, Azospirillum, phosphate-solubilizing bacteria (PSB), Vesicular Arbuscular Mycorrhiza (VAM), and Plant Growth Promoting Rhizobacteria (PGPR). Mycorrhizae, for example, are mutually beneficial relationships between fungi and plant roots that can help plants acquire nutrients more efficiently. Phosphate-solubilizing bacteria (PSB) culture can increase yield up to 200-500 kg/ha, which can save up to 30-50 kg of superphosphate. Rhizobia are well-known for their ability to fix atmospheric nitrogen in plant root nodules, with some species capable of fixing up to 50-300 kg N/ha[28,29,30].

2. **Integrated nutrient management (INM)**

These practices combine the use of chemical fertilizers with organic or biofertilizers. This approach can help to reduce the amount of chemical fertilizer needed while still providing adequate nutrients for the crops. The impact of organic fertilization and the combined use of chemical and organic fertilizers on crop growth and soil fertility depend on the type and amount of fertilizers applied. Usually, organic fertilizer application rates are based on crop nitrogen needs and estimated organic fertilizer nitrogen supply, which results in excess phosphorus addition compared to the crop's requirement. Moreover, the long-term or heavy use of organic fertilizers with high levels of phosphorus, potassium, and salt can lead to nutrient, salt, or heavy metal accumulation in the soil. The presence of suitable conditions for the growth of soil microorganisms is crucial for ensuring an adequate supply of nutrients to plants. Studies have shown that phosphate-solubilizing bacteria, such as Bacillus megatherium var. phosphaticum, can enhance plant growth and improve soil phosphorus availability. When used in conjunction with phosphorus fertilizers, PSB can reduce the required dosage of P fertilizers and can even replace expensive superphosphate with cheaper rock phosphate[31,32,33].

3. **Slow release fertilizers**

The excessive use of chemical fertilizers has led to negative impacts on soil health, crop productivity, and the environment. To address these issues, slow-release fertilizers have been developed to improve the efficiency of nutrient uptake, reduce labor and energy consumption, and mitigate environmental harm. Slow-release fertilizers, including controlled-release fertilizers and intelligent fertilizers, release mineral components according to the nutrient requirements of plants, resulting in gradual nutrient release and proper plant nutrition. By using these fertilizers, the negative environmental impact of conventional fertilizers can be reduced due to the high solubility of nitrogen compounds left unused. Additionally, the slow and gradual release of nutrients during the vegetation season means that these fertilizers only need to be applied once, reducing both time and energy consumption. The efficient use of nutrients can reduce waste material and natural resource consumption, benefiting both the fertilizers industry and the environment. There are two main types of commercially important slow-release fertilizers. The first type is made from the reaction of urea and aldehydes and includes Urea-formaldehyde products, Isobutylidene diurea, Crotonylidene diurea and Glycoluril. The second type is composed of other synthetic organic products, such as oxamides, guanylurea sulfate, and melamine. Therefore, this approach can help to improve nutrient use efficiency and reduce fertilizer losses[34,35,36].

4. **Nanofertilizers**

Phyto-nanotechnology involves using nanofertilizers in plant production systems to enhance crop yield and sustainability. Nanofertilizers offer more efficient absorption and utilization of nutrients with minimal losses. They also help reduce the risk of environmental pollution by minimizing nutrient losses. Compared to conventional synthetic fertilizers, nanofertilizers have higher solubility and diffusion. They gradually deliver nutrients in a controlled manner to crop plants, which is the opposite of the rapid and spontaneous delivery of nutrients from chemical fertilizers. Plants can easily absorb nanoparticles through nano-sized pores, molecular transporters, and root exudates, which can lead to a higher nutrient uptake through various ion channels. Due to their low nutrient loss nature, smaller amounts of nanofertilizers are sufficient compared to synthetic fertilizers. These fertilizers, which are of nano-size, release essential plant nutrients in various ways, including quick release when in contact with a surface, specific release in response to a chemical or enzyme, moisture release when in contact with water, heat release when exposed to temperatures above a set point, pH release in specified acid or alkaline conditions, ultrasound release when in contact with an external frequency, and magnetic release when exposed to a magnetic field. For example, treating seeds with nano-TiO2 resulted in plants with higher dry weight, photosynthetic rate, and chlorophyll-a formation [37,38].

Precision farming can be utilized to optimize the rate and timing of fertilizer applications. Thi involves the use of sensors and other technology to monitor soil conditions and plant growth, allowing farmers to apply fertilizers more precisely and sparingly. Conservation practices such as cover cropping, reduced tillage, and crop rotation can also be implemented to improve soil health and reduce the need for chemical fertilizers. These practices can help to maintain healthy soil, allowing plants to access nutrients more efficiently and grow more effectively. In addition, nutrient recovery and recycling techniques like composting, manure management, and crop residue management can be used to capture and reuse lost nutrients, reducing fertilizer use and its associated environmental impacts. These methods can lead to improved crop productivity while minimizing the negative effects of excessive fertilizer use.

Conclusion:

Fertilizer application is crucial for modern agriculture crop production to replenish soil nutrients and promote crop growth and yield. However, excessive use of fertilizers can cause various environmental hazards. Therefore, it is essential to use fertilizers judiciously and to ensure sustainable agricultural production various mitigation strategies must be implemented.

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IMPACT OF SUSTAINABLE AGRICULTURE ON SOIL

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Introduction:

Across the United States, farms and ranches produce vast quantities of food, fuel, fodder and fiber that are available at relatively affordable prices. This abundance is a measure of success, yet it often comes at the expense of the public health, environment and even long-term agricultural productivity (Liebman and Schulte, 2015; Kremen and Miles, 2012). Many fields are planted with the same crop year after year, subjected to intensive mechanical soil disruption to suppress weeds and incorporate crop residues and left bare when not in production. Such practices can erode, degrade and in other ways pollute the soil. Likewise, large amounts of fertilizer are often applied to maximize productivity, but much of it either is lost via surface runoff or groundwater leaching, leading to toxic algal blooms and aquatic dead zones, or escapes to the atmosphere, where it contributes to climate change and emission of greenhouse gases.

The combined use of chemical herbicides with the widespread planting of herbicide-resistant crops is another problem. This has led to the development of herbicide-resistant "super weeds," the drifting of herbicides onto neighboring farms, and new challenges for certified organic produces and other farms producing crops that are not resistant to herbicides. Intensive use of pesticides has also raised concerns about the environmental impacts and human health risks of exposure to these chemicals. Taken together these serious issues, point to the urgent need to enhance the sustainability of agriculture. The studies have shown that agro ecological systems, which feature farming practices that work with nature, can provide long-term environmental benefits while maintaining productivity (Davis *et al*., 2012).

Concept of sustainable agriculture

Since the end of World War II, agriculture has changed dramatically with enhanced food and fiber productivity. It all occurs due to adoption of new technologies, farm mechanization, increased chemical use, specialization and government policies that favored maximizing production and reducing food prices. These changes have allowed farmers to produce more food and fiber at lower prices.

Despite the fact that these technologies have numerous positive benefits and greatly decreased hazards in farming, they also have significant costs. Loss of topsoil, groundwater contamination, air pollution, greenhouse gases emission, the decline of family farms, disregard for the living and working conditions of farm labourers, new dangers to public health and safety resulting from the spread of new pathogens, economic concentration in the food and agricultural industries, and the dissolution of rural communities are prominent among these. From the past four decades, there has been a growing movement to challenge the need for these exorbitant prices and to propose creative solutions. Now, the movement for sustainable agriculture is gaining acceptance and support within our systems for producing food.

Definition

Sustainable agriculture is defined as the "successful management of natural resources for agriculture to satisfy the changing human needs, while maintaining or enhancing the quality of environment" CGIAR/TAC,1998

American Society of Agronomy (ASA) in 1989 adopted a more holistic approach of sustainable agriculture with following definition:

"A sustainable agriculture is one that over the long-term, improves environmental quality and the resource base on which agriculture depends; provides for basic human needs, economically viable; and enhances the quality of life for farmers and society as a whole.

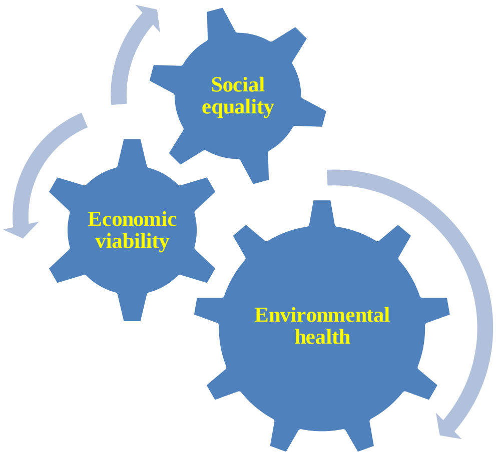

Figure 1: Objectives of sustainable agriculture

Three key objectives of sustainable agriculture are social equality, economic viability and environmental health. These objectives have been influenced by a range of ideologies, laws, and practices, but most definitions of sustainable agriculture have a few fundamental themes and tenets.

Agricultural sustainability relies on the principle that we must meet the needs of the present without compromising the ability of future generations to meet their own needs. Hence, long-term stewardship of both natural and human resources is of equal importance to short-term economic gain. Stewardship of human resources includes consideration of social responsibilities such as needs of rural communities, working and living conditions of laborers and consumer health and safety both in the present and the future. Stewardship of land and natural resources involves enhancing or maintaining the quality of these resources and using them in ways that allow them to be regenerated for the future.

Studies of different types of systems have taught us that systems that survive over time usually do so because they are highly adaptive, resilient and have high diversity. Resilience is critical because most agro ecosystems face conditions (including climate, population, political contexts, pest and others) that are often highly unpredictable and rarely stable in long run.

Adaptability is an important component of resilience, as it may not always be possible or desirable for an agro ecosystem to regain the precise form and function it had before a disturbance, but it may be able to adjust itself and take a new form in the face of changing conditions. Diversity often aids in conferring adaptability, because more variety that exists within an agriculture system, whether in terms of types of crops or cultural knowledge, the more tools and avenues a system will have to adapt to change.

Ultimately, sustainable agriculture is not a single, well-defined end goal. A scientific approach about what constitutes sustainability in environmental, social and economic terms is continuously evolving and is influenced by contemporary issues, values and perspectives. For example, agriculture's ability to adapt to changing climate was not considered a critical issue 30 years ago, but is now receiving increasing attention. Therefore, it is more important and advisable to think of agricultural systems as ranging along a continuum from unsustainable to very sustainable, rather than placed in a sustainable/unsustainable contrariety.

Principles of sustainable agriculture

1. **Conservation of natural resources:** This involves reducing the use of non-renewable resources, such as fossil fuels, and preserving renewable resources, such as water and soil.
2. **Biodiversity:** Sustainable agriculture promotes the preservation of natural habitats and the protection of diverse plant and animal species.
3. **Soil health:** The use of natural fertilizers, crop rotation, and other techniques are used to maintain soil fertility and structure.
4. **Integrated pest management:** This approach involves using natural methods, such as crop rotation, biological control, and cultural practices, to manage pests and diseases.
5. **Social and economic equity:** Sustainable agriculture strives to improve the livelihoods of farmers and their communities by promoting fair trade practices, reducing poverty, and ensuring equitable access to resources.
6. **Local and seasonal production:** This approach focuses on producing food locally and in-season, which reduces transportation costs and supports local economies.

Soil health

Soil is a dynamic interface between the atmosphere (air), lithosphere (rock), biosphere (living things) and hydrosphere (water). It is the zone in which organisms and rocks, and the air and water that move in and around and through them, interact. Soil is not just the physical parts that make it up, but also the active interactions between its various chemical, physical and biological parts. In general, soil characteristics determine how the soil functions as a foundation of the ecosystem. Soil health is the condition of the soil in a defined space and at a defined scale relative to a set of benchmarks that enclose healthy functioning. Soil health refers the idea that soil is an ecosystem full of life that needs to be carefully managed to maintain and regain our soil’s ability to function optimally. Soil health can also defined as the ecological equilibrium and the functionality of a soil and its capacity to maintain a well balanced ecosystem with high biodiversity above and below surface, and productivity.

"The continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal and human health" is termed as soil health (Doran and Safley, 1997).

Management of soil health (improved soil function) is simply maintaining suitable habitat for the countless number of creatures that comprise the soil food web. This can be accomplished by growing as many different species of plants as practical, disturbing the soil as little as possible, keeping living plants in the soil as often as possible and keeping the soil covered all the time. Soil physical condition represents the degree of compaction, capacity for water storage and ease of drainage is also critical to soil and plant health. Good soil tilth promotes uniform rainfall infiltration, reducing runoff and thereby allowing moisture to be stored for later plant use. It also promotes proper root development. When aeration and water availability are optimum, plant health and growth benefit. For example, plants growing in friable soils with adequate aeration are less adversely affected by wet and dry conditions as compared to those growing in compacted soils. Soils having good physical structure remain sufficiently aerated during wet periods, and in contrast to compacted soils they become less physical barriers to root growth as conditions become very dry.

Among various important chemical determinants of a soil health are levels of available nutrients, pH and salt content. Less availability of nutrients, high levels of toxic elements such as aluminum and high concentrations of salts can adversely affect the growth of plants. Healthy soils have sufficient but not excessive nutrients. Excessive availability nitrogen can make plants more susceptible to insects, and over abundant nitrogen and phosphorus can pollute surface and ground water. Well-decomposed organic matter helps healthy soils to hold calcium, magnesium, potassium and keeping these nutrients in the plant's root zone. Soil microorganisms can be classified as bacteria, fungi, actinomycetes, protozoa, algae and viruses. Each of these groups has different characteristics that define the organisms and their different functions in the soil. Importantly, these organisms do not exist in isolation, they interact and their interactions influence soil fertility as more than the organism's individual activities.

In recent years, the application of cultivating soil fungal biodiversity to improve soil quality and increase productivity of agricultural ecosystems has been highlighted as a new and very promising development in plant productivity (Bagyaraj and Ashwin, 2017), which may be called **'the 2nd Green Revolution'**. The enactment of such solutions may offer an alternative to the current over use of fertilizers toward more sophisticated manipulations of plant productivity. Beneficial soil microorganisms participate in decomposition of organic matter and deliver nutrients for plant growth. Their role is very important in protection of plants against pathogenic microorganisms as biological agents, which influences soil health (Frac *et al.*, 2015). The evaluation of micro-organisms or biodiversity as quality indicators cannot be limited only to the determination of biodiversity indexes, but also should include a structure analysis of micro organism's population in order to determine the functions they play in affecting soil quality and plant health. The application of different kinds of organic manures has a strong influence on soil health, through indirect effects (i.e., *via* changes in physio-chemical characteristics) and a direct effect on soil microbes communities.

Soil functions related to sustainable agriculture production

- Supporting the production of food, fiber, fuel and feed
- Retaining and cycling of nutrients
- Supporting plant growth and development
- Sequestering carbon
- Allow infiltration and facilitate storage of water
- Suppressing weeds, pests and diseases
- Detoxifying toxic chemicals

Characteristics of a healthy soil

i. **Soil tilth:** Soil tilth refers to the overall physical characteristic of the soil in the context of its suitability for crop production. Soil with good tilth is crumbly, well structured, dark colored with organic matter and has no hard clods.

ii. **Soil depth:** Soil depth refers to the extent of the soil profile through which roots are able to grow to find sufficient water and nutrients. A soil with a shallow depth as a result of compaction layer is more susceptible to damage in extreme weather fluctuations, thus predisposing the crop to flooding, pathogen or drought stress.

iii. **Nutrients supply:** An adequate supply of nutrients is necessary for optimal plant growth and for maintaining balanced cycling of nutrients within the system. An excess of nutrients can lead to leaching losses and potential ground water pollution, high nutrient runoff and emission of greenhouse gases, as well as toxicity to plants and microbial communities.

iv. **Water infiltration and drainage:** During heavy rainfall, a healthy soil has large and stable pores to take in water. These large pores conduct water to the medium and small pores where it will be stored for later use by plants. This range of pore sizes in a healthy soil allows increased water storage for plants during dry spells. During extended rainy periods, the large pores will still empty by gravity and allow fresh air to enter for plants and soil organism to grow.

v. **Population of beneficial organisms:** Soil organisms are important to the functioning of soil and they help in decomposing organic matter, cycling nutrients, biologically suppressing plant pests, maintaining soil structure, etc. A healthy soil will have a diverse population of beneficial organisms to carry out these functions and thus help to maintain a healthy soil status.

vi. **Population of plant pathogens and insect pests:** In agricultural systems, plant pathogens and pests can cause diseases and damage to the crop. In a healthy soil, the population of these organisms is less active and this could result from direct competition from other soil organisms for nutrients or habitat. In addition, healthy plants are better able to defend themselves against a variety of plant pathogens and pests.

vii. **Weed pressure:** Weed pressure is a major constraint in sustainable crop production. Weeds compete with crops for water and nutrients that are essential for growth and development of plants. Weeds can interfere with stand establishment and harvest, cultivation operations, and harbor disease causing pathogens and pests.

viii. **Free of chemicals and toxins:** Healthy soil is either devoid of excess amount of harmful chemicals and toxins, or can detoxify or bind such chemicals. These processes make these harmful chemical compounds unavailable for plant uptake, due to richness of soil in stable organic matter and diverse microbial communities.

Table 1: Sustainable soil management suggestions for soil physical properties

S. No.	Parameters	Short term management	Long term management
1	Available water capacity	• Addition of stable organic materials • Addition of compost or biochar	• Reduce tillage • Rotation with sod crop • Incorporate high biomass cover crop
2	Surface hardness	• Use of some mechanical soil loosers (strip till, aerators, spader) • Grow shallow rooted cover crops • Use a living mulch or interseed cover crop	• Shallow-rooted cover/rotation crops • Avoid traffic on wet soils • Avoid excess tillage/loads
3	Sub-Surface hardness	• Use targeted deep tillage (subsoiler, chisel plough, spader) • Plant deep rooted cover crops	• Avoid disk plough that create pans • Avoid heavy loads • Reduce traffic when soil is wet
4	Aggregate stability	• Incorporate fresh organic matter • Grow shallow rooted cover crops • Add green manure and manures	• Reduce tillage • Use a surface mulch • Rotation with sod crops
5	Organic matter	• Addition of stable organic materials • Addition of biochar or compost	• Reduce tillage • Rotation with sod crop • Incorporate high biomass cover crop

Table 2: Sustainable soil management suggestions for soil chemical properties

S. No.	Parameter	Short term management	Long term management
1	Low soil pH	• Addition of lime as per the soil test report • Addition of gypsum in addition to lime if aluminum is high • Use less ammonium or urea	• Test soil annually and add "maintenance" lime as per the soil test recommendations • Raise organic matter to improve buffering capacity
2	High soil pH	• Add elemental sulphur/ gypsum as per the soil test report	• Test soil annually • Use higher percentage of ammonium or urea
3	Low extractable Phosphorus	• Add phosphorus amendments as per the soil test recommendation • Grow cover crops to recycle fixed P • Adjust pH to 6.2-6.5 to free up fixed P.	• Promote mycorrhizal population • Maintain pH 6.2-6.5 • Grow cover crops to recycle fixed P.
4	High extractable Phosphorus	• Stop adding manure and compost • Choose low or no P fertilizer blend • Apply only 20 lbs/acre P starter P if necessary • Apply P at/below crop removal rate	• Use cover crops that accumulate P and export to low P fields
5	Low extractable potassium	• Add wood ash, fertilizer, manure or compost as per soil test recommendations • Use cover crops to recycle fixed K. • Choose a high K fertilizer blend	• Test soil annually and add "maintenance" K as per the soil test recommendations each year to keep K consistently available.
6	Low minor elements	• Add chelated micronutrients as per soil test recommendation • Do not exceed pH 6.5 for most crops	• Promote mycorrhizal population • Improve organic matter • Decrease soil P
7	High minor elements	• Raise soil pH to 6.2-6.5 • Do not use fertilizers with micronutrients	• Maintain a pH of 6.2-6.5 • Monitor irrigation or improve drainage • Improve soil calcium levels

Sustainable agriculture practices for good soil health

- **Tillage practices**

Tillage practices affect soil physical and chemical properties, as well as quality and yield of crop as reported in watermelon and rice-maize cropping systems (Sahu *et al.*, 2019). Adopting proper tillage practice is a pre-requisite to sustain crop production and soil health (Jabro *et al.*, 2009). Conservation tillage practices (no-till, reduced and strip) can increase soil moisture, soil microbial activities, organic content, stability of soil aggregates, cation exchange capacity and crop yield (Gathala *et al.*, 2015; Gozubuyuk *et al.*, 2014). Conservation tillage using permanent beds and strip tillage can increase farmer net income and benefit-cost ratio by increasing water use efficiency of plants and reducing amount of irrigation water and labor use compared to conventional (Jat *et al.*, 2013). Al-Kaisi *et al*. (2014) also found that intensity of tillage significantly reduces soil aggregate stability. Conservation tillage practices increased available P in the topsoil (0–20 cm) by 3.8%, K by 13.6% and organic matter by 0.17% compared to conventional (Shao *et al.*, 2016). Maintaining crop residues on the soil surface (full cover, no till; partial cover, strip tillage) can also reduce soil erosion and increases soil moisture content (Celik *et al*., 2013).

Conservation tillage increase population of bacteria and fungi; and earthworm, nematode and gram-positive bacteria than conventional system (Sengupta and Dick 2015). Research findings of a 10-year study on tillage practices on tomato production found that the total number of nematode under conventional tillage (moldboard plow) was 52% lower than of conservation strip tillage (Overstreet *et al.*, 2010). However, nematode luxuriance does not necessary equate to soil health nor function. For example, strip tillage increased total bacteria by 49%, active bacteria by 27%; and active and total fungi by 37% when compared to conventional tillage (Leskovar *et al.*, 2016). Although, the same study showed that strip tillage potentially reduced soil nutrient content (P and NO_3^-) and increased (~9 fold) root-feeding nematodes (harmful to plant roots) as compared to conventional. This could be due to the feeding behavior of nematodes and the reproductive rate, which respond quickly to rhizosphere changes. Conservation tillage provides superior feeding sources for nematodes as compared to conventional. Major disadvantages of conservation tillage practices, particularly no tillage systems, are the higher weed pressure, higher soil bulk density and compaction in the top layer of soil (Cannell and Hawes 1994). On the contrary, conventional tillage practices provides proper aeration to soil, reduces soil compaction, reduces weed pressure and incorporates crop residues.

- **Crop rotation**

Growers use plant and animal based organic fertilizers to meet the essential crop requirements. Crop rotation with legumes usually stabilizes the soil aggregates and also a good source of N for successive crop production. Commercially available organic fertilizers are more costly than chemical fertilizers, because they are very difficult to produce and require large biomass (plant-based fertilizers). Therefore, the choice of plant or animal based organic fertilizers is critical for crop yield and gain profits in sustainable agriculture. Plant-based fertilizers such as, leguminous crops and green manuring have been used widely as crop rotation to increase the availability of N in the soil (Vyn *et al.*, 2000; Fauci and Dick 1994). Legumes can fix atmospheric N in the soil, reduce the risk of NO_3^- leaching, improves soil chemical and physical properties. Leguminous crops such as, *Sesbania* spp. and *alfalfa* are used widely have been known to increase soil organic matter (*Sesbania rostrata* yielded 16.8 t ha^{-1} dry matter in 13 weeks), N supply capacity and soil N sequestration by about 50% as compared to mineral fertilization (Gong *et al.*, 2011; Matoh *et.al.*, 1992). Long term application of plant based fertilizers can be an ideal choice for improving soil health.

- **Biofertilizer**

Biofertilizers are sustainable and eco-friendly agricultural approaches to crop improvement and mainly supplement the chemical fertilizers to maintain soil fertility. Continuous application of chemical fertilizers causes reduction of organic matter content in soil and also microbial activities. The main objective behind the application of biofertilizers or microbial inoculants to seed or soil is to increase the number and biological activities of useful microorganisms that accelerate certain microbial processes to amplify the extent of availability of nutrients in the available forms which can be easily assimilated by plants. Biofertilizers are basically supplementary component to soil and crop management traditions *viz.*, tillage maintenance, crop rotation, organic amendments, recycling of crop residue, soil fertility renovation and the biocontrol of pathogens and insect pests.

Azospirillum inoculation could significantly enhance the growth in terms of height; number of leaf/plant; size of leaf; and fresh and dry weight/ plant of rice plant (Hossain *et al.*, 2015). Inoculation with Azospirillum has been found to cause significant increases in growth and yield of rice crop which is equivalent to that is attainable by application of 15-20 kg N ha^{-1} (Rodrigues *et al.*, 2008). The inoculations with PSB in the soils become mandatory to restore and maintain the effective microbial populations for solubilization of chemically fixed phosphorus and to enhance the availability of other macro and micro nutrients to harvest good sustainable yield of various crops (Mishra *et al.*, 2013).

- **Organic farming**

Organic farming as the most sustainable agricultural system is rapidly growing worldwide because it not only improves the physical, biological and environmental resources such as soil nutrient mineralization, microbial activity and diversity and ground water quality (lower NO_3^- concentration), but also yield and quality of crops. A long term study with rice (*Oryza sativa*) and corn (*Zea mays*), showed that organic farming using compost and peat sources had higher microbial population and enzyme activities compared to conventional system (Chang *et al.*, 2014). Growing vegetable crops such as tomato (*Solanum lycopersicum*) and lettuce (*Lactuca sativa*) under organic and conventional conditions for three years revealed that organic farming using compost increased soil CO_2 respiration (soil health indicator) and enzyme activities compared to conventional mineral fertilizer (Iovieno *et al.*, 2009). Organic farming also suppresses soil pathogens, such as Fusarium wilt in cucumber (*Cucumis sativus*) and plant parasitic nematodes *Pratylenchus* and *Meloidogyne* in maize and bean compared to conventional culture systems (Atandi *et al.*, 2017).

Conclusion:

Sustainable agriculture practices can have a significant effect on soil health. Soil is a finite resource and plays a crucial role in food production, nutrient cycling and carbon storage. Soil degradation can result in drastic change in agricultural productivity and even desertification. Sustainable agricultural practices, such as crop rotation, reduced tillage and cover cropping can help to maintain and improve soil health. These practices can reduce soil erosion, increase organic matter content, improves soil structure and increases biodiversity in soil. Maintaining soil health through sustainable agriculture practices can also have important environmental, social and economic benefits. It can help to reduce emission of greenhouse gases, improve water quality and promote biodiversity. Additionally, healthy soils can support the livelihoods of small farmers and enhance food security of a nation.

In conclusion, sustainable agriculture practices can help to improve or enhance and maintain soil health, which is crucial for sustainable agricultural production and environmental conservation. It is important that these practices are adopted at a global scale to ensure that soil resources are protected for future generations.

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ROLE OF REMOTE SENSING IN SOIL SCIENCE

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Introduction:

India and the developing nations throughout the globe which are facing challenges due to severe land degradation require accurate and quantitative soil resource information that can be used by planners, scientists, and stakeholders for preparation suitable action plan. India about 5334 m-tonnes of soil is being removed annually due to various reasons (Narayan and Babu, 1983; Pandey *et al.*, 2007).

Remote Sensing and GIS tools are very helpful in delineating waste lands through satellite image and digital soil mapping/ DEM to observe, predict, analyse, interpret and characterize the land according to suitability and capability for current or future land use plan (Klingebiel, 1961).The advancements in the field of computer technology, image processing, global position system and mathematical morphology have resulted in the development of Geographical Information System (GIS) technology. The efforts are going onto use GIS in crop yield modelling, developing measures for reclamation / management of Salt-affected soils, quantification of soil loss to suggest suitable conservation processes, evaluation of soils for various land use. Application of Remote sensing and GIS includes Soil mapping, natural resource management, determine land use/land cover changes.

Since the first commercial satellite (ERTS-1, also known as LANDSAT-1) was sent into orbit in 1972, remote sensing (RS) of soils has emerged as an appealing method for analysing and mapping the soil environment from a distance. Since then, both data collecting technologies and data processing methods have advanced significantly. Remote sensing of the Earth is a useful tool for many applications because to the availability of cutting-edge analogue and digital data, collected from sensors both in the sky and in orbit. Currently, the science of remote sensing has more uses than merely scientifically based methods, and many new users are learning about its potential for useful applications.

An important stage in the detection of the environmental limit in sustainable land use planning is the evaluation of land adaptability potential. It deals with evaluating the performance of the land for the particular use of crop production. Soil texture, organic matter content, soil depth, slope, and land use/land cover were among the factors taken into account. While toposheet and auxiliary data were utilised to create slope maps and determine soil parameters, satellite photos were used to categorise the land use/land cover. These difference layers were integrated according to their importance using geographical information system (GIS). The surveyor/ researcher might utilise RS to connect with the most accurate and current chemical and physical data on experimental farms on a pixel-by-pixel basis. It appears that quantitative remote sensing of soils could be the next step given the major advancements made in the field of remote sensing in terms of data processing and acquisition methods.

Because of processes of soil formation over landscapes and management-induced soil changes, soil variations within farmed fields have formed that have an impact on crop yield (such as increased erosion with tillage, compaction, etc.). Farmers have noticed through yield monitoring that soil and landscape characteristics account for a large portion of the variability in production within fields. . It has previously been used to statistically interpolate between sample points obtained over a predetermined grid, but due to the time and expense involved in collecting samples, this method is not always practical. Using remotely sensed data to evaluate changes in soil physical properties is becoming increasingly important.

1.1 Remote Sensing

The measurement or acquisition of information of some property of an object or phenomenon by a recording device that is not in physical or intimate contact with the object or phenomenon under study. First time term Remote Sensing was used by Ms Evelyn L Pruitt, a geographer of US in mid 1950s.

Basic processes of remote sensing are listed as follows:

- Energy source (sun or transmitter)
- Transmission of energy from source to object.
- Energy interaction with object surface.
- Transmission of energy to sensor.
- Scattering and absorption by atmosphere.
- Detection, measurement and output by sensor.
- Data acquisition, recording, pre-processing and analysis/interpretation.

1.2 Types of Remote Sensing

1.2.1 Based on Source of energy

Passive	Active
Source of energy is either Sun, Earth or atmosphere.	Source of energy is part of remote sensor system.
Sun Wavelength: 0.4-5 micrometre Earth or itsatmosphereWavelength:3-30 micrometre	Radar- Wavelengths: mm-m Lidar- Wavelengths: UV, Visible and Near Infrared.
Advantage: Cost effective images available in multi-spectral Bands.	Advantages: All time weather, height detection, able to penetrate ground up to certain depth.

1.2.2 Based on Sensor platform used

- Ground based: spectroradiometer, scatter meter
- Airborne: UAS, flight
- Satellite based: Sun Synchronous, geostationary

1.2.3 Based on number of Spectral band used

Multispectral: -Bands of (Green, red, NIR, SWIR) of multispectral sensors are usually varies between 3 to 10. Satellite: IRS series of India, Landsat of USA, SPOT of France are multispectral satellite.

Hyperspectral: -Narrow and more than 200 bands.

Hyperion of EO-1 (on satellite) and AVIRIS of NASA (air borne platform) are hyperspectral sensors.

1.3 Remote sensing images

- Digital: 2D array of pixel i.e., satellite picture by using EM sensors
- Analog: Aerial photographs

Pixel: Individual picture element, having intensity value and location address in two dimensional image

- Spectral information can be stored in different bands and integrated by combining by mean of displaying each band into one of the three primary colour as: red, green and blue.
- Every combination is used to create a composite image is called as **false colour combination (FCC)**

1.4 GIS (Geographical Information System)

GIS is a tool for organising, accessing, comparing, and storing spatial data in order to facilitate analytical procedures. A system known as a GIS (hardware + database engine) is created to effectively assemble, store, update, analyse, edit, and display spatially referenced data (Data identified by their locations). GIS consists of the system's data inputs as well as the users' operating system.

Prerequisite for Soil Mapping and Land Evaluation:

- The substance that rests on top of the bedrock and supports the growth of rooted plants is known as soil. It is made up of organic remains and mineral-composed particles. It is believed that soil is a continuous, heterogeneous, fourth-dimensional body that extends throughout the terrain. Soil forming factors:
- CLORPT model: S = f (cl, o, r, p, t) Jenny (1941)
  S= soil, cl = climate, o = organisms (plant, animal and humans) r = relief,
  p = parent material t= time.
- SCORPAN model : S = f (s, c, o, r, p, a, n) Mc Bratney *et al*. (2003)
  soil (s), climate (c), organisms (o), relief (r), parent material (p), age (a), and spatial location (n).This Scorpan model helps in assessment of quantitative relationships between environmental covariates and the soil properties or soil classes to be predicted (Boettinger, 2010) and also in estimation of the error or uncertainty of the prediction.
- The first soil surveys in India were conducted in the early 1920s, when intermittent attempts were made to describe and categorise soils, primarily based on edaphic factors. The foundation of the All India Soil and Land Use Survey Organization set the door for systematic soil surveys in the nation with the acceptance of the Steward Report and action on the particular recommendations of Dr. Rickens, a soil specialist from the USA.

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- About ten years later, soil survey methods were standardised and mostly refined. Several recommendations, a soil survey manual, and the use of aerial photo bases in mapping activities were also developed.
- The development of systematic aerial photo-interpretation techniques for soils mapping was substantially hastened by the establishment at Dehradun of the Indian Photo-Interpretation Institute, which is today known as the Indian Institute of Remote Sensing (IIRS).

2.1 Objectives of Remote Sensing

To characterize the soil for quality parameters:

i. Collection and processing of Landsat 8 remote sensing and SRTM DEM data
ii. Survey of India topographical sheets
iii. Identification of sites and collection of soil samples

2.2 Principles of Remote Sensing

The term "electromagnetic energy" describes all energy that travels in a harmonic wave pattern at the speed of light. Despite the fact that electromagnetic energy can only be observed in the context of its interactions with matter, the wave notion explains how it spreads. The components of electromagnetic radiation are a magnetic field (M) directed at a right angle to the electrical field (E), and an electrical field (E) that fluctuates in magnitude in a direction perpendicular to the direction of the radiation. As fast as light, both of these fields move (C). Depending on the qualities of the matter, such as whether it is solid, liquid, or gas, a variety of interactions can occur when electromagnetic energy comes into contact with it. Energy can be I transmitted by a substance, (ii) absorbed by a substance, (iii) released by a substance, (iv) scattered, or diverted in all directions and lost, and (v) ultimately reflected. Specular reflectance is the term used to describe an object's surface when it reflects light unmodified at an angle that is equal to and opposite to the angle of incidence (as in a mirror). The term "diffuse" refers to radiation that reflects evenly in all directions. In the middle are real materials. Remote sensing is the study of how electromagnetic radiation varies, including changes in intensity, direction, wavelength, polarisation, and phase. Remote interpretation is used to determine the properties of the substance that changed the electromagnetic radiation collected from the resultant images and data.

2.3 Types of Sensor and Platforms Used in Remote Sensing

1. Ground based Remote Sensing: A wide variety of ground based platforms are used in remote sensing. Some of them are hand held spectroradiometer, and scatter meter.
2. Airborne Remote Sensing: Mostly used platforms for sensors are flight, unmanned aerial system (UAS) at desired height.
3. Satellite Remote Sensing: Carrier of the sensors is the satellite which may be placed in low earth orbit (LEO), at height earth ranging from 160 to 2000 km or geostationary earth orbit (GEO) at a height more than 30,000 km away from earth surface.

2.4 Different platforms used in remote sensing : Balloon, Kite, Pigeon, Rocket/Aircraft, Wing aircraft (low altitude), Satellite (High altitude)

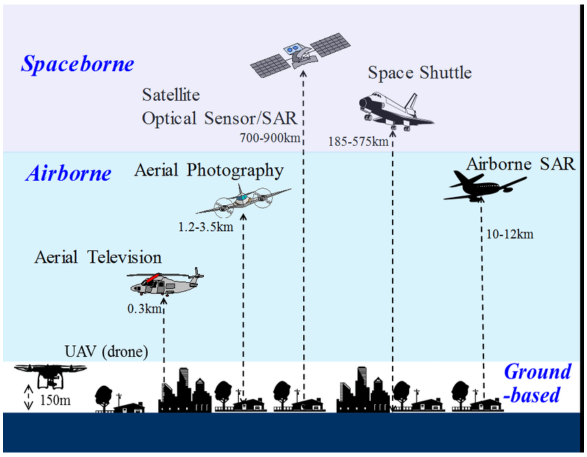

Figure 1: Pictorial representation of different platforms used in remote sensing

The progressive chart here represents the various stages involved in aerial photography which acts as a prior pre-requisite to mapping and land evaluation.

Survey aircraft

↓

Pilot and navigator

↓

Flight planning and flight map Aerial camera and its suspension

↓

Actual flight

↓

Illuminated terrain, Atmosphere, camera lens, filter

↓

Light sensitive emulsion on aerial film or glass plate

↓

Exposure

↓

Formation of latent image

↓

Development, fixing, washing and drying of negative

↓

Photographic paper contact or diapositive prints

↓

Aerial photography in India is controlled and co-coordinated by the Survey of India and flown by a flying agency.

Interpretation of aerial surveyed photographs captured by various sensors and platforms:

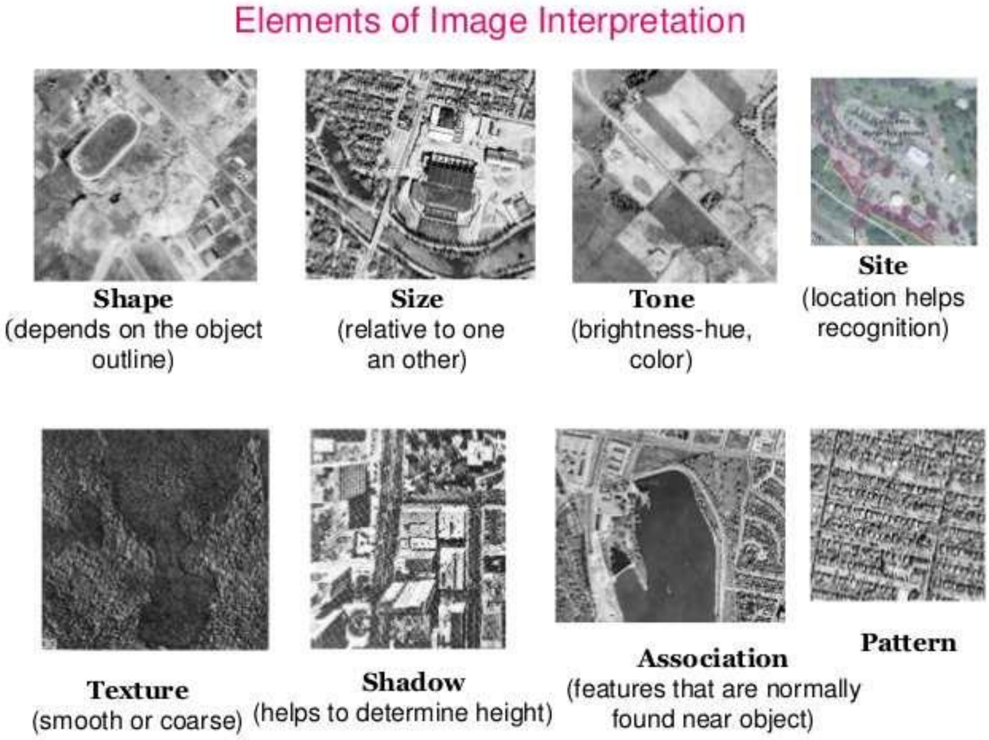

Figure 2: Elements of Image Interpretation

3. Soil mapping using Remote Sensing:

3.1 Why Digital Mapping?

Accurate and quantitative information about soil resources is required for countries like India that are experiencing significant land degradation so that planners, scientists, and stakeholders can develop effective action plans. Several organisations are now doing soil surveys at various scales. Products made in India by DSM (Digital soil mapping) could make a substantial contribution to global FAO and Global Soil Map activities. Conventional soil mapping, however, is also crucial for creating DSM tools since it offers the fundamental data for creating models that relate to soil.

3.2 General overview about Maps:

- **Reference map:** It normally shows natural and human-made objects from the geographical environment with an emphasis on location. Examples of general reference maps include maps found in atlases and topographic maps.
- **Thematic map:** It is used to display the geographical distribution of one phenomenon or the spatial associations that occur between different phenomena.

Map Scale = Map Distance/Earth Distance

3.3 Soil mapping using remote sensing

Stage I: Pre field interpretation

For the purpose of analysing the region, bands 2, 3 and 4 of the IRS P6 LISS III standard geocoded false colour composites in 1:50,000 scales were used. Digitally generated pictures were combined with FCC to identify and define the landforms. Based on physiographic variances, each landform was recognised and mapped.

Stage II: Ground truth verification

Fieldwork was conducted to gather ground information about the study area. Prior to conducting detailed field checks, a rapid reconnaissance survey of the study area was conducted to understand the broad landforms, land use, and their relationship with soils. A topographical map of the study area at 1:50,000 scale was used to traverse and locate observation points in imagery. Representative soil profiles, pits, and auger bores were studied and recorded on a field sheet that included detailed profile site and morphological characteristics for each mapping unit. Following standard procedures, soil samples were collected from different layers of the profile.

Stage III: Post field Interpretation

Post-field interpretation entails modifying and reinterpreting pre-field interpreted mapping units of imagery using ground observation. With the help of image features such as tone, texture, pattern, shape, landform, slope, and elevation, necessary changes and corrections were made in delineating the entire study area logically.

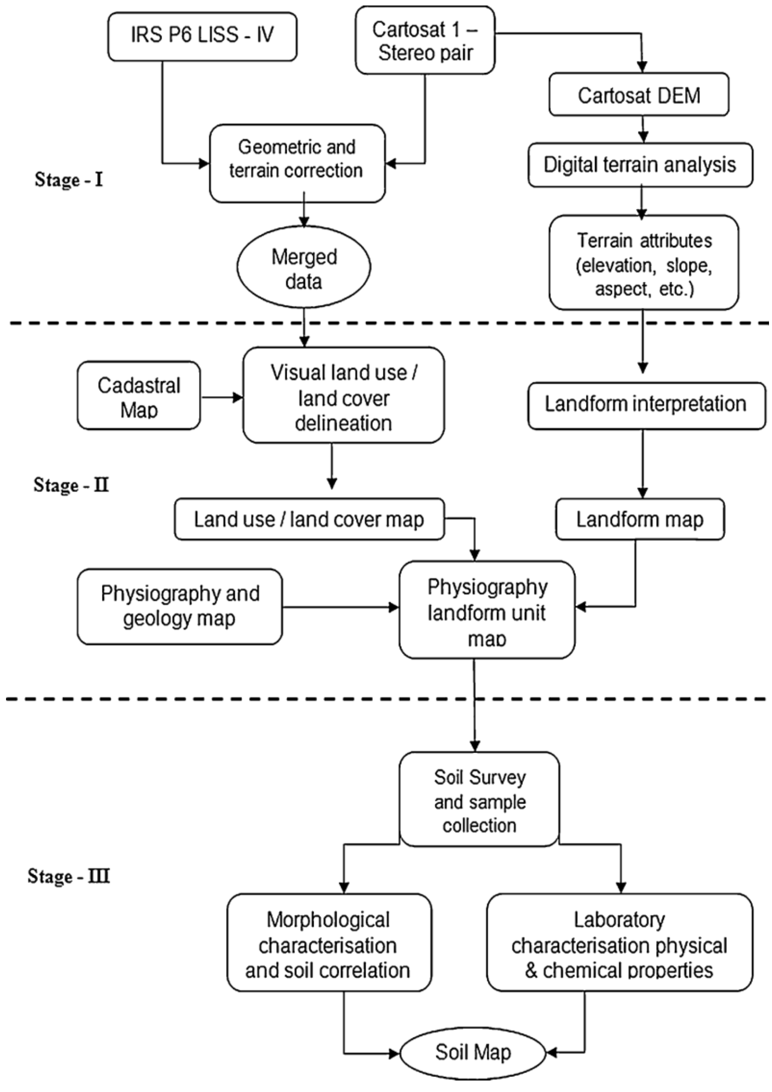

Figure 3: Pictorial representation of the stages involved in making soil map

3.5 Soil survey methodology

Soil surveyors use physiographic variation as a base when mapping soil variability (while holding other soil formation elements constant). The general methodology of soil survey includes pre-field interpretation using cadastral maps, survey of India toposheets, aerial photographs, and satellite data (depending on availability) to delineate various physiographic units, ground-truthing for physiographic unit verification, soil profile study, developing physiography-soil relationship, and extrapolation of this relationship to other similar areas. In general, topographical maps are published at scales of 1:25,000, 1:50,000, and 1:250,000. These maps depict not only physical characteristics but also topographical information in the form of contours and height. Aerial black-and-white or panchromatic photos with 50-65% overlap for viewing.

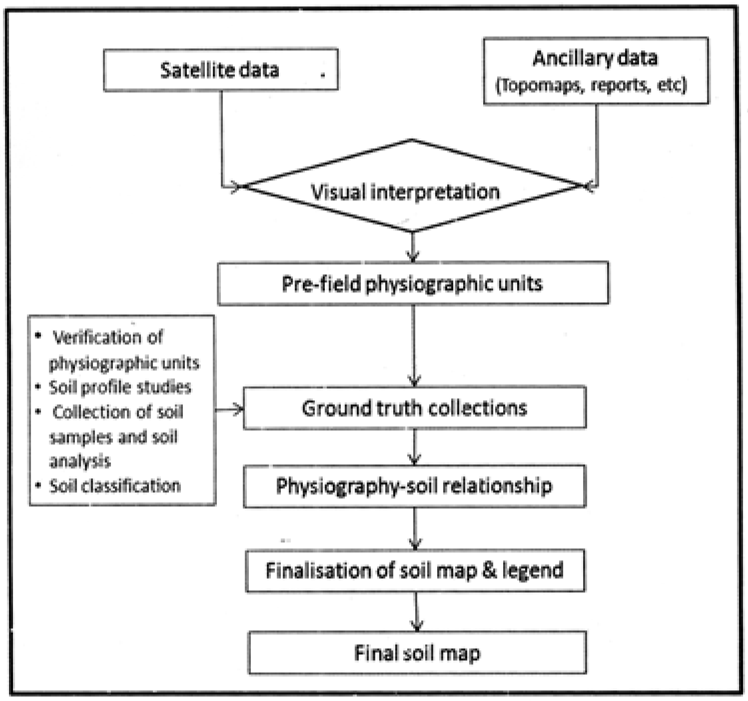

Figure 4: Flow chart depicting general methodology for soil mapping

The former approach is more commonly used in soil mapping than the latter in remote sensing data interpretation. Shape, size, tone, shadow, pattern, site, and association are used to visually interpret satellite imagery. This has the advantage of being simple and inexpensive. Computer-aided techniques in digital interpretation use spectral variations to classify data. Remote sensing pattern recognition aids in the identification of homogeneous areas that can be used as a foundation for conducting detailed field investigations. The spatial and spectral resolution of remote sensing data is essential for determining mapping scale. NBSS & LUP, Nagpur used coarse resolution data from IRS LISS-I, WiFS, AwiFs and LANDST-MSS sensors to create soil maps at 1:250,000 scale or smaller. Medium resolution remote sensing data from LANDSAT-TM, IRS LISS-II/LISS-III, and SPOT-MLA are mostly used to map soils at

1:50,000 scale. IRS-P6 (LISS-IV sensor), Cartosal-1 and Cartosat-2 and IKONOS satellite data are now being used for detailed soil characterization at 1:10,000 scale and larger.

3.6 Processing, analysis and interpretation of IRS data for Soil Evaluation

IRS images will be corrected geometrically and radiometrically using ERDAS image rectification and processing modules. Consider using standard procedures. The images will be georeferenced using the standard tie-points point method, which employs UTM (Universal Transverse Mercator) coordinates, as well as WGS datum and ellipsoid parameters. False Colour Composites (FCC) will be created by combining B321 and B432 bands to identify salt affected and waterlogged areas, respectively. To prepare homogeneous data sets, a principal component analysis will be performed, and filters will be used to improve the sharpness of the images for visual analysis. Clusters and visual image interpretation will be applied to the image. Before image interpretation, the ratio indices NDVI (Normalized Difference Vegetation Index), VI (Vegetation Index) and SAVI (Soil Adjusted Vegetation Index) will be evaluated to separate cropped and non-cropped areas. The spectral pattern will be used to characterise image elements such as crop, riverine sand, salt affected, and waterlogged soils. The digital variation of image features will be evaluated using multivariate statistical analysis. The visual interpretation of images will be based on standard guidelines such as tone, texture, pattern, shape, size and contrast.

3.6.1 Preparation of base map: The base map of the study area will be created using topographical maps from the Survey of India at a scale of 1:50,000. The topographical maps will be geo-referenced using UTM projection with WGS 84 datum and ellipsoid system and digitised to develop four thematic layers for administrative and political boundaries; infrastructure: roads and railways; irrigation and drainage: canals and rivers; and settlements: state, district, sub-division HQs and villages. In ArcGIS, these layers will be overlaid to create a composite base map of the study area.

3.6.2 Spectral characterization using multi-spectral remote sensing: In order to characterise complex image signatures of sodic, non-sodic, reclaimed, saline, non-saline and waterlogged soils with and without the association of important crops like rice and wheat under the normal and poor-quality ground and canal water irrigated zones (Saxena, 2004; Sharma *et al.*, 2008). Spectral characterization of the RS imageries will be done using digital numbers of the images in various bands and study the changes with respect to seasons (Dwivedi 1994; Rao *et.al*., 1998).

4. Land evaluation using remote sensing

Despite the fact that the terms "land cover" and "land uses" are sometimes used interchangeably, they actually have very different meanings. The term "land cover" refers to the material that covers the surface of the ground, such as vegetation, urban infrastructure, water, bare soil, or another material. For the purpose of resource management, planning, and global monitoring studies, it is crucial to identify, delineate, and map the land cover. The baseline from which monitoring operations (change detection) can be carried out is established by identifying the land cover, which also supplies the ground cover data for baseline thematic maps. Land use is the term used to describe the usage of a piece of land, such as for agriculture, wildlife habitat or recreation. Since accurate information is needed to know how much land is currently being used for what purposes and to track changes in land use over time, land use applications need both baseline mapping and follow-up monitoring. With this information, methods to balance development demands, competing uses and conservation can be developed. The destruction or disruption of agricultural land, the encroachment of cities, and the depletion of forests are issues that are driving land use studies. Land cover and usage data can be used for planning, monitoring, and assessment of development, industrial activities, or reclamation in addition to aiding sustainable land management. The foundation of terrestrial global monitoring is the detection of long-term changes in land cover that may indicate a response to a change in local or regional climatic conditions.

5.0 Application of remote sensing

5.1 Soil Mapping: Resource information about a location is provided by soil mapping. Understanding how well different types of soil can be used is made easier by this. It is crucial to stop environmental damage brought on by improper land usage. GIS aids in defining soil boundaries and identifying the different soil types (Sheng *et al.,* 2010). It is employed for soil characterization and identification. In affluent nations, farmers utilise soil maps extensively to preserve soil nutrients and produce their highest output.

5.2 Natural Resources Management: The agricultural, water, and forest resources may be efficiently maintained and managed with the aid of GIS technology. Foresters can quickly assess the state of the forest. The geographic distribution of water resources is analysed using GIS. They are connected; for example, the forest cover lowers storm water runoff while the tree canopy holds about 215,000 tonnes of carbon. GIS is also used in afforestation.

5.3 Determine land use/land cover changes: The term "land cover" refers to the structure that covers an uninhabited area. Land use is the portion of the surface that is put to a specific use. GIS technology is used in land use and land cover applications so that we can track changes in land use and land cover across various regions. Additionally, it can track and estimate changes in the pattern of land use and land cover over time. It makes it possible to identify unexpected changes in land use and land cover brought on by either natural factors or human activity, such as deforestation.

5.4 Application of remote sensing in agriculture

- Understanding the spatial variability of soil and water and creating thematic maps of soil and water pollutants and quality are critical steps in locating the problem area.
- This will aid in the development of alternative agricultural crop management practises. Remote sensing is used in the following agricultural applications: crop classification, crop health evaluation, yield estimation, mapping of crop properties in soil, and crop compliance monitoring (farming practices).
- Mapping of general cover types, shorelines, and watersheds, as well as monitoring of cutting practises and regeneration, are all global needs.
- Mapping techniques along with satellite and airborne images are used to classify crops, assess their health and viability, and monitor farming methods

Conclusion:

The detection and delineation of various physiographic units was greatly improved using digital image processing and temporal satellite data. The investigation of soils from various physiographic units revealed that the nature of parent material, topography, and time are the factors responsible for the paedogenic differences in soils developed on various physiographic units. Apart from hills, there was little difference in profile stratification between various physiographic units. The study established a clear relationship between soil physiography and development. Soil erosion is the most serious problem in the hills and piedmont, and it is exacerbated by the loss of forest cover. In cultivated areas, patches of poor land management and low soil organic carbon content are impeding land productivity.

Spaceborne satellite data have evolved into valuable resources for determining the geographic extent of degraded lands and tracking changes over time as a result of reclamation and conservation efforts. On an operational level, methodologies for obtaining accurate and timely information on many elements of degraded lands in a cost-effective manner are well established. At the moment, remote sensing techniques are frequently used in the study of degraded lands.

Future generations of satellites with higher spatial and spectral resolution (e.g.IRS-1C) and advanced GIS techniques not only allow for the extraction of information on degraded land, but also the storage and manipulation of data to arrive at environmentally friendly plans. The idea of using optical RS for mapping soils directly is not possible since soil development is in depth and we could see that satellite images just reflect the soil surface or land cover. In the generation of soil ancillary data layers, RS and Pedometric are inextricably linked. As a result, they have enormous soil mapping potential. Traditional mapping can benefit greatly from RS, especially now that there are so many different satellite images and aerial photographs available with varying spatial, spectral, and temporal resolutions. RS is being researched in various unexplored fields, and they will undoubtedly be promising tools for soil mapping in the near future. Traditional soil mapping activities are criticised as time-consuming and expensive. As a result, modern soil scientists are working to develop methodologies and tools to accelerate the process. However, we can draw the conclusion that RS is a helpful tool, but it cannot take the place of direct contact with the item, particularly when working with a complex system like soil.

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SOIL CONDITIONERS

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Introduction:

A "soil conditioner" is defined as any substance, both synthetic and natural, that improves the physical properties of soil (Wallace and Terry, 2020). Soil conditioning includes the formation and stabilisation of soil aggregates propitious for the germination of seeds and the emergence of seedlings. A good soil stabiliser for such functions will strengthen aggregates against breakdown from the impact of raindrops and will preserve a high-water infiltration capacity (Gabriels *et al.*, 1981). Similarly, controlling soil degradation is an essential need, as is improving soil air-water relations, drainage, and aggregation; reducing soil crusting and compaction; overcoming water repellence; and so on. When considering the role and function of soil conditioners in crop production, it is important to remember that the addition of such materials to the soil can affect many soil properties, either positively or negatively.

Soil conditioners as defined include many kinds of organic materials, such as gypsum, lime, natural deposits, various water-soluble polymers and cross-linked polymers that hold water in soil, living plants, microbes, many industrial waste products, and others.

Soil conditioner is defined as a substance that improves the physical properties of soil. Soil conditioners include both synthetic and natural products. This definition obviously includes substances commonly known as soil amendments; there is then overlap in the meanings of such terms as soil conditioners, amendments, and agricultural minerals. The general use of the term "amendment" usually implies substances that enhance any and all of the physical, biological, and nutritional properties of soil. All polymers, lignite or humates, wetting agents, and various microbial products are used on soil as auxiliary soil and plant substances rather than conditioners or amendments. These are defined as any substance(s) that contain limited amounts of nutrients but are managed primarily for the benefit of the soil's biological, physical, or chemical nature. They can also be used as a growing medium for plants. A soil conditioner is a product that is added to soil to improve its physical qualities, typically its fertility (ability to provide nutrition for plants), and occasionally its mechanics. In general, the term "soil conditioner" is often thought of as a subset of the category soil amendments (or soil improvement, soil condition), which includes a wide range of fertilizers and non-organic materials. Soil conditioners can be used to improve poor soils or rebuild damaged soils.

Soil conditioners can be organic, such as compost or wood waste, or inorganic, such as lime or perlite. Organic soil conditioners typically have high levels of organic matter but are not an immediate or significant source of plant nutrients and have a carbon to nitrogen ratio greater than 30 to 1. The addition of soil amendments with a high C:N ratio may result in crop-available nitrogen being tied up (immobilized). Nutrients will be temporarily tied up in the soil, unavailable for plant use unless nitrogen is added to the soil to decrease the C:N ratio.

Due to the enormous demand from consumers in various nations throughout the world, ensuring the sustainable production of wholesome foods and environmentally friendly products has drawn the interest of agricultural scientists and ecologists, as well as legislators and practitioners. (Willer and Lernoud, 2018). One of the key elements affecting the sustainability of food production is maintaining soil fertility. Uncontrolled use of chemical fertilizers, neglectful preservation of the soil's health, and the application of destructive techniques have resulted in the loss or eradication of the current population of soil organisms. (Geisseler and Scow, 2014; Ebrahimi *et al.,* 2016). Fertilizers meet the immediate nutrient needs of agricultural products, while farmers and agricultural producers neglect long-term soil fertility. According to studies, using chemical fertilizers excessively and unbalanced over time reduces crop output, biological activity, soil physical qualities, nitrate and heavy metal buildup, and soil acidity. (Ghosh and Bhat 1998; Adediran *et al.,* 2005; Aseri *et al.,* 2008; Yoshida *et al.,* 2016). Soils' physical constraints, such as surface crusting and hardening, subsurface hardpan and compactness, high or slow permeability and extremes of consistency, soil water-related constraints, wind and water erosion, and so on, can all be attributed to a significant reduction in their production capacity. This makes the assumption that, in order to increase crop production, soil must be preserved in a physical condition that allows adequate crop growth.

Farmers are continually searching for alternatives to synthetic inorganic fertilizers to alleviate the escalating production costs associated with the increasing costs of energy and fertilizers and the problems of soil and surface water deterioration associated with intensive use and release of inorganic fertilizers such as N and P fertilizers. Soil is not really renewable in a short term and must be cared for not only to maximize output or maximize other values within reason but also to make it possible for future generations to obtain similar benefits from the land. The concept of soil conditioners should state that their use is to enhance soil quality and that they are soil enhancers. Soil is usually subjected to severe problems that require the use of various soil conditioners to keep it tillable, fertile, and chemically and biologically healthy, and also to prevent its loss to various kinds of erosion. In many ways, intelligent use of soil conditioners can help reach these goals. Conditioners generally do not degrade soil and their value is often long term. It is quite safe to assume that major advances in improvement of crop yields in the future are possible through management. will come from several different soil conditioners. Near maximum amounts of fertilizers are being added, but average yields are less than half of those theoretically possible. Increased output due to fertilizer is getting smaller than in the past. A hypothesis is offered that interactions among different conditioners and amendments is an important key to more efficient crop production.

Purpose for using soil conditioners

1. **Soil structure**

Soil conditioners are most commonly used to improve soil structure. Over time, soils tend to compact. Soil compaction inhibits root growth, reducing the plant's ability to absorb nutrients and water. To keep the soil loose, soil conditioners can add more loft and texture. Soil nutrients improve the ability of the soil to support healthy plant growth. Some of these materials, like compost, clay, and peat, are still widely used today. Many soil amendments also include beneficial bacteria as well as nutrients like carbon and nitrogen. Additional nutrients, such as calcium, magnesium, and phosphorus, may also be supplemented with amendments.

2. **Cation exchange**

Soil amendments can also significantly increase soil cation exchange capacity (CEC). Soils serve as nutrient reservoirs for plants. The relative ability of soils to store one type of nutrient, cations. Calcium, magnesium, potassium, ammonium, hydrogen, and sodium are the most common soil cations. The greater the CEC, the greater the negative charge and the greater the number of cations that can be held and exchanged with plant roots, providing them with the nutrition they require.

3. **Water retention**

Soil conditioners may be used to improve water retention in dry, coarse soils which are not holding water well. The addition of organic material for instance can greatly improve the water retention abilities of sandy soils and they can be added to adjust the pH of the soil to meet the needs of specific plants or to make highly acidic or alkaline soils more usable. The first synthetic soil conditioners were introduced in the 1950s, when the chemical hydrolysed polyacrylonitrile was the most used.

4. **Ecological concerns:**

While adding a soil conditioner to crops or a garden may appear to be a great way to get healthier plants, too much of some amendments can cause ecological problems. For example, salts, nitrogen, metals, and other nutrients found in many soil amendments are ineffective when used in excess and can be harmful to plant health.

The difference between fertilizers and soil conditioners

If you've ever cared for a garden or lawn, you'll know that, once your plant sprouts from its seed, it relies on the surrounding soil for all its nutrient needs. Unfortunately, due to soil depletion, there are increasingly fewer nutrients in the soil now than there were a few decades ago. A study has found that there are reliable declines in the amount of calcium, protein, iron, phosphorus, vitamin B2, and vitamin C in the soil over the past 50 years. Both macronutrients and micronutrients have become present only in limited quantities. This is where soil conditioners and fertilizers come in. These two – both easily found in landscape supply stores – allow you to improve the level of nutrients in plant soil. However, they influence plant growth in different ways. Soil conditioners improve the texture of the soil rather than boost the nutrients in it. When used correctly, soil conditioners change the soil so that growing becomes simpler. The roots will be able to penetrate the surrounding soil more readily, for example, making it easier for them to grow deeper and stronger as it improves water filtration.

Soil amendment sources

The addition of amendments restores soil quality by balancing pH, adding organic matter, increasing water holding capacity, re-establishing microbial communities, and alleviating compaction. As such, the use of soil amendments enables site remediation, revegetation and revitalization, and reuse. The sources of soil amendments include:

On-Farm Sources: These amendments include bedding, compost, crop residue, manure, contaminated runoff, silage juice, spoiled feed, wash-water, spent soilless media, spent mushroom media, and spent nutrient solution.

Off-Farm Sources: These are usually purchased and include chemical fertilizers, chemical conditioners such as lime, soilless media constituents such as perlite, manure from other farms, compost, wood waste, and non-agricultural wastes such as municipal biosolids.

Table 1: Off-farm sources of soil amendments

Off-farm soil amendment sources	
Soil Amendment Sources	**Characteristics**
Biosolids	• Exhibits low nutrient release often applied as both fertilizer and soil conditioner.
Compost	• Exhibits low nutrient release often applied as both fertilizer and soil conditioner.
Commercial Fertilizer (Solid or Liquid organic or inorganic base)	• Contain metals • Variable nutrient levels
Fish Wastes	• Exhibits low nutrient release applied as both fertilizer and soil conditioner.
Food Processing Wastes	• Have low nutrient release • Often applied as both fertilizer and soil conditioner.
Liming Materials	• Contain metals • pH impact varies with source
Off-Farm Manure–Liquid	• Variable nutrient levels
Off-Farm Manure–Solid includes bedding containing significant amounts of manure	• Normally a fertilizer but may be used as a soil conditioner if low in nutrients and if C:N ratio greater than 30:1
Off-Farm Spoiled Feed	• Variable nutrients levels, high BOD
Sand or Other ‘Clean’ Soil Material	• Check nutrient and metal levels
Spent Mushroom Media	• Variable nutrient levels • Used a fertilizer but can be used as a soil conditioner if low in nutrients and if C:N ratio greater than 30:1
Whey	• Blend with liquid manure
Wood waste (Fresh or composted)	• High C:N ratio

Types of Soil Conditioners:

Precision, extensive soil analysis, and a comprehensive approach to soil management can all help you maximize the use of soil conditioner techniques. The soil conditioners can be classified on the basis of two criteria:

(1) Origin of the materials - Synthetic or Natural occurring

(2) Composition of the materials - Either organic or inorganic

A. Organic Soil Conditioners - Organic conditioners are composed of substances sourced from living things (e.g., plants and animals). Soil organic matter is made up of decomposing animal and plant remains as well as microorganisms (fungi and bacteria) that feed on these remains. Temperature and aeration are the two main factors affecting the organic matter content of soil. They are applied to increase infiltration and soil water retention, promote aggregation, provide substrate for soil biological activity, improve aeration, reduce soil strength, and resist compaction, crusting, and surface sealing. Soil organic matter acts as a nutrient reservoir, improves soil structure, drainage, aeration, cation exchange capacity, buffering capacity, and water-holding capacity, and serves as a food source for microorganisms. In general, soils with more organic matter have better physical conditions than similar soils with less organic matter. Organic amendments do not always boost the nutritional value of harvested fruits and vegetables. Plants grown hydroponically (in water) in the absence of organic matter have mineral and vitamin contents comparable to those grown in soils rich in organic matter, as per controlled experiments. Another thing to keep in mind is that organic nitrogen, phosphorus, and sulphur cannot be used by a growing plant unless they are released in inorganic form through decomposition. A commercial fertilizer contains elements that are already inorganic. A plant cannot tell the difference between a nitrogen atom that came from organic amendments and one that was added as a fertilizer. The nutrient variability and release pattern of organic fertilizers is critical for providing plants with enough nutrients to achieve maximum productivity while also rebuilding soil fertility and ensuring environmental and natural resource protection. Soil organic matter is usually less than 10 per cent of the total weight of mineral soils.

Table 2: Carbon: Nitrogen ratios of organic material and soil microbes

Crop	C:N Ratio	Crop	C:N Ratio
Alfalfa hay	12:1	Sawdust	500:1
Food wastes	15:1	Wood	700:1
Rotted manures	15:1	Bacteria	5:1
Grass clippings	19:1	Fungi	10:1
Fruit wastes	35:1	Actinomycetes	6:1
Leaves	60:1	Peat moss	58:1
Cornstalks	60:1	Sewage sludge	10-12:1
Straw	80:1	Cattle manure	30:1

Compost, FYM, crop residues, green manures, peat, biochar, bone meal, blood meal, coffee grounds, compost tea, coir, sewage, sludge, sawdust lignite, humate, and vermiculite are examples of organic conditioners.

1. **Composts:** Compost is produced when microorganisms decompose the organic waste in the oxygen-rich environment. Compost as a soil conditioner provides numerous benefits, including increased organic C content and microbial activity, a source of plant nutrients such as N, P, K, and Mg, and root reinforcement (Donn *et al.,* 2014). Compost's ability to influence soil microflora by suppressing many soil-borne pathogens such as Pythium, Phytophthora, and Fusarium spp. is an important feature. Thus, in general, the use of compost maintains and improves the agricultural soil's stability and fertility (Zhou *et al.,* 2016). Composting, in general, maintains and improves agricultural soil stability and fertility (Angin *et al.,* 2017; Zhou *et al.,* 2016). Compost has the ability to influence soil microflora by suppressing many soil-borne pathogens such as Pythium, Phytophthora, and Fusarium spp. Composting is one of the most widely used treatments for stabilising N in wastes and improving their handling characteristics, particularly by reducing the volume of organic materials to be applied to land.
2. **Farmyard manure (FYM):** FYM is indeed the bulky organic manure produced by a naturally decomposed mixture of farm animal dung and urine, as well as litter (bedding material). It contains a lot of nutrients and improves the soil's physical, chemical, and biological properties by adding organic matter (Gore *et al.,* 2011a and b). It is appropriate for use in all types of problematic soils and crops. Farmyard manure is composed chiefly from cow dung, urine, waste straw, and other dairy wastes. FYM is high in nutrients and contains a high proportion of organic material, which feeds soil organisms and is required for active soil life. A small amount of nitrogen is available to plants directly, while the majority is released as Farmyard Manure decomposes. Plants receive balanced nutrition when cow dung and urine are combined. The availability of potassium and phosphorus from farmyard manure is comparable to that of inorganic sources. Farmyard manure is divided into two components: solid phase (dung) and liquid phase (urine). The use of farmyard manure improves soil fertility. Farmyard manure is made from simple ingredients (cow dung), but the process of converting it into a useful product takes time and effort. Farmyard manure is especially beneficial to vegetables like carrots, tomatoes, sweet potatoes, potatoes, radishes, onions, and so on, as well as crops like rice, sugarcane, Napier grass, coconuts, mango, bananas, and oranges.
3. **Green Manures:** Green manures are crops grown primarily to add nutrients and organic matter to the soil; they are grown in rotation with other crops, ploughed, and incorporated into the soil to serve the same functions as manures. Green manures contribute to the stable soil structure required for plant growth and development. It promotes soil aeration, drainage, and aggregation, increasing microbial activity and soil fertility (Shinde *et al.,* 2017).

Types of green manure crop

Green manures are essentially of two types:

Legumes (clover family)

Legumes form nodules on their roots (in collaboration with special bacteria) that can take nitrogen from the air and convert (fix) it into a form that the plant can use. This can then be used by crops grown after the legume has been ploughed into the soil and incorporated.

Non-legumes

Non-legumes do not fix nitrogen, but they can provide valuable organic matter and help to retain nutrients that would otherwise be leached. Some non-legume green manures grow quickly and can be incorporated into production gaps during the growing season.

Table 3: Green Manure crops

S.No.	Legume-based	
	Crop or mixture	**Typical issues**
1.	**Red clover**	Medium term in vegetable rotation
2.	**Red clover / Italian ryegrass**	2-year in vegetable rotation or during set-aside or for composting
3.	**Alsike clover**	Medium term - tolerates acidic, damp soils
4.	**White clover**	Undersowing in vegetables and polytunnels - for example, variety Kent Wild
5.	**Field beans**	Autumn sown - overwintered - spring incorporated
6..	**Vetches (tares)**	Medium or long term (overwintered) - smothers weeds
7.	**Peas / oats / vetch**	Medium term - bulky - can be composted
8.	**Lupins**	Late spring sown – incorporated prior to autumn planting - tolerates acid soils – produces a lot of nitrogen
	Non-legume-based	
	Crop or mixture	**Typical issues**
1.	**Grazing rye**	Grazing rye Autumn sown - bulky - builds soil structure
2.	**Mustard**	Late spring sown - short term catch crop
3.	**Fodder radish**	Autumn sown - overwintered
4.	**Sunflower**	Late spring sown - incorporated prior to autumn planting
5.	**Buckwheat**	Short term during summer

4. **Sewage and Sludge:** Sewage sludge, also known as biosolids, are organic solids that have undergone several treatments to stabilise organic matter in order to reduce unpleasant odours and prevent pests and disease spread (Goss *et al.,* 2013). Biosolids, which contain nutrients and organic matter, can be applied to agricultural soils, but only under strict regulatory controls that limit heavy metals, weeds, and human and plant pathogens. Metals, microbes, organic and inorganic chemicals from industrial sources, and runoff from roofs, roads, and parking lots can all be found in municipal waste. Faecal amendments may also contain metals that are not absorbed from food and water, antibiotics used to treat disease or as a preventative measure, as well as sex and growth hormones.
5. **Crop residues:** The plant parts that remain after harvesting the usable portions are a valuable source of organic materials. Stalks and stubble (stems), leaves, and seed pods are among the residues. Crop residues are an important source of organic matter that can be returned to the soil to recycle nutrients and improve the physical, chemical, and biological properties of the soil. Crop residue incorporation improves nutrient cycling, soil and water conservation, and subsequent crop yield (Grace *et al.*, 2013; Sharma *et al.*, 2014 and Shinde *et al.*, 2019). One of the most effective ways to mitigate the negative effects of waste and other plant residues is to separate the waste materials and convert them into compost, which can then be reused as organic fertilizer and soil conditioner (Vogtmann and Fricke 1988; Fricke and Vogtmann 1994; von Fragstein and Schmidt 1999; Olowoake *et al.*, 2018).
6. **Peat Moss:** It is a build-up of partially decomposed vegetation or organic matter. It is found in peat lands, bogs, and moors. Peat is formed when plant material fails to decompose completely in acidic and anaerobic conditions. It improves soil structure by increasing water retention capacity. Peat moss is typically characterised by a low number of plant pathogens and weed seeds, which reduces the risk of pest introduction or spread (Reddy, 2005).
7. **Humates:** It is a mined ancient organic soil or lignite-derived products; an earthy, coal-like substance associated with lignite outcrops. It contains up to 35% humic acids, which dissolve other nutrients for use by plants. It can be obtained by using humate concentrates, which are salts of humic acids obtained from natural sources and can be added directly to soils alongside regular commercial fertilizers. Humate application to plants has numerous benefits, including increased soil water retention, growth of beneficial soil microorganisms (especially when exposed to contaminant toxicity), root respiration, enzyme activity, root growth, and plant yield (Lyons and Genc, 2016).
8. **Biochar:** Biochar is a solid, fine, granular, and black charcoal material created through the slow pyrolysis of biomass, which is frequently sourced from agricultural or forestry industries. Biochar's larger surface area, negative surface charge, and high charge density enable it to adsorb cations and retain and exchange nutrients with the soil environment, including microorganisms and plant roots. Biochar stabilises biomass and native soil

organic matter, which improves soil aeration, microbial activity, and N immobilisation, all of which reduce the emission of major greenhouse gases such as CH_4, CO_2, and N_2O.

9. **Blood meal:** It refers to the blood produced as a by-product of slaughtering at meat packing plants. It is usually cow blood, but it can be any animal slaughtered for its meat. Before being packaged for sale as blood meal, the blood is dried into a powder.

B. **Inorganic soil conditioners:** Inorganic soil conditioners are either mined or manufactured by-products, and some are both or man-made. They can be naturally occurring or synthesised. Mineral conditioners such as gypsum, lime, pyrites, crushed rocks, fly ash, sulphur, zeolites, phosphor-gypsum, and others are examples of inorganic conditioners. Water soluble polymers used to stabilise clay, hydrogel polymers, and synthetic binding agents such as anionic and catalytic polymers, non-viable polymers, and so on are examples of synthetic conditioners.

Soil conditioning with inorganic soil conditioners implies an improvement in soil physical properties, allowing for more efficient use of soil and water resources. Thus, the use of various soil conditioners (VAMA, Krilium, PVA, and Hygromull (a urea formaldehyde soil conditioner) improves aggregation, porosity, and hydraulic conductivity, while decreasing bulk density, improving porosity, improving infiltration, permeability, and increasing soil profile water (Doyle *et al.,* 1960 and Nimah *et al.,* 1983).

C. **Mineral conditioners:** This conditioner is used to retrieve problematic soil. Examples include Gypsum, Lime, sulphur, Crushed rocks, dolomite, etc.

1. **Gypsum:** Gypsum is a moderately soluble source of calcium and sulphur, two essential plant nutrients that can improve overall plant growth. Gypsum has the ability to displace exchangeable sodium from sodium-rich soil cation exchange sites. It can be used to reclaim sodic soil, saline areas, or slick spots, as well as soften and crumble alkali hard pans (Deshpande *et al.,* 2012). It provides calcium to soils with low exchange capacity and improves infiltration in some puddled soils. It also improves soil physical, chemical, and biological properties (Gore *et al.,* 2011b), reducing soil erosion and nutrient concentrations (particularly phosphorus) in surface water runoff.
2. **Lime:** Lime is made up of calcium-containing inorganic minerals, primarily oxides and calcium hydroxide, and contains 75-95 percent $CaCO_3$. In highly acidic soils, it is used to restore soil pH balance. It acts as a calcium source and helps to raise soil pH. Lime is especially useful in overly acidic soil (pH less than 6.0), where the soil's ability to absorb nutrients, including those from fertilizers, is impaired.
3. **Fly ash:** Fly ash is a by-product of thermal power plants. Fly ash is a waste product that is primarily produced during the production of electricity. It can serve as a source of materials for large-volume, low-tech applications (Scheetz and Russell,1998). It is used in both soil amendment and plant nutrient sources. Fly ash is helpful in improving crop productivity and soil fertility. It not only helps in improving crop growth and yield in low fertility soils but also mobilizes macro and micronutrients in soil. It is used to produce novel soil condition known as "Biosil".

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4. **Other mineral conditioners:** When applied at several tonnes per acre, limestone, dolomite, crushed rock, elemental sulphur, and other products high in calcium and/or magnesium help to improve the physical condition of problematic soils.

D. **Synthetic binding agents:** These are the polymers that have been promoted as soil conditioners at much lower rates. The compounds are very high molecular weight, polymeric, organic compounds with long chains that bind particles together and form stable aggregates. Organic polymers, primarily polysaccharides (PSD) and polyacrylamides, are used to improve aggregate stability, maintain fertility, and reduce seal formation (PAM). Small amounts of these polymers (10-20 kg ha1) were found to be effective in stabilising and cementing aggregates together at the soil surface, and thus in maintaining soil fertility in soils with ESP (>20). It is composed of anionic and catalytic polymers, along with non-viable polymers.

    1. **Cationic polymers:** Cationic polymers like polyvinyl chloride (PVC) and polyphenol hydrochloride (PPH) are absorbed by clay via cation exchange, with calcium acting as a bridge between the clay and the polymers. Cationic polymers have excellent flocculating properties.
    2. **Anionic polymers:** Hydrolysed polyacrylonitrile (HPAN) and vinyl acetate-maleic acid (VAMA) copolymers are examples of anionic polymers. It is used to keep highly sodic soils from crusting. The anion polymer peripheral complexes form a series of hydrogen bonds that connect the clay lattice in an edge-to-edge arrangement. They have no flocculating power but help to stabilise flocculated clays. They adsorb on the surface of dispersed particles and bind them by forming a bridge between them.
    3. **Non-Ionic Soil conditioners:** Polyvinyl alcohol (PVA), for example, forms intermicellar complexes with expanding lattice type clay by suppressing swelling and the stability of soil aggregates, which is caused by lining the pores with polymers.
    4. **Polyacrylamide:** These polymers were created to improve soil physical properties in order to reduce surface sealing, increase seedling emergence, reduce runoff and erosion, and reduce fertilizer and pesticide losses. It is a synthetic binding agent that can be used to investigate the physical quality of coarse-textured soil, which is frequently poor due to high macrospore concentrations.
    5. **Other Soil Conditioners:** Industrial waste, enzymes, microorganisms, and activators are examples of soil conditioners.

Factors to consider when choosing a soil amendment

There are multiple things to think about when choosing the right soil amendment for your garden. First, think about how long the amendment will last in the soil. Specifically, ask yourself if you’re trying to make quick improvements or if you’re looking for something that will create long-lasting change. Secondly, for fast results, choose an amendment that decomposes quickly, giving your soil all the benefits in the shortest amount of time. If you want something long-acting, go for an amendment that decomposes slowly, drawing out the benefits for as long as possible.

The third option is a combination of amendments that gives both a quick boost and long-lasting results. Most of the products we chose can be used in conjunction with one another. Be sure to read the directions carefully just to be sure.

Next, consider the texture of the soil. Sandy soils have a gritty texture made of large particles while clay soil particles are smaller and much harder and more compact. Each of these is challenging in their own way.

With sandy soils, you want to make it easier for the soil to hold onto nutrients and water. Clay soils have the opposite problem. They're not permeable enough so you need to increase aeration and drainage.

Finally, consider the pH and salt content. Some plants, like beans, carrots, strawberries, and trees like pine and maple are very sensitive to salts. In this case, use plant-based composts. Determine what pH your plants prefer. Even neutral soil amendments can change the pH level. If your plants are particularly sensitive and like something a little higher or lower on the scale, adding a neutral pH can shift this, affecting your plants' growth.

How to use soil amendments?

One can add soil amendments at any time of year but it's a good idea to test the soil and make changes at the beginning of the planting season and again before winter. This way, the soil is adequately prepared for supporting your plants as they grow through the summer and to keep things stable throughout the winter. The application depends on the product so make sure you read the instruction carefully. Generally, you add the correct amount of the amendment then use a rake or spade to work it into the top of the soil. Soil quality is one of the defining factors in whether or not your plants thrive. You can't rely on Mother Nature to make everything right. Soil amendments let you control the quality of the soil.

Soil conditioner application

Rate: The criteria for application rate are:

1. At rates sufficient to compensate for a soil's deficiencies in specific chemical, physical, or biological characteristics.
2. At rates consistent with the soil's ability to absorb the specific soil conditioner
3. At rates that will not cause crop toxicity or suffocation
4. At rates that do not risk releasing soil conditioner into the environment through leaching or runoff.
5. For high moisture soil conditioners, such as crop wash water, at rates that do not exceed the infiltration capacity of the soil.
6. Understanding Your Soil Test Recommendation for Liming

Methods: Implement the following procedures for the best soil conditioner application and placement.

1. Soil amendments can be added at any time of year, but it's best to test the soil and make changes at the start of the planting season and again before winter.
2. For most field crops, such as annual vegetables and forages, evenly distribute soil conditioners and incorporate them into the soil as soon as possible.

3. For soil conditioners used as "mulches" to improve water conservation or to alter soil conditions within the rooting zone of the target crop (e.g., sawdust placed around blueberry plants).
4. For perennial crops where certain soil conditioners, such as lime, cannot be applied on a regular basis.
5. To avoid toxicity, reduce the annual application rate.
6. To compensate for the lower rate, increase the frequency of application.

Measurement of Application Equipment - To achieve the desired result with any soil conditioner, calibrate the application equipment to ensure that the actual rate of application and material placement match the intended rate and placement.

Conclusion:

The use of naturally occurring materials as soil stabilizing conditioners has been part of agriculture and general land management for millennia. Some of the most familiar conditioners in use since ancient times include animal and green manures, peat, crop residues, organic composts, and lime. Commonly used amendments include municipal biosolids, animal manures and litters, sugar beet lime, wood ash, coal combustion products such as fly ash, log yard waste, neutralizing lime products, composted biosolids, and a variety of composted agricultural by-products, as well as traditional agricultural fertilizers. The early uses of conditioners resulted from knowledge gained from trial and error long before there was scientific understanding of how efficacy was derived. Other conditioners in use for centuries or decades include composted manures, various organic debris, including sawdust or other milling residues, food, textile, and paper processing wastes and other organic industrial wastes, as well as mineral materials such as rock phosphates, gypsum, coal dust, rock flour, and sand. The type of conditioner depends on the plant type and the current soil composition. Some soils are deficient in nutrients necessary for proper plant growth. Several examples include peat, coffee grounds, compost tea, fertilizers, lime, vermiculite, and sphagnum moss are examples of soil conditioners. Aside from that, the mechanical properties of soil must be improved for some engineering aspects such as dam and bridge construction. As a result, soil conditioners play an important role in increasing soil strength. Soil conditioner use and technology, since ancient times, has, in great part, been a marriage of convenience between the agricultural necessity for chemical and physical maintenance or enhancement of the land, and for the disposal or management of waste materials from the full spectrum of human activities. However, since about the early nineteenth century, as modern physics and chemistry were applied systematically to agriculture, soil conditioner identification, development, and use became more creative and deliberate. The terminology and concept of soil amendments and conditioners was gradually assigned primarily a physical-conditioning connotation. Chemical conditioning, vis-a-vis supplying plant nutrients to soil, has been largely ascribed to materials termed fertilizers. Many fertilizers affect soil physical properties, both directly and indirectly, and many soil conditioners affect soil fertility both directly and indirectly. The overlap of physical and chemical effects occurs because of the intimate association of all soil physicochemical process and their coupling, as well, to soilsupported biotic processes, cycles, and functions. The designation of fertilizer versus conditioner is often based on the dominant effect intended.

Advantages of soil conditioners:

Inadequate soil physical condition can impede soil aeration, plant root development, and water ingestion into the soil and subsequent movement. Both farmers and scientists are interested in improving crop productivity through enhanced physical state of the soil. By employing effective management strategies, these objectives can be partially achieved. Also, there are modifying substances that promise to enhance the soil's physical quality. The formulation, application rate, and predicted or claimed mechanism of action of soil conditioners vary widely. Among the claims made for different goods are

- Increased water-holding capacity
- Reduced compaction and hardpan conditions
- Improved soil structure and aeration
- Improved cation exchange
- Alkali soil reclamation
- Increased availability of water to plants
- Better root development
- Improved tile drainage effectiveness
- Better chemical incorporation
- Higher yields and quality
- Release of "locked" nutrients

Understanding the composition, application, and effectiveness of these products is crucial. The water-holding capacity, water availability to plants, and effective drainage depend on soil porosity. Hence the presence of soil conditioner affects porosity. Understanding the composition, application, and effectiveness of these products is crucial. The water-holding capacity, water availability to plants, and effective drainage depend on soil porosity. Hence the presence of soil conditioner affects porosity (Mukherjee and Mukherjee, 2013).

Disadvantages of soil conditioners:

- Soil conditioners might be costly depending on the soil requirements
- The soil improvement via soil conditioners could be time consuming
- Soil conditioners can also negatively impact the soil by releasing excess nutrients in the soil therefore impacting the growth of plants and if washed away in water bodies can be a serious concern.

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HEAVY METAL CONTAMINATION IN SOIL AND ITS MANAGEMENT

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Abstract:

By the accumulation of heavy metals and metalloids, soil contamination may occur. Emissions from the rapidly expanding industrial areas, disposal of high metal wastes, mine tailings, leaded gasoline and paints, land application of fertilizers, animal manures, sewage sludge, pesticides, wastewater irrigation, coal combustion residues, spillage of petrochemicals, and atmospheric deposition are of the principal reasons. This paper explores the issue of heavy metal contamination in soil and its potential impact on the environment and human health. Heavy metals are toxic elements that can accumulate in soil due to human activities such as industrial activities, agricultural practices, and improper disposal of waste. The paper provides an overview of the sources, transport, and fate of heavy metals in soil and their effects on soil fertility and plant growth. Various methods for detecting and measuring heavy metal contamination are also discussed. It focuses on the management of heavy metal contamination in soil. This includes the use of physical, chemical, and biological remediation methods, as well as sustainable approaches such as phytoremediation and biochar application. Each method's effectiveness, advantages, and limitations are discussed. Overall, the paper highlights the importance of identifying and managing heavy metal contamination in the soil to protect the environment and human health. It also emphasizes the need for a multidisciplinary approach involving collaboration between scientists, policymakers, and stakeholders to develop sustainable solutions for managing heavy metal contamination in soil.

Keywords: Environment, fertilizers, pesticides, phytoremediation, soil fertility.

Introduction:

Heavy metal pollution of soil is a global issue with serious consequences for human health and the security of food supplies. Mining, smelting, conflicts and military training, the electronic industry, fossil fuel consumption, garbage disposal, pesticide use, and irrigation are some of the anthropogenic activities that inadvertently introduce heavy metal pollutants to soils. The combustion of coal releases heavy metals into the environment in the form of vapour, flue gas particulate matter, fly ash, and bottom ash. These heavy metals include mercury (Hg), cadmium (Cd), chromium (Cr), cobalt (Co), zinc (Zn), and nickel (Ni) (Nalbandian, 2012). Deposition of bio-toxic major heavy elements like mercury, cadmium, lead, and chromium, as well as other heavy elements, can lead to concentrations in the soil that are significantly higher than natural background levels. Metals are not biodegradable; their concentrations can be amplified hundreds of times through biological means, with serious consequences for human health. Recent years have seen an increase in soil heavy metal concentrations due to the discharge of huge amounts of heavy metals from industrial activities and mining. The widespread application of pesticides and fertilizers may also be to account for rising heavy metal levels in soil (Malidareh, 2014).

Heavy metal pollution has skyrocketed in recent years due to the fast growth of metropolitan areas and industrial activity, severely damaging the natural environment. There is widespread agreement that heavy metal poisoning of soils and crops is a serious environmental threat in many parts of the world, including the United States, Europe, Australia, and Asia (Reddy, 2014). Surface capping, soil flushing, electrokinetic extraction, solidification, vitrification, and phytoremediation are only some of the in-situ and ex-situ remediation methods that have been developed over time to confine, clean up, or repair heavy metal-contaminated soils. These methods can be broken down into three groups: those that focus on containment (such as capping or encapsulation), transformation (such as stabilization or immobilization), and transport (such as extraction or removal). In general, each of these approaches to soil remediation relies on a unique set of mechanisms to achieve its goals, and each has its own set of benefits and drawbacks in practical use. More importantly, there is a huge disparity between the effectiveness and expense of various methods in actual field use (Khalid *et al.*, 2017).

Sources of heavy metals in soil:

Heavy metal contamination of soil has been linked to negative outcomes for human health, ecological systems, and crop yields. Hence, to safeguard the environment and human health, it is essential to locate and control potential sources of heavy metal contamination.

Heavy metals are a class of elements characterized by their relatively high atomic weights and their potential toxicity to life systems at higher than background levels. Lead, cadmium, mercury, arsenic, chromium, and others fall under this category of toxic metals. In various forms, heavy metals are ubiquitous in the natural world, and they have been linked to negative outcomes for human and animal health as well as ecological systems.

1. Natural sources

Geological processes can cause heavy metals to be present in the environment. Heavy metals can be released into the environment through a variety of natural processes, including volcanic eruptions, rock weathering, and erosion. Plants and animals may be exposed to heavy metals found in soils and sediments in high concentrations due to natural processes.

2. Human activities

Heavy metals can be released into the environment for a variety of reasons, including human activity. Heavy metals can enter the environment through human-caused pathways, including mining, smelting, and refining. The use of fertilizers and pesticides, as well as improper disposal of industrial and municipal waste, can also lead to heavy metal contamination of the environment.

3. Contaminated water

Heavy metals like lead and mercury can end up in water supplies. Agricultural runoff, industrial discharges, and municipal garbage are all potential entry points for heavy metals into streams. Heavy metals, once released into water, can biomagnify via the food chain, exposing humans to the chemicals when they consume contaminated fish and shellfish.

4. Atmospheric deposition

Pollutants and other airborne particles eventually fall to the ground, a process known as atmospheric deposition. Particulate matter released into the air by activities such as industry, transportation, and cooking can act as a carrier for heavy metals and deposit them in the environment. These heavy metals, once deposited, can pose a threat to plant and animal life. Exposure to heavy metals can also come through common consumer goods. Paint, jewellery, and pottery are just a few examples of things that may contain harmful levels of lead or other heavy metals. Ingestion or environmental release of heavy metals during the production or disposal of these items can create a risk of exposure.

When exposed to heavy metals, humans, animals, and ecosystems can all suffer negative consequences. Heavy metals are known to cause developmental difficulties, brain damage, cancer, and reproductive issues in humans when exposed to high enough concentrations. Exposure to heavy metals can have devastating impacts on wildlife, including lowered reproduction, stunted growth, and compromised immunity. Heavy metals can accumulate in sediments and soil, making it harder for plants to get the nutrients they need to flourish.

Physical methods:

1. Soil pore water

The soluble concentrations of heavy metals at the water-soil interface have been determined using speciation analysis of soil pore water, provided that the metals did not undergo any changes in chemical form throughout the sample period (Zeng *et al.,* 2020). Marble sludge, compost, and synthetic Fe oxides were all found to considerably lower trace metal concentrations in soil pore water compared to untreated acidic and polluted soil in a study by Gonzalez *et al.* (2013). Soil pore water concentrations of heavy metals in the surface and intermediate layers of the planted columns were found to be significantly reduced by the addition of compost, pig slurry, and hydrated lime (Pardo *et al.,* 2014a, b). The As concentration in soil pore water treated with 1%FeSO4 and 0.37% lime during 3 times was found to be lower at 48 days (the sampling time) than at 14 days (the treatment time) in a study conducted by Fresno *et al.* (2018). In a similar vein, Cui *et al.* (2020) employed hematite to immobilize Cu and Cd in red paddy soil under wet conditions. As the hematite dosage grew from 1% to 5%, the Cu2+ and Cd2+ contents in the pore water declined from 2.75 mg/L to 0.64 mg/L and from 34.5 g/L to 10.6 g/L, respectively, in their studies.

2. Column leaching experiments

Column leaching experiments, which mimic the dynamic field circumstances, are superior to static batch experiments for elucidating metal leaching behaviours within a specific region. The effects of leaching with water, acid, salt, and a chelating agent were investigated in a column leaching study. Researchers have recently used column leaching tests to assess the effectiveness of metal stabilization in polluted soils. Fan *et al.* (2011) conducted column leaching experiments to estimate the Cu stabilization capability by calcium water treatment residue (Ca-WTR), and they found that after 10 leaching events, Cu concentrations in the leachate from 0.5% Ca-WTR amended soils were even below the US EPA drinking water limit. Column leaching experiments conducted by Michalkova *et al.* (2014) revealed that amorphous Mn oxide (AMO) was the most efficient stabilizer for decreasing Cu concentrations in the leachate during the first 1000 minutes of the experiment. Using compost to stabilize Cd and Pb, Gul *et al.* (2019) found that leaching concentrations of these metals were reduced in the soil column. During DTPA-assisted column leaching, 3-mercaptopropyltrimethoxysilane-modified palygorskite (PAL) and sepiolite (SEP) treatments were more effective at immobilizing Cd than for Cu and Zn, according to a study by Wang *et al.* (2020a). Column leaching studies are useful for researching the dynamic leaching behaviour of heavy metals in low-permeable solid wastes but are inappropriate for studying the same behaviour in highly permeable solid wastes.

3. Diffusive techniques

The in-situ sampling method of a diffusive gradient in thin films (DGT) proved useful in the investigation of the dynamic availability of heavy metals in saturated soils. If performed under diffusion-limited conditions, the DGT method can provide a direct representation of plant heavy metal uptake and accumulation (Bidar *et al.*, 2019). As a result, numerous scientists have successfully employed the DGT method to indirectly assess the availability of metals in soil solutions. For instance, after applying lime to contaminated soils at a former smelter site, Bade *et al.* (2012) observed an increase in Pb in DGT uptake (MDGT) and a decrease in Zn, Cu, and As in MDGT, correlating to changes in heavy metal concentrations measured in the first and second steps of the European Community Bureau of Reference (BCR) and In vitro physiologically based extraction test (PBET) (Egene *et al.*, 2018).

The low resupply of Cd and Zn released from soil solid to soil solution in both unamended and amended soils demonstrates the clear advantage of the DGT technique in giving meaningful information concerning the resupply metal kinetics. Direct interaction between KDP and Pb decreases Pb mobility. Xu *et al.* (2019) found that PbDG content in an alkaline silty loam soil amended with 300 mg/kg KDP was lower than the control. Almas *et al.* (2019) found that in polluted soils from a shooting range, the slag & FeSO4 and slag&organic treatments resulted in a significant reduction in MDGT, by 78% for SbDGT and 90% for PbDGT, respectively. Unfortunately, the lack of a consistent operating technique, variations in species concentration, and batch-to-batch incomparability of DGT data severely restrict its utility and popularity.

4. Electrokinetic extraction

The goal of electrokinetic extraction is to decontaminate polluted soils using electrical adsorption, thus removing the source of the contamination. As a result of the attractive force of the formed electrical field, cations in the solution phase of the contaminated soil migrate to the cathode and anions migrate to the anode when low-density direct current (DC) electricity is provided via electrodes put in the ground. Electroplating, co-precipitation, solution pumping, or ion exchange resin complexation are then used to remove the metal impurities concentrated at the polarized electrodes (FRTR, 2012). Testing of electrokinetic extraction for decontaminating soil began in the late 1980s (Alshawabkeh, 2009). As a rule, the method can be used on either water-saturated or water-free soils, and it works well for decontaminating fine-grained soils with poor hydraulic conductivity. However, the types and quantities of contaminants present, as well as the soil type, pH, and organic content, all play a role in whether electrochemical remediation is successful in the field (Figueroa *et al.,* 2016).

5. Vitrify technology

The organic matter in the soil is either volatilized or decomposed by the use of the vitrify method, which involves heating the soil to temperatures between 1400 and 2000 degrees Celsius. The off-gas treatment system gathered the steam and pyrolysis products that were generated. When the molten material cools, it solidifies into a vitreous rock, which prevents the migration of heavy metals. It has been said that vitreous has ten times the strength of concrete. For ex-situ remediation, the necessary energy is generated either by burning fossil fuels or by heating electrodes directly and is then delivered through arc, plasma, or microwave. When doing in-situ remediation, heat can be applied via electrodes embedded in the soil. In a nutshell, this method is highly effective in removing heavy metals. Unfortunately, it is difficult to use and requires a great deal of energy during the melting process, therefore it is expensive (Zhang *et al.,* 2010).

6. Surface capping

Capping the surface of a polluted area entails only covering it with a protective layer of impermeable material. As no effort is taken to remove the heavy metal contaminants or at least lessen their reactivity in the soil, this containment-based methodology cannot be considered a true soil "remediation" method. However, the approach is effective in preventing further contamination of the soil and any subsequent skin contact or accidental ingestion. The surface cover also acts as an impermeable barrier to the infiltration of surface water, stopping the spread of soil contaminants to nearby water sources. Yet, when soil is capped, it loses its ability to perform its ecological role, particularly in fostering plant growth. As a result of the treatment, the land can be put to other, more practical uses, such as a parking lot or a sports field (NJDEP, 2014).

Depending on the features of the site and the goals of the remediation project, a unique capping system should be chosen. There are a variety of capping material options, such as clay, concrete, asphalt, and high-density polyethene, allowing for the use of both single-layer and multi-layer systems. Extending 60–90 cm beyond the horizontal extent of the contamination site is recommended for a surface cover with sufficient structural strength and dynamic stability (Rumer and Ryan, 1995). Ditches, dikes, and slopes are common water management structures used to redirect water away from surface caps. Replanting is possible in multi-layer cap systems by adding topsoil on top of the impermeable cover.

7. Encapsulation

Encapsulation is a corrective strategy analogous to surface capping that is also known as the "barrier wall," "cutoff wall," or "liner" method. Using a physical barrier system with low permeability caps, enclosing underground barriers, and, in exceptional cases, barrier floors, toxic soil can be contained and cleaned up. Pollutants are contained and contaminated areas are sealed off, which prevents the spread of harmful substances and the exposure of organisms to them Meuser (2013). The low permeability caps, which are often synthetic textile sheets or clay layers, restrict the infiltration of surface water into the subsurface and stop the leaching of contaminants. These impenetrable barriers below the earth prevent the contaminated source from spreading laterally to other locations through diffusion or subsurface movement.

The most difficult part of encapsulation is erecting subsurface, impermeable barriers where pollution is present. A wide variety of wall types have been developed over the years Meuser (2013). For instance, a trench is dug to the required depth with a trench cutter to begin the slurry wall procedure. Afterwards, a slurry of cement, bentonite, and water is poured into the trench, and it hardens into a wall that is anywhere from 0.4 to 1 meter in thickness. HDPE (high-density polyethene) membranes, sheet piling, and glass tiles can be placed into the still liquid slurry to boost the wall strength and impermeability. While the wall's panels might be built in stages at different periods, they must all make watertight contact with one another to prevent the structure from collapsing. For thin wall building, a pressure jet is used to vibrate a heavy steel beam into the earth, creating a tiny trench. The trench is then lined with a thin layer of 0.15 m thick wall made of a slurry of clay, cement, and water. When digging a trench, compacting the earth further increases the structure's resistance to water seepage. Locks can be used to secure the neighbouring piles of steel/aluminium sheets, precast concrete plates, or wood boards that have been driven into the ground to create a sheet pile wall.

Chemical methods

Most environmental recommendations for soil restoration are still, in many countries, based on the sum of heavy metal pollution concentrations. To prevent an overestimation in the evaluation of remediation results, it is vital to stress that the bioavailable concentrations of heavy metals in treated soils rather than their total contents should be recommended as an effective indication. Most experimental programs documented in the scientific literature have used chemical approaches, such as toxicity leaching, chemical extraction, and sequential extraction procedures, to evaluate the effectiveness of metal stabilization in contaminated soils (Bagherifam *et al.*, 2014).

1. Bioavailability extraction methods

Heavy metal pollution in soils is measured by how much of it is absorbed by organism receptors, and this is known as the metal's bioavailability. Chemical extraction techniques, plant metal uptake, and earthworm bio tests are commonly used to determine metal bioavailability. The metal bioavailability in treated soils can be estimated using several chemical extractants, such as water, salt solutions (0.01 M CaCl2), mineral acids (0.1 M HCl), buffer solutions (1 M NH4OAc), and chelating agents (0.05 M EDTA and 0.005 M DTPA) Huang *et al.* (2020).

For instance, Han *et al.* (2020) evaluated five extraction methods to evaluate the stabilization effects of limestone and steel slag for Cd and Zn in polluted soils from seven defunct Au and Ag mines, and they discovered that the extraction results obtained from the CaCl2 and Mehlich-3 methods were more reasonable than those obtained from the EDTA, DTPA, and TCLP methods. Among four distinct extractants, EDTA-NH4OAc had the best results to predict the As bioavailability in polluted soils, based on a comparison between the chemical metal fraction from chemical extraction methods and the metal bioavailability from earthworm bioassay. The Cd uptakes by fruits of tomato and cucumber were significantly decreased by 24-30% and 36-54%, respectively, according to the results of greenhouse experiments conducted by Khan *et al.* (2019) to examine the effects of four organic stabilizing materials on the Cd availability by vegetables planted in mine degraded soils. DTPA is one of the existing extractants that has been utilized for assessing the bioavailability of Cu, Fe, Mn, and Zn in slightly acidic soils Bakircioglu *et al.* (2011). To estimate the amounts of micronutrients like Cu, Fe, Mn, Zn, and P that are available to plants, the Mehlich-3 method is used.

2. Sequential extraction methods

Heavy metal speciation about geochemical phases in polluted soils can be determined through chemical sequential extraction, shedding light on the potential environmental concerns posed by heavy metal mobilization (Nevidomskaya *et al.*, 2020). The most used methods for determining heavy metal speciation in stabilized soils are the sequential extraction technique (SEP) created by Tessier *et al.* (1979) and the European Community Bureau of Reference (BCR). Phosphate rock (PR) activated by oxalic acid (APR) was found to be more effective than PR at converting Pb, Zn, and Cd from the labile fraction into the residual fraction in a study conducted by Zhang *et al.* (2018), adapted the BCR method for assessing the potential metal mobility in amended soils. Lian *et al.* (2019) observation of a similar outcome utilizing the Tessier SEP method provided further evidence that reactive nano-silica was very successful at converting most labile Pb and Cd into more stable species. Yet only a small number of sequential extraction procedures were developed with the express purpose of studying chemical forms of As and Hg in polluted soils. Sequential extraction results showed that synthetic iron material (Fe-Ce oxide) could reduce the non-specifically and specifically adsorbed As fraction by 22-31% and 5-17%, respectively, in contaminated soil using the five-step method described. To determine the Hg chemical forms in the rhizosphere, Li *et al.* (2019b) used a selective sequential extraction procedure based on the work of Wang *et al.* (2011). They found that, compared to the control, the residual Hg fraction decreased to 45.4% and 35.6% in contaminated paddy soils treated with 500 mg/kg and 1000 mg/kg of elemental S, respectively. However multi-sample analysis is desperately needed for a reduced sequential extraction process because of the time-consuming, difficult, and accurate nature of the current method. In addition, the extraction conditions might affect the metal fractionation in soils, leading to inconsistent results amongst laboratories.

3. Standardized toxicity leaching methods

The efficacy of stabilization treatment for heavy metal-polluted soils is often assessed using standardized toxicity leaching procedures. To assess the leaching potential of heavy metals in bentonite-amended soils, Yu *et al.* (2017) conducted a toxicity characteristic leaching procedure (TCLP) test and found that metal leachability was significantly reduced after unmodified bentonite treatment, from 19.4 to 12.2% for Cu, from 24.3 to 15.4% for Zn, and from 17.5 to 11.3% for Cd. Amorphous Mn oxide (AMO) was shown to be more successful in reducing As content in leachate due to its high dissolution at low pH values, as investigated by Michalkova *et al.* (2016) using pH-static leaching tests to investigate the influence of pH on the immobilizing capability of Fe and Mn oxides. The three stabilizing materials (5% SPP, KPM, and KP) resulted in a 92% reduction in leachable Pb from S/S treated soils due to higher remediation capability, as determined by Zhang *et al.* (2015), who used the China National standard leaching toxicity method (GB HJ/T300-2007) to select effective S/S materials for an industrial contaminated site. To assess the Cr stabilization capacity of hexadecyltrimethylammonium (HDTMA) modified montmorillonites, Yang *et al.* (2017) modified TCLP. Their results showed that Cr leachability drastically decreased from 16.8% to 11.2% to 3.5% with increasing the loading concentrations of HDTMA from 50% to 100% to 200%. In a related study, Li *et al.* (2018) found that following S/S treatment, the leached As content rose in synthetic precipitation leaching procedure (SPLP) testing because As was more mobile in an alkaline SPLP leachate. Unfortunately, a comprehensive understanding of the release kinetics of heavy metals under variable settings was not possible to obtain through batch leaching testing (Lei *et al.*, 2020).

4. Bioaccessibility extraction methods

Heavy metals in polluted soils are only partially absorbed through the gastrointestinal tract, hence assessing the danger to human health based on bioaccessibility is more reliable (Paltseva *et al.,* 2020). Because of this, there has been a lot of focus throughout the world on studies including bio accessibility concerning the assessment of remediation efforts and the management of risks at metal-contaminated sites (Xu *et al.,* 2020). Bioaccessibility of metals in the human digestive system is typically evaluated using in vitro techniques like the physiologically based extraction test (PBET), solubility bioaccessibility research consortium (SBRC), the bioaccessibility research group of Europe (BARGE), unified BARGE method (UBM), and in vitro gastrointestinal method (IVG). For instance, Fan *et al.* (2020) used IVG to test the stabilization effects of nZVI-embedded biochar for As in two polluted soils (GX and JX), and they discovered that the bioaccessibility of As in the gastric phase was reduced by 77.5% for GX and 85.4% for JX and that it was reduced by 86.5% and 91.1%, respectively, in the intestinal phase. Using a recently established mouse kidney model and four in vitro bioaccessibility approaches, Li *et al.* (2017b) investigated the effect of 0.5% phosphoric acid (PA) on Pb relative bioavailability (RBA) in contaminated soils (PBET, SBRC, UBM, and IVG). They found that Pb-RBA was reduced by 1.51–19.1% in gastric PBET and by 0.15–20.4% in intestinal SBRC, numbers that are more in line with the 4.10%–32.7% reduction seen in a mouse model. These techniques, however, call for a great deal of expertise in the laboratory and a significant investment in biological reagents.

5. Chemical leaching

Soil contamination can be removed using a process known as chemical leaching, which involves flushing the area with clean water, chemicals, and other fluids or gases. Phosphoric acid was the most effective extractant, able to remove 99.9 per cent of the arsenic in a sample with a 9.4 per cent acid concentration in just 6 hours. Extraction rates of sulfuric acid were likewise quite high. An eco-friendly and cheap extraction method for arsenic from polluted soil has been investigated. Several authors, including Lee (2007). Arsenic (V)-contaminated soil with a yellowish-brown colour was employed as a soil sample. Out of several different potassium and sodium salts, potassium phosphate proved to be the most efficient arsenic extractor. At 40 degrees Celsius and a phosphate concentration of 300 mM, arsenic was successfully removed.

Among extractants, EDTA has the most versatility since it can create a stable composite with most heavy metals across a wide pH range. Arsenic (As)-contaminated stream sediments near a defunct mine in Goro, Korea were cleaned up using a soil washing procedure (Ehsan *et al.*, 2007). Fine sediments were removed at an efficiency of >95% after washing for 1 hour with 0.2 M citric acid. The As removal efficiency was maximized when 0.2 M citric acid and 0.1 M potassium phosphate were used. It's good knowing that using a single extractant for all the soil's various toxins yields a mediocre result at most. Hence, we were able to combine or sequentially employ numerous extractants. Results showed that Na2EDTA solutions were significantly more effective than Na2S2O5 in removing heavy metals from soil samples. When compared to its effects on zinc and cadmium removal, Na2EDTA was less effective at removing chromium and more effective at extracting lead. The addition of 0.1 M Na2S2O5 to a 0.01 M Na2EDTA solution significantly improved its ability to remove cadmium and zinc. Hence, combining the two chemicals may be the most cost-effective option for remediating some types of contaminated soil (Ehsan *et al.*, 2007).

6. Chemical fixation

Chemical fixation is to add reagents or materials into the contaminated soil and use them with heavy metals to form insoluble or hardly movable, low toxic matters, thus decreasing the migration of heavy metals to water, plant and other environmental media and achieving the remediation of soil Kos and Leštan (2003). Clays, metallic oxides, biomaterials, etc. were used as soil conditioning materials. Hodson *et al.* (2000) evaluated the ability of bone meal additions (finely ground, poorly crystalline apatite, Ca10(PO4)6(OH)2 to immobilize pollutant metals in soils and reduce metal bioavailability through the formation of metal phosphates has been evaluated. Batch experiments and subsequent extraction of metals from controls and bone meal-amended soils using 0.01 M CaCl2 and DTPA indicated that bone meal additions decreased the availability of the metals in the soils. Li *et al.* (2009) studied the efficiency of sodium bentonite, bentonite, and diatomaceous earth in the remediation of Cd-contaminated soil. The results showed that the concentration of Cd reduced by 21.40, 27.63, 27.24, and 32.30% as compared with the control when the additive amount was 20, 30, 50, and 40 g/kg, respectively. There was also a report on the remediation of contaminated soil by attapulgite clay (Hong *et al.*, 2002). Results demonstrate that by adding moderate attapulgite clay, Cd concentration reduce 46% in the soil, while the soil productivity and quality were not affected. (Zhang *et al.*, 2010) found the chemical fixation efficiency of phosphate rock, furfural dreg and weathered coal on the contaminated soil. The results showed that three conditioning agents could reduce the concentration of Cu, Zn, Pb, and Cd to some degree. The chemical fixation could remediate the soil with low-concentration contaminants; however, the bioavailability of fixed heavy metals may be changed with the changing environmental condition (Bolan *et al.*, 2003). In addition, the use of conditioning agents could change the soil structure to some degree and have effects on the microbes in the soil.

7. Industrial waste-based materials

Due to the significant annual production, industrial by-products have drawn a lot of attention. The sustainable use of these low-value by-products can be accomplished by recycling them as soil supplements. Fly ash from coal combustion is a typical by-product of the coal industry; it is thought that 780 million tonnes are produced yearly. All varieties of fly ash contain sizable amounts of SiO_2, Al_2O_3, Fe_2O_3, and CaO and have a comparable metal immobilization mechanism with oxides, even though the chemical compositions of fly ash may vary due to varied sources and compositions of the coal burned (i.e., liming & precipitation, surface complexation). Red mud is a by-product of the alumina industry's Bayer process (Taneez & Hurel, 2019). Red mud is a mixture of oxides, including Fe_2O_3, Al_2O_3, SiO_2, Na_2O, CaO, and TiO_2, much like fly ash (Zia-ur-Rehman *et al.*, 2019). Red mud can therefore be used to immobilize heavy metals as it possesses comparable remediation mechanisms (Taneez & Hurel, 2019). For the long-term cleanup of heavy metals, other oxide-containing industrial wastes, such as steel slag and coal gangue, have also been used. Nevertheless, hazardous metals and organic pollutants may be present at significant levels in industrial wastes. These toxins may be released and travel over time after being applied to the soil, causing threats to the ecosystem.

8. Natural minerals

Due to their low production costs and inherent safety for the environment, minerals make excellent GSR material candidates. Among the many factors that make clay minerals appealing for metal stabilization are their high specific area, liming (pH-increasing) action, superior ion exchange capacity, and abundance of surface hydroxyl groups, clay minerals have garnered a lot of attention Doni *et al.* (2020). The three most common stabilization mechanisms in clay-based S/S methods are liming, surface complexation, and precipitation. However, unaltered clay minerals have problems with a lack of adsorption capacity, selectivity towards metal types, and a rapid decline in stabilizing ability (Xu *et al.*, 2017). (Many attempts have been undertaken to modify natural clays to create more "strong" immobilizing agents to overcome these challenges. Montmorillonite's ability to bind heavy metals like Cd and Hg has been improved, for instance, by adding humic acid (Wang *et al.*, 2020e). Leachable metal concentrations (> 65% for both metals) were reduced because the oxygen-containing hydroxyl, amino, carbonyl, and carboxyl groups in the humic acid layer favoured surface complexation. An innovative mercapto-modified attapulgite was used for the immobilization of soil Cd by Liang *et al.* (2019). Because of the increased sorption of bioavailable Cd onto the modified clay mineral, modified attapulgite has the potential to reduce Cd accumulation in plants by 75%. Intriguingly, Wang *et al.* (2019a) discovered that sulphur-modified organoclay enhanced the efficacy of phytoextraction by mobilizing soil Hg (the water and acid-soluble fractions of soil Hg rose by 700%). Clay isn't the only natural material that can help get rid of heavy metals, though. Examples include the alkaline aluminosilicate mineral zeolite, which has a highly developed microporous structure and can immobilize hazardous metals by non-specific adsorption and the liming effect (Lee *et al.*, 2019). Due to its high Si concentration, the naturally occurring siliceous mineral diatomite can stabilize metals by surface complexation and non-specific adsorption while also encouraging plant development (Radziemska *et al.* (2020). Minerals have fewer negative effects on soil than additions obtained from metal-rich industrial waste.

9. Soil washing

Soil washing can significantly lower pollutant concentrations and bring the soil back down to levels that are compliant with environmental regulations. To get rid of the less contaminated coarse particles, the soil typically needs to be screened first. To remove the harmful metals, the remaining fine material must be combined with a washing solution Hou (2020). The appropriate washing solution for this process, which is metal-specific, should be able to increase metal mobility while preserving the soil's physicochemical qualities (for reuse purposes). Soil cleaning can be thought of as a resource recovery technique (to reuse the soil). The success of soil washing depends on choosing the right extractant. The washing process can make use of water, chelating agents, bases, acids, solvents, and surfactants, according to the US EPA (2017b). Conventional cleaning methods, however, might be bad for the environment. For instance, the EDTA that is still in the soil after being washed with chelants is difficult to degrade and will harm soil organisms Duo *et al.* (2019). Furthermore, EDTA, which is regarded as a major contaminant in aquatic bodies, may migrate from the remedied soil into groundwater or surface water, causing water contamination (EEA, 1996; WHO, 2011). Strong acids, such as HCl or H2SO4, cause the soil to become acidified, rendering it unusable for agricultural purposes (Ash *et al.,* 2016). Surfactant addition can help with the remediation of soils that have been co-contaminated with metal and organic pollutants, but it may have negative effects on the soil microbes. Several attempts to find "greener" washing solutions have been explored to reduce the influence on soil qualities. Humic substances, for example, are organic compounds found in nature (Kulikowska *et al.* (2015).

10. Solidification

Ex-situ soil solidification involves removing metal-contaminated soil from the site, moving it to a facility for treatment, screening out coarse materials (like N5 cm), and then combining it with a binder in an extruder. The binding ingredient permeates the soil and creates a solid, water-tight shell around the impurities. The method is also known as "microencapsulation." Ex-situ stabilization is the term for a technique that uses a stabilizing agent rather than a binding material to chemically immobilize impurities (FRTR, 2012). Molten bitumen, emulsified asphalt, modified sulfur cement (a thermoplastic substance melting at 127-149 °C), polyethene, pozzolan cement (fly ash, kiln dust, pumice, or blast furnace slag), and Portland cement are some of the binding materials used for pollutant encapsulation. If soluble phosphate or lime is applied, the substance immobilizes the heavy metals in the soil rather than hardening it. The direct encapsulation of contaminated soils in polyethene or bitumen wraps to create solid waste blocks that can be dumped in a nonhazardous landfill is another possibility (FRTR, 2012).

11. Soil flushing

By flushing an extraction fluid through the soil, pollutants can be removed from the soil in their natural environment. The fluid from the extraction process is collected, recycled, and eventually disposed of. It works best on highly permeable, homogeneous, coarse-textured soils (CLU-IN, 2017). Extraction fluid is often injected or absorbed into the soil during a soil flushing process. Heavy metals from soil require a specially formulated extraction fluid to be successfully removed. Studies on a variety of chelating and acidic solutions have all pointed to EDTA as the most potent agent. At 0.01 M and a 1:25 soil/solution ratio, Wuana *et al.* (2010) discovered that EDTA was more effective than citric acid and tartaric acid for extracting heavy metals from a fortified loamy sand (pH 6.1, organic matter (OM) content 8.7%) using batch studies. The efficiency of metal mobilization in the solutions varied over the spectrum of coexisting metal species (Cu, Ni, Zn, Cd, and Pb). A sequential extraction study revealed that while citric acid and tartaric acid were successful in mobilizing organic matter-bound and residual metal fractions, EDTA mobilized all non-residual fractions of metals. For the removal of Cu, Zn, and Pb from industrially contaminated loam sand (pH 7.0, OM 11.1%), Reddy *et al.* (2011) found that 0.2 M EDTA was the most effective extraction fluid compared to water, surfactants, and cyclodextrin.

Although the process of flushing soil is straightforward, implementing solution-collecting wells or subsurface drains can be difficult and expensive. Commonly, groundwater is removed if the water table is not very deep to recover the flushing elutriate. Soils rich in cation exchange capacity (CEC), buffering capacity, organic matter (OM), and clay typically have a low metal extraction efficiency. In addition to its potential for removing Pb from acidic sandy soils, Cd from low CEC, low clay, and moderately acidic soils, and Cr (VI) and As from low iron oxides, low clay, and high pH permeable soils, the technique has also shown promise in removing these contaminants from low CEC, low clay, and high pH permeable soil (Shammas, 2009).

Biological remediation

1. Phytoremediation

After the atmosphere, the soil is generally agreed upon as the most influential factor in the human environment. Soil is not only the primary dwelling place for many terrestrial organisms, including human communities but also a distinctive ecosystem for the development of all forms of life, notably plants. Soil contamination by chemical composition is difficult to measure, and there is no universally accepted definition of "clean" soil; hence, prospective soil contamination issues should be studied in the context of hazard prediction and damage assessment. Phytoremediation is the practice of using live, green plants to remove or sequester toxins, therefore reducing or eliminating the hazards associated with those substances. The three primary methods of phytoremediation are called phytovolatilization, phytoextraction, and phytoaccumulation. When plants are used for Phyto stabilization, the heavy metals are held in place through adsorption, precipitation, and reduction at the root level. And so that less of it can go into the groundwater and the food chain through reduced bioavailability at the roots (Hong *et al.*, 2002). Heavy metals can be rendered harmless by a process called phytovolatilization, which employs root exudates to convert the metals into a gaseous state. Among heavy metals, mercury has been the subject of the most research. Bizily *et al.* (1999) used the model plant Arabidopsis thaliana to test the expression of a modified bacterial gene (merBpe) encoding organomercurial lyase (MerB) under the control of a plant promoter, thereby investigating the possibility of plants as a source for mercury extraction and detoxification. A wide variety of doses of monomethyl mercuric chloride and phenylmercuric acetate did not stunt the development of transgenic plants expressing merBpe. Similarly, high amounts of organomercury were lethal to plants lacking the merBpe gene. This study provided preliminary evidence that natural macrophytes (such as trees, shrubs, and grasses) modified to express merBpe could be employed to digest methylmercury at polluted locations and sequester Hg (II) for subsequent removal. This method, however, can only be used for volatile pollutants, limiting its usefulness (Hodson *et al.,* 2000).

2. Phytomining

Because it has less of an impact on the environment than opencast mining, phytomining is considered a "green" method of metal extraction. It is possible to use phytomining to clean up heavily polluted soils. Phytomining provides a relatively quick method for the restoration of degraded lands (i.e., shortening the restoration duration to several years), in comparison to the hundreds of years it may take for natural revegetation of a mining-affected area (Sheoran *et al.,* 2009). Because of the plant cover, wind erosion and runoff are reduced, and harmful element movement into the rhizosphere is slowed. As a result, it is a popular method since it is good for the environment, harmless to the community, and aesthetically beautiful.

Heavy metals in soil can cause a variety of responses in plants. While most plant species can't stand being exposed to high levels of metals, some have evolved the ability to tolerate and even thrive in these environments. It has been shown by Wang *et al.* (2020d). Hyperaccumulation refers to the condition in which plants accumulate abnormally high levels of harmful metals in their tissues. Hyperaccumulator is "a plant that can accumulate metals to a concentration that is over 100 times higher than conventional plants growing in the same environment". Phyto mining is the practice of using hyperaccumulation to extract precious metals from plants. Hyperaccumulators translocate metals from soils rich in metals (such as mine tailings, low-grade ores, and metalliferous soils) to tissues above ground. Metals in plant tissues can be recovered through a process called sintering or smelting, which is performed after the plant has been harvested, dried, and reduced to ash Novo *et al.* (2017). A successful phytomining technique relies on a high biomass output and metal concentration in crop tissues. The harvesting of metals involves several factors that must be considered. It is well known that significant bioaccumulation in plant tissues arises from increased metal bioavailability; hence, an increase in labile forms of metals favours Phytomining.

3. Biological remediation

Heavy metals are resistant to degradation and destruction by microbes, but they can alter their movement and transformation by altering their physical and chemical properties. Extracellular complexation, precipitation, an oxidation-reduction process, and intracellular accumulation are the remedial mechanisms. Microbial leaching is a straightforward method of mining precious metals from low-grade ores and mineral concentrates. Microbial leaching also has potential use in mining site cleanup, sewage sludge detoxification, mineral waste product treatment, and soil and sediment cleanup from heavy metal contamination (Bosecker, 2001). Yet, conditions such as temperature, oxygen level, moisture level, and pH value can all have an impact on the success of the biological restoration. Certain microorganisms can only break down certain toxins, thus the use of microbes/zymin may lead to secondary contamination.

4. Animal remediation

Certain smaller animals can absorb heavy metals, and then later degrade and migrate the metals, reducing and limiting their toxicity as part of a process called "animal remediation." Results demonstrated that the combination of earthworms and straw mulching improved plant Cu concentration, though to a lesser extent than either treatment alone (Lambert and Weidensaul, 1991). Predicting heavy metal bioavailability to rice in polluted soils using single extraction methods. The findings demonstrated the feasibility of measuring heavy metals in soil (Zhang *et al.,* 2010).

Microbial remediation of heavy metal-contaminated soil

Heavy metal availability is an important factor in effective phytoremediation. By processes including methylation, changing the soil pH, redox reactions, producing and secreting siderophores, organic acids, and biosurfactant, microorganisms associated with plants can convert heavy metals into a more bioavailable form, hence improving the efficacy of phytoremediation. Microbe-aided phytoremediation is depicted in a simplified form by Ma et al (2011). Mobility, heavy metal uptake, and phytoremediation are all influenced by a wide range of biogeochemical processes (such as transformation, translocation, chelation, solubilization, immobilization, volatilization, precipitation, and complexation of heavy metals) (Rajkumar *et al.,* 2012). Here, we describe the compounds secreted by the microbial population associated with plants in the rhizosphere, and their involvement in the tolerance, sequestration, and transport of trace metals.

Remediation Mechanisms

1. Siderophores

The siderophores are the iron chelators with a low molecular weight that dissolve and store the element to make it available to the plant-microbe community **(**Chen *et al.*, 2017). Microorganisms that are connected with plants produce these chemicals when they are experiencing an iron deficiency. Current research suggests that siderophores can stimulate more than only iron (Fe) by binding to and forming stable compounds by complexation with metals like Al, Cd, Cu, and Ga (Gupta and Kumar, 2017). Specifically, Chen *et al.* (2017) looked at the tactics used by Enterobacter sp. strain EG16 in the presence of Cd stress and its potential function in metal stabilization in soil. The accumulation of cadmium in the Hibiscus cannabinus plant was much reduced due to the bacterium's increased synthesis of siderophores, which inhibited metal mobilization or bioavailability in the soil.

2. Biosurfactants

Microorganisms from all around the world produce biosurfactants, also known as surface-active agents (Das *et al.*, 2017). Surface and interfacial tension can be reduced with the use of biosurfactants, which are amphiphilic molecules with both hydrophobic and hydrophilic groups (Ma *et al.*, 2016a). Desorption of metals from the soil matrix by biosurfactants enhances the solubilization, mobilization, and bioavailability of heavy metals in plants, thus enhancing the phytoremediation process. To maximize phytobiomass and cadmium uptake, tomato plants were treated with a biosurfactant-producing strain of Bacillus sp. J119. The uptake of zinc by the sunflower plant was recently found to be improved by rhamnolipid (a glycolipid kind of biosurfactant) amendment in soil, as reported by Liduino *et al.* (2018). Whereas biosurfactants have been shown to aid in the phytoremediation of metal-contaminated soil, additional study is required to provide a clear explanation of their function in this process.

3. Organic acid

Soil microorganisms' production of organic acids raises metal bioavailability by lowering soil pH and raising chelation efficacy, which improves the phytoextraction of toxic elements (Ma *et al.,* 2011). Gluconic acid, tartaric acid, oxalic acid, citric acid, humic acid, malic acid, and oxalic acid are all examples of common organic acids. The uptake of nutrients and heavy metals by plants is said to be increased by these acids, which in turn improves phytoremediation Yang *et al.* (2018). Brassica napus's uptake of Pb was evaluated by Sheng *et al.* (2008), who looked at the part played by Pb-resistant endophytic bacteria (Pseudomonas fluorescens G10 and Microbacterium sp. G16). Scientists found that the endophytes studied enhanced Pb phytoavailability in plant shoots by secreting organic acid or siderophore. Citric acid improved Brassica napus' phytoextraction capacity for lead, according to research published by Shakoor *et al.* (2014), without negatively impacting plant development. Canola plant heavy metal bioaccumulation was shown to be proportional to the content of organic acids (such as humic acid, citric acid, and malic acid). Citric acid and oxalic acid were found to improve Suaeda vera's phytoremediation of zinc and cadmium, respectively (Gómez-Garrido *et al.*, 2018). Solubilizing and mobilizing the Cd in soil, gluconic acid generated by the cadmium mobilizing phosphate solubilizing bacteria has also been observed to improve phytoremediation (Yang *et al.*, 2018).

4. Metal Reduction

It is widely established that the microbial biogeochemical redox process results in a wide variety of chemical changes in metal pollutants. Metals are either oxidized (turned into oxides) or reduced (made into a reducing agent) by microbes (Olegario *et al.*, 2010). As, Cr, Hg, Fe, Mn, and Se are some of the most frequent heavy metals that undergo redox reactions, changing their speciation and their mobility in soil. By converting harmful and mobile metals into non-toxic and immobile forms, redox processes mitigate the phytotoxicity of heavy metals (Ma *et al.*, 2016a). Geobacillus sp. and Bacillus sp., two metal-resistant As-oxidizing bacteria, were reported by Majumder *et al.* (2013) to convert As3+ (a mobile and hazardous form) to As5+ (less mobile and less toxic form). Another study found that when a Cr-resistant bacteria (Cellulosimicrobium cellulans) was introduced to the soil, the green chilly plant's uptake of Cr6+ was reduced by 37% in the shoot and 56% in the root, compared to the control. Chatterjee *et al.* (2009) concluded that C. cellulans could reduce Cr from the mobile and toxic form of Cr6+ in the soil to the less mobile/immobile and non-toxic form of Cr3+. The phytoremediation potential of the Cr hyper-accumulator grass Vetiveria zizanoids is greatly enhanced by the isolation of a strain of Bacillus cereus that has recently been shown to be particularly successful in reducing heavy metals (Cr, Fe, Cd, etc). (Nayak *et al.*, 2018).

5. Polymeric substances

Exopolysaccharides, mucopolysaccharides, and glomalin are examples of extracellular biopolymeric compounds secreted by microbes that bond with heavy metals via a complexation process, thereby decreasing the mobility and bioavailability of these elements in the soil. Glycosyltransferases play a key role in the transport of polysaccharides out of cells Gillan, (2016). Azotobacter sp., according to a study by Joshi and Juwarkar (2009), can create extracellular polymeric compounds that trap Cd and Cr in soil, hence decreasing the metal intake in Triticum aestivum. The arbuscular mycorrhizal fungus produces globulin, a metal-sorbing glycoprotein. Lead, cadmium, copper, and manganese are only some of the dangerous heavy metals that it may be able to store. Wu *et al.* (2014) conducted an in-situ field experiment to evaluate the sequestration of Pb and Cd, and they discovered that glomalin considerably impacts metal mobility and, thus, minimizes heavy metal uptake by plants. This is why glomalin has been proposed for the bio-stabilization/immobilization of heavy metals in soil Malekzadeh *et al.* (2016).

Biosorption

Soil microorganism biosorption of heavy metals also affects metal bioavailability (Ullah *et al.*, 2015). There are many variables involved in the biosorption process, including the kind of metal ion, metal concentration, cell wall structure, pH, temperature, contact time, etc. It has been observed that the bacteria Pseudomonas aeruginosa, Stenotrophomonas maltophilia, and Bacillus subtilis can biosorbent lead, copper, and zinc (Pb, Cu, and Zn) Wierzba (2015). Both passive accumulation and active sorption exist within the realm of biosorption. Biosorption of metals occurs on the surface of nonliving or dormant microbes due to their interaction with functional groups (such as hydroxyl, carboxyl, phosphate, thiol, sulfate, amide, amino, and carbonyl groups) (Fomina and Gadd, 2014). Active sorption, on the other hand, is carried out by living cells, which take up heavy metals from the soil through a variety of methods. Metals are associated with metallothioneins (bacteria and fungi) and phytochelatins (fungi) inside the cell, where they precipitate and are sequestered in particular intracellular organelles.

Heavy metals in the soil can be accumulated by microbes by adsorption or absorption. As a fluid (the absorbate) is dissolved in or permeated through a liquid or solid (the absorbent), this process is called absorption Sozer N (2009). Hence, adsorption occurs only on the surface, but absorption occurs across the total volume of a substance. Precipitation, chemical adsorption and ion exchange, surface precipitation, creation of stable complexes with organic ligands, and redox reaction are part of the overall sorption mechanisms. Due to the complexity of the soil matrix and the limits of existing analytical tools, the precise immobilization mechanisms remain unclear Chiapusio G (2007). The complexation of heavy metals on the cell surface is the first step in their uptake during adsorption Fang C (2001). Heavy metals are easily adsorbed and absorbed by the body due to the nature of the cell surface, especially the cell wall and mucus layer. Coordinating atoms in metal ions can form complexes with several ions found in functional groups on the cell surface Wang J (2008), including nitrogen, oxygen, sulfur, and phosphorus. Most heavy metals have a cationic group on their surface that interacts with the cell wall and allows the metal ions to attach to or pass through the cell membrane; this is because both phosphoric acid anions and carboxyl anionic groups on the surface of the microbial cell wall are negatively charged.

Bioleaching

Bioleaching, the process by which positive heavy metal ions are extracted from insoluble ores through biological dissolution or complexation processes, is one type of biomining, while bio-oxidation is secondary Jordahl JL(1997). Low molecular weight organic acids and other secretions produced by microbial metabolism are capable of dissolving heavy metals and soil particles containing heavy metal minerals, microorganisms may efficiently utilize resources and energy to release organic acids and increase the leaching of Cd in nutrient-rich circumstances. A 9% leaching rate was observed in nutrient-free conditions, but a 36% leaching rate was seen once glucose and other nutrients were added Schwab AP (1995). Studies have shown that some bacteria, such as Citrobacter, can produce free inorganic phosphate, which then forms an insoluble metal phosphate layer that can entrap a significant amount of hazardous metals Siciliano SD (1998).

Conclusion:

Heavy metals are ubiquitous environmental pollutants, and their presence in the environment can have significant adverse effects on human health, wildlife, and the environment. Understanding the sources of heavy metals and implementing strategies to reduce their release into the environment is essential to protect human health and the environment. By reducing exposure to heavy metals, we can work towards a healthier and more sustainable future. In conclusion, heavy metal contamination in soil is a serious environmental issue that poses significant threats to human health and the ecosystem. The sources of heavy metal contamination in soil are numerous, including industrial activities, agricultural practices, and improper waste disposal. However, effective management strategies can help mitigate the impact of heavy metal contamination on the soil. Preventive measures such as reducing the use of chemical fertilizers and pesticides, proper waste disposal, and controlling industrial emissions can minimize heavy metal contamination. Moreover, remediation techniques such as phytoremediation, bioaugmentation, and soil washing can help to remove heavy metals from the soil. It is crucial to develop and implement appropriate management practices that suit the local environmental conditions to reduce the impact of heavy metal contamination. It requires a concerted effort between governments, industries, and individuals to address heavy metal contamination in soil effectively. By working together, we can mitigate the risks associated with heavy metal contamination and protect our environment and public health.

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FATE OF FERTILIZER IN SOIL

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Abstract:

Any substance, whether of natural or synthetic origin, applied to soil or plant tissues to provide plant nutrients is referred to as a fertilizer. It's possible to distinguish fertilizers from liming agents or other non-nutrient soil additives. There are numerous natural and man-made sources of fertilizer. The three main macronutrients of nitrogen (N), phosphorus (P), and potassium (K) are the focus of fertilization for the majority of modern agricultural techniques. Supplements for micronutrients, such as rock flour, are occasionally used. Fertilizers help plants develop more rapidly. This objective is achieved in two ways, the conventional one being nutrient-rich additions. The soil's ability to retain water and breathe is improved by various fertilizers, which is their second method of action.

Introduction:

Fertilizers are chemicals with significant amounts of one or more plant-food components. This group also includes certain artificial organic compounds like urea. These could be manufactured goods or natural substances. In variable amounts, fertilizers often supply the following nutrients:

- three main macronutrients:
  - Nitrogen (N): leaf growth
  - Phosphorus (P): development of roots, flowers, seeds, fruit;
  - Potassium (K): strong stem growth, movement of water in plants, promotion of flowering and fruiting;
- three secondary macronutrients: calcium (Ca), magnesium (Mg), and sulfur (S);
- micronutrients: copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), zinc (Zn), bor on (B). Of occasional significance are silicon (Si), cobalt (Co), and vanadium (V).

Fertilizers

Straight Fertilizers

When a fertilizer contains a single nutrient, it is called a straight fertilizer. Such fertilizer is called nitrogenous or phosphatic or potassic. Example urea

Complex or Compound Fertilizers

Two or more nutrients in one compound is known as complex or compound fertilizers. These fertilizers are granular and easy to apply. Examples are:

Nitrogenous Fertilizers

The nitrogenous fertilizers are broadly classified into 4 groups

Classification of Nitrogenous Fertilizers

Sources of nitrate	Name of fertilizer	Percentage of nitrogen	%P	Reaction (Acidity/Basicity)
Nitrate	Sodium nitrate ($NaNO_3$) Calcium nitrate $Ca(NO_3)_2$ Potassium nitrate (KNO_3)	16.0 15.0 13.0		Basic Basic Basic
Ammonium	Ammonium sulphate $(NH_4)_2$ SO_4 Ammonium chloride (NH_4Cl) Diammonium phosphate $(NH_4)_2HPO_4$	20.6 25.0 18.0	– 46	Acidic Acidic Acidic
Nitrate and Ammonium	Ammonium nitrate (NH_4NO_3) Ammonium sulphate nitrate $(NH_4)_2$ SO_4, (NH_4NO_3) Calcium ammonium nitrage	33.5 26.0 20.5		Acidic Acidic Neutral
Amide	Urea $CO(NH_2)_2$ Calciumcynamide ($CaCN_2$)	46.0 22.0		Acidic Basic

Characteristics of nitrogenous fertilizers

Nitrate fertilizers

The most commonly used types of nitrate fertilizers are sodium nitrate and calcium nitrate. These fertilizers are soluble in water and have a tendency to absorb moisture from the air, which makes them sticky. They have an alkaline nature, but consistent use of sodium nitrate can cause the clay particles in the soil to separate and lead to poor drainage. While nitrate fertilizers contain less nitrogen than other types of fertilizers, they are still completely soluble in water and easily absorbed by plants without any changes to the soil chemistry. However, this also means that the nitrate is not retained by the soil and can quickly wash away through leaching. As a result, nitrate fertilizers are typically applied in small doses at intervals on established crops (known as top dressing). It's important to note that they are not suitable for rice crops during the early stages of growth since rice plants require nitrogen in the ammoniacal form.

Ammonium fertilizers

This category of fertilizers is extensively used, especially ammonium sulphate. Ammonium fertilizers can dissolve in water, but they don't absorb moisture from the air. They are acidic in nature and contain a higher percentage of nitrogen than nitrate fertilizers. However, plants cannot easily access the nitrogen in ammonium fertilizers compared to nitrate fertilizers since it must first undergo nitrification in the soil to convert it into nitrate before being taken up by plants. When ammonium sulphate is applied, the soil immediately fixes (adsorbs) the ammonia, which prevents leaching. However, if ammonium sulphate is used repeatedly and in large quantities without sufficient lime in the soil, it can lead to soil acidity. These fertilizers can be applied as a base application or top dressing.

Nitrate and Ammonium fertilizers

This category of fertilizers dissolves easily in water and has a slight tendency to absorb moisture from the air. For example, Ammonium Nitrate is highly hygroscopic, Ammonium Sulphate Nitrate is slightly hygroscopic, and Calcium Ammonium Nitrate is slightly hygroscopic. This group contains both nitrate and ammonium, which are both readily available to plants. The plant can quickly utilize the nitrate-nitrogen, while the ammonium form provides a steady source of nitrogen. Additionally, the presence of ammonium helps to reduce leaching losses. Although these fertilizers are acidic in nature, Calcium Ammonium Nitrate is neutral. They can be applied as top dressing or basal dressing.

Amide fertilizers

Amide fertilizers dissolve in water and have a tendency to absorb moisture from the air. They are converted into ammonium carbonate and then nitrates by microorganisms. The conversion process takes around 6-7 days. Leaching loss is minimal because once the amide is converted to ammonium form, it is adsorbed by soil colloids and slowly released and nitrified to nitrates. Urea and calcium cyanamide are examples of synthetic organic fertilizers in the amide group.

Urea:

Urea is slightly acidic and can cause a small loss of calcium from the soil upon application. It contains a high concentration of nitrogen, with 46% nitrogen content, which can potentially harm plant roots or germinating seeds if applied in high concentrations. To avoid any risks of injury to plants, it is recommended to mix urea with ashes or a small amount of soil to ensure even distribution. The toxic ingredient in urea is biuret. Urea is an economical fertilizer and can be used in liquid form as a foliar application.

Phosphatic fertilizers

Phosphorus fertilizers can be divided into three categories: (A) water-soluble, (B) citrate-soluble, and (C) insoluble. Fertilizers that belong to the water-soluble category contain soluble phosphate, which acts quickly and has minimal leaching loss. These fertilizers are recommended to be applied in neutral and alkaline soils.

Name of fertilizer	Chemical composition	Percentage composition	Acidity of alkalinity
Sulperphosphate (ordinary) (single super phosphate)	$Ca(H_2PO_4)_2$	16-20	Neutral
Superphosphate (concentrated) (triple super phosphate)	$3Ca(H_2PO_4)_2$	40-48	Neutral or acidic
Diammonium phosphate	$(NH_4)_2HPO_4$	46-48	Acidic

Fertilizers containing citrate-soluble phosphorus characteristics

Fertilizers that are insoluble in water but soluble in citric acid are not readily available to plants. Although there is no leaching loss, these fertilizers act slowly and are recommended to be applied in the soil 15-30 days prior to sowing. They are suitable for use in natural and acidic soils.

Fertilizers containing citrate-soluble phosphorus

Name of fertilizer	Chemical composition	Percentage composition P_2O_5	Acidity or alkalinity
Basic slag (Indian)	$(CaO)_3.\ P_2O_5.SiO_2$	3-5	Alkalinity
Dicalcium phosphate	$CaHPO_4$	35-40	Acidic

Fertilizers containing insoluble phosphorus characteristics

Due to their slow availability and insolubility, fertilizers in this category should be applied in the soil approximately two months prior to sowing. Phosphorus is present in the form of tricalcium phosphate. In highly acidic soils, deep placement is usually performed.

Fertilizers containing insoluble phosphorus

Name of fertilizer	Chemical composition	Percentage composition P2O5	N	Acidity or alkalinity
Rock phosphate	Ca3(PO4)2	20 - 30		
Bone meal	--	18 - 20	3	Alkaline

Potassic fertilizers

Potassium fertilizers are water-soluble but not hygroscopic in nature. They are readily available to plants. There is not leaching loss. As they are neutral in reaction so have little or no effect on the soil pH..

Potash containing potassic fertilizers

Fertilizer	Chemical form	Percentage composition of K_2O	Reaction
Potassium chloride (mutriate of potash)	KCL	60	Neutral
Potassium sulphate	K2SO4	50	Neutral

Sulphur containing fertilizers

Most sulphur-containing fertilizers are soluble in water, and their sulphur content is easily available to plants, except for elemental sulphur, which requires sequential oxidation to convert it into SO4-2 form. The prolonged use of fertilizers containing sulphur can result in a decrease in soil pH.

Sulphur containing fertilizers

Fertilizer	Sulphur content (%)
Ammonium sulphate	24
Elemental S	95-98
Single super phosphate	12

Nitrogenous Fertilizers

Fate of Nitrogen in the Soil

The nitrate-nitrogen of the soil, whether added in form of fertilizer or formed by nitrification, may loss in four ways:

(1) volatilization (gaseous loss),

(2) leaching loss

(3) denitrification loss

(4) used by microorganism and weeds.

(1) **Volatilization loss**

When urea or ammonium fertilizers are applied to the soil surface, nitrogen is lost during this chemical reduction process in the form of gaseous nitrogen loss. Nitrogen is lost as ammonia, particularly in alkaline soils. The nitrification process is harmful at high ammonia concentrations (large doses of ammonia-containing or amide fertilizers), which leads to an unusual buildup of nitrates. When these nitrites are in touch with specific ammonium salts or urea under acidic circumstances, they are transformed into gaseous elemental nitrogen or nitrous oxide. It might appear in the following response:

$$\underset{\text{Nitrite}}{2HNO_2} + \underset{\text{Urea}}{CO(NH_2)_2} \longrightarrow CO_2 + 3H_2O + 2N_2$$

(2) Denitrification loss

In the absence of air or due to inadequate drainage, the nitrates may turn gaseous. Denitrification is the term for the metabolic process whereby microorganisms convert nitrate-nitrogen to gaseous molecules. Nitrous oxide is the gas that is lost most frequently in the field, though elemental nitrogen is also occasionally lost. Acidic circumstances favour the most rapid depletion of nitric oxide.

$$2NHO_3 \quad 2NHO_2 \quad N_2O \xrightarrow{-2(O)} N_2 \xrightarrow{-2(O)} 2NO \quad \xrightarrow{-(O)} \quad \xrightarrow{-(O)}$$

Nitrates Nitrites Nitrous oxide Elemental nitrogen Nitric oxide

(3) Leaching loss

Nitrate nitrogen is lost by drainage or water that percolates. Leaching of nitrate results in considerable losses of nitrate in humid regions or waterlogged circumstances, depending on the environment and cultural settings. Such losses are comparatively small in arid and semi-arid regions.

(4) Used by soil microorganisms and weeds

Nitrate-nitrogen is easily assimilated by soil microbes. Nitrates are used more quickly by microorganisms when they have an available food source (organic matter). One of the reasons crops receive around half the nitrogen added in the form of nitrogenous fertilizer is due to this.
The nitrogen given to the soil as nitrates may also be used by weeds (or present in the soil). As a result, crops might not receive enough nitrogen.

Management of nitrogen in the soil to improve the nitrogen fertilizer economy is given below:

1. These lines discuss ways to minimize nitrogen loss through proper management:
   a. Deep placement of nitrogen fertilizers in the soil before transplanting/sowing increases nitrogen use efficiency and reduces loss.
   b. In flooded soils, ammonia volatilization losses can range from negligible to almost 60% of applied nitrogen. Incorporation of ammonium fertilizers into the soil minimizes NH_3 volatilization loss.
   c. Top-dressing urea on the surface of rice crops can result in NH_3 losses from 27% to 47%, but rates of NH_3 loss are limited to 10-15% when urea is applied.
   d. Nitrogenous fertilizers should be applied in split doses to minimize losses.
   e. Slow and controlled-release fertilizers can sustain the crop with adequate nitrogen nutrition throughout the growing season, as they release plant nutrients slowly, reducing volatilization loss.

f. The use of nitrification inhibitors can also increase controlled availability of plant nutrients. These inhibitors block the conversion of ammonium to nitrate-nitrogen by inhibiting the growth or activity of Nitrosomonas bacteria. Examples of such inhibitors are dicyandiamide (DCD), acetone extract of neem, etc. Meliacins, which are organic compounds found in neem seeds, have the ability to inhibit nitrification. Urea that has been treated with neem cake can reduce nitrification by 40% and 74% after 1 and 2 weeks of incubation, respectively. To coat urea, a technique was used that involved coal tar solution in kerosene oil 1kg/2 litres, sufficient for 100 kg urea) as a binding agent to adhere the finely produced neem cake. One quintal of urea was placed in a seed treatment drum, and coal tar-kerosene solution was gradually added while rotating the drum. Then, 15-20 kg of neem cake was added, and the drum was rotated to prepare the neem cake for use. This method is straightforward and is only used by individual farmers. It has not been implemented on an industrial scale. At IARI in New Delhi, a novel method has been developed to coat urea with neem oil micro-emulsion. Urea coated with this emulsion has been shown to have clear advantages in terms of nitrogen use efficiency. This technology has two significant benefits: firstly, it only requires 0.5 kg of neem oil per tonne of urea, and secondly, the product is environmentally friendly.
g. Proper timing of fertilizer application is crucial for efficient use of nutrients.
h. Soil amendments can be used to correct nutrient deficiencies and improve soil health.
i. To minimize volatilization losses from nitrogenous fertilizers, a 1:5 mixture of urea and soil should be dried under shade before use.

Alternatively, nitrogenous fertilizers can be mixed with oilseed or neem cake prior to broadcasting.

a. To reduce denitrification loss, it is important to ensure proper drainage in the field and promote adequate aeration.
b. Efficient use of irrigation water can help minimize leaching loss of nitrogen.
c. A technique for minimizing nitrogen loss involves applying the initial dose of nitrogen to a dry puddled field, followed by introducing water 4 days after transplanting.
    1. Weed control: Weed removal from the field can minimize N loss.
    2. Differences in nitrogen use efficiency among varieties: Rice variety IR 42 is more efficient in N use compared to IR 36 and IR 8. The use of varieties such as IR 42 can increase N efficiency.

Phosphatic fertilizers

Superphosphate and soil reaction

To explain the effects of superphosphate on the soil, it should be noted that when it is applied to neutral or alkaline soil, it produces soluble monocalcic phosphates, which are referred to as "reverted" phosphates. These reverted phosphates are chemical precipitates that have a large surface area for the soil solution to act upon. As a result, even tricalcic phosphate becomes slowly and gradually soluble, becoming available to plants. However, in acidic soil with a pH of 5.5 or lower, the iron and aluminum in the soil become soluble and combine with the soluble phosphates in superphosphate, forming iron and aluminum phosphates, which are very insoluble and not easily available for plant use. In this case, the phosphates are "fixed" or "tied up" in the soil.

In the future, the practice of applying phosphates may be affected by the fact that the presence of organic matter in the soil can prevent phosphates from becoming fixed in insoluble forms and can even release phosphates that have already been fixed.

Rock phosphate

To achieve optimal outcomes, it is recommended to apply rock phosphate in substantial amounts, especially in combination with organic matter. The presence of decomposing organic matter can enhance its accessibility. In acidic soils, it is necessary to finely grind rock phosphate before its application

Phosphorus Use Efficiency

The main issue with phosphorus fertilization is the fixation of phosphate. After applying water-soluble phosphatic fertilizers to the soil, they react quickly, resulting in initial phosphate reaction products.

Measures to improve phosphorus use efficiency are as follow:

- To enhance the efficiency of phosphorous utilization, it is recommended to minimize the contact between phosphatic fertilizers and the soil.
- In acidic soil, applying lime can help increase the efficiency of phosphorus use by raising the pH.
- The most efficient way to apply phosphorus for rice cultivation is to broadcast it on the surface, followed by mixing during puddling, which is even more effective than placing it at various depths.
- For wheat cultivation, placing phosphate in seed furrows or drilling it just below the seeds is more advantageous than broadcasting it.
- The recovery of fertilizer phosphorus in a single season is low, but there is a significant residual effect of phosphatic fertilizers in the next succeeding crop.
- The use efficiency of phosphatic fertilizers can be increased by applying them together with organic manures.
- The utilization of phosphorus by crops may be limited to only 10 percent of the fertilizer applied by broadcast and incorporation into the soil due to fixation. However, when applied as a concentrated band along the plant row, up to 30 percent or more may be utilized. Mixing phosphatic fertilizers with the soil increases fixation, but localized placement through banding allows the fertilizer to react with a smaller portion of the soil near the band. Clay soils have a higher capacity to fix phosphate than sandy soils.
- Phosphorus fixation is lower for citrate soluble form compared to water-soluble form. Hence, broadcasting phosphatic fertilizers in citrate soluble form may be beneficial. Ground rock phosphate, which is neither water nor citrate soluble, should be applied to acid soils and thoroughly mixed with the soil to ensure reaction with soil acids, which makes phosphorus available for plants.

Potassic fertilizers

Potassium sulphate

When applied to light and medium soils with high pH, this fertilizer is more efficient (alkaline and calcareous soils). Using potassium sulphate rather than potassium chloride in wet situations is preferred. In heavy soils, soils retain SO_4 (sulphate) ions more strongly than Cl (chlorine) ions. The heavy soil becomes poisonous when sulphate ions are present in excess.

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CARBON SEQUESTRATION

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Introduction:

Since the late nineteenth century, global surface temperatures have risen by 0.88C and according to IPCC report an increase of 950 Mha of forest will be necessary to check global warming to 1.5ºC by 2050 (IPCC 2019). In the twenty-first century, it is predicted that the average temperature of Earth will rise by 1.5 to 5.88C. Since 1975, the rate of global temperature rise has been 0.158ºC per decade. Along with the 15–23 cm sea level rise that has occurred over the past century and there have also been significant changes to ecosystems. According to reports, anthropogenic activities such as: land use change, deforestation, biomass burning, draining of wetlands, soil cultivation, and fossil fuel combustion are responsible for these and other observed climatic changes. As a result, the population of humans has grown, so the high concentration of atmospheric greenhouse gases (GHGs) and their radiative forcing but this has been especially true since the beginning of the industrial revolution around 1850. Carbon dioxide (CO_2) content increased from 280 ppmv in 1850 to 380 ppmv in 2005, and it is currently increasing at a rate of 1.7 ppmv yr^{-1} or 0.46% yr^{-1}. Throughout the same time span, concentrations of nitrous oxide (N_2O) and methane (CH_4) have also continuously increased. Since 1850, the total radiative forcing of all GHGs is estimated to be 2.43 W m^{-2}, an externally induced disruption in the Earth's climate system's radiative energy balance (IPCC 2019).

To reduce the hazards of global warming, there is a great interest in stabilising the atmospheric abundance of CO_2 and other GHGs. There are three ways to reduce CO_2 emissions and slow down climate change: (i) developing low or no-carbon fuel, (ii) reducing the global energy use and (iii) removing CO_2 from point sources or the atmosphere using engineering and natural methods. Between 1850 and 1998, anthropogenic emissions was estimated at 270±30 Pg by fossil fuel combustion and at 136±30 Pg by land-use change, deforestation and soil cultivation. Presently, approximately 7 Pg C yr^{-1} is emitted by fossil fuel combustion and 1.6 Pg C yr^{-1} by deforestation, land-use change and soil cultivation. Of the total anthropogenic emissions of 8.6 Pg C yr^{-1}, 3.5 Pg C yr^{-1} is absorbed by the atmosphere, 2.3 Pg C yr^{-1} by the ocean and the remaining by an unidentified terrestrial sink probably in the Northern Hemisphere. Elevated soil management practices are vital to tackle these problems by increasing soil fertility, agro-ecosystem productivity and carbon sequestration (Tiefenbacher *et al.*, 2021). In order to slow down the net rate of increase in the CO_2 concentration in the atmosphere, the purpose of this chapter is to discuss the method and technological options for CO_2-C sequestration in one of the long-lived global C pools. While there is general discussion of CO_2-C sequestration, the terrestrial C sequestration in soils and forests receives special attention.

The global carbon cycle:

During the close of the nineteenth century, Arrhenius (1896) identified the significance of atmospheric CO_2 concentration on global temperature but anthropogenic disturbance of the global C cycle throughout the twentieth century has been a historically unprecedented phenomenon. For effective climate change mitigation methods to be developed, it is crucial to comprehend the global C cycle and how anthropogenic activities disturb it. The anthropogenic activities, the impact of biogeochemical and climate processes on the global C cycle and interactions among the major C pools will all affect how quickly atmospheric CO_2 concentrations rise in the future. Very active humus and comparatively inert charcoal C make up the soil organic carbon (SOC) pool. It consists of a combination:

a) live microorganisms and small animal's bodies as well as their decomposing by-products
b) plant and animal residues at various stages of decomposition
c) substances synthesised microbiologically and/or chemically from the breakdown products.

The soil inorganic carbon (SIC) pool consists of primary and secondary carbonates as well as elemental C and carbonate minerals like calcite, dolomite, and gypsum. The weathering of source material produces the main carbonates. Contrarily, secondary carbonates are created when atmospheric CO_2 reacts with Ca^{+2} and Mg^{+2} that have been introduced from outside the local environment (e.g. calcareous dust, irrigation water, fertilizers, manures). In the soils of arid and semi-arid regions, the SIC plays a major role. The enhanced attentiveness in bio-based construction materials resulted in emergence of the concept of "buildings as a carbon sink" (Arehart *et al.,* 2021).

Strong interactions between the terrestrial and atmospheric C pools are occurring. The rate of photosynthesis is 120 Pg C each year, with most of it being exhaled by plants and soil which is released back into the atmosphere. The influence of CO_2 fertilization and changes in land use and management may be to blame for the increase in the terrestrial sink capacity. With deforestation and biomass burning, the biotic pool also contributes to a rise in atmospheric CO_2 concentration.

Carbon sequestration:

Between 1980 and 2000, emissions from the combustion of fossil fuels increased by 40%. Yet, the amount of CO_2 building up in the atmosphere stayed the same over this time due to the fact that oceans, forests, soils and other ecosystems are removing the extra CO_2 emitted. Carbon sequestration is the process of transferring and safely storing atmospheric CO_2 into other long-lived C pools that would otherwise be released or remain in the atmosphere. Soil carbon (C) sequestration indicates transferring of atmospheric CO_2 through plants into soil of a land unit (Lal *et al.,* 2015). C sequestration could therefore in this situation be a natural or anthropogenically induced process. The goal of a C sequestration process driven by humans is to balance the global C budget so that future economic growth is based on a "C neutral" approach of no net increase in the atmospheric C pool. A method like this would require sequestering practically all of the CO_2 produced by humans using procedures that are secure, stable and environmentally acceptable with little chance of leakage. Yet, even a slight leak of 2-3 Pg C yr^{-1} from the C sequestered in one of the pools can have a negative effect on the long-term strategic planning. CO_2 sequestration is a set of technologies which can be divided into three groups: carbon capture and storage (CCS); carbon capture and utilization (CCU); and carbon capture, utilization, and storage (CCUS) (Tcvetkov *et al.*, 2019). There are 15 ways to keep CO_2 levels in the atmosphere at 550 ppm by 2050. Three of the 15 possibilities depended on the sequestration of carbon in terrestrial ecosystems.

A number of technological solutions exist for storing atmospheric CO_2 in one of the other global reservoirs (figure 1). For the purpose of developing energy policies for future economic growth and development at the national and international levels, it is crucial to select one or a combination of different technologies. These choices can be divided into two groups in general: Sequestration by biotic and abiotic factors:

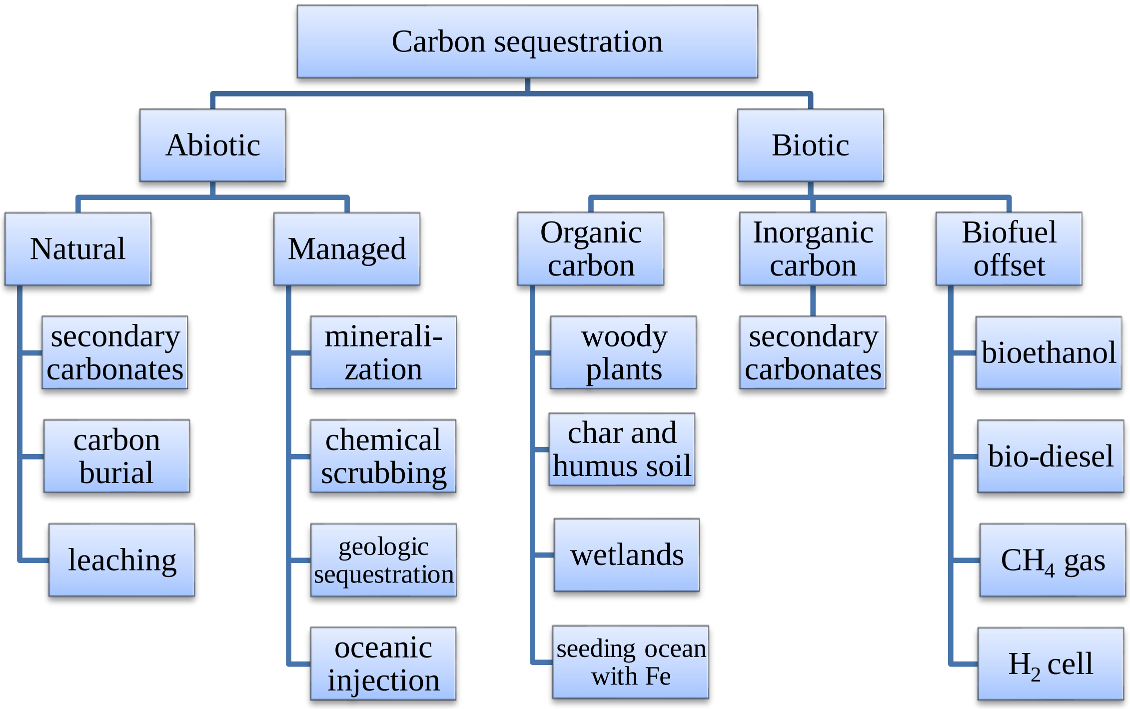

Figure 1: The technological options and processes for C sequestration in industrial, agricultural and natural ecosystems

(A) Abiotic sequestration

Abiotic sequestration relies on physical, chemical and technical processes without the involvement of biological things (e.g. plants, microbes). Because theoretically abiotic sequestration has a greater sink capacity than biotic sequestration, the abiotic technique of sequestering carbon in oceanic and geological structures has attracted a lot of attention.

Technology development and testing for CO_2 capture, transport and injection are moving forward quickly.

(i) Oceanic injection

On decadal to millennial timescales, open ocean waters store (sequester) carbon away from the atmosphere; this has a significant impact on the global climate by regulating the partial pressure of atmospheric carbon dioxide (Boyd *et al.,* 2019). Scientists have been researching the prospect of injecting a pure CO_2 stream deep into the ocean for approximately three decades. CO_2 must be injected at great depths in order to remain stable and reduce outgassing. Hence, one of the four methods listed below can be used to introduce liquefied CO_2 from industrial sources into the ocean:

a) It is injected from a manifold on the ocean floor below 1000 m and because it is lighter than water, it rises to a depth of around 1000 m generating a droplet plume.
b) Around 500–1000 m depth, it is also injected as a thicker CO_2-seawater mixture which sinks into the deeper ocean.
c) It is released from a huge pipe being pulled behind a ship.
d) It is pushed into a depression in the ocean floor where it creates a CO_2 in lake.

Due to the ocean's rising stratification and its constant turnover due to natural processes, the stability of such an injection must be addressed in addition to its economics.

(ii) Geological injection

Industrial CO_2 must be captured, liquefied, transported and injected into deep geological strata. The CO_2 may be injected into stable rock layers, saline aquifers, old oil wells (to boost yield), coal seams, or old oil wells (Gale 2004). Saline aquifers are layers of exceptionally porous sediments beneath the earth's surface that contain brackish (saline) water. Typically, an impermeable layer separates the saline aquifers from the freshwater reservoirs. It is possible to inject industrial CO_2 into the aquifer where it is sequestered hydrodynamically and by forming carbonates when it reacts with other dissolved salts. The liquid brine that it replaces has a substantially lower density and viscosity than the supercritical state of carbon dioxide that is used for injection. In situ, it creates a multiphase, multicomponent environment by dissolving in the aqueous phase and forming a gas-like phase. An economically viable method of improving oil recovery could involve injecting CO_2 into reservoirs where it displaces oil or gas (EOR). CO_2 enhanced recovery increases production from oil and gas fields which has been declining. Texas, USA use this CO_2 sequestration technique to inject 20 million Mg of CO_2 every year at a cost of \$10–\$15 Mg^{-1}. The major worries about geological sequestration are similar to the oceanic such as: (i) reliability of large-scale CO_2 storage in geological strata and (ii) the cost. Additionally, when formulating guidelines for suitable regulatory and monitoring controls, it may be necessary to take into account the chemical interactions of CO_2 with the geological formations.

(iii) Scrubbing and mineral carbonation

Mineral carbonation is accomplished by simulating CO_2 inorganic chemical transformation in nature. Industrial-strength CO_2 emissions are converted into geologically and thermodynamically stable mineral carbonates such as $CaCO_3$, $MgCO_3$ and other minerals. Scrubbing is the first step followed by mineral carbonation. The most popular technique for carbon capture is scrubbing which involves chemically absorbing CO_2 using an amine or carbonate solvent. By passing through an absorption column with an amine solvent, the CO_2 is purified. Lithium silicate, K_2CO_3, ceramics and nickel-based compounds are some additional solvents used. By heating the CO_2-rich amine, pure CO_2 gas is recovered and re-precipitated through mineral carbonation. As a result, carbonates are a stable type of rock where CO_2 is permanently trapped. The following are the aqueous mineral carbonation reactions that produce magnesite ($MgCO_3$), olivine (Mg_2SiO_4) and serpentine ($Mg_3Si_2O_5(OH)_4$). All of these reactions can be reproduced in industrial settings and happen in nature. A slurry of water and minerals with fine particle sizes, at solid concentrations of 15–30%, is used in these processes. According to the following theorised reactions (Gerdemann *et al.* 2004), the mineral dissolution and then carbonation occurs in single step.

According to geological studies, there are enough ultramafic (ultrabasic) mineral reserves to supply the raw materials needed for the mineral carbonation of industrial emissions for a very long time. These however are slow-moving geological reactions. The trick is to speed up the reaction by using catalysts, increasing temperature and pressure and reducing particle size. However, speeding up reactions costs money and requires energy.

(B) Biotic sequestration

Biotic sequestration relies on the controlled removal of CO_2 from the atmosphere by higher plants and microorganisms. It is distinct from management strategies that lower or balance emissions. Another strategy for controlling the terrestrial C pool is to increase resource efficiency (e.g., water and energy use). Below is a brief description of a few biotic sequestration options:

(i) Oceanic sequestration

Through photosynthesis, C is sequestered in the ocean by a number of biological processes. One such mechanism is phytoplankton photosynthesis which fixes about 45 Pg C yr^{-1}. A portion of the organic particulate matter produced by phytoplankton is dumped at the ocean floor and is subsequently sequestered. One of the factors limiting phytoplankton growth in oceanic ecosystems is the availability of iron (Fe). Due to this, the impact of Fe fertilization on biotic CO_2 sequestration in the ocean has been evaluated by Boyd *et al.*, 2019. Additionally, it is asserted that incremental C might be exchanged for credits in the expanding global C market. Similar to deep injection, ocean fertilization may also change the ecology of the ocean. However, with the current state of knowledge, the topic of ocean fertilization remains a debatable issue.

(ii) Terrestrial sequestration

Terrestrial carbon sequestration is the process of transferring atmospheric carbon into biotic and pedologic carbon pools. Only 3.5 Pg, or 40%, of the 8.6 Pg C yr^{-1} emitted by humans remains in the atmosphere. This is primarily because of unidentified terrestrial sinks that sequester atmospheric CO_2 and are crucial to the global C cycle. Due to photosynthesis and the storage of CO_2 in both living and dead organic matter, terrestrial ecosystems serve as a significant carbon sink. Terrestrial C sequestration is frequently referred to as a win-win or no-regrets strategy because of its many ancillary benefits (such as increased crop yield, improved soil and water quality, and restoration of damaged ecosystems). Even without the threat of a global warming, it has many advantages. The three main elements of terrestrial C sequestration are wetlands, soils, and forests.

As lignin and other relatively robust polymeric C compounds, forestry ecosystems store carbon. Currently, the net rate of carbon sequestration in forest ecosystems is 1.7 Pg C yr^{-1}. This excludes ecosystems that are being deforested. The forest C is enclosed by woody debris, wood products, and other woody plants that are encroaching on grasslands in addition to the harvestable timber. Increased carbon sequestration and simultaneous protection of natural forests could result from incentives for both forest sequestration and wood-based bioenergy (Favero *et al*, 2020) One of the practical methods for storing carbon in terrestrial ecosystems is reforestation. Restoring damaged tropical forests is a crucial alternative. The 350 Mha of tropical forest are thought to have been converted to other land uses, and another 500 Mha of forests have undergone varying degrees of degradation (Lal, 2005 a,b,c). Thus, the establishment of fruitful, monoculture Acacia, Eucalyptus, and Pinus plantations can improve the terrestrial C pool in these ecosystems. In degraded tropical landscapes, there is also a chance to improve management of secondary or regrowth forests. Afforestation and growth were the main causes of China's increase in C sequestration in forests, which increased at an average rate of 21 Tg C yr^{-1} between 2008 and 2018.

The management of temperate and tropical forests is one of the 15 options to keep the atmospheric CO_2 concentration at 550 ppm by 2050. They measured that if the current rate of clear-cutting of primary tropical forests were reduced to zero over 50 years by 2050, 0.5 Pg C emission would be avoided. By reforesting or afforesting roughly 250 Mha in the tropics or 400 Mha in the temperate zone, an additional 0.5 Pg C yr^{-1} would be sequestered. By establishing roughly 300 Mha of plantations of non-forested lands, an additional 0.3 Pg C yr^{-1} can be sequestered. Between 2000 and 2050, sequestration of 25 Pg C may be attributed to afforestation.

Large-scale afforestation, however can have an effect on water resources. Afforestation causes significant losses in stream flow as well as an increase in soil salinization and acidity. According to their findings, the development of tree plantations reduced stream flow by 227 mm yr^{-1} globally (52%), with 13% of streams drying up entirely for at least a year. So, any proposals for extensive afforestation for carbon sequestration must take into account any potential negative effects on the availability of water.

Hence, the consequences of monoculture plantings on essential ecosystem services (such as biodiversity, water availability, elemental cycling and carbon sequestration) must be carefully evaluated. Regulatory regulations must be developed, especially those addressing the costs of selling C credits and acquiring licences. The opportunity cost relative to the cost of C sequestration must also be taken into account.

Soil C sequestration

Implies adopting recommended management practises (RMPs) in agricultural, pastoral, and forestry ecosystems and restoring degraded and severely disturbed soils in order to increase the concentration/pools of SOC and SIC as secondary carbonates. Another choice is to create charcoal and utilise biochar as fertilizer (Fowles 2007). In contrast to geological sequestration, which entails injecting CO_2 at a depth of 1-2 km, SOC sequestration includes infusing C through humification processes into the surface layer at a depth of 0.5–1 m. Due to the depletion of the SOC pool in cultivated soils, the majority of soils in managed ecosystems have lower SOC pools than their counterparts in natural ecosystems. The transition from natural to agricultural ecosystems takes place most quickly in the first 20–50 years in temperate regions and in the first 5–10 years in the tropics. In general, 50–75% of the original SOC pool is typically present in cultivated soils. Leaching, erosion, and oxidation all contribute to the SOC pool's depletion.

There are several different types of deteriorated soils with low SOC levels. Among them, those impacted by erosive processes, nutrient depletion, acidity and leaching, structural deterioration, and pollution and contamination are significant. Repairing damaged soils and ecosystems is an approach that has many advantages for improving biomass productivity, improving water quality and lowering net CO_2 emissions. There are roughly 750 Mha of degraded lands in the tropics that have the potential to be reforested and have improved soil quality. The capacity for SOC sequestration in dry and semi-arid soils to range from 0.4 to 0.7 Pg C yr^{-1}. Using data analyses of 67 long-term studies from throughout the world it was evaluated that the SOC sequestration rate upon switching from plough tillage to no-till farming. The average rate of SOC sequestration which was 570±140 Kg C ha^{-1} yr^{-1} may result in a new equilibrium SOC pool in 40–60 years.

In order to increase SOC, integrated nutrient management (INM) is also required. Lack of N, P, S, and other essential components of soil humus can significantly limit the humification process. Insufficient C and N balance reduces the effectiveness of C sequestration. Consequently, increasing the application of biomass C and N increases the rate of SOC sequestration. SOC sequestration was influenced by the rate and source of N application. The application of manures and other organic amendments is also a vital SOC sequestration approach.

Due to monoculture, diverse cropping systems typically result in soils with higher SOC pools. Another strategy for reducing losses to the SOC pool is to eliminate summer fallow. SOC sequestration improves soil quality when a winter cover crop is grown. In arid and hot climates, the rate of sequestration is negative or nil, while in humid and temperate climates, the rate is about 1000 Kg C ha^{-1} yr^{-1} (Lal, 2005 a,b,c). Agricultural soils typically sequester SOC at rates between 300 and 500 Kg C ha^{-1} yr^{-1}. No-till farming, crop residue retention as mulch, growing cover crops during the rotation cycle, adoption of complex agricultural systems like agroforestry, INM incorporating manuring, and soil restoration through afforestation are all methods that provide high rates.

Agricultural intensification through the use of RMPs enhances soil quality and agronomic productivity as well as water quality, non-point source pollution by lowering dissolved and sediment loads and the net rate of CO_2 emission through SOC sequestration. That happens in a very natural way (Morris 2006). The stabilising processes, limitations of biophysical ecosystems in C sequestration and pertinent economic and policy problems must all be understood for the

SOC sequestered to be stabilised. Several permits (at the federal, state, and municipal levels) and marketing procedures may be needed for trading C credits.

(iii) Secondary carbonates

In SIC, soil carbon sequestration can also take the form of secondary carbonates and bicarbonate seeping into the groundwater. Secondary carbonates can be found as films, threads, concretions and pedants among other forms. They can also be found as calcrate, caliche and laminar caps. Secondary carbonates form as coatings on the lower surfaces of stones and pebbles in skeletal soils with high gravel concentrations. There are four main processes that cause secondary carbonates to develop. According to Marion *et al.* (1985), secondary carbonates are generated by CO_2 dissolving in the surface layer, moving and re-precipitating with CaC_2 and MgC_2 in the subsoil. The second mechanism was based on the capillary rise of CaC_2 from shallow ground water and its re-precipitation in the surface layer. The third mechanism was in situ dissolution and re-precipitation. The pedogenic/secondary carbonates are biogenic and are created by the action of soil fauna (e.g. termites).

In the 7.3 to 8.5 pH range, secondary carbonates are generated in the soil. Therefore, the soil system must have an adequate amount of CaC_2 and MgC_2. Secondary carbonates are more likely to form when there is less water present, less CO_2 or HCO_3^- in the soil air and more CaC_2 or HCO_3^- products present in the soil. The rate of formation of secondary carbonates is slower than that of SOC.

Another method of transferring SIC into a less active pool is by the leaching of bicarbonates into ground water, particularly in soils irrigated with high-quality water. In irrigated soils, the rate of HCO_3^- leaching may range from 0.25 to 1.0 Mg C ha^{-1} yr^{-1}. Globally, total irrigated land area is 250 Mha. The potential for HCO_3^- leaching in these soils ranges from 62.5 to 250 Tg C yr^{-1}. There are few technical solutions to speed up the deposition of secondary carbonates with the exception of irrigated soils. Using organic amendments (such as crop leftover mulch, manure and other biosolids) may increase the activity of termites and other soil fauna as well as the development of secondary carbonates via biogenic processes. Another viable alternative for irrigated soils is to increase HCO_3^- leaching by the use of high-quality irrigation water.

Biofuels:

Using biomass-derived sugars to create ethanol and plant-derived oils and fats to create biodiesel is a practical way to cut back on the usage of fossil fuels and create more sustainable and alternative energy sources. In 2019, the primary energy supply for the entire globe was 11.2 Pg of oil equivalent and of that 35.03% came from oil, 24.6% from coal, 20.44% from gas, 6.33% from nuclear and 13.61% from renewable sources. Traditional biofuels (such as animal dung, crop byproducts, and wood products) contributed 2.48% of the renewable sources, whereas contemporary biofuels made up 1.91%. Hydro, solar, windmand geothermal sources only made up 3.22% of the main energy. Biofuels high on the political and scientific agenda are related to C sequestration in two distinct but have interrelated aspects:

a) soil C sequestration through restoration of the depleted SOC pool, especially when agriculturally degraded/ marginal soils are converted to energy plantations

b) recycling of atmospheric CO_2 into biomass-based biofuels.

With choice of the appropriate species and prudent management, biofuels produced from energy plantations established by dedicated crops (e.g. poplar, willow, switch grass, miscanthus, karnal grass, Andropogan, Pennisetum) can sequester C in soil, offset fossil fuel emissions and reduce the rate of abundance of atmospheric CO_2 and other GHGs. Despite the positive effects, some claim that there will be more competition for land and water to build energy plantations.

Crop residues (like corn, wheat, sorghum, millet, and barley) are increasingly being considered as a source of the biomass with the long-term goal of producing 1 Pg of lignocellulosic biomass in the USA and 4-5 Pg globally. Some claim that switching from gasoline to ethanol made from corn grain only results in an 18% reduction in greenhouse gas emissions. Consequently, cellulosic biomass ethanol is a preferred substitute for ethanol made from grains. In addition, corn grain costs in the USA have risen to over \$330 Mg^{-1}, which has a cascading effect on food costs in Mexico and other countries. Some nations (such as the USA, China, and India) intend to use 300–400 million Mg of crop residue annually as a source of renewable energy which could have detrimental effects on the environment and soils. In fact, removing crop residues carelessly can seriously impair soil quality. For instance, in South Asia and sub-Saharan Africa, the ongoing removal of crop residues for a variety of competing uses (such as fodder, household fuel, and construction material) and the use of animal dung as fuel for cooking have resulted in widespread and serious issues with soil degradation, low crop yields, and hunger and malnutrition.

Although full life cycle analyses for fertilised and irrigated soils rarely show net carbon sequestration and active management of agricultural soils may also minimize losses of soil organic matter (McGill *et al.,* 2018). They are valuable resources and maintaining soil quality requires their use as soil amendments. Before constructing large-scale cellulosic ethanol plants adverse effects of residue removal on soil quality must be objectively and critically examined. Cellulosic biomass must therefore be generated on specially designed energy plantations. Additionally, native grassland perennial mixtures with low input and high density (LIHD) can be used to produce biomass.

Farming carbon:

Like any agricultural product, carbon sequestered in soils and trees can be traded. The market for trading C credits is expanding quickly. The market is well established in both the United States through Chicago Climate Exchange and Europe. In the USA, the "cap and trade" movement is gaining ground. The focus of the conversation at this time is on potential policy measures to reduce GHG emissions. Important choices from this list include:

a) Providing government subsidies
b) imposing a "C tax" on carbon emissions and
c) trading C credits

The cap-and-trade system would guarantee that environmental goals would be met. The strategy may be very helpful to the resource-poor and small landholders of developing countries in Asia and Africa where the market for trading carbon sequestered in soils and biota is still being developed. A vital incentive to invest in soil restoration (such as erosion control, irrigation, and fertilizers), end agrarian stagnation and advance food security can be found in trading C credits.

Merits and limitations of biotic versus abiotic carbon sequestration:

A natural process, biotic C sequestration relies on the removal of atmospheric CO_2 through photosynthesis. Due to the CO_2 fertilization effect, woody plants in managed and natural ecosystems will likely remove more CO_2 through photosynthesis in the future. Essential nutrients (such as N, P, K, Ca, Mg, S, Zn, Cu and Mo) and water management can be used to control the process. The sequestration of biotic and terrestrial carbon has a wide range of additional advantages. Among them, these are important:

a) reduced ecosystem nutrient losses
b) increased input use efficiency
c) improved water and soil resource quality
d) better habitat for wildlife
e) increased water conservation
f) restored degraded soils
g) reduced soil erosion

The natural process of soil C sequestration both as SOC and SIC is also crucial for the recycling of elements and water. Similar to the terrestrial pool, expanding the SOC pool has a variety of additional advantages that influence local, regional and global processes. Soil depth also plays a crucial role in determining SOC sequestration (Nayak *et al.*, 2019). Following are the main advantages of SOC sequestration to soil quality:

a) Improvement in soil quality
b) low amount of non-point source pollution
c) augmentation of soil structure
d) an improvement in agricultural productivity and food security
e) denaturing of pollutants
f) increased available water reserves for plants
g) a rise in the soil's aesthetic and economic value
h) reduced soil erosion
i) increased plant nutrient storage in soil

As a result, biotic C sequestration strengthens and improves ecosystem services while boosting agricultural output. The method is affordable and RMPs for adoption on agricultural and forest soils/ecosystems are accessible for the majority of the world's ecoregions. However, only 50–100 Pg C over a 25–50-year period is the total sink capacity for biotic C sequestration, particularly in terrestrial ecosystems (Lal 2004a,b). Additionally, changes in land use (such as deforestation) and soil management (such as ploughing) can cause C that has been sequestered in soil and biota to be released again.

Abiotic sequestration is an engineering process, in contrast to biotic sequestration. Technology is being developed and could be regularly accessible by 2025 and beyond for deep injection in the ocean, geological strata, coal mines, and oil wells, among other places. These methods are currently expensive and the injected CO_2 is prone to leakage. In addition to being expensive there are other problems with measurement and monitoring, negative ecological effects and the need to create and implement regulatory measures. However, abiotic techniques have a very large sink capacity for carbon, often estimated to be greater than fossil carbon reserves at thousands of Pg C. Systems that are biotic and abiotic work together harmoniously. There may be ecological niches for biotic and abiotic sequestration options that are site-specific and dependent on the characteristics of the ecosystem. Options for biotic sequestration are already available. These options buy us time until C-neutral energy production technologies of fossil fuel alternatives and methods of abiotic sequestration come into play.

Conclusions:

Although the 8.6 Pg C yr^{-1} emissions are currently being absorbed by natural terrestrial and oceanic sinks to a degree of about 60%, natural sink capacity and rate are insufficient to absorb all the projected anthropogenic CO_2 emissions during the twenty-first century or until the C-neutral energy sources come into use. Through conversion to judicious land use and adoption of RMPs for forestry, agricultural crops, pastures and managed ecosystems (such as forests, soils, and wetlands) can increase their capacity as sinks for pollutants. With the adoption of regulatory measures and the identification of policy incentives, deliberate manipulation of biological processes can hasten the CO_2 sequestration process. However, an integrated systems approach is crucial for the success of these management systems. The effectiveness of biotic/terrestrial sequestration depends on scientific understanding of these coupled cycles which include cycles of H_2O, other elements (such as N, P, and S) and the global C cycle. It is necessary to develop appropriate policy and regulatory measures, particularly with regard to the measurement, monitoring, residence time and trading of carbon credits. The significance of reducing emissions through the development of carbon-neutral technologies cannot be overstated even though carbon sequestration is a crucial strategy. The latter could entail measures for producing and using energy efficiently as well as the search for fossil fuel substitutes. Biofuels, such as bioethanol, biodiesel, methane gas from biodigesters, and hydrogen cells from biomass, are crucial elements of alternative energy sources.

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SILICON: A BENEFICIAL ELEMENT

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Introduction:

Silicon is an element that helps plants growth. Although it has not been demonstrated to be necessary for all higher plants, it is crucial to the plant life cycle. Due to its significant presence in plant components, silicon was once thought to be a crucial element for plants (Table 1). According to other studies, it might only be necessary for a few plant species, such sugarcane, barley, and rice. Silica (Si) has been identified by several studies as a key inorganic component of higher plants, and many crop species depend heavily on it for production.

Silica (silicon dioxide: SiO_2), silica gel (a highly porous form of silica capable of adsorbing 40% of its weight water from the saturated vapour), silicate (a salt of silicic acid, H_2SiO_3, that occurs in a very large number of rocks, earths), and other minerals made of silicate of calcium, aluminium, magnesium, and/or other elements are all found in soils. Furthermore, it can be found as orthosilicic acid and metasilicic acid ($SiO_2.H_2O$) ($SiO_2.2H_2O$).

The non-metal silicon has an atomic weight of 28.086 and an atomic number of 14, and it may be found in two allotropic forms: a dark grey crystal and a brown amorphous powder. Both of these forms have a specific gravity of 2.42 and a melting point of 1410 ^{0}C.

Table 1: Average values of the contents of certain elements in higher plants

Element	mg kg^{-1} DM
N	1.5
K	1.0
P	0.2
Ca	0.2
Mg	0.5
S	0.2
Si	1.2

(Source: Elsokkary, 2018)

Silicones are compounds having the general formula: R_2SiO, where R stands for hydrocarbon radicals, and defined as polymeric organic silicones of the general type: $(R_2SiO)_n$.

Si's main biological relevance is related to specific plant species, specifically monocotyledons like grains. This element has been demonstrated to be essential to plants in small concentrations. The assessment of this part in soils could allow a quantitative estimation of the plant's need for Si supplementation because ancient soils may be deprived of acceptable levels of accessible Si. Investigating Si's function in the growth performance of various plant species, in the reduction of various abiotic stresses on plants, and in the enhancement and fertilization of soils were the goals of this chapter.

Silicon in soils

After oxygen, silicon is the element that is most prevalent in the lithosphere. Its content in soils ranges from 5 to 40% Wt, although its typical concentrations range from 23 to 35% Wt, with an average value of 32.0% (Kovda, 1973 & Lindsay, 1979). Wedepohl (1995) noted that the average soil Si content was 28.8% Wt.

Despite being widely present in soil, Sulphur is rarely found alone; instead, it is almost always coupled with other elements to create oxides and silicates (Richmond and Sussman, 2003). As a result, silicon dioxide (SiO_2) makes up between 50 and 70 per cent of the soil mass by weight (Ma and Yamaji, 2006).

The majority of Si compounds are insoluble in soil solution and resistant to weathering and decomposition despite the fact that soil contains a high amount of Si overall. As a result, the concentration of Si in soil solution is quite low, typically between 0.1 and 0.6 $mMSiL^{-1}$ (Epstein, 1994; Sommer *et al.,* 2006).

Both the solid and liquid forms of silicon are present in soil. There are three types of solid phases: crystalline, imperfectly crystalline, and amorphous (Sauer *et al.,* 2006). Opal is an example of pedogenic amorphous inorganic silica. Biogenic silica includes phytoliths, which are formed when opal is polymerized in plants (Iller, 1979). In addition to modest amounts of carbon and traces of Fe and Al, the phytoliths' composition is roughly 92% weight silica and 6% weight water (Richmond and Sussman, 2003). In soils, phytolith concentrations range from 0.03 to 0.06% Wt (Desplanques *et al.,* 2006). Typically, silicates in their crystalline state are inert to biogeochemistry (Savant *et al.,* 1999).

Particle size and surface area of the Si-fertilizer, soil pH, organic complexes, the presence of Al, Fe, and P ions, temperature, soil moisture content, and precipitation/dissolution processes are some dynamic parameters that affect the solubility of Si in soil (Berthelsen *et al.,* 2001).

Plant uptake and silicon content

The ability of plants to absorb and store Si in their tissues varies greatly among species. Due to this, the Si concentration in plant shoots varies widely depending on the species of plant and ranges from 0.1 to 10.0% DM.

Plants are divided into accumulator, intermediate, and excluder categories based on the amount of Si present in the shoot (Takahashi *et al.,* 1990). Plant species with more than 1.0% Si are classified as Si-accumulators, those between 0.5 and 1.0% Si are classified as Si-mediators, and those with less than 0.5% Si are classified as Si-excluders (Table 2). These variances have been linked to variations in plant roots' capacity to absorb Si (Ma and Yamaji, 2006). Rice, sorghum, and sugarcane are examples of monocotyledons that contain the majority of Si-accumulators (Ma *et al.,* 2001; Ma and Takahashi, 2002). According to Jones and Handreek (1967), the majority of plant species Si content tends to rise with age, with older leaves often having higher concentrations of silica.

Table 2: Silicon concentration in the shoots of different plant species

Plant species	Common name	Si % Wt
Lactuca serriola	Lettuce	0.97
Helianthus annuus	Sunflower	1.88
Glycine max	Soybean	1.39
Lupines nanus	Lupine	0.28
Phaseolus vulgaris	Bean	0.95
Menthe longifolia	Mint	0.73
Menthe piperita	Peppermint	1.22
Allium fistulosum	Onion	0.31
Musa basjoo	Banana	0.98
Hordeum vulgare	Barley	1.82
Oriza sativa	Rice	4.17
Saccharum officianum	Sugarcane	1.51
Sorghum bicolor	Sorghum	1.54
Triticum aestivum	Wheat	2.45
Zea mays	Maize	0.83

Source: Ma and Takahashi (2002); Hodson *et al.* (2005)

Due to water loss through transpiration, silicon that was transferred from roots to shoots via the xylem is subjected to additional concentration. Certain transporters mediate the process of xylem loading with Si in rice, where the concentration of Si in the xylem sap is high (Mitani and Ma, 2005). As comparison to cucumber and tomato, rice typically has a 20–100 fold higher content of Si in its xylem sap (Mitani and Ma, 2005). Moreover, the amount of Si in cucumber and tomato xylem sap is typically smaller than the amount in the external solution. Because of this, the rate of Si polymerization in cucumber and tomato shoots is quite low (Mitani and Ma, 2005). The concentration of Si increases under these circumstances and as more silicic acid is taken by plant roots, which causes it to polymerize into colloidal silica and ultimately silica gel ($SiO_2.nH_2O$). As a result, silica gel makes up more than 90% of the total Si in a rice shoot. Cucumber shoot Si build-up exhibits a pattern resembling that of rice, but with a lower concentration (Ma and Yamaji, 2006).

Silicon as a beneficial / an essential element

Si was acknowledged as one of the 15 essential elements for plant life in the early 1900s (Tubana *et al.*, 2016). Despite the fact that it is highly accumulated in plants, it is not regarded as a nutrient element that is necessary for higher plants (Ma and Takahashi, 2002). Yet, a wide range of higher plants have been shown to benefit from its positive benefits (Richmond and Sussman, 2003; Ma, 2004). On the other hand, diatoms and certain rushes and algae have knowledge of its necessity (Epstein, 1999). Several other abiotic stimuli, including salt stress (Liang *et al.*, 2003; Ashraf *et al.*, 2010), drought stress (Hattori *et al.*, 2005; Chen *et al.*, 2011), and heavy metals stress (Neumann and Nieden, 2001; Nwugo and Huerta, 2008). can all be more tolerable by silicon for plants.

Recently, Epstein and Bloom amended Arnon and Stout's (1939) well-known notion of an element's essentiality (2005). The necessary plant nutrient should therefore meet one or both of the following requirements: The plant can be so severely deficient in the element that it exhibits abnormalities in growth, development, or production, i.e. performance, when compared to plants with lower deficiency. This is because (1) the element is a part of molecule that is an intrinsic component of the structure of the metabolism of the plant, and (2) the plant can be so severely deficient in the element. This freshly developed definition suggests that Si may be a crucial component of higher plants that may eventually become widely used (Epstein and Bloom, 2005).

Si has positive effects, although they are less noticeable under ideal growth settings and more noticeable under stressful circumstances (Epstein, 1994; Ma *et al.,* 2001). In this regard, there is no evidence that Si is involved in plant metabolism, and higher plants do not contain any organic molecules that include Si (Ma *et al.,* 2001; Knight and Kinarde, 2001).

Plant Eerection (Rigidity)

The contribution of Si to the strengthening of cell walls by the deposition of solid silica is one of tremendous significance (Currie and Perry, 2007). Hence, silicon treatment enhances plant designs by increasing erectness, enhancing leaf angle and light interception, preventing excessive self-shading, boosting structural rigidity of plant tissue, lowering lodging, and postponing senescence (Ma and Yamaji, 2006; Gong and Chen, 2012). In a similar vein, Si lessens lodging, enhances plant structural integrity, and lessens leaf freckling in sugarcane (Epstein, 1999; Ma, 2004). Si improves cell wall flexibility during extension growth, strengthens the cell wall, and adds to its rigidity, according to Marschner (1995).

Silicon supports monocotyledons mechanically by promoting the silicification, lignification, and suberization of the cell wall. The binding of Si with cell wall hemicellulose, which is a helpful process in times of water deprivation, accounts for the structural stability of monocots (Saqib *et al.,* 2008; Ma *et al.,* 2015; Coskun *et al.,* 2016).

In plants, biosilicication occurs when silicic acid polymerizes within the apoplast, creating an amorphous silica barrier that prevents harmful metals from entering the symplast and transporation stream (Wang *et al.,* 2004; Ma *et al.,* 2015; Coskun *et al.,* 2016).

Plant growth:

In typical soil, silicon supplementation had no discernible impact on plant development (Wu *et al.,* 2015), and its favourable effects are typically diminished (Epstein, 1994; Kaya *et al.,* 2006; Ma and Yamaji, 2006). However in stressful circumstances, it has been discovered that adding Si to plants increases their crop output and biomass (Wu *et al.,* 2015; Adrees *et al.,* 2015; Farooq *et al.,* 2016).

The majority of plant species were spurred to grow by silicon treatment, and strawberry yields of total marketable fruit, total fruit number, and dry weight all increased (Miyake and Takahashi, 1986). Increased alfalfa root volume, plant height, and leaf area (Wang and Han, 2007), increased soybean, common bean, and peanut seed yield (Crusciol *et al.,* 2013), as well as common bean yield (Zuccarini, 2008), simulated the size a chrysanthemum stem and height (Sivanesan *et al.,* 2013), increased rice biomass and yield (Savant *et al.,* 1997; Farooq *et al.,* 2016), and produced the highest grain yield of wheat (Maamoun, 2014). Plant height, leaf area index, and grain production of maize were all dramatically boosted by the silicon treatment (Amin *et al.,* 2016); increased sweet pepper fresh and dried weight, branch and leaf count, and plant height (Tantawy *et al.,* 2015); Egyptian clover's plant height, branches per plant, heads per plant, seeds per head, and straw end increased (Ibrahim *et al.*, 2015); a rise in the cotton plant's height, root length, leaf area index, and grain yield (Adrees *et al.*, 2015); and improved biological yield (Abou Baker *et al.*, 2012); According to Al-Saeedi *et al.* (2017), the use of nano-silica improved the growth and development of common beans as well as the number of leaves and branches and the seed dry weight of soybeans (Suciaty *et al.*, 2018).

Macronutrient content:

Si addition has boosted potassium contents in the roots and shoots of barley cultivated under salt stress. Si addition, according to Maamoun (2014), led to higher K+ and lower Na+ concentrations in wheat grains. Silicon improved rice's ability to utilise nitrogen and phosphorus while maintaining acceptable levels of P, K, Ca, and Mg in the shoots and roots of rape seed. Moreover, it raised the K/Na ratio in plants, maintained acceptable K+ levels and K+ absorption, and boosted K+ levels in the roots and shoots of barley and wheat (Imtias *et al.*, 2016). Moreover, it was discovered that silica (diatomite) foliar spraying improved N, P, and K uptake and content in wheat plants cultivated in clay soil (Hellal *et al.*, 2012).

Enzyme activities:

Barley plants cultivated with potassium silicate showed a two-fold increase in ATPase activity compared to plants grown without Si (Liang, 1999). In plants cultivated under salt stress, silicon increased the activity of antioxidant enzymes (Liang, 1999; Wang *et al.*, 2011) while decreasing hydrogen peroxide (H_2O_2) concentrations (Gong *et al.*, 2005). In two alfalfa cultivars cultivated under Cd stress, Wang *et al.* (2011) discovered that Si supplementation boosted ascorbate peroxidase (APX) activity in roots, shoots, and leaves, catalase (CAT) activity in leaves, and peroxidase (POD) activity in shoots.

While superoxide dismutase and catalase activities increased after silicon was applied to spinach grown under salinity stress, H_2O_2 and lipid peroxidation (LPO) decreased (Eraslan *et al.*, 2008). The Si treatment boosted the SOD, CAT, and APX enzyme activity in the leaves of tomato and spinach plants. Si addition boosted the activities of sucrose phosphate synthase and sucrose synthase in tomato plants. Moreover, according to Bu *et al.* (2016), Si treatment of cucumber seedlings enhanced SOD, CAT, and APX activity.

Photosynthesis:

One of the benefits of adding Si to plants is improved photosynthetic efficiency (Gong and Chen, 2012), while plants grown in Si-deficient soil showed disturbances in leaf photosynthetic efficiency. Si addition has been shown to improve chlorophyll content and ultrastructure of chloroplasts (Liang *et al.*, 2003). It has been found that the photosynthetic rate in the leaves of soybean has increased by 21% as a result of Si addition (Shen *et al.*, 2010).

Recent research revealed that the addition of Si had boosted the levels of photosynthetic pigments, including chlorophyll and carotene, in wheat (Hellal *et al.*, 2012), maize (Amin *et al.*, 2016), wheat (Hijiboland *et al.*, 2017), and chrysanthemum (Sivanesan *et al.*, 2013). Moreover, it was discovered that spraying wheat leaves with Si enhanced the levels of carotenoids, chlorophyll pigments, and both chlorophyll a and b. (Ibrahim *et al.*, 2015).

Cell membrane stability:

Si treatment reduced excessive cell membrane damage in rice and soybean that was brought on by salt stress, dehydration, or UV radiation (Feng *et al.*, 2011). Applications of Si have maintained the ability to prevent damage to the cell membrane of maize cultivated under drought stress (Kaya *et al.*, 2006). Silicon was added to rose (Rosa x hyprida L.) and gerbera (*Gerbera jamesonii*) cuts in order to prevent cell membranes from harm and restore membrane integrity and function. Gunes *et al.* (2007) discovered that Si treatment of tomato and spinach cultivated under the toxicity of Na+, B, and salt protected against oxidative membrane damage.

Water content in plants:

Rice, maize, tomato, wheat, gerbera cut, bean, sorghum, papper, and soybean water status were all improved by the silicon application. In drought-like conditions, the plants treated with Si sustained larger water contents than those that weren't (Ma *et al.*, 2001; Kaya *et al.*, 2006; Gong and Chen, 2012).

Si addition to plants cultivated under salt stress has been observed to boost economic water productivity (EWP), relative leaf water content, irrigation water use efficiency (IWUE), and water usage efficiency (WUE) (Amin *et al.*, 2016). Si addition improved the water status in plants' leaves and kept it there at a high level, which has been linked to less water loss through transpiration. By Si deposition as a layer of silica gel on the epidermal cell walls, this low transpiration has been made possible (Tuna *et al.*, 2008). The improved structural integrity of plants treated with Si was also found to increase water retention in leaf tissue and maintain plant water balance.

An important element in enhancing plants' water status is the supply of Si compounds. K-silicate foliar spraying was superior than Mg-silicate for increasing plant water content. This is because K helps to reduce salt stress and Na+ toxicity (Abou-Baker *et al.*, 2012). Increased water content in plants would cause salt to be diluted in plant tissues, reducing salt toxicity and promoting greater plant development.

Role of silicon in plant under stress conditions

According to some reports, silicon reduces a variety of abiotic stresses, such as chemical and physical stresses like salt, metal toxicity, and nutrient imbalance, as well as physical stresses like drought, radiation, hot and low temperatures, and freezing.

Reactive oxygen species (ROS) are produced in plants under stress under specific circumstances, which might surpass the antioxidant capacity of plant cells and subsequently result in oxidative damage to those cells.

In the absence of Si, quantities of proline, hydrogen peroxide, lipid peroxidation, and hydrogen peroxide are increased (Gunes *et al.*, 2007). Proline concentrations are higher in plants under salt and water stress than they are under normal conditions, and adding Si to pepper plants reduced proline concentration relative to plants not receiving Si treatment (Pereira *et al.,* 2013).

The formation of a subcuticular double layer by silica deposition beneath leaf cuticles lowers water loss through transpiration, improving the water status of stressed plants.

Radiation stress:

Ultraviolet-B radiation adversely affects plant cell biology, causing the generation of reactive oxygen species (ROS), which leads to plant damage (Lizana *et al.,* 2009). It also causes intensification of lipid peroxidation (LPO) and cell membrane damage in soybean seedlings and rice. Reactive oxygen species–mediated lipid peroxidation is considered the most damaging process in living organisms (Gill and Tuteja, 2010).

Silicon supplementation improved soybean and sorghum seedlings' resistance to UV-B radiation exposure and minimised cell membrane deterioration (Fang *et al.*, 2011). According to certain research, Si can protect sugarcane leaves from UV-B radiation damage by blocking the dangerous rays. Also, it has been discovered that adding Si to sugarcane increases the activity of SOD molecules in plants' leaves that have been exposed to UV-B rays.

Drought stress:

One of the major factors in crop loss that lowers the typical crop yield is drought stress. It has been demonstrated that adding silicon increases the drought resistance of sorghum, cucumber, wheat, soybean, and rice.

Si plays a role in increasing drought stress through a number of physical, physiological, and biochemical processes, including (i) maintaining leaf erectness and xylem vessel structure, water balance, and photosynthetic efficiency (Hattori *et al.,* 2005), and (ii) promoting the activity of antioxidant enzymes and phosynthetic rate (Gong *et al.,* 2005) and (iii) boosting antioxidant metabolite concentrations (Qian *et al.,* 2006).

In comparison to the control treatment, silicon application increased the water status of soybeans grown under drought stress by 30%. (Shen *et al.,* 2010). It also increased the relative water content in the leaves of drought-stressed wheat (Gong *et al.,* 2005) and maize (Amin *et al.,* 2016).

Silicon supplementation decreased plant membrane deterioration, cucumber, alfalfa, and common bean Na^+ absorption, plant leaf H_2O_2 concentration, lipid peroxidation (LPO), and membrane permeability (Farooq *et al.,* 2015).

Salt stress:

By the specific actions of certain ions, by increasing the osmotic pressure of the solution in the growth medium, or by using both of these strategies, salinity negatively impacts plant growth. The concentrations of proline, H_2O_2, and LPO in spinach are all increased by salinity (Eraslan *et al.,* 2008). In tomato and spinach, stomatal resistance, membrane permeability, lipid peroxidation, hydrogen peroxide, and proline are increased in the absence of Si (Eraslan *et al.,* 2008). The ameliorative benefits of Si under salt stress have been attributed to a number of pathways, including improved plant uptake of water and nutrients from the soil and activation of antioxidant defence (Zhu and Gong, 2014).

In barley cultivated under salt stress, silicon supplementation preserved membrane integrity and reduced plant membrane permeability. The activities of root plasma/membrane H^+ ATPase and tonoplast H^+ ATPase were mimicked by silicon supplementation, enhancing Na^+ efflux and K^+ influx in barley plants. Superoxide dismutase, peroxidase, catalase, glutathione reductase, and glutathione content in salt-stressed plants have all been reported to replicate the activity of silicon. In salt-stressed barley, silicon reduced the quantity of malondialdehyde, the byproduct of lipid peroxidation, which associated favourably with Na^+ content and negatively with Ca^{2+} and K^+ absorption (Coskun *et al.,* 2016). Si reduced Na^+ uptake in response to salt stress, but improved the K^+/Na^+ ratio and reduced Na^+ toxicity in barley.

Si has been proposed as an ameliorative agent to enhance plant development under salt stress through a number of processes, including enhancing plant uptake of nutrients and water from the soil and activating antioxidant defences in plants (Zhu and Gong, 2014). When silicon was applied to wheat grown under salt stress, Na+ content in the cell sap fell and its concentration in the cell wall-bound fraction increased, indicating that Si is a mediator of the Na+ detoxifying mechanism (Hajiboland *et al.,* 2017).

Heavy metals stress

Plant growth is inhibited by heavy metal toxicity, and physiological and biological processes are disturbed in plants (Bu *et al.,* 2016; Farooq *et al.*, 2016). Moreover, it impairs membrane functioning, damages membrane permeability, and produces reactive oxygen species (ROS) (Farooq *et al.,* 2016). Cadmium changes the structure of leaves, lowers antioxidant enzyme activity, and limits photosynthesis in plants by reducing stomatal conductance and photosynthetic pigment concentration (Mohsenzadeh *et al.*, 2012; Kabir *et al.,* 2016).

Silicon increases the ability of plants to withstand harmful metals like Al, As, Cd, M, and Zn. Following are some ways to implement Si's techniques to lessen the poisonous impact of metal on plants: (i) Si deposition in roots decreases apoplasmic bypass flow, which inhibits metal uptake and translocation in plants (Ma and Yamaji, 2006), (ii) Alters the sub-cellular distribution of metal and improves its adherence to the cell walls of roots, stems, and leaves, (iii) increases antioxidant enzyme activity and lowers membrane lipid peroxidation when exposed to toxic metal stress (Mohsenzadah *et al.*, 2012).

By immobilising the metal in the cell wall of the plant root and preventing its transit to the cytosol, silicon can also promote tolerance to hazardous metals. This is made possible by Si's capacity to covalently bond to the metal, resulting in the formation of a metal-silicate complex that subsequently inhibits metal toxicity (Greger *et al.*, 2016; Kabir *et al.*, 2016).

In rice, alfalfa, tomato, peanut, and tomato, silicon provided to plants reduces Cd concentration in shoots and its translocation from roots to shoots (Kabir *et al.,* 2016). This may be because Cd absorption sites in roots have been blocked, the exodermis tissues have been strengthened, increasing Cd retention in roots, or the apoplastic bypass flow has been physically blocked, preventing apoplastic transfer of Cd (Ma and Yamaji, 2006; Imtiaz *et al.*, 2016).

Silicon improved the resistance of wheat to the toxicity of Cd and Cu, barley to the toxicity of Cr, rice to the toxicity of Zn, and cotton to the toxicity of Ni. Si treatment improved the activity of SOD, CAT, and POD enzymes in plants growing under heavy metal stress, reducing oxidative damage and increasing plant GSH content (Shen *et al.*, 2010).

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SOIL MICRO BIOTA EFFECT FOR SUSTAINABLE AGRICULTURE

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Introduction:

Soils are heterogeneous habitats that support microorganism populations of minute size and diversity. In agriculture, sustainability refers to the long-term management of soil productivity through the use of natural resources without causing environmental degradation. Auxin, cytokinins, and gibberellins are some examples of the growth regulators produced by PGPMs. They also improve the uptake of water and nutrients (with the aid of N_2 fixers, phosphate solubilizers, and siderophore producers), suppress the production of stress hormones like ethylene, inhibit pathogens by producing antibiotics or cell wall lytic enzymes (chitinase), and stimulate plant defence mechanisms. (Dubey *et al.*, 2019). Hydrolytic enzymes help in penetration of endophytic microbes into plant tissues which improves the plants quality and affects maintenance of the agricultural ecosystem (Abhilash *et al.*, 2016). Microbes play important role in bioremediation, waste water filtration and they create medicines and drugs (Dubey *et al.*, 2019). Several studies showed that Plant growth promoting microorganism (PGPM) that promotes the growth of a particular species of plant might not be beneficial for other plants species. For example, fungi belonging to *Trichoderma sp*. and *Penicillium sp.* showed diversified effectiveness in enhancing the growth of varied wheat (*Triticum aestivum* L.) variety.

Hiltner coined the term 'rhizosphere' in 1904 to describe the zone of soil under the influence of plant roots. His observations were initially based on the interactions between symbiotic N2-fixing bacteria and the legume root, but were then expanded to include all interactions. This zone of soil ranges from only a few hundred micrometres to > 5 mm from the root surface. Rhizosphere is defined as the zone of chemical, biological, and physical influence generated by root growth and activity. The concept usually pertains to the soil-root interface but is sometimes extrapolated to other media-root interfaces (Pinton *et al.*, 2007)

The term '*phyllosphere'* was given by *Ruinen* in year 1956. The "aerial part of the plant" or "parts of a plant above the earth, mainly the surface of leaves, recognized as a habitat for microorganisms" is referred to as the "phyllosphere." Microbes can colonise and develop their relationships with plants, typically epiphytes, in the phyllosphere. The phyllosphere's microbial communities are extremely complex and contain both cultivated and naturally occurring microbes. (Johanand Leveau, 2006).

Sustainable agriculture is a balanced management system of renewable resources including soil, wildlife, forest, crops, livestock, crops, ecosystems and plant genetic resources without degradation and to provide food, livelihood for current and future generations maintaining or improving productivity and ecosystem services of these resources. In general terms, sustainable agriculture is a form of agriculture aimed at meeting the needs of present generation without endangering the resources base of the future generations. Sustainable agriculture has to be economically viable both in long and short term perspectives.

Sustainable agriculture is also known as *Ecoforming*or *organic farming* or *permaculture* and natural farming. It is known as eco farming as ecological balance is given importance.

Soil microbiota, microbiome and theatre of life:

Soil microbiota refers to the diverse community of microorganisms that live in soil. These microorganisms include bacteria, fungi, viruses, archaea, and protozoa, and they play important roles in the soil ecosystem. Soil microbiota are essential for the breakdown of organic matter, nutrient cycling, and the maintenance of soil structure (Jansson and Hofmockel, 2020). They also play important roles in plant growth and health, as they can form symbiotic relationships with plants, provide nutrients, and protect against pathogens. The composition and diversity of soil microbiota can vary depending on a variety of factors, including soil type, climate, vegetation, and land use. Some practices, such as the use of pesticides or fertilizers, can have negative impacts on soil microbiota diversity and function. Therefore, it is important to maintain healthy soil microbiota for sustainable agriculture and ecosystem health.

The soil microbiome refers to the collective genomes of all the microorganisms that inhabit the soil. This includes bacteria, fungi, archaea, viruses, and protozoa. It plays a crucial role in the functioning of ecosystems and global nutrient balance. Soil microbiome is associated with symbiotic relationships with plants through plant-microbe interactions (Bradgett *et al.*, 2013; Verma *et al.*, 2017; Yadav, 2021). The microbes present in the rhizosphere region may proliferate onto exudates secreted in soil by the plant roots due to the presence of the principal nutrients such as glucose, fructose, sucrose and amino acids (Hayat *et al.*, 2017). These microbes have the capability to produce phytohormones, atmospheric nitrogen fixation, and solubilization of phosphorus and potassium which finally help plant systems in their growth and development (Dubey *et al.*, 2019). This association also protect plants from pathogen through secretion of secondary metabolites such as siderophores, ammonia and hydrolytic enzymes. Recent advancements in DNA sequencing technology have allowed for the study of the soil microbiome at a much deeper level, revealing the vast complexity and diversity of microorganisms present in soil ecosystems (Fierer, 2017). Understanding the soil microbiome and its interactions with other components of the ecosystem is essential for the development of sustainable agricultural practices and ecosystem management (Hesham *et al.*, 2021).

The soil microbiome can be thought of as a "theatre of life" due to the diversity of microorganisms and their interactions with one another and with the environment. In this theatre of life, different microorganisms play different roles. For example, some microorganisms, such as nitrogen-fixing bacteria, are responsible for converting atmospheric nitrogen into a form that plants can use (Bradgett *et al.,* 2014). Other microorganisms, such as mycorrhizal fungi, form symbiotic relationships with plant roots, helping them to absorb nutrients and water from the soil. There are also predators in the soil microbiome, such as protozoa and nematodes that feed on other microorganisms, helping to maintain a balance of populations.

1. Soil Microbiota role in nutrient cycling

Soil microbiota, also known as soil microbes, play a crucial role in nutrient cycling. These microbes are responsible for decomposing organic matter, releasing nutrients back into the soil, and making them available to plants (Prasad *et al.*, 2021). There are different types of soil microbes, including bacteria, fungi, protozoa, and nematodes, all of which contribute to the nutrient cycling process in different ways (Harman and Uphoff, 2019). Bacteria and fungi, for example, are important decomposers that break down dead plant and animal matter, releasing nitrogen, phosphorus, and other nutrients into the soil. In addition to decomposers, some soil microbes are nitrogen fixers, which means they have the ability to convert atmospheric nitrogen into a form that plants can use. This process is essential because nitrogen is a vital nutrient that plants need to grow and develop. Other soil microbes, such as mycorrhizal fungi, form symbiotic relationships with plant roots, exchanging nutrients with the plant in a mutually beneficial relationship (Kour *et al.,* 2019). The fungi help the plant absorb water and nutrients, while the plant provides the fungi with carbohydrates.

The nitrogen cycle involves the conversion of atmospheric nitrogen into a form that plants can use. The soil microbiota is responsible for several key processes including:

- Nitrogen fixation: Some soil microorganism species like *Bacillus, Klebsiella, Azotobacter* and *Clostridium* have the ability to convert atmospheric nitrogen into ammonia (NH_3) and other forms of nitrogen that can be used by plants (Li *et al.*, 2018). This process is known as nitrogen fixation and is essential for the growth and development of plants.
- Nitrification: Once the nitrogen has been fixed into ammonia, soil bacteria like *Nitrosomonas*and *Nitrobacter*can convert it into nitrite (NO_2^-) and then into nitrate (NO_3^-). These forms of nitrogen can be easily absorbed by plant roots and used for growth (Schloter *et al.,* 2018).
- Denitrification: In some cases, soil bacterial species like *Micrococcus, Pseudomonas, Aerobacter, Spirillum, Bacillus, Flavobacterium, Enterobacter* and *Proteus* can also convert nitrate back into atmospheric nitrogen, completing the nitrogen cycle (Sergaki *et al.,* 2018). This process, known as denitrification, helps to regulate the amount of nitrogen in the environment and prevent excess nitrogen from accumulating (Sanchez-Canizares *et al.*, 2017).

Soil microbiota plays a critical role in phosphorus cycling by facilitating the transformation of organic and inorganic phosphorus into plant-available forms. Microorganism's species such as *Aspergillus, Rhizobium, Penicillium, Bacillus* and *Pseudomonas* break down complex organic matter and release phosphorus in the soil, making it available to plants (Kaur and Reddy, 2014). They also help solubilize inorganic phosphorus by secreting organic acids that dissolve minerals and release phosphorus into the soil solution (Lucaciu *et al.*, 2019). Additionally, soil microbiota play a role in the immobilization of phosphorus in the soil. Microorganisms can sequester phosphorus through the production of extracellular polymeric substances (EPS), which can bind to and immobilize phosphorus in the soil (Kour *et al.*, 2021). This helps to prevent leaching of phosphorus from the soil, which can lead to eutrophication of nearby water bodies.

Potassium is an essential nutrient for plant growth and development, and it is one of the three primary macronutrients that plants need in large quantities. Microorganisms species such as *Paenicacillus, Pseudomonas, Burkholderia, Acidothiobacillus ferrooxidans, Bacillus circulans, Bacillus edaphicus* and *Bacillus mucilaginosus* in the soil break down organic matter, releasing potassium ions into the soil solution (Zhong *et al.*, 2010). These potassium ions are then available for uptake by plants. Microorganisms in the soil also play a critical role in the mineralization of potassium from mineral sources. In the case of potassium, mineralization involves the conversion of insoluble potassium minerals into soluble potassium ions. Some soil microorganisms also have the ability to solubilize potassium minerals directly. For example, some bacteria and fungi as mentioned above produce organic acids that can dissolve potassium minerals, releasing potassium ions into the soil solution (Yang *et al.*, 2017). Therefore, the soil microbiota plays a vital role in potassium cycling by releasing potassium ions into the soil solution through the breakdown of organic matter, mineralization of potassium from mineral sources, and direct solubilization of potassium minerals.

Soil microbiota, which includes bacteria, fungi, and other microorganisms, play a crucial role in the cycling of sulfur in soil ecosystems. Sulfur is an essential element for plant growth and development, and soil microbiota can influence its availability to plants (Sharaff *et al.*, 2020). The process of sulfur cycling involves the transformation of sulfur from one form to another, including elemental sulfur, sulfates, and organic sulfur compounds (Zoner *et al.*, 2018). Some soil bacteria, such as *Thiobacillus* and *Acidithiobacillus*, can oxidize elemental sulfur and sulfur-containing compounds to sulfate, which is the form of sulfur that is most readily available to plants (Singh *et al.*, 2019). Other bacteria, such as *Desulfovibrio*and *Desulfotomaculum*, can reduce sulfate to sulfide, which can be used by plants as a source of sulfur. Fungi also play an important role in sulfur cycling by decomposing organic matter and releasing sulfur compounds into the soil. Some fungi, such as mycorrhizae, can form mutualistic associations with plants, enhancing their ability to absorb sulfur from the soil (Tiwari *et al.*, 2021).

2. Soil Microbiota role in enhancing crop production

Soil microbiota play an important role in enhancing crop production through various mechanisms. One of the most significant roles of soil microbiota in crop production is nutrient cycling (Kour *et al.*, 2020). The relationship between soil microbiota and crops is complex and multifaceted. Microorganisms in the soil can directly affect plant growth by aiding in nutrient uptake, protecting against pathogens, and influencing plant hormone levels (Bradgett *et al.*, 2013). Some bacteria are known to fix nitrogen from the air and make it available to plants, while mycorrhizal fungi can help plants absorb phosphorus. Additionally, the diversity and abundance of soil microbiota can impact crop productivity and disease resistance. Microorganisms in the soil decompose organic matter and convert it into forms that plants can use as nutrients, such as nitrogen, phosphorus, and potassium. They also play a key role in the uptake and availability of other micronutrients such as iron, zinc, and copper. Soil microbiota also help to improve soil structure and water-holding capacity. Bacteria and fungi form networks of filaments in the soil, creating pore spaces and channels that allow water and air to flow through the soil. This improves soil structure, making it easier for plant roots to penetrate and access nutrients and water (Compant *et al.*, 2019). In addition to these benefits, soil microbiota also helps to protect crops from disease and pests. Beneficial microorganisms can outcompete harmful pathogens and pests, or directly attack them, helping to keep them in check and preventing damage to the crops. Certain soil microorganisms can break down contaminants in the soil, such as pesticides and heavy metals, making the soil safer and healthier for crops. Soil microorganisms can produce plant growth-promoting substances such as auxins, cytokinins, and gibberellins, which can enhance plant growth and yield (Devi *et al.,* 2020). Finally, soil microbiota can also contribute to the production of plant growth-promoting substances, such as hormones and enzymes that enhance plant growth and development (Chiappero *et al.,* 2019). Maintaining healthy soil microbiota through practices such as crop rotation, cover cropping, and reduced tillage can help to improve soil health and increase crop yields.

Soil microbiota role in abiotic stress, heat stress, cold stress, salt stress and their management on sustainable agriculture:

An ecosystem is a group of living organisms that interact with one another and their surroundings, known as the abiotic environment or environmental elements. It is difficult to understand due to its complexity and multivariate interactions. Understanding how different elements like abiotic and biotic factors that affect an ecosystem are essential for understanding and its functions. Research has shown that biota on the soil's surface can have an impact on the biota underneath it. The rhizosphere is the region of the soil that is affected by plant roots. This micro-ecosystem is made up of a biota (microorganisms) that lives in the soil and may develop intricate communities that interact with plants in either a useful or destructive manner. Beneficial plant-microbe interactions are especially interesting because we can use them to enhance and promote plant growth, development, and health for a variety of uses, including agriculture. The microbial communities that inhabit the rhizosphere are important for physiology and development of the plant. Similarly, the microbes are also benefited by the plants by increasing their population by production of hormones and also providing the food for their survival during the stress conditions.

There are many studies that are focused on the study of effect of climatic / abiotic factors that influence the growth of the microbes. Everything is present everywhere but environment decides weather it is fit for the place or not. As of now the abiotic factors that affect the growth of the soil microbes like type of soil, temperature, pH, geographical factors and other environmental factors. Moreover, Climate change has a negative effect on all of the planet's biota, including life in the soil. To mitigate this, the rhizosphere microbiome can be used to enhance plant development, with an emphasis on agricultural crops.

The rhizosphere creates the micro environment for microbes which resides and has a significant impact on the growth plants. Exudates, secondary compounds that are expelled by plant roots and have an impact on it. The exudates containing carbohydrates, organic acids, vitamins, or amino acids may function as chemo-attractants to microbes, helps in absorption of the nutrients and increase in the population. Phenolic derivatives, in particular flavonoids, specifically attract rhizobia bacteria, a heterogeneous group of bacteria that includes the genera Rhizobium, Bradyrhizobium, Sinorhizobium, Mesorhizobium, and Allorizhobium. As a microbially diverse environment, the rhizosphere is an excellent place to look for novel taxa and genetic material with enormous biotechnological potential. PGPR, or plant growth-promoting bacteria, include nitrogen-fixing Rhizobia, Bacillus, Pseudomonas, Arthrobacter, Erwinia, Serratia, Azotobacter, Azospirillum, Burkholderia, Caulobacter, and Chromobacterium. Plants benefit from PGPR, which gives them resilience to many conditions such drought, temperature, salt, toleration of heavy metals, and biocontrol pathogens. They have coevolved with plants by having considerable impact on the growth, wellbeing, and survival in adverse situations. It is challenging to categories the soil and rhizosphere ecosystems as different parts since they are influenced and modified by several external variables. The investigation of the precise impacts of one abiotic factor is sometimes complicated by the presence of two or more abiotic variables that have an impact on the soil or rhizosphere microbiome.

1. Soil type and Structure

In order for plants to flourish sustainably, soils must include a variety of elements, including minerals, gases, liquids, organic matter, and living things. Sand, silt, and clay are examples of mineral elements that are classified based on their mineral composition, which has an impact on porosity and soil moisture. Many soil-resident interfaces, including gas, moisture, or mineral content, enable nutrient, pH, and gas gradients, resulting in a variety of microenvironments that provide biological niches. In addition to playing important ecological functions, soil-dwelling organisms including bacteria, fungus, and viruses take part in the cycling of nutrients that is necessary for plant development. Plants that live in soil directly promote microbial development while having an effect on abiotic variables that indirectly affect them. The architecture of soil microbial communities is substantially influenced by soil characteristics and geographic considerations, but soil microorganisms have a big impact on how soil aggregates develop. Especially, soil moisture has a far stronger influence on the composition of microbial communities than do nutrients *Azospirillum*, for example, moved 40-60 mm in 96 hours in sandy soil with a moisture level of 16%; but, in soils with a moisture content of 10%, this distance was reduced to 20 mm during the same time period (Ochoa *et al.*, 2010).The richness of bacterial species in soils from the Arctic desert is connected with moisture content, according to research on soils from severe environmental conditions. To colonize the soil or rhizosphere regions in close proximity to root exudates or nutrients, bacteria must be mobile. Bacterial abundance dropped in relation to precipitation but was independent of the precipitation gradient, which is crucial for the production of the distinct kinds and structures of soil. The size of the pore pores can also affect the community composition (Huber *et al.*, 2016). Soil aggregates are essential for the existence or collection of certain microbial group species Acidobacteria is frequently found only within soil macroaggregates.

Several soils have been studied to determine which bacterial groups are most effective in promoting plant development, and Egamberdiyeva (2007) noted that it was predicted for taxa, such as Pseudomonas, Bacillus, and Mycobacterium, to thrive in nutrient-deficient soils as opposed to nutrient-rich soils since they may effectively boost NPK absorption in maize plants. Although there are many factors that affect the species composition in the rhizosphere, plant roots have a highly selective impact through the production of exudates (Lareen *et al.*,2016).

2. Soil pH

The hydronium ion $[H_3O]^+$ concentrations in soil are measured as PH, which identifies the soil's acidity or alkalinity. Significant fluctuations in soil pH upset microbial communities and soil microorganisms, and it is a common component that determines the organisation of microbiome populations. Several researchers, including Fierer and Jackson (2006) and Bell *et al.* (2011) in a continent-wide survey, have concentrated on the impact of pH at various scales. pH was shown by Fierer and Jackson (2006) to be the main determinant of changes in bacterial community composition in North and South America. The Jaccard and Bray- Curtis index studies revealed an inverse association between the compositional similarity of Acidobacteria and elevation. Acidobacteria is a major soil genus with great metabolic adaptability. Because it is directly linked to the availability of nutrients for plants and also acts as an indirect restraint on microbial communities, soil pH was identified as a significant element for such inverse connections. There is, however, no correlation between soil pH and bacterial diversity in ecosystems, according to some studies. In different Croatian regions, Sinorhizobiummeliloti was assessed in relation to several abiotic parameters, although only the soil type and other geographical factors that are responsible for the diversity of 126 isolates of the study.

3. Soil nutrients

On a global scale, the effects of soil nutrients on plant development and yields have been well investigated. A significant barrier to agricultural output is infertile soil, which can be identified by the levels of nitrogen, carbon, and phosphorus. Iron is one such element that affects how diverse the bacteria in the microbiome. Synthetic fertilizers, which may have detrimental impacts on the environment, human health, and animal health, can be used to manage nutrient shortages (Idrees *et al.*, 2017). Microorganisms play a crucial role in the breakdown of organic matter and the cycling of nutrients for plants, which together determine soil fertility. The variety and richness of the rhizosphere microbiome are influenced both directly and indirectly by soil nutrients and their bioavailability (Pérez-Jaramillo *et al.*, 2016). Yet, at the expense of lessening the diversity and abundance of the plant and bacterial communities, experimental nitrogen enrichment also influences microbial abundance and plant production. The structure and function of microbial communities in soil are similarly influenced by carbon, and land use can lower soil organic C reserves and reduce the diversity of soil bacteria that catabolize (Yang *et al.*, 2015). Moreover, human actions can expand the supply of nutrients that are helpful for the growth of the population.

4. Geographical factors: altitude, latitude, and longitude

Many studies have examined how geographic elements like height, latitude, and longitude affect the distribution and variety of living species. Van Horn *et al.*, (2013) documented the effects of various abiotic parameters on the diversity of soils in Antarctica, including pH, sulphates, and organic matter. Actinobacteria and Acidobacteria were prevalent at low elevations, while Firmicutes and Proteobacteria dominated at high elevations. The degree and direction of these relationships differed between basins and data, indicating the importance of geographical scale sampling in identifying the precise geographic parameters that influenced the characteristics of soil microbial communities. It is also acknowledged that the diversity of bacteria may decrease when elevation changes, but this impact is not widespread.

5. Climatic factors (UV radiation, CO_2, and temperature)

Many locations throughout the world may experience increases in temperature, droughts, ozone depletion, UV radiation, atmospheric CO2, and irregular precipitation as a result of the abrupt and quick climate changes. Although the causes of climatic changes vary, it is evident that these modifications have an impact on life and associated biological processes on Earth. Climate changes also have a significant impact on the biology of microbes and plants, which together affect the rhizosphere microbiome.

5.1. UV radiation

UV radiation (UVR) exposure has increased due to the ozone hole created by the accumulation of CO_2 and chlorofluorocarbons, especially in the polar areas. Microorganisms in the soil are directly affected by UV light, whereas the rhizosphere is predominantly affected by carbon sources and nutrient cycling. Plants change the metabolism of their root cell tissues to defend themselves from stress, which aids in the choice of various bacterial communities (Formánek *et al.*, 2014). In contrast to soil or rhizospheric communities, the phyllosphere community is often more susceptible to UV (and other environmental conditions) and is dominated by a small number of species. However, species can vary in how sensitive they are to UV-B radiation, and different bacterial species have different strategies for tolerating UVR. Pigments were produced by isolated bacterial phyllosphere populations as a means of UVR survival and protection. *Erwiniaherbicola's* carotenoid is crucial for cellular health.

5.2. CO_2

The industrial revolution has caused a substantial rise in atmospheric CO_2 levels, which has resulted in global warming and decreased precipitation. Ecosystems on surface as well as the underground carbon cycle have been negatively impacted by this. Due to accelerated plant development and diminished degradation capability, high CO_2 concentrations can lower pasture microbial breakdown rates and lower the available N for microorganisms. The dynamics of organic matter in the soil are impacted by elevated CO_2, which has indirect impacts on soil structures. Yet, because it depends on root exudates and plant output, the effect of higher aCO_2 on the soil microbiome is quite unpredictable. The effects of aCO_2 on soil bacteria are also directly influenced by a number of additional biotic and abiotic variables. Elevated CO_2 has not, however, led to changes biomass and activity (Wang *et al.*, 2017; Yu *et al.*, 2018).

5.3. Temperature

The amount of water in the soil decreases as the temperature rises, which also limits the capacity of microorganisms to spread, survive, and colonise soil spaces. Increased outside temperatures heat the soil and change the microbiome's composition in the rhizosphere. Sorensen *et al.,* (2019) incubated root development and exclusion cores across a winter climate-elevation gradient for 29 months to examine the effect of winter air temperature upon soil bacterial and fungal populations in northern hardwood woods. When the northern latitude tundra soils were heated in situ by 1.1 °C above the surrounding air temperature, Johnston *et al.,* were able to observe the difference in archaeal populations. When the temperature was raised (0–3 °C) above the ambient level, coprophilous white rot fungi were found to be more abundant (Deltedesco *et al.,* 2020).The growth of soil bacterial and fungal communities shows a trending increase from the temperature of 7.3 to 35 °C, but continuous exposure of soil to high temperature results in reduction in growth, according to Nottingham *et al.,* studied how microbial communities respond to temperature sensitivity and created a hypothetical curve to illustrate how the development of soil bacterial and fungal communities trends upward from 7.3 to 35 °C but declines when soil is continuously exposed to high temperatures.

Role of microbiota in heavy metal remediation:

Recent technical developments in agriculture saw an increased use of chemicals affecting ecosystem by releasing large quantities of hazardous waste, organic contaminants and heavy metals. Heavy metal contamination is becoming the global environmental concern. Release of heavy metal causes significant threat to soil as well as human health because of its persistence, lack of proper treatment biomagnification and accumulation in food chain (Rajendran *et al.,* 2003). Heavy metals like lead (Pb), arsenic (As), mercury (Hg), cadmium (Cd), uranium (Ur), selenium (Se), chromium (Cr), zinc (Zn) are useful for plants when they in trace amount. They reduce plant growth upon excess uptake by imposing negative effects on plant mineral nutrition, photosynthesis and activities of essential enzymes (Yadav *et al.,* 2017). Microbial bioremediation of heavy metal is emerging as an effective technique due to its low cost, high efficiency and eco-friendly nature.

1. Sources of heavy metals

- Natural sources: weathering of minerals, erosion of soil and volcanic activity.
- Residue, smelting, electroplating, pesticide and phosphate fertilizer discharge, application of biosolids such as composts, livestock manures, municipal sewage & sludge, atmospheric deposition, waste combustion and vehicle exhaust (Dixit *et al.,* 2015).

2. Dominating microbial populations in heavy metal contaminated soil

One kilogram of soil can contain 1 to 100,000 mg of heavy metal as soil is the major sink for heavy metal contamination (Gadd, 2010). Soil microbes play an important role for heavy metal detoxification in contaminated soil. Pires *et al.,* (2017) studied the bacterial population structure in heavy metal-contaminated soil and concluded that Firmicutes, Proteobacteria, and Actinobacteria are dominating in soil and that the dominant genera were Bacillus, Pseudomonas, and Arthrobacter. Nodule formation and nitrogenase activity of rhizobia are affected due to heavy metal. Heavy metal-tolerant rhizobial strains were found in contaminated soil and improve the quality of contaminated soil (Checcucci *et al.*, 2017; Dhakal *et al.*, 2015). Arbuscular mycorrhizal fungi are dominant in nutrient-poor heavy metal-contaminated soil. Ascomycota and Basidiomycota are the dominant fungi in heavy metal-contaminated soil.

Table 1: A list of microbes involved in heavy metal remediation

Microorganisms	**Strain**	**Functions**	**References**
Bacteria	*Achromobacter* sp. AO22	Volatilizes Hg^{+2} by M*er*A reductase to Hg^0	Kiyono and Pan-Hou (2006).
	Bacillis subtilis	Bind with metals to form less harmful complex. Removes ferrous by active bioaccumulation involving displacement of other ions	Holan *et al.* (1994)
	Bacillus licheniformis	Removes heavy metals by bioaccumulation	Zoubouliset *al.* (2004)
	Desulfovibrio radiodurans	Removes heavy metals through transformation	Brim *et al.* (2000)
	Escherichia coli	Expresses different proteins and peptides and activates different molecular mechanisms for the remediation of Zn, Cu, As, Cd, and Hg from soil	Murtazaet *al.* (2002), Kostal*et al.* (2004), Kang *et al.* (2007)
	Enterobacter cloacae	Bioremediation of heavy metals (Pb, Cd, Ni) occurs by antioxidant enzyme activity, flocculant production, and protein expression	Kang *et al.* (2015)
	Klebsiella pneumonia M426	Volatilizes Hg (II) to Hg (0) by a reductase enzyme and removes mercury as insoluble Hg through the formation of volatile thiols	Essa *et al.* (2002)
	Pseudomonas fluorescens	The biosorption of nickel ions (Ni) occurs in free cells or immobilized cells. Produces low-molecular-weight cystine-rich proteins called metallothioneins for removing Hg and Cr from contaminated soils	Lopez *et al.* (2002), Gupta and Diwan (2017)
	Sulfate-reducing bacteria	Biosorption of arsenic occurs in free or immobilized cells	Teclu*et al.* (2008)

Fungi	*Aspergillus niger*	Capable of accumulating heavy metals (Au, Cu) within their structure	Dursun*et al.* (2003)
	Penicillium chrysogenum; Penicillium spinulosum	Remove metals (Zn, Pb) by biosorption	Nemec*et al.* (1977), Tobin *et al.* (1984), Townsley*et al.* (1986), Niu*et al.* (1993)
	Saccharomyces cerevisiae	Heavy metals [Zn (II) and Cd (II)] removed through an ion exchange mechanism	Chen and Wang (2007), Talos*et al.* (2009)
Algae/ cyanobacteria	*Asparagopsis armata*	Removes metals (Cd, Ni, Zn, Cu) by biosorption	Yang *et al.* (2015)
	Spirogyra spp.	Binding of heavy metal (Pb) onto the cell surface and to cytoplasmic ligands, phytochelatins, metallothioneins, and other intracellular molecules	Gupta and Rastogi (2008)
	Spirulina spp.	Remove heavy metals (Cr, Cu, Mn, and Zn) by adsorption, phytosorption, and affinity to negatively charged cell wall components	Mane and Bhosle (2012), Coelho *et al.* (2015)

3. Microbial mechanisms for heavy metal tolerance

Some conventional techniques used for the removal of heavy metals from the environment:

- Adsorption processes
- Chemical oxidation/reduction
- Reverse osmosis
- Sludge filtration

However, the above techniques have some limitations like high reagent requirement, and in a few cases these methods are not sensitive enough to recover the heavy metal ions, which may behave unpredictably.

Bioremediation is the removal of heavy metal ions from polluted environment using the activities of algae, bacteria, fungi, or plants. Bioremediation using microorganisms is sustainable because they help to restore the natural state of the polluted environment with long-term environmental benefit and cost-effectiveness. Detoxification of heavy metals by microorganisms can occur naturally or through the addition of electron acceptors, nutrients, or other factors.

4. Techniques used by microorganisms for heavy metal detoxification:

Biosorption: Microorganisms employ biosorption, bioaccumulation, biotransformation, and biomineralization to survive in the metal-polluted environment (Gadd, 2000; Varma *et al.*, 2017).

Adsorption: It is the physical binding of ions and molecules onto a surface. Microorganisms carry different functional groups, like –SH, –OH, and –COOH, on their cell surface that adsorbs metals from the polluted environment.

Metal binding: Metal binding is another important mechanism of microbes that occurs through different chelators such as metallothioneins, phytochelatins, and metal-binding peptides. Chelators bind to the metal to facilitate microbial absorption and transport of metal ions. Microbes also secrete chelating agents or disrupt particular transporter system to reduce metal ion accumulation in the cell.

Vacuolar compartmentalization: Microbes also bind metal ions intracellularly to molecules such as thionein and change the distribution pattern of metal ions in the vacuole and mitochondria (Siddiquee *et al.,* 2015). Compartmentalization of heavy metals into intracellular molecules takes place.

Volatilization: Microorganisms can remove volatile heavy metals from contaminated environment. Heavy metals like mercury (Hg) and selenium (Se), which have volatile state, can be volatilized by microorganisms. By using the M*er*A enzyme, mercury-resistant bacteria reduce Hg^{2+} to the volatile elemental form Hg (0). Se (V) is also reduced to elemental Se (0) to remediate the contaminated environment (Wu *et al.,* 2010).

Valence transformation: The valence transformation of heavy metals is a key mechanism for detoxification, especially for those metals whose toxicity depends on valence state. For example, mercury-resistant bacteria use organomercurial*lyase* to convert methyl mercury to Hg (II), which is one hundred times less toxic than methyl mercury (Wu *et al.,* 2010; Meena *et al.*, 2016). Chromium-resistant bacteria convert Cr (VI) to Cr (II), which is less toxic and less mobile.

In brief, microorganisms use cell wall-associated binding, intracellular accumulation, metal chelators, extracellular polymeric reactions with transformation, extracellular mobilization or immobilization of metal ions, and volatilization of metal ions to reduce the active concentration of metal ions present in the polluted environment. The high load of heavy metals in nutrient-poor soil is not a problem for arbuscular mycorrhizal fungi and other microbes because they bind metal ions on their external cell surface or transport them into the cells for compartmentalization (Ehrlich, 1997). Metal speciation, toxicity, mobility, dissolution, and deterioration are significantly influenced by microbes (Gadd, 2010). Bioavailability and accumulation of heavy metals are heavily influenced by the type and texture of soil, the physicochemical properties of the soil, plant genotype, and soil-plant-microbe interaction as well as agronomic practices such as fertilizer application, water management, and crop rotation system. Interaction of metals and microbes is a complex phenomenon that depends on physicochemical properties of the soil, type and concentration of metal species, metabolic activity and the diversity of microbes. Behaviors of soil metals towards its mobility, biological activity, availability, and chemical nature are dependent on the ability of metals to react with organic compounds (low-molecular-weight organic acid, carbohydrate, and enzyme secreted by microorganism) (Patel *et al.,* 2008).

5. Use heavy metal by microorganisms for their own growth and development

- Nickel (Ni) is not only a primary nutrient for microbes but also plays essential roles in many microbial cellular processes. When Ni enters into the cell, it incorporated into several microbial enzymes like urease, NiFe hydrogenase, acetyl- CoA decarbonylases/synthase, methyl coenzyme Ni reductase, etc. (Mulrooney and Hausinger, 2003), but Ni is toxic to bacteria at higher concentration. Therefore, different species of bacteria have developed different strategies to regulate the level of intracellular Ni to overcome this problem. For instance, *Bradyrhizobiumjaponicum*HypB has been shown to be able to bind up to 18 Ni ions per dimer and exhibits GTPase activity (Fu *et al.,* 1995).
- Metals like Cu, Zn, Co, and Fe are essential for survival and growth of microbes, but the same metals also exhibit toxicity at higher concentration and may inactivate protein molecules (Meena and Lal, 2018).
- Upon accumulation in microbial cell Al, Cd, and Hg may affect enzyme selectivity, interfere with cellular function, damage DNA structure, and may result in cell death (Belyaeva *et al.,* 2012).
- The Cu, Mo, and Mn ions bound predominantly with Fe to siderophores, resulting in an 84- to 100-fold increase in siderophore production (Balogh *et al.,* 2003; Bellenger *et al.,* 2007).
- Cobalt (Co) is essential for a broad range of physiological and biochemical functions of microbes (Jayakumar *et al.,* 2008; Okamoto and Eltis, 2011). For example, nodulation and nitrogen fixation in soybean has been found increased when Co is applied (Das *et al.,* 2000; Meena *et al.,* 2014). Rhizobial inoculation along with Co application significantly increased the total uptake of N, P, K, and Co by summer groundnut (Almeida *et al.,* 2007; Kumar *et al.,* 2017).

Future prospects:

The amount of data on how agricultural practises affect changes in soil microbial diversity is very limited. However, even this limited data shows that significant difference occur in the diversity of important micro-organisms involved in nutrient cycling, antibiosis, pathogen control and growth promotion in response to various soil managing practices which are part of conventional agriculture. Reducing the use of agro-chemical and chemicals fertilizers in conventional agriculture systems and move to organic farming will improve the microbial diversity or population.

Plant growth-promoting bacteria, commonly known as rhizobacteria, have been engineered to increase the production of stressinduced antibiotics, proteins, hormones, antifreeze trehalose, and lytic enzymes for improving plant growth and stress tolerance.

Biosensors are analytical device which are used to convert change in biological reaction into an electrical signal output and are made of a combination of a biological component, transducer, and electronic reader. It may use the concept of a general microbial bioassay, based upon estimation of the reduction in light transmittance (Rubban *et al.,* 2015; Yadav *et al.,* 2017).

Biosensor technology also used in the Bacterial luminescence properties. For example, the bioluminescent bacterium *Vibrio fischeri* has been used to develop biosensors **(**Belkin, 2006).

Metal pollution was detected by use of genetically modified microbial biosensors. Some example of genetically modified biosensors, the *zra*P and *cus*C promoters of *E. coli*XL1 fused with *rfp* and *gfp* reporter genes were used to detect Cu and Zn at 5.10 mg l^{-1} and 2.59 mg l^{-1}, respectively (Ravikumar *et al.* 2012). *E. coli* modified by the introduction of the *mer*R and *lux*CDABE genes was able to detect Hg (II) at a concentration of 1 μg l^{-1} (Ivask *et al.*, 2007) and 3×10^{-3}μg l^{-1} (Ivask *et al.*, 2009). The specificity of genetically modified microbial biosensors is very high for definite group of metals.

Genetically engineered microbes are used to the transformation of organic xenobiotics to overcome the limitations of traditional methods of bioremediation. Genetic engineering techniques were used by different companies and academia during the 1990s to exploit microbial metabolism for the bioremediation of xenobiotics (Zwillich 2000), but they were hampered due to regulatory challenges involved in genetic engineering research. However, increased degradation of 3,4-chlorotoluene and 3-chlorotoluene was observed by Abril *et al.* (1989) and Brinkmann and Reineke (1992) in genetically modified Pseudomonas sp. Although the radiation-tolerant genetically modified microbe Deinococcusradiodurans was developed for toluene degradation, it was not used for bioremediation purpose in the field due to potential risks and regulatory challenges (Lang and Wullbrandt, 1999; Ezezika and Singer, 2010; Mitran *et al.*, 2018).

Conclusion:

Soil microorganism play beneficial role in the biological, chemical, and physiological process through directly and indirectly by affecting growth and development of plants and animals. It is responsible for nutrient cycling through organic matter decomposition and ecosystem functioning by recycling different nutrients like carbon (C), nitrogen (N), phosphorus (P), potassium (K), zinc (Zn), calcium (Ca), manganese (Mg), and silicon (Si) by microorganisms. Nutrient recycling is not only essential for plants but also for other forms of life because it provides the materials to produce amino acids, proteins, DNA, and RNA, those that are essential for all plants and human being. Modern agricultural practices and industrialization are putting increasing negative pressures on agricultural water and soil by releasing large quantities of harmful waste, heavy metals, and organic contaminants that are a serious problem not only for agriculture but also for living things. Bioremediation is a pathway for the removal of heavy metal ions from polluted environment using the activities of microbes (algae, bacteria, fungi) or plants. Bioremediation using microbes is sustainable because they help to recover the natural state of the polluted environment with long-term environmental benefit and cost-effectiveness. Soil microbiome with plant growth promoting organisms will act as important and emerging tool in sustainable agriculture. It not only helps in increasing nutrient content in soil for plant use but also helps in protection of plant species from different stresses and pathogens. More emphasis should be given in research to know the deep insights of soil microbiota to understand the plant-microbe interaction deeply.

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SOIL BIOLOGICAL FERTILITY

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Soil biology:

Soil biology is the study of microbial and faunal activity and ecology in soil. Soil life, soil biota, soil fauna, or edaphon is a collective term that encompasses all the organisms that spend a significant portion of their life cycle within a soil profile, or at the soil-litter interface. These organisms include earthworms, nematodes, protozoa, fungi, bacteria and different arthropods. Soil biology plays a vital role in determining many soil characteristics. The decomposition of organic matter by soil organisms has an immense influence on soil fertility, plant growth, soil structure, and carbon storage.

Soil biology involves work in the following areas:

- Modelling of biological processes and population dynamics
- Soil biology, physics and chemistry: Occurrence of physicochemical parameters and surface properties on biological processes and population behavior
- Population biology and molecular ecology: Methodological development and contribution to study microbial and faunal populations; diversity and population dynamics; genetic transfers, influence of environmental factors
- Community ecology and functioning processes: Interactions between organisms and mineral or organic compounds; involvement of such interactions in soil pathogenicity; transformation of mineral and organic compounds, cycling of elements; soil structure
- Complementary disciplinary approaches: That necessarily utilize and involves molecular biology, genetics, ecophysiology, biogeography, ecology, soil processes, organic matter, nutrient dynamics and landscape ecology.

Soil biota:

Soil biota consist of the microorganisms (archaea, bacteria, fungi and algae), soil animals (protozoa, nematodes, mites, springtails, spiders, insects, and earthworms) and plants (Soil Quality Institute, 2001) living all or part of their lives in or on the soil or pedosphere (Fig. 1).

Millions of species of soil organisms exist but only a fraction of them have been cultured and identified. Microorganisms (archaea, bacteria, fungi, algae and cyanobacteria) are members of the soil biota but are not members of the soil fauna. The soil fauna is the collection of all the microscopic and macroscopic animals in a given soil. Soil animals can be conventionally grouped by size classes: macrofauna (cm; enchytraeids, earthworms, macroarthropods), mesofauna (mm; microarthropods, mites and collembolan), and microfauna (µm; protozoa, nematodes) (Figure 2). The size of a soil organism can restrict its location in the soil habitat.

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Smaller members of the microfauna like nematodes are basically aquatic organisms that live in the thin water films or capillary pores of aggregates preying or grazing on other aquatic microfauna such as amoebas (Figure 1). Soil protozoa are also land-adapted members of aquatic microfauna that can dwell in water films in field moist soils. Water films are created by the adsorption of water to soil particles. Soil has a direct effect on the environmental conditions, habitat and nutrient sources available to the soil biota. The term pedosphere is often used interchangeably with soil and captures the concept that the soil is a habitat where the integration of spheres occurs. These spheres include the lithosphere, atmosphere, hydrosphere, and the biosphere (Brady & Weil, 2002) (Figure 3). Numerous biogeochemical processes regulated by soil biota occur in the pedosphere. Studies of the pedosphere range in scale from the field (km) to a soil aggregate (µm to nm).

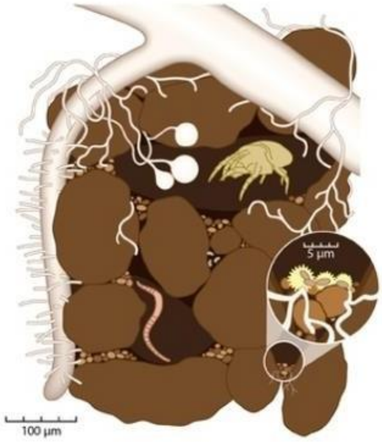

Figure 1: A soil aggregate or ped is a naturally formed assemblage of sand, silt, clay, organic matter, root hairs, microorganisms and their secretions, and resulting pores.

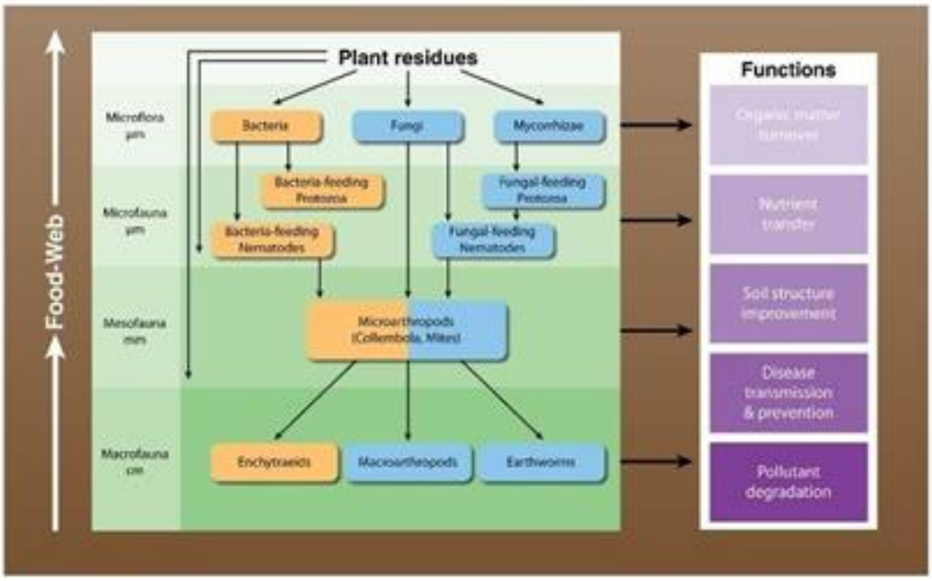

Figure 2: Trophic levels in a soil food web

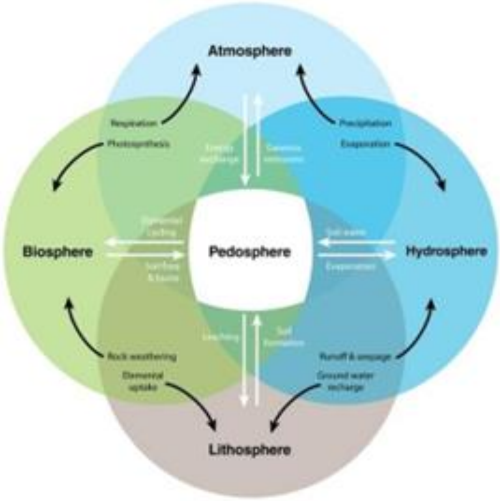

Figure 3: Interactive processes linking the pedosphere with the atmosphere, biosphere, hydrosphere, and lithosphere

The role of the soil biota in biogeochemical cycles: nutrient transformations, carbon sequestration & Greenhouse Gases (GHG)s:

Soil organisms serve numerous roles in the pedosphere. Their most critical function is the regulation of biogeochemical transformations (Table 1). Five functions mediated by the soil biota are 1) the formation and turnover of soil organic matter (OM) that includes mineralization and sequestration of C, 2) nutrient cycling, 3) disease transmission and prevention, 4) pollutant degradation, and 5) improvement of soil structure (Gupta *et al.*, 1997) (Figure 2). The by-products of metabolic oxidation or reduction of C and N compounds in soils include GHG (Madsen, 2008). The dominant soil GHGs consist of: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Soil management practices such as N fertilization and tillage can stimulate specific microbial activities such as autotrophic nitrification, denitrification and mineralization that regulate GHG emissions (Greenhouse Gas Working Group, 2010) by the oxidation and reduction of C and N.

The size and composition of the microbial biomass (the combined mass of micro-organisms in the soil) is dependent upon soil properties and the source(s) of C available for energy and cell synthesis. Carbon inputs to the soil vary in their biochemical composition (e.g., their ability to be decomposed) and nutrient content. Carbon turnover, decomposition and microbial activity often lead to increase in OM and soil aggregation (see Aggregates: Model of a Pedosphere). Different ecosystems vary in their potential to support soil organisms (Table 2) and sequester C in OM. Organic C constitutes the chemical backbone of OM and is the energy source for most soil organisms. Microbial decomposition of plant residues and OM provides access to C and nutrients such as N and P required by the majority of living organisms. Mineralization of organic N to ammonium (NH^+) and additions of N fertilizers that contain NH^+ stimulate nitrification a both nitrification and denitrification are pathways that produce nitrous oxide (N_2O).

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Table 1: Examples of physiological processes catalyzed by microorganisms in biosphere habitats

Process		**Process**	
Carbon cycle	**Nature of process**	**Nitrogen cycle**	**Nature of process**
Photosynthesis	Light-driven CO_2 fixation into biomass	N_2 fixation	N_2 gas becomes NH_3
C Respiration	Oxidation of organic C to CO_2	NH_4^+ oxidation	NH3 becomes NO_2^-, NO_3^-
Cellulose decomposition	Depolymerization, respiration	Anaerobic + NH4 oxidation	NO_2^- and NH_3 becomes N2 gas
Methanogenesis	CH_4 production	Denitrification	NO_3^- is used as an electron acceptor and converted to N_2 gas
Aerobic CH_4 oxidation	CH_4 becomes CO_2		
Anaerobic CH_4 oxidation	CH_4 becomes CO_2		
		Sulphur cycle	**Nature of process**
		S_2 oxidation	S^{2-} and S^0 become SO_4^{2-}
		SO_4^{2-} reduction	SO_4^{2-} is used as an electron acceptor and converted to N_2 gas
Biodegradation	**Nature of process**	**Other elements**	**Nature of process**
Synthetic organic compounds	Decomposition, CO_2 formation	H_2 oxidation	H_2 is oxidized to H^+, electrons reduce other substances
Petroleum hydrocarbons	Decomposition, CO_2 formation	Hg methylation & reduction	Organic Hg is formed & Hg^{2+} is converted to Hg
Fuel additives (MTBE)	Decomposition, CO_2 formation	(per)chlorate reduction	Oxidants in rocket fuel &other sources are converted to chloride electron acceptor, therefore immobilized
Nitroaromatics	Decomposition, CO_2	U reduction	U oxyanion is used as an
Pharmaceuticals, personal care products	Decomposition	As reduction	As oxyanion is used as an electron acceptor; therefore toxicity is diminished
Chlorinated solvents	Compounds are chlorinated through respiration in anaerobic habitats	Fe oxidation, acid mine drainage	FeS ores are oxidized, strong acidity is generated

Note: As, arsenic; C, carbon; CH_4, methane; CO_2, carbon dioxide; Fe, iron; FeS, Iron sulphide; H, hydrogen; Hg, mercury; Hg^{2+}, mercuric ion; MTBE, methyl tertiary butyl ether; N_2, nitrogen; NH3, ammonia; NH^{+}, ammonium; NO^{-}, nitrite; NO^{-}, nitrate; S_0, elemental sulphur; S^{2-}, sulphide; SO_4^{2-}, sulphate; U, uranium.

Table 2: Typical number of soil organisms in healthy ecosystems

	Ag Land	Prairie	Forest
	Organisms per gram (teaspoon) of soil		
Bacteria	100 million - 1 billion	100 million - 1 billion	100 million - 1 billion
Fungi	Several meters	10s – 100's of meters	1-60 kilometers (in conifers)
Protozoa	1000's	1000's	100,000's
Nematodes	10-20	10's – 100's	100's
	Organisms per square meter		
Arthropods	< 10	45-200	900-2,300
Earthworms	4-25	8-42	8-42 (0 in conifers)

The soil food web consists of the community of organisms that live all or part of their lives in the pedosphere and mediate the transfer of nutrients among the living (biotic) and non-living (abiotic) components of the pedosphere through a series of conversions of energy and nutrients as one organism and or substance is consumed by other organisms (Sylvia *et al.*, 2005). The mesofauna (collembolan, mites) play a role in nutrient turnover by shredding materials into smaller pieces with higher surface area providing greater access for microfauna (bacteria, fungi, mycorrhizae) that recycle the majority of C (Figure 2). All food webs contain several trophic levels or feeding positions in a food chain (Figure 2). The term grazing is used when organic C is obtained from living things. Soil organisms are part of the detrital food chain if their organic C is derived from dead materials. The detrital food chain creates new soil organic matter and cycles nutrients from existing OM. Biological systems and organisms contain fairly constant elemental ratios of carbon: nitrogen: phosphorus: sulfur (C:N:P:S). These ratios and mass balances (net change = input + output + internal change) allow scientists to determine biochemical shifts between organisms or ecosystems. Most members of the soil fauna are chemoheterotrophs, meaning they obtain C and energy by oxidizing (metabolizing) organic compounds (Sylvia *et al.*, 2005). Carbon sequestration limits the process of mineralization mediated by chemoheterotrophs that produce CO_2.

Arenas of activity

The ability of microorganisms to recycle C can provide indirect health benefits to plant communities. Soils that contain larger amounts of OM and microbial biomass tend to have higher rates of microbial activity and as such, some organisms may have the ability to out compete other organisms including plant pathogens. This type of suppression of plant pathogens is known as general suppression (Sylvia *et al.*, 2005). Soils that contain high levels of OM may also support specific antagonistic microorganisms that have an explicit means of suppressing pathogens such as the production of antibiotics. This is an example of specific suppression. Soils that exhibit such properties are termed suppressive soils.

Microorganisms also interact directly with plants through symbiotic relationships that provide nutrients to plants while supplying C to the microorganism(s). An example of a symbiotic relationship between a soil microbe and a higher plant is the interaction of the bacterium known as a *rhizobium* that induces the formation of nodules on roots of soybean plants in which it fixes N for the plant using carbohydrate supplied by the plant.

Figure 4: Arenas of activity in soils contain hot spots

Zones or ecosystems containing areas of activity include the "drilosphere" (the portion of the soil volume influenced by secretions of earthworms), the porosphere (the total pore space), detritusphere (dead plant and soil biota), aggregatusphere (the sum of aggregates) and the rhizosphere.

As an example of the linkages and transport of nutrients among ecosystems in a forest consider the following scenario. Leaves fall to the forest floor. This is followed by the physical breakdown of the leaf by the shredding action mediated by the members of the mesofauna (e.g., mites, collembolans) and subsequent further decomposition by microorganisms. Overtime, the decaying leaf passes through the gut of a worm and is deposited in the drilosphere. Remaining leaf matter in the drilosphere located within an aggregate and additional organic material contained within the aggregate replenish the supply of N, P, and OM used by soil organisms. These organisms decompose and mineralize detritus and OM providing a source of nutrients to plants when aggregates are part of the rhizosphere of a tree root. The mucilages that are produced by the active microorganisms feeding on detrital leaf matter and other organic materials increase the size and stability of the aggregate ecosystem. In this way, soil organisms release, transform, and relocate resources found in arenas of activity throughout the pedosphere via a number of biogeochemical cycles.

In balanced soil, plants grow in an active and steady environment. The mineral content of the soil and its healthful structure are important for their well-being, but it is the life in the earth that powers its cycles and provides its fertility. Without the activities of soil organisms, organic materials would accumulate and litter the soil surface, and there would be no food for plants. The soil biota includes:

- Megafauna: size range - 20 mm upward, e.g. moles, rabbits, and rodents.
- macrofauna: size range - 2 to 20 mm,
  e.g. woodlice, earthworms, beetles, centipedes, slugs, snails, ants, and harvestmen
- Mesofauna: size range - 100 micrometres to 2 mm,
  e.g. tardigrades, mites and springtails.
- Microfauna and Microflora: size range - 1 to 100 micrometres,
  e.g. yeasts, bacteria (commonly actinobacteria), fungi, protozoa, roundworms, and rotifers.

Of these, bacteria and fungi play key roles in maintaining a healthy soil. They act as decomposers that break down organic materials to produce detritus and other breakdown products. Soil detritivores, like earthworms, ingest detritus and decompose it. Saprotrophs, well represented by fungi and bacteria, extract soluble nutrients from delitro. The ants (macrofaunas) help by breaking down in the same way but they also provide the motion part as they move in their armies, also the rodents, wood-eaters help the soil to be more absorbent.

Microbial Biomass

Key points

- Microbial biomass (bacteria and fungi) is a measure of the mass of the living componentof soil organic matter.
- The microbial biomass decompose plant and animal residues and soil organic matter to release carbon dioxide and plant available nutrients.
- Farming systems that return plant residues (e.g. no-tillage) tend to increase the microbial biomass.
- Soil properties such as pH, clay, and the availability of organic carbon all influence the size of the microbial biomass.

Background

The microbial biomass consists mostly of bacteria and fungi, which decompose crop residues and organic matter in soil. This process releases nutrients, such as nitrogen (**N**), into the soil that are available for plant uptake. About half the microbial biomass is located in the surface 10 cm of a soil profile and most of the nutrient release also occurs here (figure 4). Generally, up to 5 % of the total organic carbon and N in soil is in the microbial biomass. When microorganisms die, these nutrients are released in forms that can be taken up by plants. The microbial biomass can be a significant source of N, and in Western Australia can hold 20 — 60 kg N/ha.

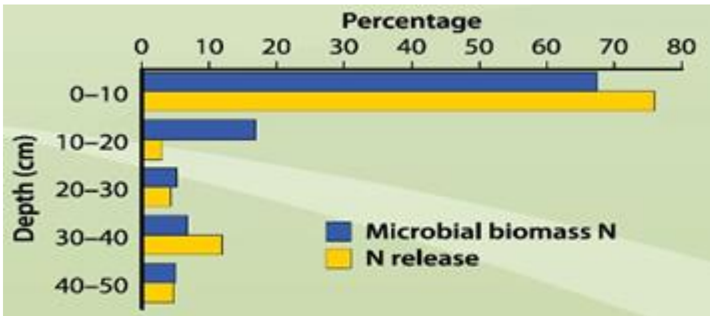


Figure 4: Microbial biomass nitrogen and release of nitrogen decreasing with depth

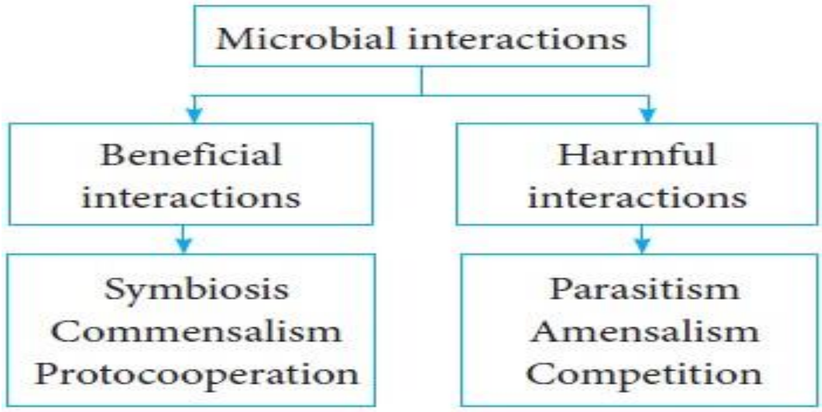
Microbial biomass is also an early indicator of changes in total soil organic carbon (C). Unlike total organic C, microbial biomass C responds quickly to management changes. In a long term trial at Merredin, no significant change in organic C was detected between stubble burnt or retained plots after 17 years. Microbial biomass C in the same plots had increased from 100 to 150 kg-C/ha (Hoyle *et al.*, 2006a).

In soil the microbial biomass is usually 'starved' because soil is too dry or doesn't have enough organic C. The amount of labile carbon is of particular importance as this provides a readily available carbon energy source for microbial decomposition. Soils with more labile C tend to have a higher microbial biomass.

Important sources of organic carbon as food for the microbial biomass are crop residues and soluble compounds released into the soil by roots (root exudates).

Microbial interactions

Microorganisms in soil interact with themselves and lead to beneficial and harmful relationships (Flowchart 1). Some of the interaction and interrelationship have been discussed in this connection in Table 3.



Flowchart 1: Microbial interactions

Table 3: Types of microbial interaction in soil

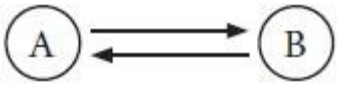
Interaction	Microorganisms A	Microorganisms B
Neutralism	No effect	No effect
Commensalism	+	No effect
Amensalism	No effect	-
Mutualism Synergism Protoco-operation Symbiosis	+	+
Competition	-	-
Parasitism	+	-
Predation	+	-
+ = positive effect – = negative effect		

Beneficial interactions

The beneficial interactions such as symbiosis (mutualism) and commensalism are found to operate among the soil inhabitants.

Symbiosis (mutualism)

Mutualism is an example of symbiotic relationship in which each organisms benefits from the association. One type of mutualistic association is involving the exchange of nutrients, between two species, a phenomenon called syntrophism. Many microorganisms synthesise vitamins and amino acids in excess of their nutritional requirements. Other have a requirement for one or more of these nutrients. Symbiosis is an obligatory relationship between two populations that benefit both the population. Both populations live together for mutual benefit.



The relationship between algae and fungi that result in the formation of lichen is a classical example of mutualistic intermicrobial relationship (Figure 5).

Lichens are composed of primary producer, the phycosymbiont (algae) and a consumer the mycosymbiont (fungus).

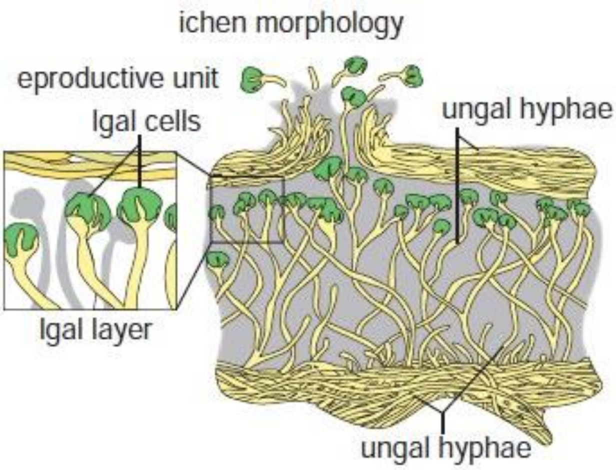
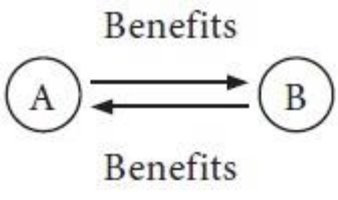


Figure 5: Lichen morphology

Commensalism

In a commercial relationship between two microbial population, one population is benefited and other population remains unaffected. Commensalism is an unidirectional relationship between two population. The unaffected population does not benefit by the action of second population. For the receiving population, the benefit provided may be essential. In commensalism, the unaffected population modifies the habitat in such a way that another population is benefited.



For example: A population of facultative anaerobes utilizes oxygen and creates a habitat suitable for the growth of anaerobes. In soil, vitamin and growth factor producing organisms benefit vitamin and growth factors requiring organisms.

Harmful microbial interactions

Harmful microbial interaction is otherwise described as negative interaction or antagonistic interaction. Any inhibitory effect of an organism created by any means to the other organism is known as harmful interaction or antagonistic interaction and the phenomenon of this activity is called antagonism

Ammensalism

Ammensalism is the phenonmenon where one microbial species is affected by other species, where as other species is unaffected by first one. Ammensalism is accomplished by secretions of inhibitory substances such as antibiotics. Certain organisms may be of great practical importance, since they often produce antibiotics or other inhibitory substances, which affect the normal growth of other organisms. Antagonistic relationships are quite common in nature. For example: *Pseudomonas aeruginosa* is antagonistic towards *Aspergillus terreus* (Figure 6).

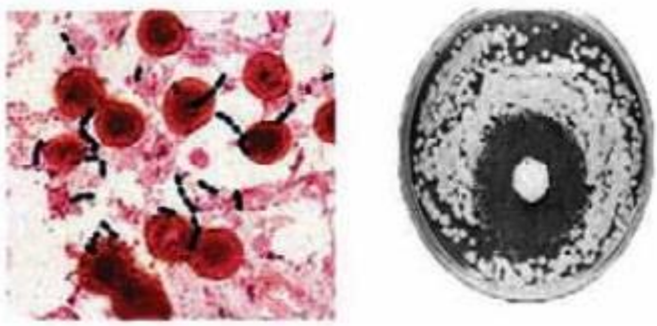
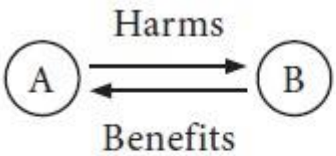


Figure 6: Microbial antagonism

Parasitism

This is a relationship in which one of the population benefits from the other and the host is usually harmed. Parasitism is one of the most complex microbial interactions. The line between parasitism and predation is difficult to define. The parasites feed on the cells, tissues or fluids of another organisms the host, which is harmed in this process.



The parasites depend on the host and lives in intimate physical and metabolic contact with the host. All types of plants and animals are susceptible to attack by microbial parasites.

The rhizospere region can be divided into two zones.

· Exorhizosphere

· Endorhizophere

However the root surface is termed as "rhizoplane".

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EFFECT OF ORGANICS ON SOIL STRUCTURE

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Introduction:

What is soil?

Soil forms the uppermost layer of the Earth's crust, and mineral soil consists of a mixture of organic matter, minerals, gases and water. Soil develops gradually over time, as weathering of the bedrock on the Earth's surface combines with decaying organic matter. Soil typically develops in layers (also known as horizons) which are distinct from one another in colour and texture. The bottom layer, the bedrock, is a solid mass of rock and provides the 'parent' material for the soil and influences its type. For example, clay particles are derived from fine-grained rocks such as shale while sandy particles tend to come from the weathering of sandstone.

What do we mean by soil structure?

The arrangement of solids and pore spaces within soil is known as the structure. In order to create aggregates, soil solids must "clump" together with metal ions, organic matter, root hairs, bacterial secretions, and fungus. The content, form, and size of aggregates, often referred to as peds, as well as their stability against the erosive pressures of water, vary. For the transportation of air, water, and nutrients, the size and continuity of the soil pores surrounding the aggregates is crucial. The foundation of many advantages is soil structure, which affects water retention and movement, root penetration, carbon storage, susceptibility to erosion, and fertility. One component of healthy soil is soil structure. So, if the soil in consideration serves as a platform for human activity or serves to preserve geological and archaeological history, a measure of soil structure may not be very important.

Trade-offs also exist for potential soil structure indicators that might be employed in a future agricultural policy to promote effective soil management. Semi-quantitative methods that can be applied quickly and cheaply by farmers and land managers themselves have the advantage of being repeatable over time and by the primary user of the land. They may be able to tell land managers, farmers, and the government whether the soil is usually improving or degrading over time by offering an overall signal of how "excellent" or "poor" various visible features of the soil were.

A description of soil and its structure is provided in figure1. For soil used in agriculture, a "well-structured soil" will have a continuous network of pore spaces to for water drainage, unhindered airflow, and root development. These characteristics allow for processes that support ecosystem services including improving soil fertility and water purification, such as nutrient cycling, water and oxygen transport, and other functions. We shall refer to soil having these characteristics as "well-structured" in this synopsis. Many of these soil structural characteristics not only promote food production but also offer a number of other advantages.

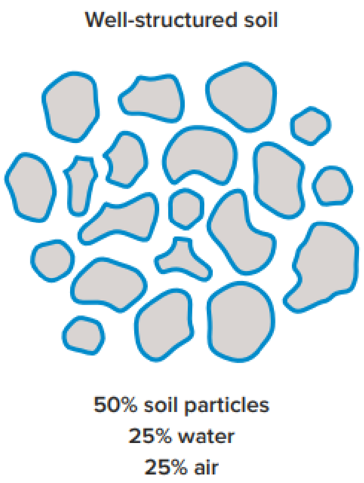
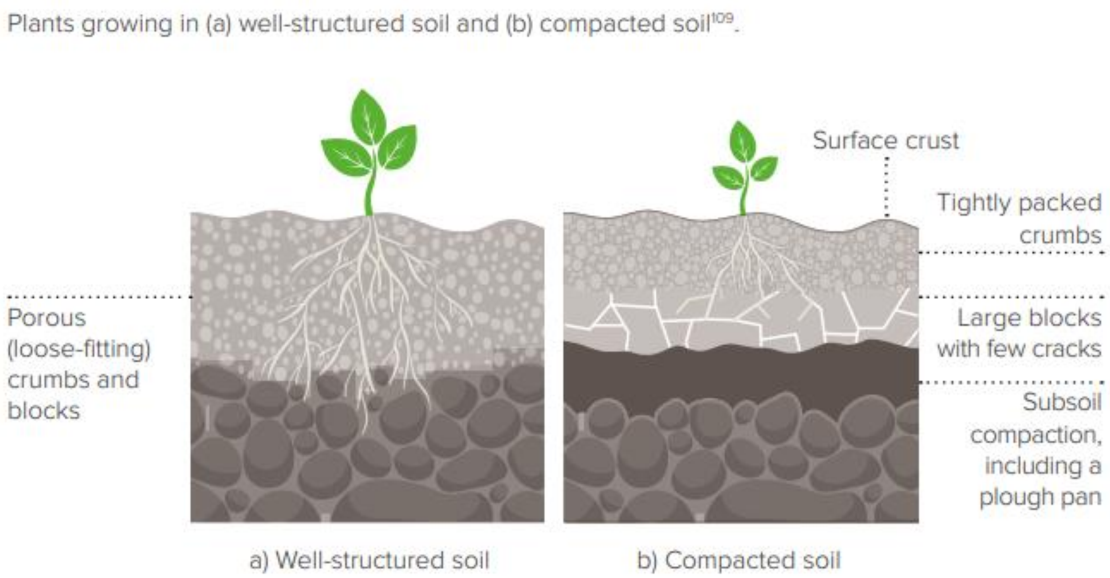


Figure 1: Soil compaction reduces the available space for soil, air and water, limiting pathways for root growth



Types of soil structure

The basic types of aggregate arrangements are: granular, blocky, prismatic, and massive structures (Fig. 2). While in the topsoil, a large structure prevents water from entering and causes poor aeration, which makes seed germination challenging. On the other side, granular topsoil allows for easier water penetration and better seed germination. The physical characteristics of soil have a significant role in plant growth by influencing water and nutrient movement, aeration for plants and microorganisms, and resistance to soil erosion and compaction. When compared to a weak soil structure, which obstructs root growth, water flow, and drainage, a strong soil structure can supply adequate water, nutrients, and oxygen to sustain plant growth and enough room for roots to penetrate. The varieties (granular, blocky, prismatic, platy, for example), sizes (fine, medium, coarse), and grades of soil structure are defined qualitatively in the field (weak, moderate, strong). Similar to how characterising soil structure is subjective, it requires a quantitative and objective approach for wider application.

Multi-stripe laser triangulation (MLT) scanners, for example, can capture 3-D objects in 360 degrees and create a 3-D structure for display and analysis. Using image analysis techniques on the created 3-D images, the surface area, volume, and geometric parameters of the 3-D object may be quantified. To calculate the volume and bulk density of soil clods and aggregates, this method has been utilised (Hirmas *et al.*, 2013). In order to identify soil structure and macropores, the MLT scanner has been utilised to scan 2-D soil profile walls or soil monoliths with a rough surface. The profile image produced by the MLT displays structural units and scan gaps that represent the pore spaces between the structural units. These features can be utilised to calculate soil structure indices and count macropores (Eck *et al.,* 2016). It can be used to assess the effects of tillage on soil structure and track the dynamics of macropores as the drying process takes place.

The ability of soil aggregates to withstand disintegration when forces from water, wind, and tillage are applied is measured by the concept of soil aggregate stability, which is a crucial indicator of soil structure. The slaking method, which describes how a large, air-dry aggregate (> 2–5 mm) breaks down into smaller aggregates (0.25 mm), can be used to assess it. To calculate the soil aggregate stability indicators, a model called Slakes has been created to evaluate the area changes over time after soil aggregates are deposited into a petri dish filled with water. This method has been used to evaluate the effects of tillage on soil aggregate stability in Vertisols (Flynn *et al.,* 2020). It provides a rapid and quantitative measure of soil aggregate and soil structure for effective soil management practices.

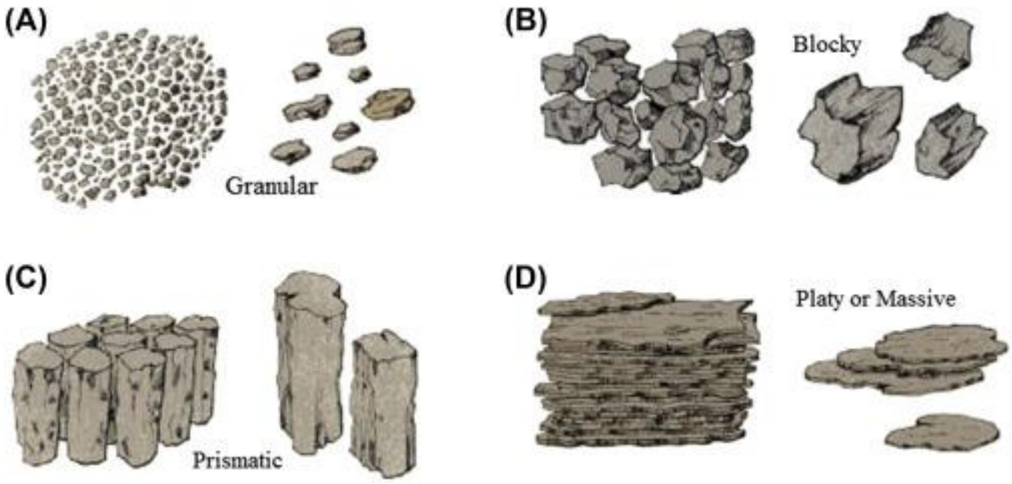


Figure 2: Basic types of aggregate arrangements. (A) Granular, (B) blocky, (C) prismatic, and (D) Platy type

Granular

In granular structure, the structural units are approximately spherical or polyhedral and are bounded by curved or very irregular faces that are not casts of adjoining peds. In other words, they look like cookie crumbs. Granular structure is common in the surface soils of rich grasslands and highly amended garden soils with high organic matter content. Soil mineral particles are both separated and bridged by organic matter breakdown products, and soil biota exudates, making the soil easy to work. Cultivation, earthworms, frost action and rodents mix the soil and decreases the size of the peds. This structure allows for good porosity and easy movement of air and water. This combination of ease in tillage, good moisture and air handling capabilities, and good structure for planting and germination, are definitive of the phrase *good tilth*.

Blocky

In blocky structure, the structural units are blocklike or polyhedral. They are bounded by flat or slightly rounded surfaces that are casts of the faces of surrounding peds. Typically, blocky structural units are nearly equidimensional but grade to prisms and to plates. The structure is described as angular blocky if the faces intersect at relatively sharp angles; as subangular blocky if the faces are a mixture of rounded and plane faces and the corners are mostly rounded. Blocky structures are common in subsoil but also occur in surface soils that have a high clay content. The strongest blocky structure is formed as a result of swelling and shrinking of the clay minerals which produce cracks. Sometimes the surface of dried-up sloughs and ponds shows characteristic cracking and peeling due to clays.

Prismatic

In prismatic structure, the individual units are bounded by flat to rounded vertical faces. Units are distinctly longer vertically, and the faces are typically casts or molds of adjoining units. Vertices are angular or subrounded; the tops of the prisms are somewhat indistinct and normally flat. Prismatic structures are characteristic of the B horizons or subsoils. The vertical cracks result from freezing and thawing and wetting and drying as well as the downward movement of water and roots.

Platy

In platy structure, the units are flat and platelike. They are generally oriented horizontally. A special form, lenticular platy structure, is recognized for plates that are thickest in the middle and thin toward the edges. Platy structure is usually found in subsurface soils that have been subject to leaching or compaction by animals or machinery. The plates can be separated with a little effort by prying the horizontal layers with a pen knife. Platy structure tends to impede the downward movement of water and plant roots through the soil.

Table 1: Criteria for soil structure grade and soil structure size class for selected structure types (adapted from Schoeneberger *et al.*, 2012)

Grade	Code	Criteria
Structureless	0	No discrete units observable in place or in hand sample.
Weak	1	Units are barely observable in place or in a hand sample.
Moderate	2	Units well-formed and evident in place or in a hand sample.
Strong	3	Units are distinct in place (undisturbed soil) and separate cleanly when disturbed.

Smallest Dimension (mm)

Size Class	Granular	Blocky	Prismatic
Very fine	<1	<10	<5
Fine	1 to <2	10 to <20	5 to <10
Medium	2 to <5	20 to <50	10 to <20
Coarse	5 to <10	50 to <100	20 to <50
Very Coarse	≥10	100 to <500	≥50

Concept and definition of organic manure

Organic manures are materials with a known chemical composition and high analytical value that provide plant nutrients in a form that is readily available to the plant. Fertilizers made from plant, human, or animal waste are known as organic manures (e.g. compost, manure). Natural ingredients are used to make organic manures, which usually refers to our biodegradable wet suit. Compost is often created through the breakdown of biodegradable garbage. Paper, leaves, fruit peelings from leftover meals, and even fruit juices are among these wastes. The soil benefits from the addition of organic manures. It improves the soil's ability to support plants.

Sources of organic manure

The main organic manures were sourced from peat, animal wastes (often from slaughterhouse), and plant wastes from agriculture and sewage sludge. The primary sources of organic manures were peat, agricultural plant wastes, animal wastes (often from slaughterhouses), and sewage sludge. Slurry, peat, and animal byproducts from the meat industry are examples of naturally occurring organic manures. Organic manures are carbon-based substances that boost plant productivity and quality of growth. Organic manures were complex compounds that added numerous secondary and micronutrients, far from being simplified and purified chemicals. Important micronutrients are present in organic materials like manures, powdered rocks (like lime, rock phosphate, and greensand), blood meal, bone meal, wood ash, and compost. Additionally, the texture of these materials would enhance soil quality rather than degrade it.

Effect of organic manure application on soil properties

A significant issue with regard to the sustainability of agriculture is the decline in soil organic matter content brought on by cultivation and erosion. Therefore, management practises that increase the organic matter content were deemed desirable to soil quality and productivity.

Also, after numerous applications of solid cattle dung, soil organic matter rises. The pH of the soil might change as a result of manure. While organic matter added in the form of manure can act to help buffer the soil against a decrease in pH, manure that is low in organic matter and high in ammonium nitrogen may result in a decrease in pH due to acidity produced when the ammonium is oxidised to nitrate in the soil. Repeated applications of N fertilizer may also lead to soil acidification. Moreover, Whalen *et al.* (2000) stated that an immediate increase in the pH of two acid soils following fresh cattle manure application and concluded that the effects of manure on soil pH would depend on the manure source and soil characteristics. The best manures for bringing an acidic soil's pH up while also acting as a buffer against pH shifts once they have been incorporated into the soil are those with high levels of organic matter and carbonate. An important gauge of the fertility and quality of the soil was its organic matter level (Haynes RJ 2005). One of the three soil components, known as organic matter, is essential for the physiochemical characteristics of soil, including its capacity as a sport and buffer, as well as its biodiversity and biological activity. Organic matter has a favourable impact on soil functionality, so it's critical that its resources be preserved or enhanced (Lal, 2011). Repeated applications of animal dung resulted in soils that were more friable to the touch and less compacted under foot than those of the unmanaged plots (Campbell *et al.* 1986). Farmyard manure has long been recognised to enhance soil structure, increase porosity and water holding capacity, and reduce evaporation rates. It has been reported that adding manure to soil decreased crust strength while applying it to cattle feed increased water infiltration into the soil. Increases in water infiltration, macro porosity, aggregate size and stability, and soil OM were usually signs of physical soil quality improvements.

Soil aggregate formation

Organic matter is an important agent responsible for binding soil mineral particles together creating an aggregate hierarch. The organic matter is still considered to provide the flexible links between the external surfaces of clay domains.

Soil permeability

The decomposition of organic matter improves the soil permeability and enhances the water-stable aggregates due to icrease in number of micro pores in the soil.

Bulk density

Soil that has higher organic matter content usually has lower bulk density value than soil with low organic matter content.

Cation exchange capacity

Clay and organic matter have negative charges and hold cations. In general, soils with larger amounts of clay or organic matter have more negative charges and therefore a higher CEC than ones with lower amounts. The addition of organic matter will increase the CEC of a soil but requires many years to take effect.

Water holding capacity

The addition of organic matter to the soil usually increases the water holding capacity of the soil. This is because the addition of organic matter increases the number of micropores and macropores in the soil either by "gluing" soil particles together or by creating favourable living conditions for soil organisms.

Coclusion:

In conclusion, organic matter plays a crucial role in soil structure by promoting the formation of stable aggregates, enhancing water-holding capacity, improving aeration, and increasing nutrient availability. The addition of organic matter to soil promotes the growth of microorganisms that break down organic materials and release nutrients into the soil, which in turn supports the growth of plants. Organic matter also helps to reduce erosion by increasing soil stability and reducing soil compaction. Overall, the incorporation of organic matter into soil is an important practice for maintaining healthy soil structure and fertility, which is essential for sustainable agriculture and ecosystem health.

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IN SITU STUBBLE MANAGEMENT FOR IMPROVING SOIL HEALTH

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Introduction:

The ability of soil to function as a living system within ecological and land use boundaries, support plant and animal productivity, maintain or improve the quality of the water and air, and support plant and animal health is known as soil health**.** In order for the soil to adapt to agricultural intervention and continue to sustain both agricultural output and the supply of other ecosystem services, soil health is presented as an integrative property. Optimizing agricultural yields while preserving ecosystem service delivery is the main problem of sustainable soil management (Porichha *et al.,* 2021). It is hypothesized that maintaining four key processes-carbon transformations, nutrient cycles, soil structure preservation, and pest and disease control is essential for soil health. The straw and crown of plants left over after harvesting are referred to as crop stubble. Stubble also refers to straw and chaff that harvesters release (header). It is also referred to as "garbage" or "residue." One of the many complicated concerns that farmers must cope with is stubble management. Grain farmers have historically burned stubble to control weeds and diseases as well as to reduce biomass to facilitate sowing. Instead of burning or cultivating the stubble, keep it in place to prevent soil erosion. Moreover, it preserves soil organic matter and moisture to support crop production. This is especially advantageous in arid regions or during arid seasons. Several factors are impacted by stubble, including traffic flow, light penetration, soil temperature, interactions with herbicides, the severity of frost, pests, weeds, and diseases (Abdurrahman *et al.,* 2020). This chapter provides information on how to manage stubble for better soil health.

Stubble management

To effectively handle both high and low stubble loads, advance planning is essential. The proper chopping and distribution of stubble residues during harvest is the first step in managing excessive stubble loads. Lighter stubble loads disintegrate more quickly than heavier stubble loads, which might make management more challenging. To minimize wind and water erosion, it is crucial to maintain adequate groundcover, stubble anchorage, and stubble height. Standing stubble increases the effectiveness of pre-emergent herbicides by reducing soil evaporation and wind speed. Cutting the stubble during harvest as short as possible, ideally to no more than the row width, with the chaff equally distributed, can be helpful in managing heavy stubble. In principle, you should be able to sow with a tuned seeder if you can push your foot through the thickest stubble in the early morning dew. Some farmers leave standing stubble but chop and spread it behind the header. After harvest, particularly dense stubble might be raised and mulched. This promotes decomposition by shortening stubble and preserving soil moisture. The stubble can be cut higher if the next crop is sown using a disc seeder rather than a tynes. It is important to evenly distribute the straw and chaff. As straw is harvested, it can be baled (Gotipati *et al.*, 2021)

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Burning of crop residues

Stubble burning is a process in which the stubble that remains after crops like paddy, wheat, rice, corn, etc. have been harvested is intentionally set on fire. This is a significant source of atmospheric aerosol and gas emissions, potentially affecting both the biochemistry of the environment and the cleanliness of the world's air. Burning biomass in open fields has been used for centuries to clear the land, enhance land usage, and get rid of both living and dead vegetation. Although only a small part of natural fires are responsible for the majority of the vegetation burned, it has been estimated that humans are responsible for almost 90% of biomass combustion. The average yearly crop residue production in India is 500 Mt. Although most of it is utilized as feed, a raw material for energy production, etc., there is a large surplus of 140 Mt, of which 92 Mt is burned annually, particularly in the Northern provinces such as Punjab, Haryana, and Uttar Pradesh (Singh, 2019). Small-scale farmers in particular resort to burning crop waste as a low-cost alternative due to a lack of technical know-how and suitable disposal choices. Large-scale crop burning increases the amounts of CO_2, CO, N_2O, and NOx in the atmosphere and has led to an alarming rise in air pollution

Burning of crop residue is a significant problem in North India, primarily due to the short 15–20 day window between the harvest of the rice crop and the sowing of wheat. The best time to plant a wheat crop is often the first two weeks of November, and it is also believed that delaying sowing by one week from the best period reduces wheat production by 150 kg per acre, thus growers do not wish to take any risks with yield losses. As a result, farmers burn the paddy stubbles in the field rather than incorporating them into the soil due to the shorter time between both the rice harvest and the wheat sowing (Swamy *et al.*, 2021). The state and federal governments of India are starting a variety of programs and schemes and inviting farmers to use new equipment in an attempt to decrease stubble burning, but farmers are not yet ready to implement them because they believe that the traditional methods of stubble-burning are simpler, less expensive, and much more time-efficient than the other alternative options, which demand more time, money, and labour.

Compared to burning residue in the land, which is free for farmers, farmers will need to spend roughly Rs 6,000–7,000 per acre if they choose to remove residue manually (Reddy and Chhabra, 2022). They also feel that burning residue not only saves money but also controls pest. However, the majority of farmers in North India, as well as other regions of the nation, lack formal education and are unaware of the dangers that air pollution poses to both human life and the ecosystem. Since they are initial victims of smoke inhalers, farmers therefore accidentally set agricultural trash on fire. Farmers in North India, particularly those from Punjab and Haryana, are helpless because they have no other practical option for clearing their crops than burning (Sandhu *et al.,* 2019).

Crop residue burning adds to the loss of soil organic carbon. Additionally, the nitrogen balance in the soil is swiftly altered by CO_2 and nitrogen is converted to nitrate, which results in the annual loss of 0.824 million tonnes of nitrogen, phosphorus, and potassium (NPK) from the soil. Repeated burns can also reduce the microbial populations by more than 50%. Despite destroying troublesome bugs and diseases carried by the soil, burning rice and wheat wastes results in a loss of roughly 80% nitrogen, 25% phosphorus, 21% potassium, and 4-60% soil sulphur.

The National Policy for Management of Crop Waste notably mentions in-situ management practices like mulching and direct incorporation into soils as measures that must be promoted in India to reduce environment pollution in farmland as well as crop residue burning.

***In-situ* incorporation**

Although there are other alternatives to burning crop residue, farmers now only have two choices: either incorporate crop residue into the surrounding soil or burn it directly in the field. Due of the lengthy period it takes for the stubble to decompose in the soil, farmers do not prefer in situ incorporation.

A six-year study period revealed that adding rice residue to the soil between 10 and 40 days prior to the sowing of the wheat crop had no negative effects on the production of following wheat and rice crops. With diverse residual management techniques, the resulting rice residue had no residual impact on the paddy straw blended with wheat, generating comparable yields of rice and wheat. Incorporating rice stubble into the soil also improves the physical, chemical, and biological characteristics of the soil, such as pH, organic carbon, water retention capacity, and bulk soil density (Singh *et al.,* 2018).

Because standing stubble slows the wind down at or near ground level, there is a decreased risk of wind erosion and protection for newly planted crops. For instance, stubble that is 5 cm high will reduce wind speeds 20 cm above the ground by 35%, but stubble that is 35 cm high will reduce wind speeds by 75-78%. Reduced soil moisture evaporation can also be achieved by decreasing wind speed at the soil's surface. By reducing the physical effect of rains on the topsoil, fallow efficiency is increased. Structural integrity of soils was preserved. Rates of water intrusion were increased. Soil erosion and water runoff were minimized. Soil evaporation was reduced after rainstorm events by delaying the flow of water on the soil surface, providing more time for penetration. However, total evaporation won't be impacted by residues if conditions are dry for a long time (6–8 weeks).

Mulching

Mulch can be defined as covering materials that applied on the soil surface (Patil *et al.,* 2013). Mulching is a practice that involves covering the soil surface with organic or synthetic mulch in order to promote plant development, effective crop production and protection (Kumar *et al.,* 2021).

Benefits of mulching (Peera *et al.,* 2020)

- It aids to conserve the soil water in rainfed areas by preventing the loss of water from soil through evaporation
- It assists in retain the soil moisture for longer period that results in reduction of frequency irrigation in irrigated land areas
- Spreading mulch over the ground helps to prevent soil erosion, slow down runoff during heavy rain and increase the quantity of water that percolates into the ground
- It prevents the leaching of fertilizers from the soil

- It helps to maintain the temperature in greenhouses
- Helps to prevent the weed growth by arresting the energy supply to weeds
- To protect the plants and their produce from insect-pest and diseases outbreak
- Organic mulches improve the fertility of soil by providing organic matter as a food for beneficial earthworms and soil micro-organisms. This also facilitates for development roots, increase the soil infiltration and water holding capacity of soil
- Organic waste after decomposing turns into a source of plant nutrients. It functions as an insulator of heat and cold by preventing soil from freezing during winter and drying out in the summer

Types of mulches

Mulches

Organic mulches
- Grass Clipping
- Straw
- Newspaper
- Dry leaves
- Bark clippings
- Saw dust
- Compost

Inorganic Mulches
- Gravel, Pebbles and crushed stones
- Plastic mulch
  - ✓ Photo-degradable plastic mulch
  - ✓ Bio-degradable plastic mulch
  - ✓ Color of film

(Kumar *et al.,* 2021)

Organic mulches

Organic mulches include the insitu incorporation of stubbles and they have the ability to degrade easily due to attract insects, slugs, and cutworms that consume them results in addition of some organic matter. Organic mulches are useful for lowering nitrate leaching, improving soil physical properties, increasing biological activity, balancing nitrogen cycle, providing organic matter, managing temperature and water retention and preventing erosion (Wang *et al.,* 2014). Organic mulches are straw, grass, newspaper, saw dust, bark, dry leaves and compost.

Straw

The most common mulching materials used as mulches on soil surface for moisture conservation are wheat and paddy straw, as well as other agricultural leftovers including stubbles, groundnut shells, cotton shells, *etc*. Although, the straw seems to have little nutritional value, when it breaks down, it improves soil fertility. Straw mulches reduce evaporation by lowering the amount of energy received by the soil and its movement above the soil.

Grass

This is one of the most abundant and inexpensive types of mulch. It incorporated into the soil will add some quantity of nitrogen and organic matter. However, the green grass materials have the capacity to develop new root system when they incorporated into the soil. Hence, the use of dry grass as mulch is suggested.

Dry leaves

Leaves are abundant and easily available mulching material. Dry leaves are useful for protecting dormant plants during the winter by keeping them warm and helping to initiate germination during the cold season. But during dry season, they are light in weight and could be blown away even in light winds. By using stone, bark or any other material that help to reduce the wind problem.

Compost

One of the best types of mulch is compost. It increases the number of microorganisms in the soil, enhances its health, and adds certain nutrients. Compost is very fine and having more nutrients but doesn't have much weed-suppressing capability. This is a main disadvantage of applying compost.

Methods in mulching adopted for stubble management (Fig 1)

Surface mulching

Mulches are spread on the surface of soil to conserve soil moisture by reducing the evaporation.

Vertical mulching

A 30 cm deep and 15 cm wide trench was made across the slope at vertical intervals of 2-4 m and filled with organic materials like stubbles, straw, grass, or organic matter at a layer of 10 cm above the ground layer. This will help to reduce the loss of water through runoff thereby increase the infiltration rate.

Live vegetative barriers

Vegetative barriers are spread over soil surface in contour lines for improving soil moisture along with nitrogen addition with an extent of 25 to 30 kg per ha. The most predominant live vegetative barriers are subabul and glyricidia.

Constrains of mulching (Kumar *et al.*, 2021)

- Many organic mulches also encourage and provide shelter or breeding sites for snails, slugs, mice, and other pests that may harm plants
- This could often provide excessive heat and moisture
- The inorganic mulch is not environmentally friendly

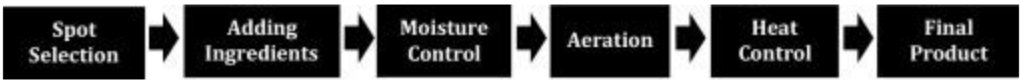
Compost mulch Straw mulch Bark mulch

Figure 1: Different types of mulching techniques (El-Beltagi *et al.*, 2022)

Composting

Composting is a biological process in which organic wastes are transformed into compost by microorganisms under regulated aerobic conditions and that can be used as a manure to supply nutrients to the crop (Sunita *et al.,* 2009). Composting is often used to handle the off-field residues as known as exsitu composting where the compost produced is not returned to the field whereas it has being utilized on fields is called as in situ composting (Kumar, 2011).

Basic steps of composting strategy:



(Hussain *et al.*, 2022)

Major biochemical reactions involved with composting process

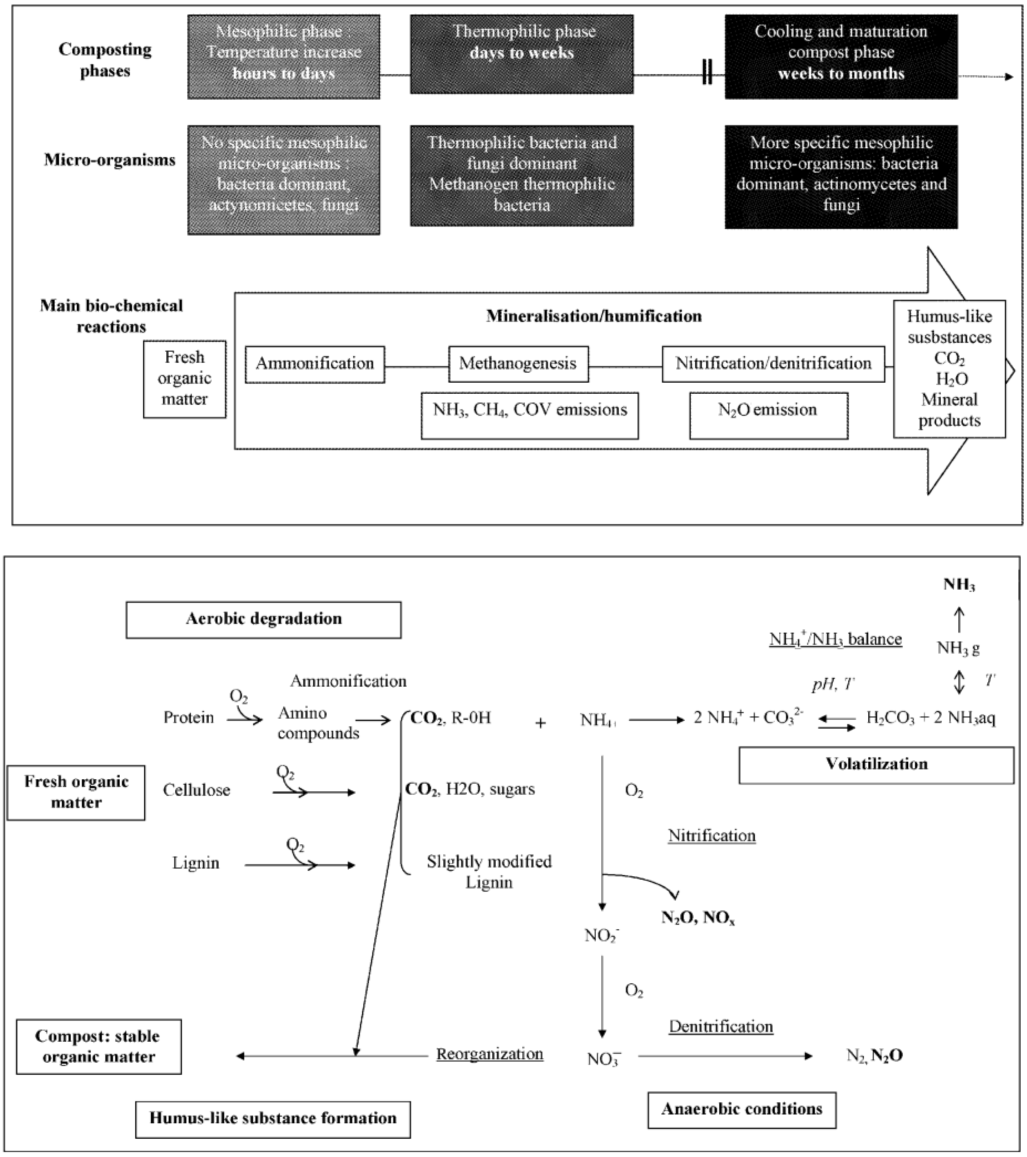


Figure 2: Biochemical processes of composting (Peigne and Girardin, 2004)

Compost contains a lot of organic matter. It not only provides plant nutrients, but it also enhances the physico-chemical and biological properties of the soil. As a result of these improvements, the soil:

(i) Becomes more resistant to environmental challenges like drought, disease, and toxicity

(ii) Helps to improve the uptake of nutrients by the crops

(iii) Possesses an active nutrient cycling capacity through intense microbial activity

Methods of composting

Coimbatore method

Composting is done in pits of varying sizes depending on the availability of residues. The pit is first covered with a layer of waste materials that was soaked with 5-10 kg cow dung in 2.5 to 5.0 I of water and 0.5 to 1.0 kg fine bone meal spread evenly over it. Similar layers are laid one over the other until the material rises to 0.75m above the ground level. Finally, it is covered with moist mud and left undisturbed for the period of 8 to 10 weeks. Then, the plaster is removed, the material is wet with water, turned and made into a rectangular heap under the shade. It should be undisturbed until it is used.

Indore method

Organic wastes are placed as bedding in the livestock shed. Every day, the urine-soaked materials with the dung are removed and compacted into a 15-cm-thick layer at selected spots. The layer of wastes is sprinkled with water and urine-soaked earth that has been scraped from livestock sheds twice or three times every day. For over a fortnight, layering was continued. A thin layer of well-decomposed compost is sprinkled on top, after which the heap is turned and reconstituted. Old compost serves as an inoculum for the decomposition of the material. Almost a month passes while the heap is undisturbed. Then it is completely moistened before being turned. After another month, the compost will be ready for application.

Bangalore method

A pit of dry waste material is spread out, then to add moisture, a thick suspension of cow dung in water is sprayed on top. A thin layer of dry waste is placed on top of the moistened layer. The pit is filled with dry layers of material and cow dung suspended alternating till it reaches 0.5 m above ground level. It is left exposed for 15 days without being covered. It is turned, coated with moist mud, and left undisturbed for about 5 months, or until needed.

Vermicomposting

Vermicompost is nothing but humus and nutrient-rich earthworm feces. Rearing the earthworms in a brick tank or near the stem/trunk of trees (especially horticultural trees) along with the waste materials. We can produce the required quantities of vermicompost by feeding these earthworms bio-mass and watering their food (bio-mass).

Advantages of composting

- Many wastes from various sources are combined together during composting hence it reduces the mass of waste materials and the final quantity of compost is less
- The temperature of composting kills pathogens, weed seeds, and seeds
- Mature compost balances out with the soil

- Excellent soil conditioner thereby it remediates soils are contaminated with hazardous waste effectively
- Saleable product and an additional revenue
- It reduces the risk of pollution
- Reduce or eliminate the need for synthetic or chemical fertilizers
- Promote higher yields of agricultural crop
- Facilitate reforestation, wetlands restoration, and habitat revitalization efforts by amending contaminated, compacted, and marginal soils
- Provide cost savings of at least 50 percent over conventional soil, water, and air pollution remediation technologies, where applicable

Happy seeder

Happy seeder is a machine which combines stubble mulching and drilling in a single machine, is a promising new technology, in which the stubble is cut and gathered before seeding, and the cut stubble is then placed as mulch behind the seed sower**.** It is a proposed approach for stubble management after paddy crop harvesting and similar to a zero till ferti seed drill developed by National Agro Industries. Crop residues are left over in the field helps to restore the soil quality and reduce environmental pollution caused by stubble burning. Sowing of wheat in the field with rice residue is challenging until the recent introduction of a happy seeder machine (Fig 3) (Porichha *et al.,* 2021). The advancement of technology has resulted in the development of a device known as the Combo Happy Seeder equipment (Sims *et al.,* 2015).

Figure 3: Happy seeder

Benefits of happy seeder

- It conserves the soil moisture through reduce evaporation and increased infiltration
- It helps to maintains the soil temperature and contributes to the control of extremeheat and radiation through which improves the soil microclimate
- It helps to improvesoil structure and fertility, reduce the rate of decomposition of organic matter and therefore reduces the loss of carbon from soil
- Sowing of wheat using a happy seeder combo machine reduces operating costs by 50-60% compared to traditional seeder (Singh *et al.,* 2017)
- A notable benefit based on profit analysis revealed that Happy Seeder systems are more profitable than other crop residue management options (Kaur *et al.,* 2017).

Constrains of happy seeder (Porichha *et al.,* 2021):

- The introduction of a happy seeder machine has some challenges, including a limited machine operating window (25 days per year), limited machine efficiency, inability to operate under wet straw condition and a shortage of spreaders on a combined harvester
- The National Academy of Agricultural Sciences (2017) states that rice residue can be managed simultaneously using a turbo happy seeder and a combine equipped with a super straw management system (SMS)

Microbial degradation

The process of composting is one of the most effective and well-known approach for the management of agricultural residues. The Bio-decomposition of crop residues promotes the utilization of organic wastes as soil amendment, as the availability of soil nutrients increases on microbial composting. This might render the good promises for improvement of soil health, thereby reduces the issue of waste disposal. Stubbles are mainly composed of cellulose, a renewable organic molecule. It is a promising method to decompose it by cellulase produced by microorganisms. Many studies have reported that microbial decomposition pattern varies for different crops (Puttaso *et al.,* 2011). The rate of decomposition was positively correlated with cellulose, while negatively to the amount of lignin and polyphenol content in residues. In order to use microbes for composting, it is necessary that the C:N ratio of residues should be in the range of 30 - 35 Sand moisture content should be between 55- 65%. This optimum range provides appropriate conditions for microbial decomposition and transformation of crop residues into organic matter (Kaur *et al.,* 2022).

Many aerobic and anaerobic micro-organisms have been manifested with activity of residue degradation. Some common bacterial and fungal organisms involved in stubble degradation are *Chaetomium, Myrothecium, Trichoderma, Fusarium, Aspergillus, Penicillim* and *Trichonympha, Clostridium, Butyrivibrio fibrisolvens* and *Bacteroides succinogenes.* The use of microbial consortia can rapidly degrade straw in the field and convert it into compost. A major advantage of using microbial consortium is that farmers will not have to shift the paddy straw anywhere for disposal or treatment. The microbial consortia spray can emerge as an effective long-term solution to the stubble or crop residue-burning problem. Ex. Microbial consortia consisting of *Aspergillus nidulans, Trichoderma viride, A. awamori* and *Phanerochaete chrysosporium* (Acree *et al.,* 2020*)*. The microbial degradation of stubbles can be accelerated using different amendments such as poultry droppings, cow dung slurry and enriched composts etc., The mesophilic micro-organisms such as *Pseudomonadaceae, Streptomycetaceae and Erythrobacteraceae* family governs the mesophilic stage of composting. A thermophilic consortium fungi of *A. nidulans, Scytalidium hermophilum* and *Humcola sp* was found to be beneficial in soybean trash and rice straw decomposition. At low temperature, the composting can be accelerated by some psychrotrophic microbial consortium comprising *Eupenicillium crustaceum, Paceliomyces sp. and Bacillus sp*., was employed for biodegrading rice straw. Among the different microbial agents, fungi prove to be the best and most essential form of group that forms colonization over the solid substance very quickly and degrades faster (Sangwan and Deswal, 2021).

Bioenergy production

Another promising alternative method of residue management is the production of bioenergy from crop residues. Liquid biofuels are commonly produced from the crop residues i.e., conversion of biomass into liquid fuel or electricity or bio-power. The most commonly produced biofuel from crop residue is cellulose based ethanol (Porichha *et al.,* 2021). The production involves breaking down of polysaccharides enzymatically within the straw into its element sugars, that will be thereafter fermented into ethyl alcohol. The direct combustion of straw alone is known as direct firing and the combustion of straw with another fuel is known as co-firing. The bio-power can be generated from both direct firing and co-firing (Jenkins *et al.,* 1998). The alternative method for direct combustion is gasification, in which the straw is gasified by steam or air to generate a fuel-gas mixture of N_2, H_2, CO, and CO_2, followed by the generation of electricity (Rao *et al.,* 2010). Bioenergy can also be generated from crop residues by anaerobic digestion method to produce biogas. The CH_4 produced is collected and combusted to produce electricity.

Some studies have reported the production of bioenergy along with organic fertilizer from crop residues. The use of cattle and buffalo manure along with crop residue as a feed stock for anaerobic digestion results in the production of biogas and an organic fertilizer (Gross *et al.,* 2021). The biogas produced from the mixture of agricultural waste (lettuce leaves, potato peels and peas peels) and live stock manure by co-digestion was observed to have high CH_4 production (Abdelsalem *et al.,* 2021). The alkheri, Fatehgarh Sahib District thermal plant is the first plant in India, that uses agricultural and forestry residues for bio-energy production. This plant uses rice husk, wood chips and stalks from different crops like wheat, paddy, local farm wastes including rice paw and sugarcane bagasse. There are several challenges in the large-scale production of bioenergy from crop residues with respect to both economy and efficiency. For instance, most crop residues contain more content of alkaline ash, that can cause operating issues like corrosion and deposition in boilers for electricity generation. Since the crop residues are bulky, the feedstock transportation and processing cost will be very high for large scale bio-energy production (Parmod *et al.,* 2015).

Government support and policies

The harmful consequences in the practice of stubble burning of agricultural residues on soil, environment and human health led to the implementation of several laws and regulations in India. In order to stop burning of stubbles in field, section 144 is called upon by government to stop paddy straw burning, but it is not adapted at the farmer level. This is due to the insufficient efforts on increasing awareness among farmers (Gathala *et al.,* 2011). The plan was signed in early 2018 by the present Prime Minister of India, Narendra Modi and his cabinet ministers. The National Institution for Transforming India (NITI Aayog), a government policy advisory group initially proposed the expenditure of $600 million per year to the government. As per the proposed plan, inorder to avoid burning, money will be given for subsidizing the cost of machinery to extract crop residues from field to the growers of three states bordering Delhi– Punjab, Haryana, and Uttar Pradesh (Lohan *et al.,* 2018). Other proposals were put forward to deal with stubbles including the purchase of crop residues from farmers by the state electricity company NTPC as a fuel in its coal-fired power stations. Some of the potential future strategies are as follows

- Providing incentives to farmers, not to burn crop residue outdoors.
- Promoting the generation of bioenergy from sustainable, environmentally friendly, and cost-effective use of crop residues.
- The use of crop residues as fertilizers or amendments should receive government support.
- Providing more subsidy to farmers, who retain and utilize their crop residues.
- Increasing the awareness among farmers on the negative impats of open field stubble buyrning
- Promoting the insitu management of crop residues for microbial degradation, use of machines such as double disks, zero tillage and happy seeders and valorization of crop residues for useful products.

Conclusion:

Undoubtedly, the lack of proper management of abundant crop residue has had an adverse influence on the soil, environment and human health not only in India but also in the world. Agricultural field burning has created many environmental problems, particularly causing a threat to the soil fertility and the emission of toxic gases such as CO_2, CO, SO_2 etc. Consequently, a variety of alternative approaches should be considered as substitutes for open field burning, e.g., in situ incorporation, mulching, composting, Happy Seeder machines, and bioenergy use. In conclusion, this book chapter provides an overall understanding of the adverse impacts of open burning of crop residues in terms of ecology and environment and more promising alternative management practices for the crop residues, which, if widely employed, could not only reduce the environmental impacts of crop residue management, but generate additional value for the agricultural sector globally.

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OVERVIEW OF RECENT TRENDS AND CURRENT APPROACHES IN SOIL SCIENCE

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Bio-fortification through green technology:

Bio-fortification is the method of increasing the nutritional content of crops or foods by adding important micronutrients and other health-promoting substances without affecting the agronomic features (such as insect resistance, yield, or drought tolerance) (Klikocka and Marks, 2018). Green technology includes the use of microorganisms for the improvement of the soil nutrient status by enhancing nutrient accessibility to the crops. This is necessary as the diets of almost two-thirds of the global population is lacking in one or more important mineral elements, and the three main crops, rice, maize, and wheat, which supply roughly half of the calories eaten by people, are deficient in micronutrients. Microutrients such as iron, zinc, copper, manganese, iodine, selenium, molybdenum, cobalt and nickel are preset in anecdotal amount in the edible part of the plants and are often taken from the soil, therefore a shortage in the soil may also lead to a deficiency in the plant. Research in agriculture over the last 50 years has led to greater output and yields of several staple crop species, but these advancements also bring some disadvantages. Micronutrient levels in the crop has drastically decreased as a result of the widespread use of chemical-based fertilizers and pesticides, which in turn lowered soil fertility and disturbed the soil's microbial ecology (Bouis *et al.*, 2011a,b; Bouis and Saltzman, 2017).For proper growth and development, plants need just 14 mineral elements, but humans need at least 22 (Graham *et al.*, 2007). If we don't get enough of these vital micronutrients, we might end up with a characteristic deficiency disorder since they play a crucial role in metabolism or as a cofactor in certain biological processes (Welch and Graham, 2004). Reports indicate that almost 60% of the global population suffers from iron (Fe) deficiency, 30% from zinc (Zn) and iodine deficiencies, and 15% from selenium deficiency. Other than this, Mg, Ca, and Cu deficiencies are also common in many developing and developed countries (Thacher *et al.*, 2006).

Humans have tried various mineral supplements to cope up with these mineral deficiencies, but this has not always worked. To address this issue, it is crucial to boost the staple crop's micronutrient content. Different approaches are there to increase the mineral supplements in the crops (Fig. 1), including transgenic (use of biotechnology), conventional (use of crop breeding) and agronomic (involving the use of chemical fertilizers and nanofertilizers (Singh and Yadav, 2020).

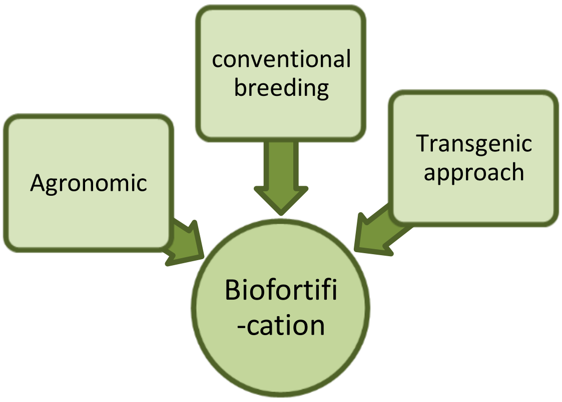

Figure 1: Different approaches of bio-fortification

But these methods are more expensive and time-consuming, and the use of chemical fertilizers pollutes our soil and ultimately the environment and has never been plenty nor is effective in the nutrient supply to the plant because of the complexes they form in the soil. In light of this, microorganisms mediated biofortification is not only a viable alternative to chemical fertilizer and pesticide, but also a low-cost solution to addressing the issue of micronutrient-related malnutrition (de Santiago *et al.*, 2013). Microbes and plants have evolved together and are physiologically and environmentally interdependent; together, they play a crucial role in nutrient cycling through the breakdown and mineralization of organic matter and the transformation of inorganic nutrients into usable forms (Rana *et al.*, 2012).

Mechanisms of biofortification through green technology:

Microbes in soil uses different strategies to enhance availability of micronutrients in soil which include:

1. Production of siderophores and other chelating substances
2. Organic acid secretion and proton extrusion
3. Modification in root morphology and anatomy
4. Upregulation of Zn and Fe transporters
5. Reduction of phytic acids or anti-nutritional factors in food grains
6. Secretion of phenolics and related reducing moieties

1. Production of siderophore and other chelating substances

Siderophores are Fe chelating chemicals with a low molecular weight and a high affinity for Fe (III) (Ganz, 2018). Siderophores are produced by different kinds of microbes to overcome the deficiency of Fe in soil (Schalk *et al.* 2011). Although Fe (III) is poorly soluble in soil, its availability is increased by siderophores via the formation of siderophore-Fe (III) complexes (Fig:2) (Saha *et al.* 2013). Key microbial activity in the rhizosphere that aids plant Fe uptake is the synthesis of siderophores, which have a solubilizing impact on Fe hydroxides (Desai and Archana 2011; Hayat *et al.* 2012). Zn, being more reactive species in soil, are present in very small concentration in soil solution (Alloway 2009); hence, their bioavailability in soil is poor. However, Zn chelating chemicals (man-made or from plants and microbes) may improve the mobilisation and solubilization of Zn fractions in soil (Obrador *et al.* 2003). The interactions of

Zn^{2+} with other soil components are reduced when these chelators form soluble complexes with Zn^{2+} (Tarkalson *et al.*, 1998). The bioavailability of Zn in soil and absorption by plant roots were shown to be significantly influenced by Zn chelator metallophores, which were reported to be formed by bacteria (*Microbacterium saperdae, Pseudomonas monteilii*, and *Enterobacter cancerogenes*) by Whiting *et al.* (2001). *Penicillium bilaji* inoculation boosted Zn solubilization and uptake in plants, as reported by Kucey (1988), more so than that accomplished by the ethylene diamine tetra acetate (EDTA) chelating mechanism.

2. Organic acid secretion and proton extrusion

Several biochemical pathways are used by plants to mobilise and solubilize metal cations through root exudates. These pathways include I acidification of the rhizosphere via proton ions or organic acids in root exudates; (ii) formation of soluble complex of metal ions with amino acids or organic acids and other chelators; (iii) enzymatic redox reaction reactions; and (iv) biostimulation effect of root exudates on beneficial microbes in the rhizosphere (Pérez-Esteban *et al.* 2013). Root exudates are dominated by organic acids, which play an important role in rhizosphere metal solubilization (Luo *et al.* 2014). According to a study conducted by Kim *et al.* (2010), the micronutrient absorption and translocation in plant tissues were greatly improved by the oxalic and citric acids released by *Echinochloa crusgalli*. Soil pH has a significant impact on the solubility of micronutrients; even small changes in pH have been observed to have a large impact on micronutrient availability. In addition to organic acids, proton excretion by microbes may also cause acidification of the rhizosphere, which in turn makes more nutrients available to plants. Phosphorus solubilizing fungus, such as *Penicillium bilaji* and *Penicillium cf. fuscum,* have been shown to dramatically increase phosphorus availability in soil by secreting protons and thus lowering soil pH (Asea *et al.*1988). Other than phosphate-solubilizing bacteria (PSB), mycorrhizae are also reported to excrete H^+. As a result the presence of protons in micronutrient-deficient soils may facilitate the crop plant's absorption of micronutrients.

3. Modification in root morphology and anatomy

Plants that are able to store large amounts of zinc or iron have specialised morphological, anatomical, and physiological adaptations, such as elaborate root hairs, increased root surface area, and root exudates that mobilise metals (Genc *et al.* 2007). According to research by Singh *et al.* (2005), a robust root system is a key tactic for increasing plant absorption of micronutrients. Differential Zn efficiency across genotypes is mostly explained by the increased percentage and longer length of fine roots ($\leq$ 0.2 μM) in Zn-efficient plants (Rengel and Wheal 1997). Zn-efficient plants, in general, have thinner roots with greater surface area, which allows them to explore the soil more deeply and so find more sources of Zn and other nutrients (Singh *et al.* 2005). The inoculation of plant growth-promoting rhizobacteria and endophytic bacteria has been shown to significantly alter the morphology and architecture of the plant's roots (Delaplace *et al.* 2015). Root shape isn't the only thing that plant growth-promoting microorganisms may alter; they can also change the root's internal structure, allowing the plant to absorb more nutrients from the soil. (Ortz-Castro *et al.*, 2008) Expansion of the root cortex and volume of xylem vessels, more elaborative root hairs, thickening of the endodermis, and vascular bundles have all been linked to increased nutrient absorption (Kotula *et al.* 2009). Rêgo *et al.* (2014) studied the impact of a bioinoculant (bacteria and a fungus) on the structure and function of rice plant roots. They found that inoculation with *Trichoderma asperellum, Burkholderia pyrrocinia, and Pseudomonas fluorescens* significantly altered root architecture, notably with regards to root cortex diameter, vascular bundle dimension, and vessel count in the protoxylem and metaxylem.

4. Upregulation of Zn and Fe transporters

Translocation of micronutrients from the root to the shoot and then to the grains is a separate process from micronutrient absorption, which may be exceedingly efficient in some crop genotypes but otherwise subpar in other (Singh *et al.*, 2018). So in order to boost the levels of micronutrients in the edible sections of the plant, it is necessary to alter the process of nutrient translocation or redistribution within plant parts. Plants rely on a variety of transporters to move micronutrients throughout their bodies, including zinc-regulated, iron-regulated transporter-like protein (ZIP), plasma membrane-type ATPase (P-type ATPase), cation difusion facilitator (CDF), natural resistance-associated macrophage protein (NRAMP), cation exchanger (CAX), plant cadmium resistance (PCR), vacuolar iron transporter (VIT), and yellow stripe- like (YSL). These transporters are involved in the transport of Zn, Fe, cobalt (Co), cadmium (Cd), copper (Cu), Mn, and nickel (Ni) in plant. Plants receive Fe2+ from the soil with the aid of the iron-regulated transporter (IRT) protein, which is a member of the ZIP family; the ZIP, nicotianamine synthases (NAS), and P-type ATPase transporter families are involved in the absorption, distribution, and transport of Zn^{2+}. Several other proteins (including NRAMP1 and FRO2) also contribute to Fe absorption from the soil. The overexpression of Zn/Fe transporter appears to be useful in increasing Zn/Fe accumulation in the plant's edible parts. OsZIP1 and OsZIP5 expression are reported to be upregulated and OsZIP4 expression to be downregulated in rice genotypes when inoculated with Zn-solubilizing *Enterobacter cloacae* strain ZSB14 (Krithika and Balachandar 2016). In 2019, LeTourneau *et al.* found that different *Bacillus spp*. increases Fe buildup in the grains and promotes transfer of Fe from the roots to the shoots. When *Rhizophagus irregularis* colonised *Hordeum vulgare*, it upregulated HvZIP13, which increased grain Zn contents even under Zn-deficient environments (Watts-Williams and Cavagnaro, 2018). Inoculation of the siderophore-producing *Arthrobacter sulfonivorans DS-68* endophyte resulted in 2.6-fold higher expression levels of TaZIP7 in shoots compared to the uninoculated control, while TaZIP3 remain unaffected by endophyte inoculation while *Arthrobacter sp. DS-179* endophyte caused a 1.7-fold increase in TaZIP3 gene expression in roots and a 40% downregulation of TaZIP7 gene expression in roots compared to the uninoculated control.

5. Reduction of phytic acids or anti-nutritional factors in food grains

The Phytic acid is myoinositol 1,2,3,4,5,6-hexakis dihydrogen phosphate. In cereals, legumes, oil seeds, and nuts, phytic acid accounts about 1-5% of the total weight and is the primary form of phosphorus storage (Vats and Banerjee, 2004). Accumulation of phytate in food grains take place during the maturation period. In legume and oil seeds it is found in the globoid crystal of the protein bodies (Erdman, 1979), whereas in cereals it is located in the endosperm of maize and in the aleurone layer and pericarp of rice and wheat (O'Dell *et al.*, 1972). Since the digestive systems of monogastric animals like chickens and humans can not produce enough phytate degrading enzymes, are unable to metabolise phytic acid and excrete it in their faeces (Singh *et al.,* 2011).

Furthermore, phytic acid acts as antinutritive agent by blocking the absorption of minerals such as Fe, Zn, and Ca. The binding results in insoluble salt with poor bioavailability of minerals **(**Feil, 2001). Cereal grains contain phytic acid, which combines with iron, zinc, calcium, and protein to create complexes. The enzymatic break down of phytic acid can increase the amount of soluble iron, zinc and calcium a number of folds. Phytases break down phytic acid from its hexa form (IP6, myo-inositol 1,2,3,4,5,6- hexakisphosphate) into more manageable forms. These forms include IP5, IP4, IP3, IP2, IP1, and myo-inositol (Ragon *et al.,* 2008). The binding ability of the lesser forms of phytic acid for metals like iron and zinc is reduced (Agte *et al.,* 1997). In contrast to plant phytases, microbial phytases have been studied extensively for industrial applications due to their superior pH and temperature stability (Bohn *et al.,* 2008). Since preparatory treatment is required, the manufacturing technique becomes time consuming, problematic, and costly, rendering phytase manufacture from plants uneconomical. Therefore, microbial phytase synthesis has more promising future applications. The synthesis of Phytase has been examined in over 200 fungal isolates from the genera Aspergillus, Mucor, Penicillium, and Rhizopus. All isolates produce active extracellular phytase. *Aspergillus niger* was identified as the most prolific fungus in terms of phytase production. When cultured on rape seed meal, more than 58 fungal strains showed evidence of hydrolyzing phytate. In comparison, *A. ficuum* was the most productive in terms of producing active phytase. *Aspergillus species* other than *A. oryzae*, *A. amstelodami*, *A. candidus*, *A. flavus*, and *A. repen* have also been discovered to produce phytase extracellularly (Hawson and Davis, 1983). Examples of bacteria that produce phytase include *Bacillus*, *Klebsiella*, *Escherichia coli*, and *Pseudomonas sp* (Greiner and Carlsson, 2006). Yeast phytase research is likewise sparse, with just a handful of studies conducted on species like *Saccharomyces cerevisiae* and *Schwanniomyces castellii.*

6. Secretion of phenolics and related reducing moieties

Nongraminaceous monocots and dicots Strategy I plants (Fig-2) rely on proton extrusion to acidify the rhizosphere, trans-plasma membrane electron transfer to reduce Fe to its more soluble ferrous form via ferric chelate reductase (FRO2), and iron-regulated transporter 1 (IRT1) to transport Fe into root cells (Kobayashi and Nishizawa, 2012) , reductants and chelators such as phenolic compounds, flavins, and organic acids are the primary components of root exudates in response to Fe shortage (Hell and Stephan, 2003). However the significance of phenolic secretion in plant Fe nutrition is not as well understood as the roles of other Fe deficiency-induced reactions (such as ferric reductase, proton secretion, and morphological alterations). The released phenolics have been hypothesised to chelate and reduce insoluble Fe in the rhizosphere soil, increasing Fe availability as an alternative or complement to the plasma membrane-bound ferric reductase (Dakora and Phillips, 2002). In a study on red clover, researchers found that removing phenolic compounds from the growth media resulted in iron-deficiency symptoms, suggesting a role for these compounds in the mobilisation of iron pools in the cell walls. This is the first direct evidence for a physiological role of secreted phenolics in the acquisition of iron (Jin *et al.*, 2007).

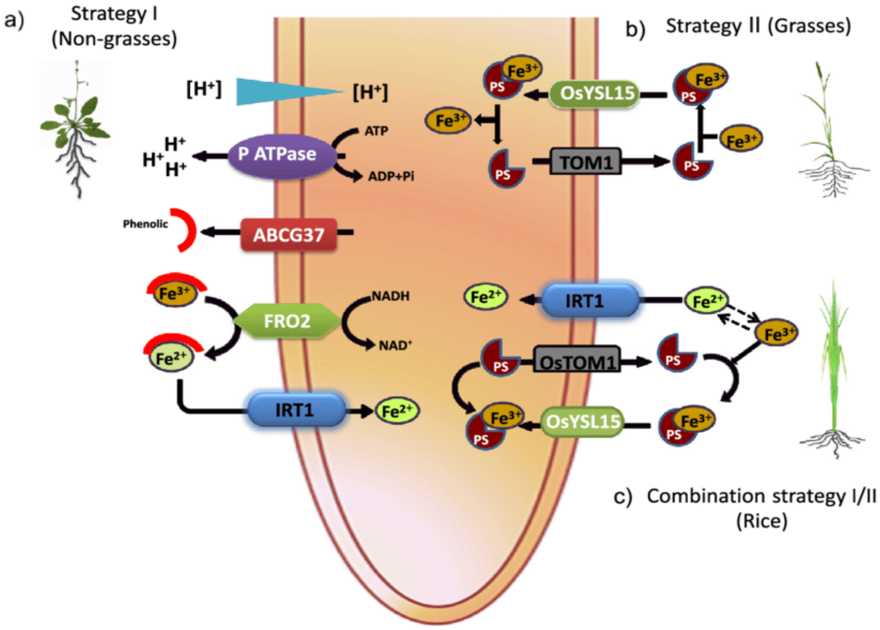

Figure 2: Ion uptake strategies in plants (a) Strategy I is a reduction based strategy found in most plants except grasses, this includes acidification of the rhizosphere by the plasma membrane H + -ATPase (P-ATPase) which increases the solubility of Fe 3 + . The soluble Fe 3 + is then chelated by the phenolics and exported by the ABCG37 transporter. FRO2 reduces chelated Fe 3^+ to Fe 2^+ and then Fe 2^+ is taken inside the plant cell by the Iron-Regulated Transporter -IRT1 transporter. (b) Strategy II is chelation strategy found in grasses, includes a phytosiderophore mediated transport, YS1 and TOM1; and (c) A combination strategy (Strategy I/II) located in rice. OsTOM1 transporter mediates the PS secretion through the plasma membrane. The OsYSL15 transporter exploited by rhizosphere formed Fe 3^+ -PS to enters in to the root cells. In addition to Fe 3^+ -PS uptake, rice also possesses the components of the Fe 2^+ uptake system. (Tsai and Schmidt, 2017)

It seems that the generation and secretion of phenolics cannot be compensated for by other responses, since the removal of phenolics aggravated iron shortage and enhanced other iron-deficiency responses such as proton extrusion and ferric reduction. Similar results were also reported for *Arabidopsis* (Fourcroy *et al.*, 2014). It's interesting to note that strategy I species aren't the only ones capable of producing and secreting phenolics. The first transporter controlling the secretion of phenolics, PEZ1, was discovered when researchers noticed that the cadmium-accumulating rice (*Oryza sativa)* mutant phenolics efflux zero 1 (pez1) was unable to secrete protocatechuic acid (PCA) (Ishimaru *et al.*, 2011). In legumes nodules play a significant role in symbiotic N_2 fixation. This process is facilitated by Fe-containing proteins (Terpolilli *et al.*, 2012). Therefore, noduled legumes have a higher Fe need than non-noduled plants. To compensate for this higher need, legumes have evolved a system to improve the root's reactions to Fe shortage during nodulation. Rhizobium nodulation has a major impact on the production of protons and reductants in the Fe-deficient roots of peanut plants (Terry *et al.*, 1988). When cultivated on sterilised calcareous soil, Jin *et al.* (2006) found that Fe acquisition and development of red clover greatly decrease, but are recovered by nodulation with Rhizobium leguminosarum bv. trifolii ACCC18002. All of these results suggest that rhizobium nodulation can systemically improve the Fe nutrition of plants through enhancing Fe-deficiency-induced responses.

2. Application of Nanotechnology in soil science

Nanotechnology is the understanding and control of matter of sizes roughly in the range of 1 to 100 nanometers. If one of the dimensions is in this range, it is considered a nanoparticle. The melting point, physical strength, surface area, penetrating power, electric conductivity, optical effect, magnetism, etc. of bulk materials may change as they are reduced to the nanoscale, allowing for their unique and interesting uses. These materials can be either natural or synthetic. Scientists from many different disciplines come together to study nanotechnology, including chemists, physicists, biologists, and engineers. The advent of nanotechnology has sparked a revolution in several sectors by facilitating the creation of previously impossible processes and products. Nanotechnology-aided applications, such as nano-nutrients, nano-pesticides, insect repellants, nano-sensors, nano-magnets, nano-films, nano-filters, etc., have the potential to alter agricultural productivity by facilitating more efficient resource management and conservation (Tarafdar *et al.*, 2013). Nanomaterials, which may be either naturally occurring, accidental, or man-made, are used in a wide range of nanotechnological investigations (Boverhof *et al.* 2015). The nanoparticles have dimensions of less than one micrometre (Jeevanandam *et al.* 2018). Nanocarriers, nanotubes, nanoclays, nanocomposites, nanosensors, nanofbers, and nanocapsules are just a few of the nanoformulations that may be found for nanomaterials. When metal oxide nanomaterials are heterogenized with biopolymer nanofibers, they become superior transporters and even soil enhancers.

1) Nanofertilizers (NFs): The NanoParticles (NPs) that contain macro-and micro-nutrients and are supplied to crops in a controlled and smart manner are called as NanoFertilizers (Shang *et al.*, 2019). It is believed that the synthesis and development of NFs represent a "Nano-Bio Revolution" since they provide a more environment friendly replacement for the expensive, high-end, yet harmful traditional synthetic fertilisation methods now in use. 50-55% of the increase in agricultural yields in developing nations may be attributed to the use of chemical fertilizers (Adhikari and Ramana, 2019). Overuse of chemical fertilizers is on the rise as farmers seek higher yields. But this practise has serious environmental and water pollution consequences, including soil quality decline, eutrophication, and ground water and air pollution. However, common synthetic fertilizers' low plant uptake efficiency (nitrogen (N) 30%–40%, phosphorus (P) 15%–20%, potassium (K) 50%–55%, and micronutrients (M) 2%–5%) (Adhikari and Ramana, 2019) triggered wastage of nutrients through leaching, volatilization, and gaseous emissions, leading to environmental destruction.

Zeolites, silver (Ag), copper (Cu), aluminium (Al), carbon (C), zinc (Zn), potassium (K), nitrogen (N), silica (Si), iron (Fe), magnesium (Mg), sodium (Na), calcium (Ca), and manganese

(Mn) are all examples of common basic minerals that may be nanostructured and exploited as NFs. Plant-based materials, such as banana peels and grape plant substrates (Sharma *et al.*, 2014), are also employed in the production of NFs. As a result of their distinct physicochemical features, NFs are preferred over conventional chemical fertilizers. Whether applied as a foliar spray or a basal drench, NFs are able to reach plant systems due to their small particle size (100 nm) (Seleiman *et al.*, 2020). In comparison to traditional, bulky chemical fertilizers, NFs have a greater absorption and retention capacity because of their ultra-small size, high surface area and surface area to volume ratio (Hussain *et al.*, 2022). Because of their larger surface area, NFs are able to pack more nutrients per unit of volume than traditional chemical fertilizers. The slow and steady release of nutrients from NFs lessens their impact on the environment. Critical properties of NFs include enhanced chemical stability, high ionising power, increased pH tolerance enhanced absorbability, higher surface tension, and mobility (Seleiman *et al.*, 2020). There are three different ways for preparation of NFs: 1. Creating nanoparticles that can transport and release nutrients. 2. the incorporation of nanomaterials within conventional fertilizers. Covering conventional fertilizers with nanoparticles. Encapsulating nutrients is the most common approach to making NFs using nanomaterials. On the basis of type of nutrient content NFs may be roughly divided into three categories: (i) macronutrient-based (ii) micronutrient-based, and (iii) biofertilizer-based NFs (Babu *et al.*, 2022)

2) Nano-Biosensors: Nanotechnology is performing an increasingly important task in the development of biosensors. Incorporation of nanoparticles into biosensors has increased their sensitivity and performance in a variety of environmental settings. In addition to being inexpensive, they also boast high levels of specificity and sensitivity, speed of reaction, ease of use, small size, and portability (Amine *et al.*, 2006). These nanomaterials have paved the path for the creation of several revolutionary signal transduction technologies for application in biosensors. With the use of nanotechnology more and more portable equipment are being developed that can analyse a wide variety of substances. Nanobiosensors are very accurate tools for determining the nutritional and hazardous chemical content of soil. So through careful planning, we can eliminate harmful elements like metals from the soil and cultivate crops that thrive best in that environment. Soil pH, moisture, pest identification, and pesticide residues are all things that nanobiosensors are used to detect. The nanobiosensors have a higher potential for application in "smart farming" because of their ability to detect substances at very low concentrations and with great sensitivity (Shang *et al.* 2019). Before beginning any farming operation, it is crucial to assess the soil's quality by measuring its pH, nutrient, and moisture levels. According to a research by Monreal *et al.* (2015), rhizosphere microorganisms' interactions with biosensors provide a basis for assessing soil quality. Microelectromechanical systems (MEMS) have been created to monitor the soil quality using microelectronic circuits, and fertilizers containing nanoparticles of zinc have been designed to enable controlled-release of the fertilizer to the plant roots and perceive the response. Strigolactones are rhizosphere-exuded plant hormones that play a crucial role in plant growth and parasitism. For the detection and high throughput screening of agrochemical compounds like strigolactone and its signalling pathways in plants, a fluorescent based nanosensor incorporating the strigolactone receptors

DAD2 from Petunia hybrid and HTLT from Striga hermonhthica embedded with green fluorescent protein has been developed (Thakur *et al.*, 2022).

Microbial biosensors are analytical devices that use a biologically integrated transducer to provide a quantifiable signal proportional to the concentration of the analyte of interest. This technique is well suited for metabolic sensory modulation and the study of extracellular substances and the surrounding environment. To overcome obstacles such as limited sensitivity, poor selectivity, and impractical mobility, these microbial sensors are combined with many more micro/nanodevices.

3) Smart Delivery of Nutrients: In order to circumvent biological barriers and ensure the effective targeted release of needed nutrients, a smart delivery system for agriculture should exhibit features like temporal control, precise targeting, highly controlled, remote regulation/pre-programming, and multifunction properties. Nanotechnology has had a significant effect on traditional delivery methods by removing their drawbacks, which included leaching, photolysis, hydrolysis, and bio-instability in the atmosphere. The constant need for herbicides and insecticides drives up production costs and pollutes the natural environment. Effective concentration, stability, solubility, time-controlled release in response to particular stimuli, improved targeted action, reduced eco-toxicity, and a safe and simple manner of administration are some of the features that nano-encapsulated agrochemicals should possess. Nanosensors made from carbonnanotubes are so tiny that they can be used to detect and quantify trace amounts of proteins and other small molecules in the earth's soil. These nano-devices are capable of triggering an electrical or chemical response if the soil and its surroundings deteriorate.

4) Nanopesticides: The potential of nanoparticles in crop protection and food production remains largely untapped. Insects are the most common kind of pest in both agricultural fields and their products, therefore NPs may play a crucial role in reducing the prevalence of insect pests and host infections (Khota *et al.*, 2012). A new nano-encapsulated pesticide formulation has been developed, with improved solubility, specificity, permeability, and stability, in addition to slow-releasing qualities. These benefits are achieved by extending the life of the encapsulated active components or preventing their breakdown for longer, both of which are useful in pest control. The formulation of nano-encapsulated pesticides has led to a decrease in both the amount of pesticides used and the amount of exposure humans have to them, making them a more sustainable option for crop protection. So,in order to boost global food production while minimising harmful effects on ecosystems, it is essential that safe and effective alternatives to conventional pesticides should be developed (Bhattacharyya *et al.*, 2016).

5) Soil remediation with the help of nanoparticles: The use of nanotechnology for soil remediation is receiving a lot of attention throughout the globe as a means to clean up polluted soil. Soil remediation often makes use of in situ methods. Adsorption/ immobilisation, Fenton-like reaction, photocatalytic reduction reaction, and different combinations of nanotechnology and bioremediation are some of the most common methods utilised for remediation of pollutants in soil. Among the above mentioned techniques immobilization/adsorption procedure is now used in the majority of remedial applications for pollutant removal since it is effective, cheap, and somewhat eco-friendly (Barzegar *et al.*, 2017). Depending on the kind of contamination and the soil conditions, choosing the right materials and/or coating chemicals is a crucial stage in the immobilisation remediation process. Carbon nanomaterials (CNTs, fullerene, C70, graphene, etc.), metal oxide nanomaterials (F_3O_4 and TiO_2), nanocomposites, and other engineered nanomaterials (ENMs) have all been extensively used for immobilising inorganic and organic pollutants in soil matrices. Metal oxide NMs and other nanocomposites immobilise heavy metals and organic molecules by surface complexation, whereas carbon NMs absorb organic contaminants through van der Waals forces and π-π interactions. Typically, nanoparticle adsorption was used to get rid of inorganic pollutants such heavy metals and metalloids, whereas reduction reaction and degradation in the presence of catalysts were used to get rid of organic impurities.

As a result of using nanomaterials, the micro-pollutants that had been stored in the soil were degraded and removed by adsorption and oxidation. Carbon nanomaterials, Iron (III) oxide (Fe3O4), Titanium dioxide (TiO2), Zinc oxide (ZnO), nanoscale zero-valent iron (nZVI), and nanocomposites are the nanotechnology applications in soil remediation that are often utilised to remove the pollutants. Due to its effectiveness in converting contaminants including hazardous metals, chlorinated organic compounds, and inorganic chemicals into less damaging molecules, nZVI has become the nanomaterial of choice for removing heavy metal pollution (Fajardo *et al.*, 2012).

Machine learning in soil mapping

Modern agriculture faces a number of difficulties, such as the rising demand for food brought on by the planet's population boom, climate change, the exploitation of natural resources, changes in dietary preferences, and safety and health concerns. It is of the utmost importance to simultaneously lessen human impact on the environment while simultaneously increasing the productivity of agricultural practices. in order to address the aforementioned problems, which put strain on the agricultural sector. These two components in particular have pushed up the transition from traditional agricultural practices to precision agriculture. The modernization of agriculture has a huge potential to guarantee environmental safety, maximize productivity, and ensure sustainability (McBratney *et al.*, 2003). In order to meet the growing demand, smart farming came into existence, which generally rests on four pillars: (a) effective management of natural resources, (b) ecosystem preservation, (c) creation of suitable services, and (d) use of contemporary technologies. The use of information and communication technology is undeniably a prerequisite for the development of contemporary agricultural practices. A few examples of how information and communications technology may be used in agriculture include farm management information systems, soil and humidity sensors, accelerometers, wireless sensor networks, cameras, drones, affordable satellites, internet services, and autonomous guided vehicles. When we use ICT in our farms, a lot of data known as "big data," characterized by volume, variety, velocity, veracity, and value, will be generated for which conventional data processing methods cannot be used. The fact that today's technologies are unable to live up to the ever-increasing standards set by the emerging area of "smart farming" one of the most significant obstacles to deriving valuable information from field data. In order to tackle this problem, machine learning (Ma *et al.,* 2019) has evolved by leveraging the exponential increase in processing capabilities. Numerous machine learning applications are used in agriculture, out of which disease detection and digital soil mapping are of utmost importance.

Digital soil mapping

Soil Mapping is the process of delineating natural bodies of soils, classifying and grouping the delineated soils into map units, and capturing soil property information for interpreting and depicting soil spatial distribution on a map In soil science, digital soil mapping (DSM), also known as predictive soil mapping or pedometric mapping, is the creation of digital maps of different soil types and soil attributes with the use of a computer. Digital soil mapping (DSM) in soil science, also referred to as predictive soil mapping or pedometric mapping, is the computer-assisted production of digital maps of soil types and soil properties. Digital soil mapping has benefited greatly from the proliferation of new tools made possible by the development of statistical methods and geospatial technology in the late 20th and early 21st centuries (DSM) (Scull *et al.,* 2003). Most recently, data mining's statistical methodology has started delivering helpful resources for DSM. Data mining is the process of using statistical tools to discover patterns within datasets and then using those patterns to create a usable information structure. In order to learn and construct a model, machine learning (ML) employs data mining methods. These methods identify and measure regularities in data. Most ML methods may be put to use with just minimum human involvement and no explicit target-specific programming. Machine learning (ML) techniques are becoming more popular in digital soil mapping (DSM), which is revolutionizing the process by which soil scientists create maps. Presently, machine learning is being used to soil mapping in much the same manner as it is being applied to other scientific disciplines. However, soil mapping presents several challenges that need for modifications to standardize machine learning techniques. Typical ML Algorithms (e.g., multiple linear regression (MLR), k-nearest neighbor (KNN), support vector regression (SVR), Cubist, random forest (RF), and artificial neural networks (ANN)) have been seeing increased use in recent years, as evidenced by the rising percentage of studies utilizing them. Formerly, the most used ML approach for DSM was artificial neural networks. For DSM, random forest (RF) has been more popular over the last decade, however KNN, Cubist, and SVR have all received considerable attention in recent years. Decision tree models like RF and Cubist are popular because both are within the capabilities of algorithms having linear and non-linear connections in the data. Furthermore, these methods often provide better results than traditional algorithms like MLR. The minimum pre-processing needed to execute these methods is another plus for these algorithms. In this case, there is no need to alter the data (Hengl *et al.,* 2015).

ML-based DSM algorithms with considerations which one to choose

When setting up an ML algorithm, you'll adjust things like the model parameters and the hyper parameters (also known as tuning parameters). Parameters are hidden from view and their values are estimated or learnt by the model as it is trained. This means that they are not manipulated by the user. It is important to note that the model's hyper parameters do not belong to the model itself. To put it another way, users tweak the hyper parameters of the model iteratively until the error in its predictions against the validation dataset is minimized. Tuning options are considered to determine an acceptable set of values for the hyper parameters in order to improve model performance without significant error variance and over fitting. Controlling the training process and achieving good outcomes relies heavily on the calibration of hyper parameters. Unfortunately, this calibration takes time and might be difficult for end users to do. For these reasons, choosing an ML algorithm should take into account the user's familiarity with the algorithm's number and kind of hyper parameters.

Multiple linear regression is one of the best machine learning approaches for determining the correlations betwixt a set of independent variables and a set of dependent ones (James *et al.*, 2013). For digitally generating soil maps, this method is widely used (da Silva Chagas *et al.*, 2016). With MLR, a linear equation with numerical coefficients (model parameters) is fitted to a set of covariates in order to predict the value of the dependent variable. There are various assumptions that must be taken into account before MLR can conduct this fitting. These are (1) multivariate normality, (2) homoscedasticity, (3) linearity, (4) absence of collinearity. In contrast to other learning algorithms, MLR includes no hyper parameters that may be adjusted during the training process.

Soil mappers employ the elementary ML method k-nearest neighbors (KNN) to generate digital representations of soil characteristics (Mansuy *et al.*, 2014). Using the proximity of the desired value to nearby values, the KNN algorithm may make predictions about the value of the target variable. For the purpose of predicting a regression curve, this approach employs a variety of nonparametric regression algorithms. Strong assumptions about the regression functions are unnecessary for nonparametric regression models. This means they may acquire knowledge from a training dataset in a number of different functional forms. Parametric models, on the other hand (like MLR), use a set of parameters to fit the curve to the data while making certain assumptions. With KNN, the number of neighbors (k) utilized to foretell the regression curve is the most crucial hyper parameter (Altman, 1992).

SVM/SVR, a kind of ML algorithm, has shown recent success in digital soil mapping (Pradhan, 2013). Using the data's support vectors, SVR keeps all variables in order to set a maximum margin for linear separation or fitting. The margin is the farthest point from any point of observation on the decision surface. SVR preserves all variables to separate or fit data linearly, with the support vectors (observations) defining a maximum margin (margin of tolerance). The margin is the farthest point from any point of observation on the decision surface. This surface guarantees the algorithm's great generalization capacity, which broadens the applicability of the findings to data that was not initially visible. Furthermore, kernel functions are used in this method to translate vectors that are not linear in a high-dimensional space in which non-linear problems may be solved (Gunn, 1998). SVM creates the best hyper plane to divide classes in the new hyperspace, while with SVR, we may make predictions about the dependent variable using minimal empirical risk. The key parameters of this method are the number and percentage of support vectors required to get the best possible profit (Cortes and Vapnik, 1995).

Digital soil mappers have lately shown an increasing interest in the rule-based algorithm Cubist (Akpa *et al.*, 2016). Cubist starts by building a tree structure out of the user-supplied variables. Subsequently, the algorithm employs boosting training to construct rules by collapsing their respective pathways across the tree. Boosting is a method that gives greater importance to the strongest learners in order to transform the weaker ones into strong ones. For making predictions on the dependent variable under the constraints of each rule, an MLR model is included. Starting at the top of the tree and working their way down, intermediate nodes smooth the forecast in order to reduce the prediction error for the nodes that follow them based on the prediction achieved at the previous nodes of the tree. The final model may be found at the leaf nodes, and it consists of many MLR models used to derive forecasts (Quinlan, 1992). In particular, Cubist, as an ensemble model, uses boosting with two hyper parameters (i.e., committees and instances) to increase prediction accuracy. Models from numerous iterations of the same algorithm are combined in ensemble learning. As a rule, the combined outputs of these models outperform those of any of them used alone, making this approach a powerful prediction tool (Opitz and Maclin,1999).

Another popular ML approach in DSM, is random forest (RF) that makes usage of decision trees. (Akpa *et al.,* 2014). Bootstrap aggregation, or "bagging" in RF, is used to reduce variability and increase result stability. This ensemble learning technique takes a decision tree as input and randomly picks a subset of observations from the training dataset (bootstrapping). This method repeats to generate several decision trees. Decision trees are provided by RF as an out-of-the-bag method for generating error predictions. Each tree in out-of-bag is built using a distinct bootstrap sample set, and only one-third of the data is utilized for training. The remaining data points are omitted so that model error may be evaluated. Random Forest (RF) randomly rearranges (permutes) the covariates and takes into account all possible ways to choose covariates from OOB samples. The mean is used as a starting point for forecasting of findings obtained by thousands of decision trees. The main parameters that matter most for this method are the number of trees to be grown, the minimal number of sample 'leaves' needed to capture noise in the training data, and the number of variables picked at random for each node (Ho, 1995).

A standard and well-established method in Digital Soil Mapping, artificial neural networks is a facsimile of human brain (Kalambukattu *et al.,* 2018). Artificial neural networks (ANN) are networks that are built from a set of nodes. Multiple levels of the network are involved in the transmission of information from neuron to neuron. Network designs, layer organization, and parameter tuning are all accomplished by the interconnection of hundreds of artificial neurons or processing components using weights. Virtually all neuronal networks have interlayer connections. In order for ANN to learn as much as possible, it needs a lot of data, which may be supplied via the training set. In order to calculate the residual, The outcome is contrasted with the input during the training phase. After adjusting the network equation and recalculating the residual, the algorithm iteratively cycles through the layers. This is done again and over again until the least possible residue is obtained. The hyper parameters may be adjusted by the user to assist ANN reduce the residuals (Haykin ,1994).

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Soil Farming Techniques for Climate Resilient Agriculture

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