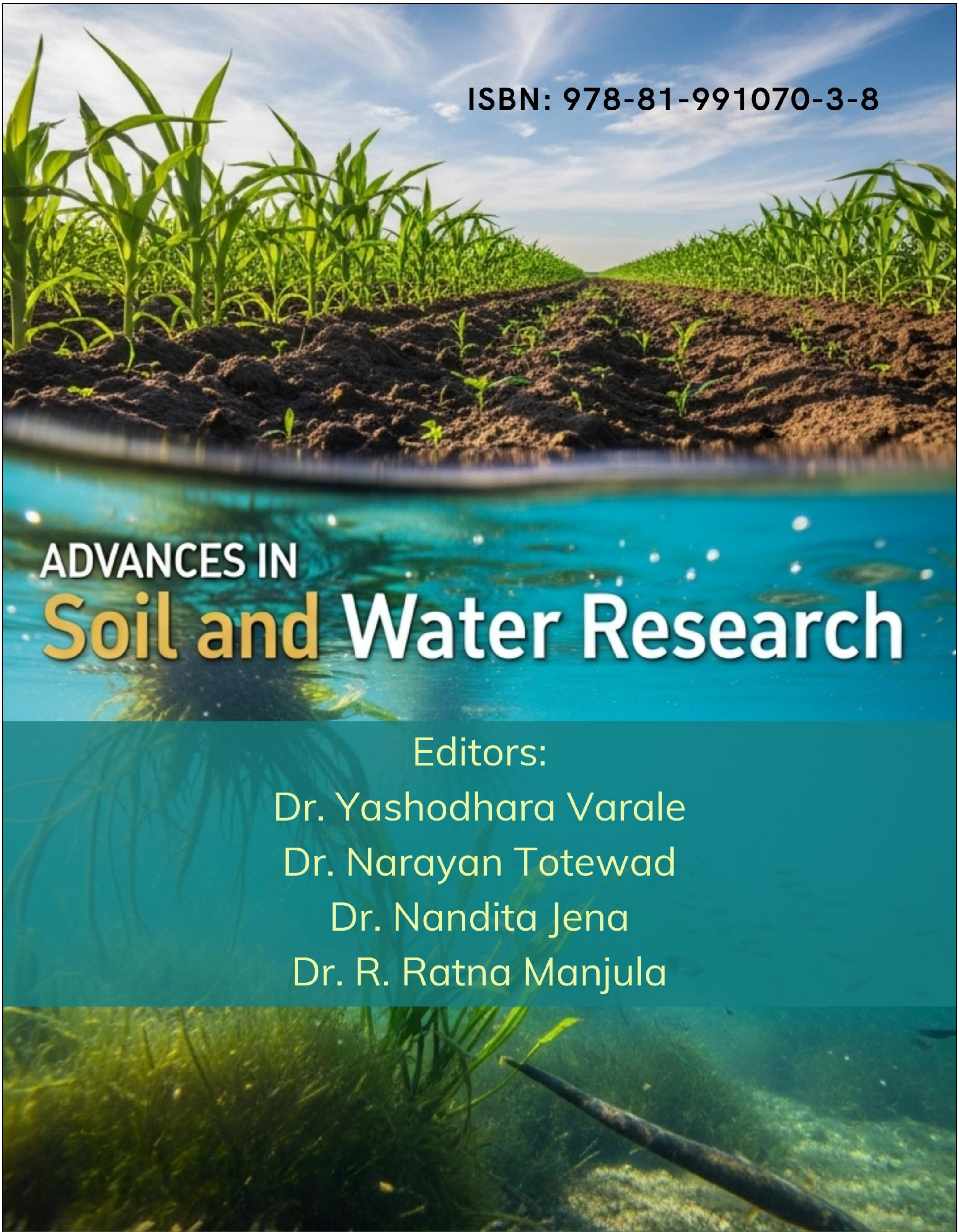

ISBN: 978-81-991070-3-8

ADVANCES IN Soil and Water Research

Editors:
Dr. Yashodhara Varale
Dr. Narayan Totewad
Dr. Nandita Jena
Dr. R. Ratna Manjula

Bhumi Publishing, India

First Edition: July 2025

Advances in Soil and Water Research

(ISBN: 978-81-991070-3-8)

DOI: https://doi.org/10.5281/zenodo.16631188

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Published by Bhumi Publishing,

a publishing unit of Bhumi Gramin Vikas Sanstha

Nigave Khalasa, Tal – Karveer, Dist – Kolhapur, Maharashtra, INDIA 416 207

E-mail: bhumipublishing@gmail.com

PREFACE

Soil and water are the most vital natural resources sustaining life on Earth. Their health, availability, and management play a crucial role in food security, environmental balance, and sustainable development. In recent decades, the global scientific community has made significant strides in understanding the complex interactions between soil systems, hydrological cycles, agricultural practices, and climate change. However, with the increasing pressures of population growth, land degradation, water scarcity, and pollution, there is a pressing need to further advance research and technologies in soil and water science.

This book, Advances in Soil and Water Research, is an effort to bring together a diverse range of contemporary studies, innovative methodologies, and applied research findings from across the globe. It aims to serve as a comprehensive resource for researchers, academicians, environmentalists, policymakers, and students working in the fields of agronomy, hydrology, environmental science, and sustainable development.

The chapters in this volume explore key themes such as soil fertility and conservation, water use efficiency, irrigation technologies, watershed management, erosion control, soil carbon dynamics, salinity mitigation, remote sensing applications, and the impact of climate variability on soil and water systems. Each contribution has been selected for its scientific rigor, relevance, and potential to inform future research and practical implementation.

This compilation is not only a reflection of current scientific knowledge but also a roadmap for future inquiries aimed at building resilient agro-ecosystems and restoring degraded landscapes. The interdisciplinary nature of the work highlights the need for integrated approaches that link soil and water management with socio-economic and ecological outcomes.

We are grateful to all the contributors for sharing their valuable research and to the reviewers for their insightful feedback. We also acknowledge the support of our institutions and colleagues who helped make this publication possible.

We hope this book will inspire continued innovation and collaboration in addressing one of the most critical challenges of our time — the sustainable management of soil and water resources.

- Editors

TABLE OF CONTENT

Advances in Soil and Water Research
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WATER POLLUTION: THREAT TO SOIL HEALTH AND FERTILITY

Brijesh Kumar*[1], Tarence Thomas[2],
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Abstract:

Water is the third most abundant molecule in the universe, after Hydrogen gas (H_2) and Carbon mono oxide (CO). A body of water, like Sea, Rivers, Lakes and a naturally - occurring water like mineral water. The first and foremost effect of water pollution in water scarcity the polluted water is highly unfit for the use of human and will need processing. Water displays capillary action because of its strong adhesive and cohesive forces. Excess fertilizers and pesticides are the main culprit behind long standing water quality problems. When it rains, from agricultural fields and lawns are washed into rivers and transported either to lacks or ocean. A good quality water becomes waste water through the dissolution of detergent, chemical fertilizers and pesticides etc. When waste water is used is becomes a serious problems resulting in water pollution. Soil fertility is the basis of all life, its origin and the place of its continuous renewal compiles use to see dynamic changes taking place in soil fertility throughout water pollution. Water pollution harms for human use and invariably causes harm to human health, soil health, soil fertility and the environment. Reuse and recycle of biodegradable waste like paper, glass, plastics, cloth, metal etc. can be recycled to conserve the natural resources, reducing pollution and minimizing landfill waste.

Keywords: Water Pollution, Soil Health, Fertility and Measures

Introduction:

Water is a precious resource and without its life is not possible on earth. Water plays a prominent role in balancing the ecosystem. Water serves as a solvent and carrier of food nutrients for the growth of plants. It itself acts a nutrient also (Daji *et al.* 1996). Water is essential for all forms of life. Water plays a very significant role in soil- plant growth relationships (Sahai, 2011). Water is also required for translocation of nutrient and dissipation of heat (Riedell and Schumacher, 2009). Soil water is depleted due to evaporation from soil surface, transpiration through the plant and deep percolation in to the soil beyond the root zone (Reddy *et al.* 1992). Water pollution can contribute to soil pollution and conversely (Ahmed, A.M. and Sulaiman, 2001; Meena *et al.,* 2023). Water is a precious resource and without its life is not possible on earth. Water plays a prominent role in balancing the ecosystem. Water plays a major role in soil-plant relationship. Soil water also regulates the soil air and soil temperature relationships. Proper soil and water governance assist in the good growth of crops. Changes to water and soil management will be central to adaptation for most farming systems. Pest and disease management will also be critical. Body of water pollution can include rivers; lakes ponds and oceans and it could endanger marine plants and animals.

Water is Life

Plants require a large amount of water for their growth and production. A good crop of Wheat requires about 1000 litres of water to produce 1 kg of Wheat. Plants require essential nutrients essential nutrients come from soil, these nutrient move from soil to plant as ions and molecules in a water solution. Availability of fertilizer depend upon the presence of water in the soil. Almost every plant process is affected directly or indirectly by water supply. An important function of water in plants is to act as a solvent entering plant cells and moving from cell to cell and organ to organ.

Soil Health

Soil health is an assessment of ability of a soil to meet ecosystem function as appropriate to its environment. The term of soil health is use to assess the ability of a soil to (i) sustain plant and animal productivity and diversity (ii) Maintain or enhance water and air quality (iii) support human health and habitation. The soil health is basically the integration of the soil physical chemical, and biological process and function. A healthy soil will be balanced for all the three components (Suri, 2007). Healthy soil is those that are able to sustain cropping under condition of minimal plant stress. Soil holds more nutrient and filters water, storing excess water during flooding and retaining moisture during drought, healthier soil also can help in the fight against climate change by the Carbon i.e. leading to hotter temperatures. Food and Agriculture Organization, warns 90 per cent of Earth's topsoil at risk by 2050 (FOA).

The main functions of water in soil are as follows:

1. To act as a solvent and transporter of nutrients.
2. To act as a nutrient itself.
3. To act as an agent in photosynthesis process.
4. To maintain the turgidity of plants.
5. To act as an agent in weathering of rocks and minerals.
6. Water protects plant from unfavorable situation like drought, frost etc. (Source: Rai, 1998)

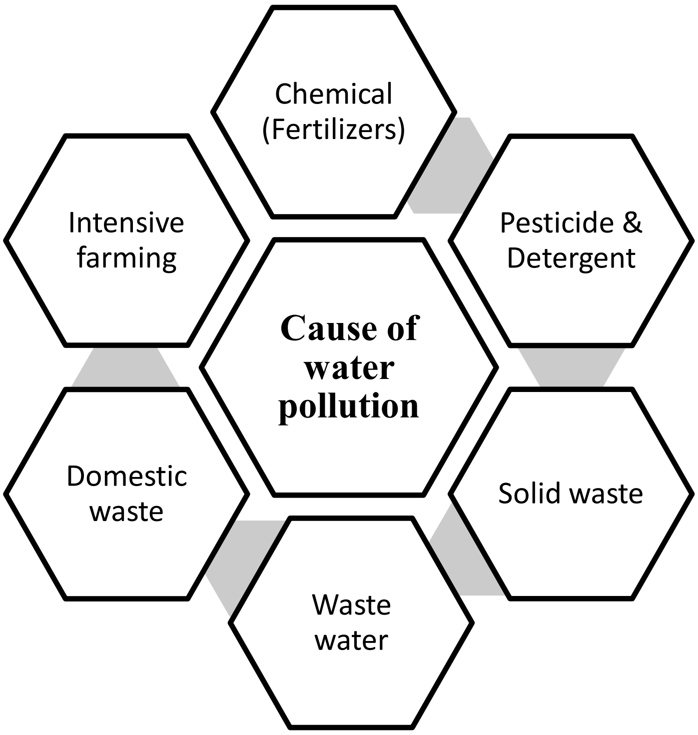

Figure 1: Major Causes of Water Pollution

Water pollution effects on our environment, it is getting polluted day by day due to excessive and careless use of harmful substances such as savage waste, solid waste, industrial waste, domestic waste and hazardous chemicals get mixed and the water becomes polluted. A good quality water becomes waste water through the dissolution of various detergents, chemical fertilizers and pesticides etc. (Singh,2018) Excess fertilizers and pesticides are the main culprit behind long standing water quality problems. When it rains, from agricultural fields and lawns are washed into rivers and transported either to lacks or ocean. When waste water is used is becomes a serious problems resulting in water pollution. The first and foremost effect of water pollution in water scarcity the polluted water is highly unfit for the use of human and will need processing. Water pollution is the leading worldwide cause of death and causes various water borne diseases like Diarrhoea, Typhoid, Cholera, Hepatitis, Dysentery, Jaundice etc. High polluted water can harm internal organs like heart and kidney.

Table 1: State-wise Cases & Deaths Due to Cholera in India 2014 – 2016

Sl No	State / U.T.	2014		2015		2016 (Prov.)	
		Cases	Deaths	Cases	Deaths	Cases	Deaths
1	Andhra Pradesh	0	0	0	0	0	0
2	Arunachal Pradesh	0	0	0	0	9	0
3	Assam	0	0	0	0	0	0
4	Bihar	0	0	0	0	0	0
5	Chhattisgarh	20	0	7	0	55	0

6	Goa	0	0	0	0	0	0
7	Gujarat	158	0	52	0	88	0
8	Haryana	7	0	0	0	0	0
9	Himachal Pradesh	0	0	0	0	0	0
10	J & K	0	0	0	0	0	0
11	Jharkhand	0	0	36	0	5	0
12	Karnataka	32	0	14	2	29	1
13	Kerala	3	0	0	0	7	0
14	Madhya Pradesh	17	0	104	0	94	1
15	Maharashtra	252	2	213	1	107	0
16	Manipur	0	0	0	0	0	0
17	Meghalaya	1	1	0	0	0	0
18	Mizoram	0	0	26	0	17	0
19	Nagaland	0	0	0	0	6	0
20	Odisha	0	0	2	0	0	0
21	Punjab	0	0	0	0	0	0
22	Rajasthan	56	0	3	0	2	0
23	Sikkim	0	0	0	0	0	0
24	Tamil Nadu	14	0	15	0	8	0
25	Telangana	NA	NA	0	0	0	0
26	Tripura	0	0	0	0	0	0
27	Uttarakhand	0	0	0	0	0	0
28	Uttar Pradesh	0	0	47	0	4	0
29	West Bengal	173	0	155	0	157	0
30	A & N Islands	0	0	0	0	0	0
31	Chandigarh	15	0	133	0	10	0
32	D & N Haveli	28	1	14	1	15	1
33	Daman & Diu	0	0	0	0	0	0
34	Delhi	65	1	91	0	228	0
35	Lakshadweep	0	0	0	0	0	0
36	Puducherry	3	0	1	0	0	0
Total		**844**	**5**	**913**	**4**	**841**	**3**

Source: National Health Profile brought out by CBHI,

Dte. GHS Note:

1. 2014: Andhra Pradesh Excludes data of 10 districts of Telangana from July 2014.

2. 2016: Data is different for different reference period.
3. NA stands for Not Available.

Table 2: State-wise Cases and Deaths due to Acute Diarrheal Diseases reported during 2014 – 2016

Sl. No.	State / U.T.	2014		2015		2016 (Prov.)	
		Cases	Deaths	Cases	Deaths	Cases	Deaths
1	Andhra Pradesh	1332145	10	1122740	5	1194005	11
2	Arunachal Pradesh	12657	5	10834	4	11715	2
3	Assam	83373	73	128392	121	88736	282
4	Bihar	550038	24	455125	36	392224	8
5	Chhattisgarh	115561	32	132278	13	157064	33
6	Goa	16097	4	13204	1	14245	4
7	Gujarat	504857	3	567123	3	641451	0
8	Haryana	197898	8	190390	4	224780	14
9	Himachal Pradesh	350459	52	334168	41	310789	56
10	J & K	515013	0	472843	2	534341	0
11	Jharkhand	81451	17	81934	0	93547	0
12	Karnataka	810781	12	832356	13	930369	4
13	Kerala	402106	9	428374	2	476686	15
14	Madhya Pradesh	768021	112	740690	74	740236	122
15	Maharashtra	664014	4	877638	27	1051445	52
16	Manipur	29954	32	29159	23	33193	21
17	Meghalaya	197024	29	167691	32	165404	29
18	Mizoram	14201	10	14215	11	13602	12
19	Nagaland	22301	0	15511	0	15062	0
20	Odisha	767575	190	782151	139	775824	103
21	Punjab	170438	22	179211	37	195281	44
22	Rajasthan	676832	17	810518	13	897209	7
23	Sikkim	39983	2	53295	3	46289	0
24	Tamil Nadu	250264	14	308358	8	367815	9
25	Telangana	NA	NA	963573	20	871497	17
26	Tripura	80388	22	88064	5	95278	6
27	Uttarakhand	90428	14	108974	6	110942	7
28	Uttar Pradesh	754582	301	814481	320	1066342	303
29	West Bengal	1896182	200	1798754	196	2045451	192

30	A & N Islands	23947	2	22398	0	23547	0
31	Chandigarh	39277	29	45284	90	49891	61
32	D & N Haveli	63337	0	51195	4	43280	12
33	Daman & Diu	12831	0	18169	2	13062	0
34	Delhi	120618	77	157445	96	135907	109
35	Lakshadweep	6750	0	4472	0	4387	0
36	Puducherry	87248	11	92599	2	92379	5
Total		**11748631**	**1337**	**12913606**	**1353**	**13923275**	**1540**

Source: National Health Profile brought out by CBHI,

Dte. GHS

Note:

1. 2014: Andhra Pradesh Excludes data of 10 districts of Telangana from July 2014.
2. 2016: Data is different for different reference period.
3. NA stands for Not Available.

Table 3: State-wise Cases and Deaths due to Enteric Fever (Typhoid) reported during 2014–2016

Sl. No.	State / U.T.	2014		2015		2016 (Prov.)	
		Cases	**Deaths**	**Cases**	**Deaths**	**Cases**	**Deaths**
1	Andhra Pradesh	186446	5	146385	0	170249	0
2	Arunachal Pradesh	4512	3	4476	10	4574	1
3	Assam	5328	29	11333	9	19328	0
4	Bihar	283679	4	265469	1	204366	2
5	Chhattisgarh	32617	1	47970	1	74632	8
6	Goa	573	0	1603	1	724	0
7	Gujarat	29505	0	35362	1	45970	0
8	Haryana	29990	1	31965	0	36442	0
9	Himachal Pradesh	48786	6	40639	6	38093	7
10	J & K	57537	1	52359	0	46904	0
11	Jharkhand	36663	7	28330	4	41731	0
12	Karnataka	92959	1	85837	1	97493	1
13	Kerala	2269	0	2862	0	2038	0
14	Madhya Pradesh	155190	25	125737	8	129998	21
15	Maharashtra	102299	0	130809	0	137617	0
16	Manipur	10636	10	5422	0	4942	2
17	Meghalaya	10395	8	13459	0	14128	0

18	Mizoram	2758	4	2804	0	3085	3
19	Nagaland	11604	0	7977	0	8267	0
20	Odisha	90363	39	90895	45	73330	18
21	Punjab	34651	1	34867	3	37896	3
22	Rajasthan	83540	4	79244	0	116470	0
23	Sikkim	716	0	453	2	474	0
24	Tamil Nadu	29937	0	40579	0	33853	0
25	Telangana	NA	NA	163747	0	133838	2
26	Tripura	10553	0	4596	1	5398	0
27	Uttarakhand	28939	14	34120	10	33904	4
28	Uttar Pradesh	225829	203	288140	221	495698	313
29	West Bengal	90086	42	112262	24	161264	22
30	A & N Islands	881	0	870	0	1127	1
31	Chandigarh	6021	0	12447	88	12237	48
32	D & N Haveli	2439	0	1406	0	4420	1
33	Daman & Diu	167	0	165	0	197	0
34	Delhi	27339	14	30698	16	30015	55
35	Lakshadweep	3	0	77	0	50	0
36	Puducherry	1477	3	2049	0	1943	0
Total		**1736687**	**425**	**1937413**	**452**	**2222695**	**512**

Source: National Health Profile brought out by CBHI, Dte. GHS

Note:

1. 2014: Andhra Pradesh Excludes data of 10 districts of Telangana from July2014.
2. 2016: Data is different for different reference period.
3. NA stands for Not Available.

Table 4: State-wise Cases and Deaths due to Viral Hepatitis (All Causes) reported during 2014 – 2016

Sl. No.	State / U.T.	2014		2015		2016 (Prov.)	
		Cases	Deaths	Cases	Deaths	Cases	Deaths
1	Andhra Pradesh	3716	1	3358	12	2662	1
2	Arunachal Pradesh	378	6	292	1	271	4
3	Assam	2033	13	809	9	2688	14
4	Bihar	20670	3	26729	2	28578	0
5	Chhattisgarh	548	4	532	6	547	15

6	Goa	182	0	162	0	121	0
7	Gujarat	4808	7	3736	0	3573	2
8	Haryana	1934	13	5184	3	2274	0
9	Himachal Pradesh	2808	9	1739	1	2716	18
10	J & K	5110	0	4028	0	3581	0
11	Jharkhand	1052	1	1258	1	1406	0
12	Karnataka	6402	8	6026	21	6013	17
13	Kerala	5567	4	3965	7	5327	18
14	Madhya Pradesh	16145	18	14030	25	12158	22
15	Maharashtra	6753	13	9738	10	12156	6
16	Manipur	443	0	88	0	182	1
17	Meghalaya	643	0	299	0	236	2
18	Mizoram	194	0	209	4	276	1
19	Nagaland	113	0	76	0	86	0
20	Odisha	5069	39	5146	24	3481	19
21	Punjab	4525	4	9330	8	8833	7
22	Rajasthan	9719	3	3247	0	2471	1
23	Sikkim	556	0	1344	0	800	0
24	Tamil Nadu	880	0	1066	1	715	0
25	Telangana	NA	NA	1735	1	2175	0
26	Tripura	177	1	183	1	363	4
27	Uttarakhand	9243	9	10242	15	10930	16
28	Uttar Pradesh	16037	50	11188	73	12530	47
29	West Bengal	4444	63	3948	83	2898	115
30	A & N Islands	262	9	123	1	177	0
31	Chandigarh	766	21	1249	27	1179	7
32	D & N Haveli	32	0	48	6	7	2
33	Daman & Diu	65	0	77	2	31	0
34	Delhi	6965	98	9145	87	10281	100
35	Lakshadweep	16	0	12	0	10	0
36	Puducherry	299	3	520	4	416	7
Total		**138554**	**400**	**140861**	**435**	**142148**	**446**

Source: National Health Profile brought out by CBHI, Dte. GHS

Note:

2014: Andhra Pradesh Excludes data of 10 districts of Telangana from July2014.

2016: Data is different for different reference period.

NA stands for Not Available.

Where, CBHI stands for Central Bureau of Health Intelligence

Dte. GHS stands for Directorate General of Health Services

How Do Water Affect the Environment?

Water is universal solvent with simply means that it can dissolve almost any substance. The cause of water pollution in the dumping of industrial wastes directly in to the water bodies and catchment areas without proper treatment. Ruthless uses of fertilizers and pesticides in agriculture are a region to pollute water bodies. The chemicals in water disrupt the nature of soil by altering the pH and reducing the fertility thus adversity affecting agricultural activities. When farmers fertilize the fields, the chemical they use are gradually washed by rain into the ground water. Water pollution can lead to water - borne diseases like Cholera, Typhoid fever, Dysentery etc. The use of fertilizer and manure (mainly nitrogenous fertilizer) can be problem the concentration of nitrate rich water, cause of "Blue baby Syndrome". Nitrate which is a problem in parts of rural Eastern Europe (Yassi *et al.* 2001). The NO_3^-N threshold for human consumption is 50 mg/L (WHO, 2017) given that exceedances of NO_3^-N concentrations in drinking water can pose health risks to humans, including the potential for cancer, methemoglobinemia and diabetes mellitus etc. Mining was the source of most of the wide spread Cadmium poisoning "Itai -Itai "disease in Japan in 1940-50 (Kawano et.al. 1986). Minamata disease is cause due to consumption of mercury (Hg) poisoned fish. Arsenicosis disease is caused by due to arsenic in water poisoning. Addition of phosphorous and nitrates to water leads to depletion of oxygen due excessive algal growth. It leads to death of fish and other aquatic life (Eutrophication).

Figure 2: Sources and Causes of Water Pollution
(Source: https://www.britannica.com/science/water-pollution)

Plant Nutrient Stress

Chemical fertilizers are expensive and their use is not being done properly and chemical fertilizers spoil the soil quality. Almost all farms grew at least two crops per year, the main chemical fertilizer used were Urea, SSP, DAP, MAP, ASN, SOP, and MOP.FYM, Compost, Biofertilizers, Green manure, poultry manure, etc. not applied to soils. Excessive inorganic fertilizer application not only damages farmers finances, but also results in losses of nutrients into the wider environment, degrading both air and water quality. Chemical fertilizers tend to cause damage to the resource base needed for sustainable food production; they pollute water and can harm soil fertility (Kumar et al.2022).

Pesticide's Pollution

When farmers spray pesticide on food items like wheat, paddy, maize, tomato, potato in their food, then these deadly elements enter in vegetables, fruits and soils. Then the effect of these chemicals remains in soil, water and air that we eat, drink water and breathe. Through all these, unknowingly they consume poison. Aldrin, Simazine, Atrazine,2,4-D etc. are applied in soils, leached water and absorption by plants and thus changes in microbiological activity in soil, pesticides approximate persistence in soils about days to several years, such like 2,4-D persistence in soils about one month and Atrazine persistence in soils about18 months.

The United Nations Environment Programme (UNEP) in 1995 identified 12 compounds known as the 'dirty dozen'. These include 8 organo-chlorine pesticides (aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, mirex and toxaphene) 2 industrial chemicals (hexachloro benzene (HCB) and the polychlorinated biphenyl (PCB) and 2 industrial by-products (dioxins and furans). Long term effects of pesticide residues in the human body include carcinogenicity, reduce life span and fertility, increased cholesterol, high infant mortality and varied metabolic and genetic disorders.

Heavy Metals Pollution

Heavy metals (Cd, Pb, Hg, As, Ni etc.) pollution in soil -water-air-organisms ecosystem can causes positive and negative effects on crop yields. The availability in soils and plants for long period and cause toxicity.

Figure 3: Contamination of water bodies
(Source: https://www.bing.com/search-lapatilla.com)

Table 5: Problems of common ions in irrigation water

Specification	No Problem	Increasing Problem	Severe Problem
Sodium (me/l)	< 10.0	10.0- 20.0	> 20
Chloride (mg/l)	< 4.0	4.0- 10.0	> 10
Boron (mg/l)	< 0.75	0.75- 2.0	> 2
NO_3^-N (mg/l)	< 5.0	5.0- 30.0	> 30
HCO_3- (mg/l)	< 1.5	1.5- 8.5	> 8.5

Source: Rathinasamy *et al.* (2014)

Table 6: Water quality standards for human and livestock consumption

Element (mg/l)	Human	Livestock
Lead	<0.10	<0.10
Arsenic	<0.05	<0.05
Selenium	<0.01	<0.01
Zinc	<15.0	<20.0
Cadmium	<0.01	<0.01
Mercury	<0.01	<0.002
Nitrate	<10.0	<40.0
Chlorides	<400	<1000

Source: Tisdale *et al.* (2007)

Table 7: Water quality Standards for Human and Livestock Consumption

	Concentration mg/l)	
Element	**Human**	**Livestock**
Pb	<0.1	0.05
Mo	-	0.01
As	<0.05	0.05
Se	<0.01	0.01
Zn	<15	<20
Cd	<0.01	0.01
Ba	<1.0	-
Ca	<200	<1000
Hg	<0.01	0.002
NO_3	<45	<200
NH_4	<0.05	-
N	<10	<50
Cl	400	<1000

Source: Lal and Edward, (1994)

Table 8: Grouping of poor-quality ground waters for irrigation

Water quality	EC (dS/m)	SAR (m mol/l)	RSC (me/l)
A. Good	<2	<10	<2.5
B. Saline			
(i)Marginally saline	2-4	<10	<2.5
(ii) Saline	>4	<10	<2.5
(iii)High SAR saline	>4	>10	<2.5
C. Alkali waters			
(i)Marginally alkali	<4	<10	2.5-4.0
(ii) Alkali	<4	<10	>4
(iii)High SAR alkali	Variable	>10	>4

Source: Gupta *et al.* (2000)

Implementation

The Govt. of India has implemented National Water Quality Maintenance programme (NWQMP), "Namami Gange" and Yamuna action Plan, Clean India Mission, Swachh Bharat Abhiyan, National River Ganga Basin Authority, Appropriate utilization of chemical on farm, cleaning of drain, appropriate transfer of waste, media contribution, educating people, fine and Laws and some other schemes are implemented on a large scale.

Salient Features of Some Important Laws

1.The Water Prevention and Control of Pollution Act, 1974 (Amended in 1988)

2. The Water Prevention and Control of Pollution Cess Act,1977 (Amended in 1991)

3.The Environment Protection Act,1986

Conclusion:

Preventive measures such as reduction in plastic consumption (solid waste) using fewer pesticides protect our natural water resources from contamination and embrace eco-friendly life concern. Recycling and reuse of biodegradable waste like paper, glass and woody materials and ban on non-degradable waste like plastic is an alternate to disposal of waste paper, plastic and glass can be recycled to conserve the natural resources. Chemical fertilizers and pesticides should be used as a last option, adoption of integrated nutrient management and integrated pest management practices.

Future Scope of the Study

Like oat and barley can grow in the soil having high metal concentrations and it is very useful in the soil where reclamation is practically impossible. Afforestation should be done on land to improve soil quality (Physical, Chemical and Biological) and reduce soil erosion.

Acknowledgement:

The corresponding author is grateful acknowledging to the department of Soil Science, Tirhut College of Agriculture, Dholi, Muzaffarpur (Bihar), India for providing suggestions, encouragement for preparation of manuscript.

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ARTIFICIAL INTELLIGENCE IN HYDROLOGY: ADVANCEMENTS IN SOIL, WATER RESOURCE MANAGEMENT AND SUSTAINABLE DEVELOPMENT

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Abstract:

Hydrology presents a range of complex challenges driven by climate variability, limited natural resources, and increasing demands for sustainable water and soil management. Traditional methods often fall short in addressing the intricate and dynamic nature of water systems. Consequently, researchers have increasingly turned to advanced data-driven approaches, particularly artificial intelligence (AI), to enhance hydrological understanding and prediction. This review explores the transformative role of AI across key areas of hydrological research, including soil and land surface modeling, streamflow prediction, groundwater forecasting, water quality analysis, and remote sensing applications. In soil and land modeling, AI enhances precision in analyzing soil texture, estimating moisture content, and predicting erosion—contributing to more effective land-use strategies. AI-driven models are also valuable tools for forecasting streamflow and groundwater levels, offering critical lead time for flood management and water resource planning, particularly in transboundary regions. In the domain of water quality, AI supports risk assessment, anomaly detection, and pollutant tracking, aiding both water treatment efforts and regulatory compliance. Furthermore, the integration of AI with remote sensing technologies provides new capabilities for spatial monitoring of water resources, from flood prediction to changes in groundwater storage. This paper synthesizes recent advancements and future directions in the application of AI to hydrology, underscoring its vast potential to promote sustainable management of water and soil systems.

Keywords: Artificial Intelligence; Soil and Water; Sustainability; Hydrology.

Introduction:

Hydrology faces increasingly complex challenges due to climate variability, limited natural resources, and growing demands for sustainable soil and water management. In response, practitioners are turning to advanced technological solutions to improve the modeling, prediction, and management of these critical resources [1,2]. Artificial Intelligence (AI) has significantly transformed hydrological research—not only through the novelty of its algorithms but also through its capacity to address critical issues in soil and water resource management. For example, AI-based models have notably improved soil moisture estimation, which is vital for drought monitoring and irrigation planning. Unlike traditional approaches that rely on sparse in situ data, AI integrates satellite observations with environmental variables, greatly enhancing predictive accuracy, especially in data-scarce regions [3].

AI is also revolutionizing soil erosion risk assessment. Predictive mapping models now allow land managers to identify degradation-prone areas in advance. These tools integrate rainfall intensity, land cover, and soil characteristics to generate high-resolution erosion susceptibility maps, which are essential for developing effective conservation strategies. In flood-prone areas, AI contributes to real-time flood forecasting by combining hydrological and meteorological datasets, enabling timely early warnings that can mitigate disaster impacts [2]. The real value of AI lies in its practical applications, serving as a toolkit to address real-world environmental and water resource management issues.

In recent years, AI and machine learning (ML) have gained momentum in hydrological studies, providing new capabilities to process large datasets and identify patterns that boost forecasting accuracy. Nonetheless, these tools have yet to achieve widespread adoption within the field [3]. Their increasing use supports hydrologists in better understanding complex ecosystem interactions, real-time monitoring, and delivering evidence-based decision support [4].

This review highlights the application of AI methods in key hydrological domains, including soil and land surface modeling, streamflow and groundwater forecasting, water quality assessment, and remote sensing. Notably, remote sensing—while not a modeling method in itself—supplies essential spatial and temporal data that enhance hydrological analyses. It supports modeling efforts across soil conditions, water flow, groundwater levels, and water quality assessments [4].

Although AI models do not fully replace traditional methods, which are grounded in well-established physical, chemical, or biological frameworks, they excel at capturing complex, nonlinear, and high-dimensional relationships that traditional models struggle with. AI systems can process vast amounts of data to detect subtle trends and interdependencies that would be difficult to identify manually or through conventional models.

For instance, ML algorithms have been used to estimate soil water content (SWC), predict erosion, and track changes in soil texture across large regions [5]. These models outperform conventional techniques in accuracy and scalability. Similarly, AI applications in streamflow and groundwater modeling help manage flood risks and monitor water resources in transboundary basins, combining complex hydrological and meteorological data for improved forecasting [6].

Water quality modeling is another critical area where AI has made substantial progress. Accurate monitoring and prediction are essential for safeguarding water resources and public health [7]. AI-driven models enable real-time monitoring of pollutants, support process control in treatment plants, and identify contamination risks—even in areas with limited data availability [7,8]. These methods aid in early threat detection and ensure compliance with environmental standards [8].

In combination with remote sensing, satellite data further extend the scope of AI-driven hydrological modeling. These tools enable wide-scale assessments of soil moisture, groundwater storage, and flood risks. Especially in data-deficient regions, remote sensing offers critical insights into environmental drivers of water systems that cannot be captured from ground-level data. Recent advances in high-resolution satellite modeling have yielded accurate predictions of streamflow, rainfall runoff, soil texture, and groundwater changes [9]. Such research enhances both short-term forecasting and long-term water planning [10].

This review consolidates recent advancements in AI applications across hydrological sciences. It aims to highlight key developments, practical challenges, and emerging opportunities, ultimately laying the groundwork for resilient and sustainable management of soil and water resources. The term "recent" refers to research primarily published between 2018 and 2024, with earlier foundational studies included when necessary. A comprehensive review of major academic databases (e.g., Scopus, Web of Science, Google Scholar) reveals a marked acceleration in AI adoption in hydrology since 2018 (see Figure 1).

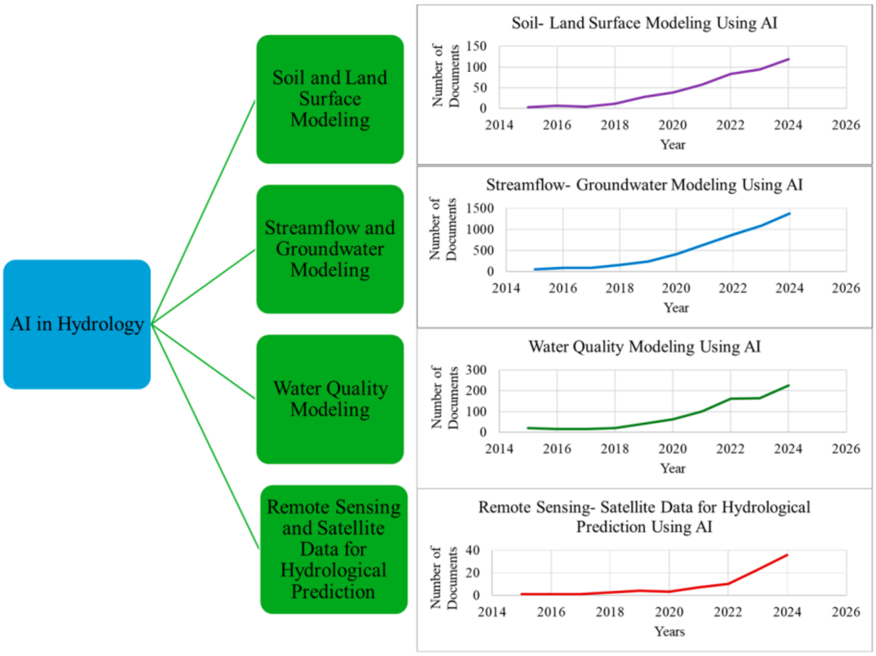

Figure 1: Key areas and trends in research growth

This review focuses on four key components of hydrology—soil and land surface modeling, streamflow and groundwater prediction, water quality assessment, and remote sensing applications—as critical domains where artificial intelligence (AI) is driving innovation. These interconnected areas collectively address the challenges of modeling, predicting, and managing soil and water resources with sustainability as a central objective. The review emphasizes how

AI technologies are being tailored to address specific issues within each domain, ultimately contributing to broader sustainable development goals.

To comprehensively examine AI's role in hydrology, a structured methodology was employed to ensure the inclusion of relevant, high-quality studies. The literature search was conducted across major academic databases such as Scopus, Web of Science, Google Scholar, and IEEE Xplore, which are known for their comprehensive coverage of environmental science and AI-related research. A refined combination of keywords and Boolean operators was used to locate relevant literature. These keywords spanned areas such as artificial intelligence ("AI," "machine learning," "deep learning"), hydrological modeling ("hydrology," "streamflow prediction," "groundwater modeling," "soil moisture forecasting"), and sustainable environmental management.

The review focused primarily on peer-reviewed journal articles and conference papers published between 2018 and 2024, with select inclusion of earlier foundational research. Studies were selected based on specific inclusion criteria: they had to address AI applications in hydrology (e.g., in modeling soil moisture, forecasting streamflow, simulating groundwater, or assessing water quality), originate from reputable sources, and offer quantitative model evaluations. Exclusions were applied to studies not directly related to AI in hydrology, reviews lacking methodological depth, or those without sufficient technical detail.

The selection process involved two stages. First, titles and abstracts were screened to eliminate unrelated research. Then, full texts were reviewed to evaluate methodological rigor and relevance. Key data extracted included the AI techniques used (e.g., neural networks, decision trees, hybrid models), specific hydrological applications (e.g., streamflow forecasting, groundwater simulation), evaluation metrics (e.g., RMSE, R^2, accuracy), study regions, and principal findings.

Selected studies were organized thematically under the four major application areas mentioned. A thematic analysis was then performed to extract trends, key advancements, and research gaps. Additionally, citation mapping and bibliometric analyses were conducted to understand the evolution of AI applications in hydrology.

This methodological approach ensures the review is both systematic and reproducible. It synthesizes the latest developments in AI-driven hydrological modeling and highlights future research opportunities to improve soil and water sustainability.

Core Applications of AI in Hydrological Science: A Review of Recent Advances

Artificial intelligence (AI) has emerged as a transformative tool in hydrological science, offering powerful capabilities for analyzing complex datasets and enhancing prediction accuracy. It expands the modeling scope in areas that are critical to the sustainable management of water and soil resources, especially under dynamic and unpredictable environmental conditions. By leveraging machine learning (ML), neural networks, and data-driven models, AI overcomes the limitations of traditional hydrological techniques across domains such as soil property modeling, streamflow and groundwater forecasting, water quality assessment, and remote sensing applications. The following section explores these core applications, emphasizing recent technological advancements and their practical implications.

In the area of soil and land surface modeling, AI and ML methods have significantly improved the ability to manage and predict key factors such as soil texture, soil moisture, temperature, and erosion. Tools like Random Forests, Support Vector Machines, and artificial neural networks (ANNs) now offer real-time insights that surpass traditional statistical methods by effectively capturing regional differences in soil characteristics. Geostatistical methods like kriging, when combined with AI, have enhanced the interpolation of missing soil data for more accurate measurements. ANNs integrated with Geographic Information Systems (GIS) have been effective in erosion mapping by utilizing inputs such as rainfall and soil moisture, while deep learning models—such as CNNs, RNNs, and LSTMs—have further improved prediction accuracy, especially in data-scarce environments. Hybrid models like the Weighted Subspace Random Forest (WSRF), Gaussian Process with Radial Basis Functions, and Naive Bayes have demonstrated high accuracy in mapping erosion-prone areas, with WSRF achieving over 91% accuracy. In eastern India, Bayesian-optimized deep learning models including DNN, CNN, FCNN, and hybrid DNN-CNN frameworks have been used to identify high erosion risks. Shapley Additive exPlanations (SHAP) analysis indicated that land use and soil type are key erosion determinants, and the DNN model achieved a high accuracy of 0.93.

Soil temperature, a vital factor influencing hydrological and agricultural processes, is impacted by evaporation, infiltration, and nutrient cycling. Given its role in energy exchange between the soil and atmosphere, accurate modeling is critical. However, direct measurement remains difficult due to complex interactions in the soil–plant–atmosphere system. Therefore, indirect methods using inputs such as air temperature and weather data are increasingly used. Machine learning models like multilayer perceptron neural networks (MLPNNs) have outperformed multiple linear regression models in estimating soil temperature, with R^2 values reaching as high as 0.98 when using solar radiation and air temperature as key predictors.

Soil moisture, despite its small proportion in the Earth's water system, plays an outsized role in hydrological cycles and biological processes. Accurate monitoring of its spatial and temporal variations is essential for predicting floods, droughts, and guiding climate-adaptive agriculture. Traditional approaches such as the oven-dry method, though precise, are destructive and localized. Machine learning techniques like LSTM and CNN, supported by sensor data and remote sensing inputs from Sentinel-1, Sentinel-2, and Radarsat-2 satellites, have become central to estimating soil moisture on broader scales. These models use ancillary data like topography and vegetation indices for improved prediction accuracy. For instance, LSTM-based models trained with in situ data can later function independently, enabling scalable soil moisture estimation.

A significant rise in machine learning adoption is evident in the literature, with over 500 publications on soil moisture modeling between 1995 and 2022. The United States leads with the highest number of studies, followed by China, Germany, India, and Canada. These studies largely rely on in situ and satellite data to train and validate AI models. Advanced AI systems like DeepQC, an LSTM-based quality control framework, have enabled real-time monitoring of soil moisture anomalies, improving agricultural decision-making. Image segmentation-based deep learning models also show high accuracy in classifying biological soil crusts (biocrusts), important for biodiversity and soil health conservation. Additionally, DNNs have outperformed shallow networks in modeling soil water retention curves (SWRC), with variables like soil texture and porosity proving most influential. Gradient boosting models like XGBoost (XGB) and LightGBM (LGB) have shown superior performance in sub-hourly soil moisture predictions, providing benefits in irrigation scheduling and precision agriculture.

Cluster-Based Local Modeling (CBLM) has been applied in conjunction with Sentinel-2 imagery to capture spatial variability in soil moisture, especially in drought- or flood-prone regions. Deep learning approaches like CNN and LSTM have proven effective within this framework. Erosion modeling efforts also illustrate AI's impact. In Algeria's Beni Haroun Dam watershed, combining RUSLE parameters with Random Forest and Random Tree models identified erosion-prone zones for land management. Similarly, in Guwahati, India, RF and DNN models integrated with RUSLE identified key erosion drivers such as rainfall and drainage patterns. In China's Hubei Province, LSTM and RUSLE models indicated a projected decline in severe erosion by 2025 due to improved conservation measures.

O ther innovations include the Multiscale Extrapolative Learning Algorithm (MELA), which extends soil moisture records using remote sensing data to simulate future climate and agricultural scenarios. In China's Loess Hilly-Gully region, a multi-model AI framework has tracked land use and ecosystem services over four decades, revealing the roles of climate and mismanagement in land degradation. Differentiable modeling (DM), which combines physical soil models with neural networks, has shown strong predictive accuracy across diverse geographic regions. For nutrient management, hybrid LSTM models paired with DSSAT crop models provide daily estimates of soil mineral nitrogen in sandy soils, reducing environmental nitrogen losses. A comparative study on deep learning techniques found that LSTM models delivered the most accurate crop yield estimations (up to 97%) when using soil and climatic variables, demonstrating the practical utility of AI in precision farming.

This extensive application of AI in soil and land surface modeling clearly illustrates its growing significance in modern hydrology, offering new levels of precision, scalability, and predictive power for sustainable environmental management.

Table 1: The number of studies on AI applications in soil properties

Year	Author(s)	Publisher(s)	No. of Publications	Ref.
1993	Jackson *et al.*; Jang *et al.*	Wiley, IEEE	2	[26]
1996	Dudhia *et al.*	National Center for Atmospheric Research	1	[43]
2011	Verma *et al.*	Elsevier	1	[20]
2018	Sheffield *et al.*; Gholami *et al.*; Zaidi *et al.*	Wiley, Elsevier, Taylor & Francis	3	[10,15,44]
2019	Heddam; Baldwin *et al.*; Aboutalebi *et al.*; Rozos	Springer, MDPI, Elsevier, MDPI	4	[23,30,45,46]
2020	Mosavi *et al.*; Barzegar *et al.*; Sit *et al.*	MDPI, Springer, IWA	3	[17,47,48]
2021	Orth; Doorn	Nature, Elsevier	2	[29,49]
2022	Imanian *et al.*	Elsevier	1	[24]
2023	Awais *et al.*; Khosravi *et al.*; Taheri *et al.*; Singh *et al.*; Shen *et al.*	Springer, Elsevier, IEEE, Nature	5	[13,14,16,19,31]
2024	Alkahtani *et al.*; Biazar *et al.*; Li *et al.*; Herdy *et al.*; Teshome *et al.*; Moosavi *et al.*; Zeghmar *et al.*; Ahmed *et al.*; Ping *et al.*; Liu *et al.*; Gupta *et al.*; Adeniyi *et al.*	Taylor & Francis, Nature, Elsevier, Springer	12	[11,21,32–39,41,42]

Accurate streamflow and groundwater level forecasts are crucial for effective flood forecasting, water resource management, and emergency preparedness, especially in large transboundary river basins. Recent studies have proposed advanced streamflow prediction models, such as time-lag-based methods tailored for large rivers. A notable example is the Dulong-Irrawaddy River Basin, where upstream data combined with historical flow patterns enabled 15-day lead-time flood forecasts despite limited data availability [50]. Another case in the Yangtze River utilized memory layers and data decomposition techniques, leading to improved long-term flood forecasting, especially in extreme flood years [51].

Artificial intelligence (AI) methods have significantly impacted hydrological practices. Groundwater forecasting, traditionally challenged by complex subsurface dynamics, has benefitted from neural network models that improve prediction accuracy and facilitate better water allocation in both agricultural and urban contexts [50,51].

Recent advances in hydrological modeling have shown the effectiveness of AI and data-driven approaches in forecasting both surface water and groundwater. For streamflow prediction, integrating real-time precipitation and water level data has greatly enhanced flood risk management. Combined rainfall and water level forecasts improve proactive flood preparedness [52]. Learning-based methods using historical data—including decision trees, nearest neighbor approaches, and neural networks—have demonstrated high predictive accuracy. For instance, in Malaysia's Dungun River Basin, these models achieved up to 90.85% accuracy in simulating flood events [31]. More advanced models like Neural Flood, using clustering algorithms and layered networks, produced flood susceptibility indices with 87% accuracy in low-risk zones [53].

Innovative deep learning models, such as attention-based Temporal Convolutional Networks (TCNs), effectively handle time-series data heterogeneity, as demonstrated in the semi-arid Wei River Basin [54]. In Romania's Buzau River, Long Short-Term Memory (LSTM) models outperformed Extreme Learning Machines (ELMs) for discharge forecasting under variable climate conditions [55]. Hybrid models like Adaptive Neuro-Fuzzy Inference Systems (ANFIS) combined with resampling methods such as Jackknife-ANN provided reliable prediction uncertainty estimates [56]. Deep Neural Networks (DNNs) effectively modeled long-term discharge patterns influenced by climatic variables [57], while the SARIMA-ANN model excelled in seasonal forecasting in India's Beas River. CNN-LSTM hybrids also demonstrated high accuracy for daily discharge estimates in the Brahmani-Baitarani basin of Odisha [58,59].

In groundwater modeling, neural networks and hybrid statistical-rule-based models have shown strong potential in managing nonlinearities and environmental variability. Memory-based models are especially adept at capturing temporal and spatial trends, enhancing sustainable groundwater planning [27]. AI-driven groundwater quality assessments have identified critical indicators, such as hardness, sodium absorption ratio, and salinity in Iraq's Alnekheeb Basin [60]. Hybrid models that analyze parameters like pH and total dissolved solids have proven effective for forecasting contamination risk and guiding mitigation strategies [61].

Comparative research has shown AI's superiority over traditional techniques. In Iran's Arak aquifer, Artificial Neural Networks (ANN) outperformed Multiple Linear Regression (MLR) in predicting groundwater depths, influenced by transmissivity, elevation, and distance from water bodies [62]. In Turkey's Kizilirmak River, machine learning models like Multilayer Neural Networks (MLNN) and ANFIS significantly improved daily discharge forecasts, with

MLNN reducing RMSE values substantially [35]. In Punjab, India, XGBoost achieved the highest accuracy in predicting groundwater recharge under different climate scenarios, with precipitation being a major influencing factor [63]. Hybrid models continue to evolve, such as those in Iran's Tabriz plain where ANN models optimized with the Wild Horse Optimizer (WHO) and Egret Swarm Optimization Algorithm (ESOA) enhanced groundwater prediction accuracy, particularly aiding irrigation planning [64]. CNNs have also outperformed conventional methods in forecasting spring potential in Iran's Norurabad-Koohdasht plain [65].
AI has also impacted flood susceptibility mapping through IoT and cloud-based systems. Decision trees and classification techniques now offer high accuracy in early warnings, although improvements are needed for varying terrain [56]. Advanced ANN variants have halved prediction error rates when estimating orifice discharge in open channels compared to traditional models [66].

Streamflow forecasting typically involves two model types: physically based and data-driven. Physically based models (e.g., SWAT, HEC-HMS, MIKE SHE, VIC) simulate rainfall-runoff relationships with site-specific parameters. Data-driven models rely purely on observed input-output relationships, bypassing complex physical processes [67].

The surge in data-driven and machine learning (ML) models for runoff prediction over recent years reflects their efficacy in identifying hydrological patterns without physical process assumptions [68–70]. These black-box models also compensate for unknown hydrological variables during modeling [71–73], and despite their opaque nature, have demonstrated high simulation accuracy [74]. Neural networks first proved their value in streamflow forecasting in the Huron River, outperforming power models in 1-day-ahead predictions [75]. Deep learning, especially with Multilayer Perceptrons (MLPs), has delivered breakthroughs in water quality, resource, and urban water management [76–79].

LSTM networks have shown superior results in 1-day-ahead discharge forecasting in the Leaf River watershed, outperforming traditional ANNs [80]. This has driven growing interest in deep learning applications in hydrology in the last five years. Overall, over the past two decades, machine learning models have transformed hydrology, notably by resolving challenges like missing data [81,82]. Commonly used ML models include ANFIS [84], ANN [85], and Support Vector Machines (SVM) [86].

Groundwater resources are indispensable for agriculture, industry, and drinking water supplies [87,88]. Groundwater Level (GWL) trends help policymakers devise sustainable strategies. However, simulating GWL is complex due to varied climatic, topographic, and hydrogeological influences [89,90].

Measuring and forecasting GWL is vital for sustainable water management. AI models provide a viable alternative to physical simulations by effectively handling GWL prediction without detailed geophysical knowledge [91,92]. Over two decades, research has shown the utility of AI in GWL modeling. Initial efforts used simple perceptron-based ANNs [94], evolving into complex ML models such as advanced ANNs [95], fuzzy systems [96], SVMs [97], tree-based algorithms [98], Genetic Programming (GP) [99], and Gene Expression Programming (GEP) [100].

Table 2: Number of Studies on AI Applications in Streamflow and Groundwater, formatted cleanly:

Year	Author(s)	Publisher(s)	No. of Studies	Reference(s)
2005	Daliakopoulos *et al.*; Lallahem *et al.*	Elsevier	2	[91, 95]
2007	Qadir *et al.*	Elsevier	1	[87]
2008	Milly *et al.*	Science	1	[101]
2010	Dash *et al.*	AGU	1	[102]
2011	Nourani *et al.*; Adamowski *et al.*	Elsevier	2	[68, 92]
2012	Bourdin *et al.*; Jothiprakash *et al.*; Valipour *et al.*; Moharram *et al.*	Taylor & Francis, Elsevier, Citeseer, Springer	4	[9, 81, 82, 103]
2013	Shirmohammadi *et al.*; Karunanithi *et al.*; Halwatura *et al.*	Springer, Elsevier	3	[70, 75, 104]
2015	Moghaddam *et al.*	MDPI	1	[98]
2016	Goodfellow; Kasiviswanathan *et al.*	Springer	2	[76, 99]
2017	Sadeghi-Tabas *et al.*; Sith and Nadaoka; Zhou *et al.*; Isazadeh *et al.*	European Water, MDPI	4	[90, 97, 105, 106]
2018	Boyraz *et al.*; Sheffield *et al.*; Zhang *et al.*	IEEE, Wiley, Taylor & Francis, Springer	4	[10, 80, 107]
2019	Wen *et al.*; Nadiri *et al.*; White *et al.*; Raji *et al.*; Abrams *et al.*; Senent-Aparicio *et al.*	Elsevier, MDPI, Taylor & Francis, Wiley, IEEE	6	[83, 96, 108–111]

2.3. Water Quality Modeling with AI

Artificial Intelligence (AI) has significantly advanced water quality management by enhancing the ability to assess contamination risks, identify pollution sources, and predict the spread of pollutants—especially in regions affected by industrial runoff [123]. Continuous changes in water quality, due to both natural processes and human activities, require robust tools for real-time monitoring and accurate prediction. AI meets this need by analyzing complex and nonlinear interactions among multiple water quality parameters, offering greater precision than traditional statistical methods [123].

AI models incorporating spatial-temporal data have shown superior performance in assessing nutrient loadings from sources such as livestock farming and atmospheric deposition [122]. Real-time prediction systems have been developed using sensors and anomaly detection models, which help differentiate between harmful and benign substances like detergents, improving classification accuracy [124]. Techniques such as MCN-LSTM, which combines convolutional networks and long short-term memory (LSTM), enhance the analysis of complex time series from multiple sensors, allowing for faster and more reliable decisions [125,126]. The integration of AI with Internet of Things (IoT) technologies enables real-time tracking and forecasting of water quality across various sectors, including agriculture, industry, and potable water systems [127].

In wastewater treatment, data-driven AI models have been employed to predict pollutant removal rates, monitor key indicators, and detect system failures, thereby increasing both efficiency and operational reliability [128]. Probabilistic methods such as the Multivariate Bayesian Uncertainty Processor (MBUP) have improved the robustness of neural network predictions, especially under conditions of data loss [129]. Ensemble learning methods—e.g., bagging and boosting—have shown success in predicting parameters like total dissolved solids (TDS) and electrical conductivity (EC), while managing data uncertainty in river systems [130]. However, these models often require large, high-quality datasets, which may not be readily available in some regions.

Hybrid and ensemble AI models have proven effective in capturing both short-term variability and long-term trends. For instance, convolutional neural networks (CNNs) combined with memory-based models have accurately forecasted dissolved oxygen (DO) and chlorophyll-a (Chl-a) [131]. Support Vector Regression (SVR) optimized with Genetic Algorithms (GA) has improved biochemical oxygen demand (BOD) prediction in wastewater [132]. Deep learning models generally outperform traditional time-series methods like ARIMA when optimal configurations of input variables and meteorological data are used [133]. Enhanced preprocessing further improves CNN, LSTM, and hybrid models for variables without seasonal patterns, such as total nitrogen [134]. Bi-LSTM models also show high accuracy even with incomplete datasets, although their computational demands can be significant for large-scale applications [135,136].

In resource-limited settings, geographical features (e.g., latitude, altitude) have been used as inputs for AI models to estimate pH, DO, and other parameters [137]. AI has also been applied to heavy metal pollution detection, aiding in treatment planning and improving ecological and operational outcomes [138,139].

Complex watershed and lake environments benefit from multi-stage deep learning models. For example, an LSTM model used in Lake Dianchi incorporated land and river inputs to predict nutrient loads and highlighted precipitation and Secchi depth as key variables [140]. Ensemble models like the Temporal Attention-based Network (TNX) and Spatio-Temporal Attention-based Network (STNX) improved both short- and long-term forecasting of DO and ammonia nitrogen by adapting to spatial and temporal data shifts [141].

Hybrid deep learning frameworks have been particularly effective in watersheds with unique hydraulic features. For example, a Bayes-LSTM-GRU model using high-frequency data improved prediction during sudden quality changes [142], while a wavelet-transformed stacked BiLSTM approach achieved accurate DO and CODMn predictions in China's Lijiang River [143].

In reservoir systems, explainable AI models have been used in data-scarce environments. At Wadi Dayqah Dam in Oman, models such as GRVS and Deep Cross identified pH, depth, and temperature as key predictors of DO [144]. Similarly, in Lake Loktak, India, machine learning models like Random Forest and Gradient Boosting identified turbidity and pH as important indicators of water quality, with Random Forest yielding the highest accuracy [145].

Integrating neural networks with fuzzy logic has further improved monitoring systems. For example, models in southwestern Iran predicted future pollution levels by combining fuzzy membership functions with neural networks [146]. Advanced 3D CNNs and Gaussian processes in wastewater treatment plants have enabled multi-horizon forecasts of parameters like total phosphorus, aiding in early warnings and better plant operations [147].

Remote sensing combined with AI has facilitated large-scale water quality monitoring. In Jiangsu, China, hyperspectral imaging with capsule networks achieved 98.73% accuracy in classifying water quality grades [148]. Likewise, a CNN-LSTM model applied to the Kaveri River accurately monitored turbidity, TDS, and pH, offering real-time alerts for rapid response [149].

Finally, satellite data from Landsat-8 and Sentinel-2 allow frequent monitoring of critical parameters like blue-green algae, Chl, and DO across regions, enhancing long-term trend analysis and anomaly detection [150]. AI models have also been used to predict harmful algal blooms (HABs), identifying phosphorus and nitrogen oxide concentrations as key contributing factors [117,139].

Table 3: The number of studies on AI applications in Water Quality in tabular format:

Year	Authors	Publisher(s)	Number	Ref.
2016	Wong and Kerkez	Elsevier	1	[151]
2019	Jalal and Ezzedine; Assumpcao *et al.*	IEEE	2	[152, 153]
2020	Bourelly *et al.*; Lu and Ma; Barzegar *et al.*; Bhagat *et al.*; Barzegar *et al.*; Peterson *et al.*	IEEE, Springer, Elsevier	4	[57, 124, 129, 131, 138, 150]
2021	Choi *et al.*; Sha *et al.*; Ighalo *et al.*	MDPI, UNU-INWEH, Taylor & Francis	3	[133, 134, 154]
2022	Aldrees *et al.*; Khullar and Singh; Banerjee *et al.*; Omerspahic *et al.*	Elsevier, Springer, MDPI, Frontiers	3	[127, 135, 137, 155]
2023	Nguyen *et al.*; El-Shafeiy *et al.*; Liu and Chen; Irwan *et al.*	Elsevier, IWA, MDPI, Springer	4	[122, 125, 130, 132]
2024	Essamlali *et al.*; Nagpal *et al.*; Maurya *et al.*; Yan *et al.*; You *et al.*; Zheng *et al.*; Wang *et al.*; Xu *et al.*; Majnooni *et al.*; Talukdar *et al.*; Mokarram *et al.*; Shaban *et al.*; Li *et al.*; Chellaiah *et al.*	Elsevier, IWA	14	[126, 128, 136, 139–149]

2.4. AI in Remote Sensing and Satellite Data for Hydrological Prediction

Artificial Intelligence (AI) has significantly advanced remote sensing applications by transforming satellite imagery into actionable data for monitoring hydrological dynamics such as groundwater depletion, land subsidence, and climate-induced changes [156,157]. While in situ measurements are often the gold standard for accuracy, they are geographically limited and may not capture broad spatial variability [8–10]. Moreover, the diverse and extensive datasets needed for hydrological modeling are frequently inaccessible or costly.

Recent advancements in satellite remote sensing have begun to address these limitations by offering large-scale, long-term, and freely available datasets, including digital elevation models, land use classifications, soil maps, rainfall estimates, evapotranspiration, soil moisture, and the leaf area index [158–160]. Many of these datasets span back more than five decades, making them invaluable for hydrological modelers. However, despite their advantages, Earth Observation (EO) data can be inconsistent across climate zones and often contain uncertainties [161,162]. Therefore, before integration into models, remote sensing data must be validated against ground truth and assessed for quality [163–165].

The integration of EO data with advanced AI models such as machine learning (ML) and deep learning (DL) provides a comprehensive framework for monitoring hydrological variables in areas lacking in situ data. These approaches have been applied in diverse studies, yielding improvements in prediction accuracy and spatial-temporal resolution.

For example, flood forecasting has benefited from the combination of satellite imagery and IoT data to address spatial heterogeneity and computational demands [166]. GeoAI combined with Landsat-8 imagery and hybrid CNN-RF models has produced high-resolution soil texture maps, aiding in agricultural land management [167]. In Malaysia, the Klang River Basin study integrated remote sensing with Random Forest and LSTM to improve streamflow predictions, highlighting the significance of air temperature as a predictive factor [168].

In the Yangtze River Basin, LSTM-based models incorporating satellite-based precipitation products (IMERG, TMPA) captured complex rainfall-runoff relationships, especially for flood events [169]. Similarly, deep learning with EO imagery enabled over 80% accuracy in landslide detection in Tibet, emphasizing vegetation cover and rainfall as primary drivers [170].

Further, a 3D CNN-Transformer model incorporating hydroclimate indices like sea surface temperature and pressure successfully forecast long-term streamflow in poorly gauged basins such as the Karkheh River [171]. Groundwater prediction in South Korea used multi-satellite inputs (GRACE, GRACE-FO) and CNN-LSTM networks to capture temporal-spatial groundwater dynamics [172].

For surface temperature monitoring, a U-Net++ model fused microwave remote sensing with dense station data to generate continuous LST datasets across China, offering insights into land-atmosphere interactions [173]. Flood modeling in smaller basins was improved by STA-LSTM models dynamically selecting inputs like precipitation and soil moisture [174,175].

Precipitation modeling in Northern Cyprus combined AI-driven temporal models with IDW spatial interpolation to forecast monthly patterns [176]. Around mining zones, optimization models using spatial features like hydraulic conductivity achieved accurate groundwater level predictions, supporting safety and cost control [177].

Remote sensing has also expanded into cryospheric and water quality monitoring. The UMelt model, built with U-Net architecture and Sentinel-1/ASCAT inputs, accurately mapped surface melting on Antarctic shelves at high spatiotemporal resolution [178]. Water quality assessments used unsupervised deep learning alongside NDWI on multispectral imagery, demonstrating enhanced long-term monitoring potential [179].

Soil erosion studies employed AI and EO data to enhance digital soil mapping and support agricultural planning. Sentinel-2 imagery integrated with RUSLE and AI increased accuracy in erosion modeling [180], while GIS-AHP methods identified erosion-susceptible zones in Ethiopia with moderate performance (AUC = 0.719), outperforming traditional models [181].

Additionally, deep neural networks predicted total soil carbon in European farmlands, emphasizing climate as a key driver [182], and deep learning with geostatistics estimated pollutant (PAH) levels in China's surface soils based on geophysical parameters [183].

Lastly, permafrost dynamics were monitored using CNNs trained on remote sensing data, achieving 95.67% accuracy in predicting freeze–thaw cycles—demonstrating a scalable approach for climate-sensitive regions [184].

These studies collectively illustrate how the fusion of AI with remote sensing enhances the resolution, accuracy, and scope of hydrological prediction and environmental monitoring.

Table 4: The Number of Studies on AI Applications in Remote Sensing

Year	Authors	Publisher(s)	Number of Studies	Ref.
1996	Kite and Pietroniro	Taylor & Francis	1	[25]
2014	Xu *et al.*	Taylor & Francis	1	[158]
2015	Karimi and Bastiaanssen	EGU	1	[160]
2017	Craglia *et al.*	GEOSS	1	[163]
2018	Rajib *et al.,* Khairul *et al.,* Sheffield *et al.*	Elsevier, MDPI, AGU	3	[10, 162, 164]
2019	Jiang and Wang; Huang *et al.,* Ding *et al.*	MDPI, Elsevier, IEEE	3	[159, 165, 174]
2020	Demb *et al.,* Nourani *et al.,* Virnodkar *et al.*	EGU, Springer, Springer	3	[161, 165, 176]
2021	Seo and Lee	IEEE	1	[172]
2022	Najafabadipour *et al.,* Li *et al.,* Ghobadi *et al.*	ACS, Elsevier, Elsevier	3	[171, 177, 179]
2023	Algarni; Hosseini *et al.,* Zhu *et al.,* Huang *et al.*	IEEE, MDPI, Elsevier, Springer	4	[166, 167, 169, 175]
2024	Wang *et al.,* Soo *et al.,* Han *et al.,* de Roda Husman *et al.,* Samarinas *et al.,* Jothimani *et al.,* Radocˇaj *et al.,* Chen *et al.*	Elsevier, Springer, MDPI	9	[168, 170, 173, 178, 180–182, 184]

Conclusion and Future Perspectives

This comprehensive review underscores the transformative potential of artificial intelligence (AI) in solving complex hydrological challenges. AI has emerged as a powerful tool in hydrological modeling, demonstrating significant advancements in streamflow forecasting, groundwater simulation, water quality analysis, and the integration of remote sensing data. While numerous individual studies have showcased AI's effectiveness in specific domains, a broader analysis reveals recurring trends, key insights, and promising directions for future research [185–192].

AI-based approaches consistently outperform many traditional hydrological modeling techniques. They offer improved predictive accuracy, real-time processing, and the ability to integrate diverse and large datasets. These capabilities have proven particularly beneficial in addressing critical issues such as soil erosion control, flood prediction, and sustainable water resource management.

Machine learning models like Long Short-Term Memory (LSTM) networks, Convolutional Neural Networks (CNN), and hybrid approaches such as SARIMA-ANN have excelled in capturing temporal and spatial patterns, essential for modeling hydrological processes influenced by climate variability [192–195]. These models have not only enhanced the accuracy of streamflow and groundwater forecasts but also supported more precise and adaptive water management strategies.

In real-time flood forecasting and early warning systems, advanced AI models such as attention-based Temporal Convolutional Networks (TCNs) and ensemble learning techniques have demonstrated robust performance, especially in data-limited environments. For groundwater studies, integrating neural networks with optimization algorithms has led to highly accurate predictions of groundwater levels, thus contributing to sustainable management of subsurface water resources [195–197].

Despite these promising developments, several challenges persist. Chief among them is the quality and availability of data. AI models rely heavily on comprehensive and high-quality datasets, which are often lacking in remote or under-resourced regions. This data scarcity hampers model performance and limits broader applicability.

Moreover, the “black box” nature of deep learning models presents interpretability challenges. Many stakeholders—including hydrologists and policymakers—require transparency and understanding of model decisions to trust and adopt AI systems. The lack of interpretability limits their practical utility, particularly in scenarios involving public safety and policy formulation [198].

AI models also show variability in performance across different climatic and geographic settings. While methods like XGBoost and LSTM may perform well in specific contexts, their generalizability remains limited. This highlights the necessity for context-specific model calibration and validation to ensure accurate and reliable results [199].

One promising direction is the integration of AI with physically based hydrological models. Hybrid frameworks that combine data-driven techniques with traditional process-based modeling can leverage the advantages of both approaches. These models not only improve prediction accuracy but also enhance interpretability and robustness [200,201].

To address the complexity and opacity of advanced AI systems, recent studies have explored explainable AI (XAI) tools. Methods like Shapley Additive exPlanations (SHAP) and Local Interpretable Model-Agnostic Explanations (LIME) are increasingly used to clarify the influence of input features on model outcomes. These tools also support the interpretation of geospatial data sources like Volunteered Geographic Information (VGI), bridging the gap between technical outputs and stakeholder comprehension [206–215].

Additional strategies include the use of visual aids such as graphs, interactive dashboards, and narrative summaries to make AI predictions more accessible and meaningful for non-specialists [202–205]. These approaches are essential for increasing trust in AI systems and enhancing their real-world applicability.

Looking forward, the future of AI in hydrology will depend on several key developments: improving data infrastructure and accessibility, creating more interpretable models, and fostering interdisciplinary collaboration among hydrologists, computer scientists, and decision-makers. These efforts will be critical to ensure responsible AI adoption and alignment with sustainable water and soil management goals.

In conclusion, while AI has already demonstrated significant promise in hydrological applications, realizing its full potential will require sustained research, ethical governance, and the development of user-centric, transparent tools. By addressing these challenges, AI can become a cornerstone of resilient and sustainable water management in the coming decades.

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HYDROGEN CYANIDE PRODUCING PLANT GROWTH PROMOTING RHIZOBACTERIA AS A PROMISING BIOCONTROL TOOL FOR SUSTAINABLE AGRICULTURE

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Introduction:

World population as on today in middle of July, 2025 is around 8 billion (Worldometer, 2025). The progressive increase in human population is projected at more than 9 billion by 2050 worldwide. The increasing population exerts demand on food supply. On 25th September, 2015, the 193 countries of the UN General Assembly adopted the 2030 development agenda for sustainable development, called as 'Sustainable development goals' (SDGs). Zero hunger which is SDG-2 has objective to end the hunger by achieving food security and improved nutrition by 2030.

Thus, the sustainable food production from agriculture sector has become the main need to improve food security globally. Intensive agricultural practices adopted by farmers to meet the increased demand for food grains include the prolonged use of inorganic fertilizers and chemical pesticides. The indiscriminate and prolonged usage of these harmful chemicals in agriculture has resulted in decreased crop yield and increased susceptibility towards biotic and abiotic stresses. The most common constrains in agriculture today that we face are plant diseases, insect infestations, weeds and abiotic stress conditions that have reduced crop yields significantly.

Diseases caused by various plant pathogens and insects account for 20-40% of annual yield losses in various cereal and legume crops worldwide (Sindhu *et al.,* 2017). Currently, plant diseases caused by various agents are mainly controlled by application of pesticides. Unfortunately, the indiscriminate use of such agro-chemicals have caused ecological and environmental problems, as well as human health hazards.

To overcome the potential pollution arising from the application of agro-chemicals, biological control is gaining importance as are considered as reliable and environmentally friendly. The application of living organisms/their metabolites to increase the fertility of soil or control of plant diseases are called as biofertilizer and biocontrol agents respectively (Lugtenberg and Kamilova, 2009). The use of potent agricultural beneficial microorganisms for sustainable agriculture is promising alternative strategy to increase crop yield without any long-term negative effects on the ecosystem.

Rhizospheric Region of Plants

The term Rhizosphere was coined by the German plant pathologist and agronomist Lorenz Hiltner in 1904. The rhizosphere is the zone surrounding plant roots influenced by the compounds released by roots that regulate the rhizospheric soil and the microbial community prevailing in the region. The rhizospheric region is categorized into three different zones- rhizosphere, rhizoplane and root itself based on physical, chemical and biological properties of the roots. Some groups of microbes are always associated with the rhizosphere of plants (Hakim *et al.,* 2021).

Microbial Community in Rhizospheric Region of Plants

Plants have co-evolved with specific communities of microorganisms in their rhizospheric area. These plant-microbes interactions are most dynamic in which plants monitor their environment and react to changes in the microbial community through signal exchange (Phour *et al.,* 2020). The diverse variety of microorganisms from rhizosphere perform different beneficial interactions with plants and play critical roles in sustainable agriculture by improving soil quality and health. Rhizospheric bacteria are a group of microorganisms that live in the rhizosphere, the soil zone immediately surrounding plant roots.

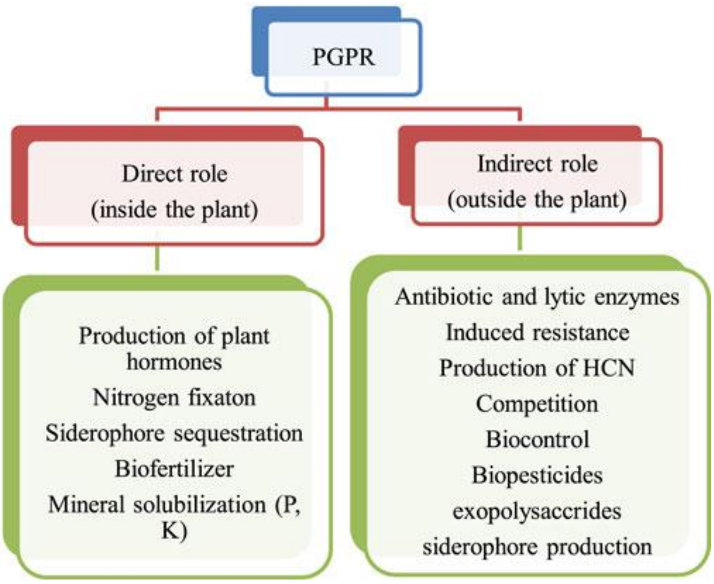

Figure 1: Different types of direct and indirect mechanisms of PGPR (Nath *et al.,* 2018)

These plant growth-promoting rhizobacteria (PGPR) enhance plant growth through both direct and indirect mechanisms (Fig.1). Direct mechanisms involve the production of substances that directly benefit the plant, such as phytohormones and nutrient solubilization (Moncada *et al.,* 2020). Indirect mechanisms focus on suppressing plant pathogens or enhancing plant defences indirectly benefiting plant growth. The major indirect mechanism of plant growth promotion in rhizobacteria is through acting as biocontrol agents (Glick, 2012). In general, competition for nutrients, niche exclusion, induced systemic resistance and antifungal metabolites production are the chief modes of biocontrol activity in PGPR (Lugtenberg and Kamilova, 2009). Many rhizobacteria have been reported to produce antifungal metabolites including HCN (Bhattacharyya and Jha, 2012). Interaction of some rhizobacteria with the plant roots can result in plant resistance against some pathogenic bacteria, fungi, and viruses which is called induced systemic resistance (ISR).

Indirect Mechanisms of Plant Growth Promotion by PGPR

PGPR can promote plant growth indirectly through several mechanisms, including biocontrol activity, competition for resources, and inducing systemic resistance in plants. These indirect mechanisms help plants overcome various biotic and abiotic stresses resulting healthier and more productive crops.

Hydrogen Cyanide Production by PGPR

Hydrogen cyanide **(**HCN) is a volatile, broad-spectrum antimicrobial compound involved in biocontrol of phytopathogens (Backer *et al.,* 2018). Many PGPR produce HCN by a process called cyanogenesis (Zdor, 2015). Cyanide functions as a biocontrol agent against certain plant diseases eliminates the soil-borne pathogens (Bakker and Schippers, 1987). The cyanide ion obstructs the action of metallo-enzymes, especially copper composed of cytochrome c oxidase. Moreover, it stops the electron transport to the target cells and disrupts the energy supply leading to the death of organisms (Hu *et al.,* 2018). Few studies reported that HCN produced by rhizobacteria forms complexes with transition metals in the mineral substrate (Fairbrother *et al.,* 2009). Others suggested that HCN in rhizosphere binds to iron and competes with phytopathogens for available iron therein and thus serve as role in biocontrol of phytopathogens. The HCN is known to negatively affect root metabolism and root growth (Schippers, 1988) and is a potential and environmentally compatible mechanism for biological control of weeds. The host plants are generally not negatively affected by inoculation with HCN producing bacterial strains and host-specific rhizobacteria can act as biological weed-control agents (Zeller et al, 2007).

Biosynthesis of HCN and its Regulatory Mechanism

HCN is a secondary metabolite synthesized from glycine and catalyzed by the enzyme HCN synthase which is encrypted by biosynthetic genes such as henA, henB, and henC gene cluster (Castelle and Banfield, 2018). The level of HCN produced in root-free soil by PGPR is generally increased with higher amounts of supplemental glycine (Owen and Zdor, 2001). Some bacterial strains contain a membrane-bound flavoenzyme, HCN synthase that oxidizes glycine to HCN and carbon dioxide, under low oxygen levels during the early stationary phase of growth (Zdor, 2015). The synthesis of HCN in *P. aeruginosa* occurs *via* the oxidative decarboxylation of glycine by HCN synthase enzyme (Blumer and Haas, 2000). This process also produces four electrons and four hydrogen ions per glycine molecule. Stressed environments and fertilization with nitrogenous and phosphate based fertilizers have been found to enhance HCN synthesis in sorghum plants.

Microrganisms Producing HCN

The members of certain soil bacteria, algae, fungi, plants and insects possess the unique ability to produce HCN as a mean to avoid predation and competition. In particular, cyanogenic bacteria have been found to inhibit the growth of various pathogenic fungi, weeds, insects, termites and nematodes. A number of bacterial species mainly *Pseudomonas* spp. and *Bacillus* spp. have the potential to produce HCN. *Pseudomonas fluorescens* and related species, including *P. protegens, P. chlororaphis* and *P. corrugata*, as well as species like *P. putida* and *P. cepacia* are widely recognized for their biocontrol potential and beneficial associations with diverse plant hosts. HCN producing PGPR from rhizosphere such as *P. fluorescens* strain CHAO, Bacillus, Stenotrophomonas, Brevibacterium, and Pseudomonas species inhibited the growth of pythium (Ambrosini *et al.,* 2018). Sandikar (2018) studied hydrogen cyanide production as a mechanism of antifungal activity of fluorescent Pseudomonas species against phytopathogenic *Pythium spp* and *Fusarium spp* and observed the direct correlation between the extent of HCN production and fungal growth inhibition. The purple non sulfur bacteria such as *Burkholderia cepacia*, *Rhodopseudomonas palustris* and *Rhodopseudomonas faecalis*, *Rhodobacter spp* and *Rhodopseudomonas spp*. were reported to be HCN producing and their role in biocontrol was also established (Pavitra, 2017; Batool and Rehman, 2017; Neerincx *et al.,* 2016).

Detection of HCN Production Ability in Microbial Isolates

Qualitative Detection of HCN Production

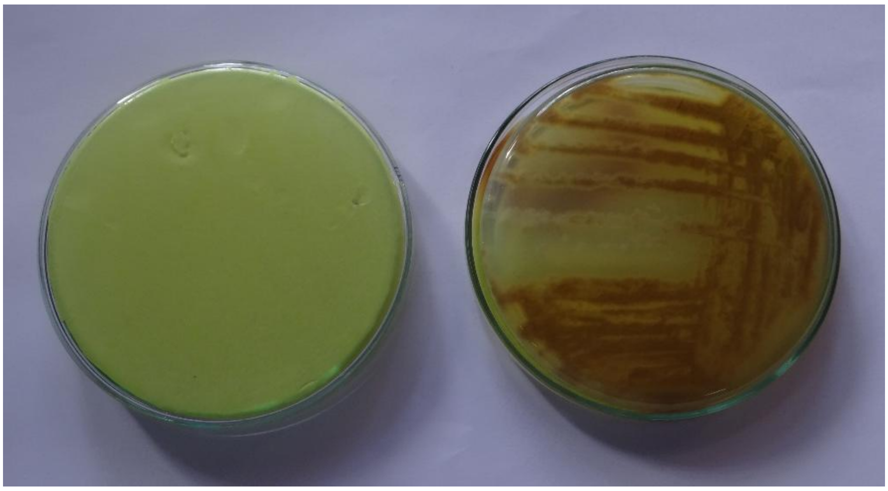

Figure 2: Qualitative detection of HCN production- Control (left) and Positive test (plate)

The qualitative cyanide determination was carried out by Lorck method (Lorck, 1948) modified by Alstrom (Alstrom and Burns, 1989). The fungal and bacterial isolates were sub cultured on King's B Agar medium were supplemented with glycine (4.4 gl-1). The production of HCN was detected 48 hour after inoculation, using picrate/Na_2CO_3 paper (2.5 g of picric acid; 12.5 g of Na2CO3, 1000 ml of distilled water)fixed to the underside of the Petri-dish lids which were sealed with parafilm before incubation at 28^o C. A change from yellow to orange, red, brown, or reddish brown was recorded at 4,24 and 48 hours as an indication of weak(+), moderate(++), or strongly(+++) cyanogenic potential, respectively. Reactions from inoculated plates were visually compared with corresponding control plates containing no culture.

Quantitative Detection of HCN Production

The fungi and bacteria were grown in King's B broth amended with glycine (4.4g/ l) and Uniform strips of filter paper (10 x 0.5 cm^2) were soaked in alkaline picrate solution and kept hanging inside the conical flask. After incubation at 28 ± 2°C for 48 hrs, the sodium picrate in the filter paper was reduced to a reddish compound in proportion to the amount of HCN evolved. The colour was eluted by placing the filter paper in a test tube containing 10 ml of distilled water and its absorbance was read at 625 nm (Sadasivam and Manickam, 1992).

Table 1: Detection of HCN

Isolate code Number	Qualitative HCN production[a]	Quantitative HCN production (Absorbance at 625 nm)
Isolate-1	+++[b]	0.090
Isolate-2	-	0.000
Isolate-3	++	0.054
Isolate-4	+	0.030

a=Intensity of HCN reaction with picrate/Na_2CO_3 indicator: none-; weak, +; moderate, ++; strong, +++. b=Reaction detectable at 4 hours after initiation of HCN assay.

Role of HCN Producing PGPR in Biocontrol

Microbial strains for biocontrol activity typically possess more than one mechanism to inhibit the growth of pathogens, weeds or pests. HCN is produced by many rhizobacteria and is postulated to play a role in biological control of several phyto-pathogens especially fungal plant pathogens and contributing towards antagonism (Rezzonico *et al.,* 2007; Siddiqui *et al.,* 2006). PGPR secretes a wide range of anti-fungal low molecular weight secondary metabolites including HCN to help plants resist stresses (Chowdhury *et al.,* 2021). They are also reported to be involved in biocontrol of weeds (Heydari *et al.,* 2015; Kremer and Souissi 2001). HCN producing bacteria also showed detrimental effect on many plant pathogenic nematodes (Insunza *et al.,* 2002; Gallagher and Manoil, 2001).

The role of HCN in disease suppression has been demonstrated by several scientists in various crops (Defago *et al.,* 1990). Meena *et al.* (2001) and Reetha *et al.* (2014) revealed the HCN production of several strains of P. fluorescens and their efficacy in controlling root rot of groundnut caused by *Macrophomina phaseolina.* Pseudomonas releasing HCN were reported in the rhizosphere of tobacco in soils suppressive to *T. bassicola*, causal agent of black root rot of tobacco (Ramette *et al.,* 2006). Wani *et al.* (2007) tested the rhizosphere isolates for HCN producing ability in vitro to find that most of the isolates produced HCN and helped in the plant growth. The rhizosphere competent *Mesorhizobium loti* MP6 produces HCN under normal growth conditions and enhances the growth of Indian mustard (*Brassica campestris*) (Chandra *et al.,* 2007).

The *Pseudomonas fragi* CS11RH1 (MTCC 8984), a psychrotolerant bacterium produces HCN and the seed bacterization with the isolate significantly increases the percent germination, rate of germination, plant biomass and nutrient uptake of wheat seedlings (Selvakumar *et al.,* 2008). The entomopathogenic bacterium *Pseudomonas entomophila* produces HCN which is implicated in biocontrol properties and pathogenicity exerted by other bacteria (Ryall *et al.,* 2009). *P. fluorescens* CHA0 produces antibiotics, siderophores and HCN, but suppression of black rot of tobacco caused by *Thielaviopsis basicola* appeared to be due primarily to HCN production (Voisard *et al.,* 1989). The majority of the HCN producing bacterial strains possess the ability to produce other PGPR traits IAA, siderophores, phosphate solubilization activity, etc.

Conclusion:

In recent years there is increased awareness and demand for the use of ecofriendly PGPR as a substitute to agro-chemicals. The application of PGPR in sustainable food production has the potential to boost crop production, enhance crop nutrition, yield, and control of diseases, and reduce environmental hazards associated with agro-chemical usage. The efficacy of PGPR in boosting plant growth and development is dependent on the specific strain of bacteria and the conditions under which it is used. The HCN producing microorganisms are highly host specific. It is now evident that HCN producing microorganisms are effective in inhibiting the growth and development of weeds and other fungal phyto-pathogens. Thus, the use of HCN producing bacteria as biocontrol and biopesticides offers an ecofriendly approach for sustainable agriculture. Further research on the additional possible benefits with reference to plant growth promotion, drawbacks and long-term impacts of cyanogenic microbial formulation on soil health and ecosystem functioning is essential to perform. Furthermore, the discovery of new isolates that are more efficient and stable under varied environmental conditions including different environmental stresses can aid in improving its effectiveness in stimulating plant growth and development.

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CLIMATE-SMART SOIL MANAGEMENT: STRATEGIES FOR CARBON SEQUESTRATION AND DROUGHT RESILIENCE

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Abstract:

Soil management practices play a pivotal role in climate change mitigation and adaptation. This chapter explores how climate-smart soil management can enhance carbon sequestration and build resilience to drought. We examine key practices such as cover cropping, conservation tillage, organic amendments, and integrated soil fertility management. The chapter also delves into the scientific mechanisms underlying carbon dynamics in soils, assesses socio-economic and policy dimensions and provides case studies illustrating the effectiveness of climate-smart soil management in different agro ecosystems.

Keywords: Soil Management, Strategies Drought Resilience climate change, Carbon Sequestration

1. Introduction:

1.1 Climate Change, Agriculture and the Role of Soils:

The global climate crisis presents on of the greatest challenges to agricultural productivity and sustainability in the 21st century. Increasing temperatures, shifting precipitation patterns, and the intensification of extreme weather events, particularly drought, pose direct threats to crop yield, soil fertility and food security. At the same time, agriculture itself is both a contributor to and a potential mitigator of climate change. The sector accounts for approximately 23 percent of global greenhouse gas (GHG) emissions, largely through land-use change, methane emissions from livestock and nitrous oxide emissions from fertilized soils. Soils are at the heart of this dual challenge. They act as both a source and a sink of carbon, storing more than twice as much carbon as the atmosphere and vegetation combined. However, unsustainable land use practices, including intensive tillage, deforestation and overgrazing have led to the depletion of soil organic carbon stocks, contributing to increased atmospheric CO_2 concentrations and exacerbating the effects of climate change. Degraded soils are also less capable of retaining water, making them more vulnerable to droughts, floods and erosion.

1.2 Climate Smart- Agriculture and the need for Soil - Centered Strategies.

In response to these interconnected challenges the concept of Climate- Smart Agriculture (CSA) has gained prominence. Coined by the Food and Agriculture organization (FAO), CSA aims to achieve three main objectives:

i. Sustainably increase agricultural productivity and incomes,
ii. Adapt and build resilience to climate change and
iii. Reduce or remove greenhouse gas emissions.

Climate-Smart Soil Management (CSSM) forms the foundation of CSA by targeting the fundamental ecological functions of soil systems. Through practices that enhance soil structure, boost organic matter content, improve water retention, and foster biodiversity, CSSM offers a science-based and ecosystem-driven approach to make agriculture more resilient and sustainable.

1.3 Aims and Scope

This chapter explores the principles and practices of CSSM with a focus on two critical outcomes:

i. **Carbon Sequestration:** Enhancing soil's capacity to absorb and retain carbon to mitigate climate change.
ii. **Drought Resilience:** Improving soil's water retention, structure and fertility to adapt to increasing water stress.

We examine how specific land management strategies, such as reduced tillage, cover cropping, organic amendments, agro forestry and nutrient cycling, contribute to these goals. Furthermore, the chapter addresses technological tools for monitoring soil carbon and moisture, identifies socioeconomic barriers to adoption and presents case studies illustrating successful CSSM in diverse agro ecological context.

By integrating biophysical knowledge with practical field strategies and policy perspectives, this chapter aims to provide a comprehensive foundation for academics, policymakers and practitioners seeking to implement or promote climate- smart soil interventions.

2. Soil Carbon Sequestration: Process and Potential

2.1 Soil carbon sequestration refers to the process of capturing atmospheric carbon dioxide (CO2) and storing it in the soil in the form of organic matter. This process is a natural outcome of the carbon cycle, wherein plants absorb CO_2 through photosynthesis and transfer a portion of that carbon to the soil via rood exudates, plant residues and microbial decomposition. When managed effectively, soils can act as long term carbon sinks, offsetting anthropogenic greenhouse has emissions and contributing to global climate mitigation efforts. There are two primary forms of carbon in sils:

i. Soil organic Carbon (SOC): Derived from plant and animal residues, root exudates, and microbial biomass.
ii. Soil Inorganic Carbon (SIC): Found mainly in arid and semi-arid regions in the form of carbonates.

2.2 Mechanisms of Soil Organic Carbon Stabilization

The stability and longevity of carbon stored in soil are determined by several interacting mechanisms. These include:

i. physicochemical protection.
ii. Microbial Processing
iii. Aggregate Formation
iv. Biochar and Recalcitrant Compounds

2.3 Potential of Soils as Carbon Sinks

Global estimates suggest that soils can sequester between 1.5 to 5.5 gigatons of CO2 per year, depending on land use, climate and management practices. The '4 per 1000' initiative launched at the COP21 Paris climate summit advocates increasing global soil organic carbon stocks by 0.4 percent per year to offset a significant portion of annual greenhouse gas emissions. However, the sequestration potential is not uniforms:

- Degraded land offers the greatest opportunity for carbon restoration.
- Peat lands and wetlands store significant carbon but are vulnerable to disturbance.
- Agricultural soils can be both sources and sinks depending on management.

2.4 Limitations and Risks.

While soil carbon sequestration is a promising mitigation strategy, it is subject to certain constraints:

- **Carbon Saturation:** Over time, soils reach a saturation point beyond which additional carbon inputs have diminishing returns.
- **Reversibility:** Sequestered carbon can be rapidly lost through erosion, tillage, or changes in land use.
- **Measurement Challenges:** Accurate quantification of SOC changes over time is technically complex and often expensive.

3. Strategies for Enhancing Soil Carbon Sequestration

Strategy	Carbons Input pathway	Key Benefits	Key Limitations
Conservation Tillage	Root biomass, residue retention	Reduces decomposition, improves structure	Weed management, slow SOC gains

Cover Cropping	Biomass, root exudates	Increases microbial activity, erosion control	Requires integration into crop cycles
Compost/Manure/Biochar	Direct organic input	Builds stable SOC, improves fertility	Resource access, risk of over-application
Agro forestry	Leaf litter, root turnover	Deep carbon storage, biodiversity gains	Long term investment
Crop Rotation	Rood diversity, residue variety	Pest control., soil biological heath	Requires market and knowledge access
Integrated livestock	Manure, grazing-induced roots	Nutrient cycling, pasture carbon inputs	Risk of overgrazing
Reforestation/Forestation	Aboveground & belowground biomass	Large-scale carbon capture	Land -use tradeoffs.

4. Soil Management for Drought Resilience

Climate change is increasing the frequency, intensity and duration of drought events globally. In agricultural systems, soil serves as the primary reservoir of plant available water, making it a critical component of drought-resilience. Resilient soils can absorb, store, and gradually release water to crop even during dry spells. Therefore, soil management practices that enhance water retention, infiltration, and plant root access are central to climate adaptation strategies.

4.1 Enhancing Soil Water Holding Capacity:

The soil water holding capacity (WHC) refers to the amount of water a soil can retain and supply to plants between saturation and the wilting point. It is influenced by several factors, notably soil texture, organic matter content, structure and porosity.

Key Practices:

- **Increasing organic matter:** Organic matter can hold up to 20 times its weight in water. Amendments like compost and manure increase water retention across soil textures.
- **Improving soil structure:** Aggregated soils have greater pore space for water retention and movement.
- **Reducing bulk density:** Practices like cover cropping and minimal tillage improve root penetration and water movement.

4.2 Mulching and Surface Cover.

Mulching involves covering the solid surface with organic or inorganic materials such as straw, crop residues, leaves or synthetic films.

Benefits:

- Reduces surface evaporation and soil temperature extremes.

- Enhances infiltration by preventing crusting and runoff.
- Suppresses weeds that complete for moisture.
- Contributes to organic carbon buildup when using organic mulches.

4.3 Promoting Deep and resilient Root Systems

Drought- resilient crops rely on extensive root systems that can access water stored in deeper soil layers. Soil management can support this in several ways:

Strategies:

- Selecting deep-rooted crops or cover species.
- Reducing compaction through controlled traffic and reduced tillage to allow better root penetration.
- Avoiding plow pans by minimizing repetitive shallow tillage.
- Agro forestry and perennials: Trees and perennial species contribute deep roots and help stabilize soil moisture across seasons.

4.4 Soil Cover and Conservation Agriculture

Conservation agriculture principles, minimum soil disturbance, permanent soil cover and crop rotation, contribute significantly to soil moisture regulation.

Effects:

- Maintain a cool, moist microclimate in the soil
- Prevents erosion and the formation of impermeable crusts
- Encourages biological activity, improving porosity and water dynamics.

4.5 Integrated Nutrient and Soil Fertility management

soil fertility and moisture are closely interlinked. Healthy, nutrient rich soils support robust plant growth, better root development and microbial communities that facilitate water uptake.

Practices:

- Combine organic and inorganic fertilizers to maintain a balanced nutrient supply.
- use precision application techniques to match plant needs, especially under water limited conditions.
- Apply slow-release fertilizers or biofertilizers to improve nutrient uptake efficiency during intermittent rainfall.

4.6 Erosion Control and Water harvesting

Drought prone areas are often susceptible to runoff and erosion, which further reduce soil water holding capacity. Techniques to reduce runoff and harvest water enhance both moisture availability and solid health.

Techniques:

- Contour farming and bunds: Slow down water movement on slopes.
- Terracing: Reduces runoff and encourages infiltration on steep land.
- Infiltration pits and swales: Capture rainwater and recharge subsoil moisture
- Rainwater harvesting: Collect and store water for supplemental irrigation.

4.7 Role of Soil Biota in Drought Resilience.

Soil organisms such as mycorrhizal fungi, earthworms, and microbial consortia enhance soil structure and plant resilience to drought.

Functions:

- Micorrhizae extend root absorption zones, improving water uptake.
- Microbes help retain nutrients and produce glomalin, which stabilizes soil aggregates.
- Soil fauna improves aeration and water infiltration through bioturbation.

Summary of Drought-Resilient Soil Management Strategies

Strategy	Key Benefit	implementation Tips
Increase soil organic matter	Boosts WHC and structure	Compost, cover crops, reduced tillage
Mulching	Reduces evaporation conserves moisture	use crop residues, maintain year-round cover
Deep-rooted and perennial crops	Access deeper moisture, stabilize soils	Combine with rotation and residue retention
Integrated nutrient management	Supports plant growth and root resilience	Balance inputs, avoid over-fertilization
Erosion control and water harvesting	Improves infiltration, prevents runoff	Use landscape-based water harvesting tools.
Soil biological enhancement	Improves soil porosity and water access	Avoid chemicals that harm beneficial microbes

5. Monitoring and Assessment Tools:

Effective soil management for carbon sequestration and drought resilience requires robust monitoring and assessment frameworks to track changes in soil properties over time.

Accurate data not only helps evaluate the effectiveness of interventions but also informs adaptive management, guides policy decisions and supports incentive based mechanisms such as carbon credits and payments for ecosystem services.

5.1 Soil Organic Carbon (SOC) Measurement

a) Direct Measurement Techniques

- **Dry Combustion (Elemental Analysis):** Considered the gold standard. Uses a CHN analyzer to combust soil samples at high temperatures to quantify carbon content.
- **Wet Oxidation (Walkley-Black Method):** uses potassium dichromate and sulfuric acid to oxidize organic matter.

b) Soil Sampling Protocols

- Consistency in sampling depth, timing and location is critical.
- Georeferencing enables repeated measurements and spatial mapping.
- Composite sampling improves representativeness and reduces variability.

c) Soil Spectroscopy

- Near-infrared and mid infrared spectroscopy allow rapid SOC estimation using soil reflectance properties.
- Portable spectrometers can be used in the field.
- Requires calibration against laboratory results.

5.2 Soil Moisture Monitoring

Monitoring soil moisture is effectual for evaluating drought resilience and irrigation efficacy.

a) In- situ Sensors

- **Time Domain Reflectometry (TDR):** Measures soil water content based on dielectric constant.
- **Capacitance Sensors:** less expensive than TDR, suitable for real-time monitoring.
- **Tensiometers:** Measure soil water tension, useful in wetter soil conditions.

b) Gravimetric Method

- Soil samples are weighed before and after oven drying to determine moisture content.
- Accurate but labor intensive, best suited for calibration and validation.

5.3 Remote Sensing and Digital Soil Mapping

Remote sensing technologies offer scalable and repeatable methods to assess sil and vegetation parameters over large areas.

Application;

- **Vegetation indices:** Indirectly reflect soil moisture and productivity.
- **Thermal imagery:** Detect land surface temperature and potential drought stress.
- **Microwave sensors:** Penetrate vegetation to detect surface soil moisture.

Digital Soil Mapping (DSM):

- Combines field observations, remote sensing data and machine learning algorithms to predict soil properties across landscapes.
- Platforms such as Soil Grids and iSDAsoil offer open access data for SOC, pH, texture and more.

5.4. Indicators of Soil Health and Functionality.

To complement SOC and moisture measurements, broader indicators of soil function are increasingly used.

Indicator	**Function Assessed**	**monitoring Methods**
Aggregate stability	Erosion resistance, infiltration	Wet sieving, visual soil assessment
Bulk density	Soil compaction, root penetration	Core sampling and oven drying
Soil respiration	microbial activity and carbon cycling	CO_2 efflux chambers, infrared gas analysis
pH and electrical conductivity	Nutrient availability and salinity	Field kits or lab based analysis
Earthworm population	Biological activity, aeration	Field counts using soil monoliths

5.5 Decision Support Tools and Models.

Several models and tools help simulate and project soil carbon dynamics and drought risk under different management scenarios.

Common Tools:

- **COMET-Farm (USA):** Evaluate SHG emissions and carbon sequestration from agricultural practices.
- RothC and Century Models: Simulate long term SOC changes under different land uses and climates.
- **DSSAT and APSIM:** Crop models that integrate soil, climate and management data for scenario analysis.

These tools are valuable for farmers, researchers and policymakers in selecting and validating sustainable practices tailored to specific environments.

6. Socioeconomic and Policy Considerations:

While the scientific and technical potential of climate-smart soil management (CSSM) is well established, its widespread adoption hinges on a complex interplay of socioeconomic drivers, institutional frameworks, and policy environments. Farmers, particularly smallholders in vulnerable regions, often face constraints that limit their ability to dropt or sustain soil enhancing practices, even when such practices are ecologically sound. Understanding and addressing these barriers is essential for the successful implementation and scaling of CSSM strategies.

6.1 Adoption Barriers

a) Financial Constraints

many sustainable soil practices require initial investments in tools, inputs or labor. While these may yield long term benefits, the upfront cost can be prohibitive- especially for resource-poor farmers without access to credit or insurance

b) Knowledge and Awareness Gaps

Farmers may lack awareness of climate smart practices or the knowledge to implement them effectively. The absence of extension services, demonstration sites and farmer to farmer learning networks limits the spread of innovations.

c) Land Tenure and Property Rights

Uncertain or insecure land tenure discourages long term soil investments. Farmers are unlikely to invest in practices such as agro forestry or composting if they do not own the land or risk losing access to it.

d) Labor and Time Constraints

practices like composting, mulching and cover cropping can be labor intensive. In regions with labor shortages or seasonal labor migration, this can act as a major constraint.

e) Risk Aversion and Yield Concerns

Farmers may be reluctant to adopt new practices that are perceived to reduce yield or introduce risk, especially in the face of climate variability and limited safety nets.

6.2 Incentives and Economic Instruments

To overcome these barriers, a range of economic incentives and policy tools can support the transitions towards climate-smart soil management

a) Payments for ecosystem Services (PES)

Farmers can be compensated for practices that improve soil health and sequester carbon, recognizing their contribution to gobal public goods such as climate mitigation and watershed protection.

b) Subsidies and Input Support

Targeted subsidies can promote the adoption of compost, cover crop seed or biochar, especially among smallholders. Smart subsidies can be deigned to taper off as practices become self sustaining.

d) Crop Insurance and Risk Mitigation Tools.

Linking sustainable soil practices with climate insurance schemes can reward resilience. For instance, farmers who implement erosion control or soil moisture retention strategies could receive reduced premiums.

6.3 Policy and Institutional Frameworks

Creating an enabling environment for CSSM requires coherent, Multi-level policies that align agricultural development, climate action and land governance

a) National soil health Strategies:

Governments should develop national frameworks that prioritize soil health monitoring restoration targets and sustainable land management in agricultural and environmental policies

b) Integration in Climate Commitments(NDCs):

CSSM should be incorporated into Nationally determined Contributions (NDCs) under the Paris Agreement, particularly under mitigation and adaptation goals for land use and agriculture.

c) Land Tenure Reform

Legal recognition of land rights, particularly for women and marginalized communities, is crucial to incentivese long term soil stewardship.

d) Capacity Building and Extension Services:

Investing in local knowledge systems, farmer trainign and participatory research helps tailor CSSM practices to diverse contexts.

6.4 Gender and Equity Considerations:

Soil management practices must account for social equity, especially in rural areas where women, indigenous peoples and marginalized groups play key roles in agriculture but often lack access to resources, training or decision making power.

6.5 Scaling and Sustainability

For CSSM to be mainstreamed at scale, interventions must be:

- locally adaptable to environmental and cultural conditions
- Economically viable for farmers and communities and
- Institutionally supported through long term investments in governance, research, and infrastructure.
- Partnerships among governments, NGOs the private sector, and international agencies are essential to coordinate funding, monitoring and knowledge exchange.

7. Future perspectives:

As climate challenges intensify and global commitments to sustainability accelerate, the role of climate smart soil management (CSSM) will become even more central to the future of agriculture, ecosystem restoration and climate mitigation. This section explores emerging innovations, future research directions and pathways for scaling up CSSM practices globally.

(ISBN: 978-81-991070-3-8)

7.1 Advancing Scientific Innovations:

a) Mcrobiome Engineering and Soil Biotech

- Recent advances in soil biology have revealed the critical role of microbial communities in carbon stabilization, nutrient cycling and water dynamics. Future CSSM may involve:
- Bioinoculants to enhance soil function
- Synthetic microbial consortia tailored to specific crops and climates.
- Soil health diagnostics using microbial fingerprints as indicators of resilience and carbon potential

b) Next Generation Soil Amendments

Beyond traditional compost and manure, emerging amendments like engineered biochar, biopolymers and hydrogels show promise for enhancing both carbon sequestration and drought tolerance

c) Carbon-Optimized Crop Breeding

Breeding crop varieties with deeper, denser root systems, improved root exudate profiles, and higher carbon use efficiency could significantly increase soil carbon inputs without compromising yields.

7.2 Digital Agriculture and precision Soil Management

- The rise of digital agriculture offers transformative potential for optimizing CSSM practices:
- Remote Sensing and soil sensors for real time monitoring of moisture and carbon levels.
- AI and machine learning models to recommend site specific practices.
- Mobile platforms and decision support tools to deliver customized guidance to farmers.
- Precision soil management enables resource efficiency, minimize risks, and strengthens accountability in carbon markets.

7.3 Policy Evolution and Global Cooperation

a) Mainstreaming Soil in Climate Policy

- Soils must be formally recognized in national and international climate policies. Future pathways include.
- Integration of SOC targets into Nationally Determined Contributions (NDCs).
- Inclusion of soil carbon in carbon accounting frameworks and sustainable land use standards.
- Development of international MRV (measurement, Reporting, Verification) protocols for soil based mitigation.

b) Incentive-Driven Approaches

Future programms may expand results-based financing, where farmers receive payments for documented improvements in SOC and soil moisture. Public private partnerships can help scale carbon farming practices through:

- Carbon offset markets.
- Green finance tools (e.g., climate-smart bonds)
- Ecosystem Service payments at landscape levels.

7.4 Scaling through education, Networks, and inclusivity

a) Participatory Research and Knowledge Exchange

Future CSSM efforts must build on co-creation of knowledge among scientists, extension agents and farmers. Farmer-led experimentation and innovation platforms will be key to context specific solutions.

b) Capacity Building and Curriculum Integration

Incorporating soil health, climate adaptation and agro ecology into agricultural education curricula will prepare the next generation of land stewards. Digital learning platforms and rural training centers can close knowledge gaps at scale

c) Equity and Inclusion in Soil Futures

Ensuring the participation of women, indigenous groups and youth in soil management initiatives will be critical for both ethical and practical reasons. Their leadership will contribute to more diverse, resilient and locally grounded approaches.

7.5 Global Soil Restoration Initiatives

- large-scale initiatives such as:
- The 4 per 1000 initiate,
- UN Decade on Ecosystem Restoration and
- AFR 100 (African Forest Landscape Restoration Initiative)

These are shaping the future agenda for soil carbon restoration. These efforts emphasize multistakeholder collaboration, landscape-level impact, and monitoring progress towards climate, biodiversity and food security goals.

Conclusion:

Climate smart soil management is a powerful tool in addressing climate change and securing food systems under increasing drought risk. Practices that enhance soil organic carbon and improve water resilience are mutually reinforcing. By integrating traditional knowledge, modern science and supportive policies, CSSM can play a transformative role in sustainable agriculture.

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FOOD INSECURITY IN INDIA: THE UNSEEN CRISIS OF PRE- AND POST-HARVEST LOSSES IN INDIAN AGRICULTURE

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Introduction:

India is a developing nation, with a population of 1.4 billion and exceeding as the world's 2nd most populous country. As the nation's population increases geometrically, food production increases arithmetically, which comes to an end called "food insecurity". India ranks 105th on the global hunger index. India's backbone is agriculture, and it supports the nation's GDP up to 15-20 per cent and employment opportunities up to 40-45 per cent, but coming to food production and feeding the hunger, it is not to that level. There are several causes and effects for food insecurity, but according to agriculture, there are two major reasons for food insecurity in the nation: pre-harvest losses and post-harvest losses. According to NABCONS, 330 million food materials are being produced, and out of it, 28-34 per cent is wasted due to a lack of post-harvest technologies like storage, transport, processing, marketing, price volatility, middle-person, supply chain gaps, export challenges and policy-institutional gaps. There is also a 10 per cent loss due to pre-harvest losses like seed quality, pest, disease, weeds, irrigation, soil degradation, climate and weather fluctuations. This paper explores the preharvest and postharvest losses in agriculture as a major cause of food insecurity in the nation and how to overcome food insecurity in the nation.

Beyond Hunger: A Deeper Dive into Food Insecurity

Food is a fundamental human right; however, for millions of individuals worldwide, the consistent availability of nutritious, safe, and ample food remains an enigmatic reality. Food insecurity, a widespread issue, encompasses much more than the basic concept of an empty stomach. The Food and Agriculture Organization (FAO) of the United Nations defines food insecurity as the absence of consistent access to sufficient safe and nutritious food for normal growth and development, as well as for an active and healthy existence. This could be the result of either a lack of resources to acquire food or the unavailability of food. In this definition, there are a variety of severity levels, ranging from mild uncertainty regarding future food access to severe situations in which individuals may spend days without eating.

Food insecurity is a multifaceted, intricate issue that is profoundly interconnected with poverty, economic instability, climate change, conflict, and inadequate infrastructure. In areas where calorie intake may appear sufficient, it can show up as both overt hunger and malnutrition, which includes under nutrition (stunting, wasting and underweight) and micronutrient deficiencies (hidden hunger). The implications are significant, affecting the socio-economic advancement of a nation, as well as individual health, cognitive development, educational attainment, and productivity.

The global struggle against food hunger encounters enduring obstacles. In spite of substantial improvements in agricultural production and the global food supply, a substantial portion of the global population remains vulnerable due to disparities in access, utilization, and stability. The vulnerability of the world's food systems has been further highlighted by the COVID-19 epidemic, geopolitical conflicts, and growing climatic crises, which have caused millions more people to experience food poverty.

Food insecurity arises when individuals do not have consistent access to adequate, safe, and nutritious food necessary for a healthy existence. India is the site of more than 190 million undernourished individuals, a staggering statistic considering that the nation generates more than 300 million metric tonnes of food cereals annually. According to the 2023 Global hunger Index, India is ranked 111th out of 125 countries, indicating a "serious" level of starvation. The crisis is further exacerbated by the loss of food due to pre- and post-harvest inefficiencies, despite the fact that poverty, inequality, and inefficient distribution systems are significant factors.

The Scale of the Problem

India experiences substantial food losses annually due to inefficiencies in the agricultural supply chain. A study by NABARD Consultancy Services (NABCONS) estimated that the country suffers a food loss of about ₹1.53 trillion (USD 18.5 billion) each year, primarily due to post- harvest losses. These losses occur at various stages, including harvesting, storage, transportation, and marketing. Pre-harvest losses are also significant, often resulting from factors such as pest infestations, diseases, and adverse weather conditions.

The International Food Security Assessment (2022-32) indicates that around 333.5 million individuals in India experienced food insecurity in 2022-23. Although anticipated to decline by 2032, the present figures remain exceedingly elevated. India was positioned 111th among 125 nations in the 2023 Global Hunger Index (GHI), signifying a "serious" degree of hunger. The GHI's emphasis on child mortality and nutrition has drawn criticism, although the general trend highlights ongoing issues. The National Family Health Survey-5 (2019-21) indicated that 35.5% of children under five are stunted, signifying chronic dietary deficits. The incidence of anemia among women aged 15 to 49 years is 57.0%. In rural India, the poorest 5% of the population consume an average of 1,564 kcal per day, which is substantially lower than the necessary 2,172 kcal. In the same vein, urban regions are also confronted with calorie deficits. Approximately 17.1% of rural populations and 14% of urban populations are classified as impoverished according to expenditure thresholds for sufficient nutrition. The persistence of food insecurity in India is exacerbated by factors such as an inefficient Public Distribution System (PDS) with leakages and exclusion errors, as well as gender disparities in food access.

The extensive magnitude of food insecurity worldwide and in India necessitates immediate, thorough, and cooperative intervention. The "unseen crisis" of post-harvest losses (PHL) exacerbates food insecurity by diminishing food supply, increasing prices, and jeopardizing the economic stability of millions of farmers. These losses are so enormous that they represent a real obstacle to attaining true food security and a huge waste of resources.

A national-level survey across 14 agro-climatic zones estimated losses worth INR 38.77 billion due to inappropriate harvesting and poor post-harvest management. The study emphasizes the need for standardized harvesting practices and improved storage infrastructure. The Research conducted in Middle Gujarat revealed that significant field-level losses in fruits like banana (6.59%), mango (2.5%), papaya (2.3%), and lime (1.01%). The study suggests mechanization in harvesting and improved post-harvest handling to minimize these losses.

A policy brief by the Indian Council for Research on International Economic Relations (ICRIER) highlighted significant post-harvest losses in soybean (15.34%) and wheat (7.87%), amounting to an annual loss of $18.5 billion. The study recommends mechanization and improved storage to reduce these losses. An experimental study on 15 onion genotypes identified varieties like LC-1 and LC-2 with minimal physiological weight loss and rotting over a 90-day storage period, suggesting their suitability for extended storage.

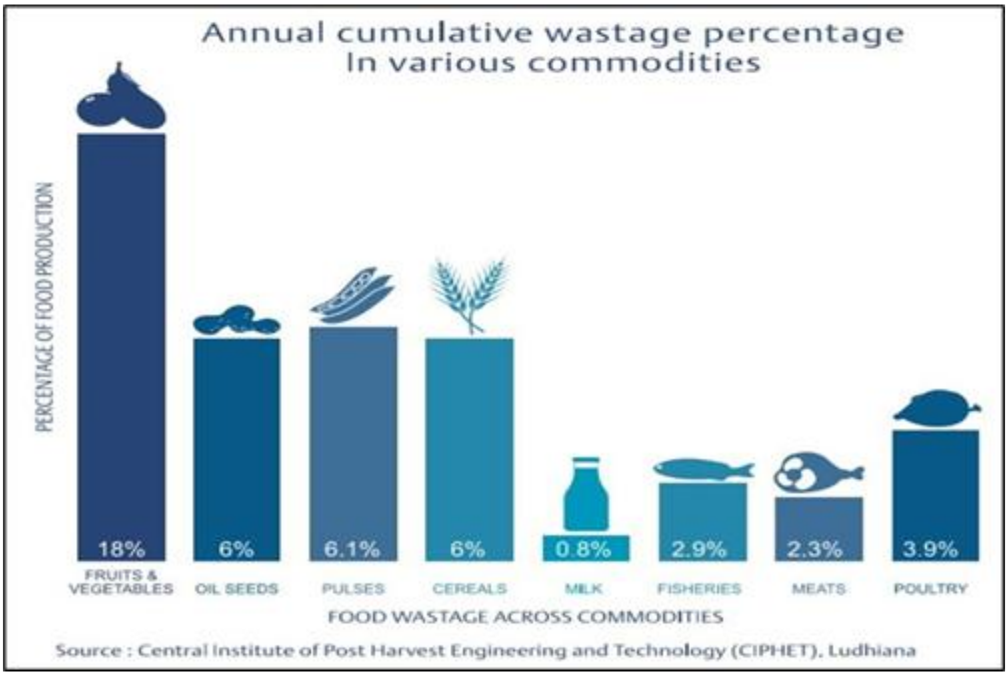

Figure 1: Percentage of post-harvest losses crop wise in India

Pre-Harvest Losses:

Biotic Factors

1. **Insect Pests** (e.g., Helicoverpa armigera, Spodoptera litura)

These polyphagous pests attack a wide range of crops like pulses, cotton, and vegetables, feeding on leaves, flowers, and pods, causing direct yield loss and increased plant stress.

2. **Pathogenic** Fungi (e.g., Fusarium oxysporum, Alternaria solani)
   Fungal pathogens lead to systemic and localized infections such as wilt, blight, and leaf spots, which reduce photosynthesis and disrupt vascular transport, thus lowering crop productivity.
3. **Bacterial Infections** (e.g., Xanthomonas oryzae, Pseudomonas syringae)
   These cause blights and rots in rice, tomato, and other crops. Bacterial toxins and enzyme secretion degrade host cell walls, leading to tissue necrosis and wilting.
4. **Viral Diseases** (e.g., Tomato Leaf Curl Virus, Yellow Mosaic Virus)
   Viruses transmitted by vectors such as whiteflies and aphids cause chlorosis, stunted growth, and malformed fruits, severely impacting crop yield and quality.
5. **Nematodes** (e.g., Meloidogyne incognita)
   These microscopic soil-dwelling organisms form root galls that impair water and nutrient uptake, resulting in plant stunting and reduced biomass accumulation.
6. **Weeds** (e.g., Parthenium hysterophorus, Cyperus rotundus)
   Weeds compete aggressively with crops for light, water, nutrients, and space. They also serve as alternate hosts for pathogens and insect pests, increasing disease spread.
7. **Rodents and Birds** (e.g., Rattus rattus, Passer domesticus)
   These vertebrate pests feed on standing crops like cereals and legumes, not only causing quantitative losses but also damaging marketable produce.
8. **Mycotoxin-Producing Fungi** (e.g., Aspergillus flavus)
   Pre-harvest contamination of grains (like maize and groundnut) with aflatoxins poses a dual threat: loss in yield and risks to food safety.
9. **Vector Populations** (e.g., whiteflies, aphids)
   These not only cause direct feeding damage but also serve as carriers of viral and phytoplasma diseases, increasing the spatial and temporal spread of infections.
10. **Parasitic Plants** (e.g., Striga, Orobanche)
    These obligate parasites attach to roots of host plants and draw nutrients, leading to reduced vigor and eventual yield decline in susceptible crops like sorghum and pulses.

Abiotic Factors

1. **Drought Stress**
   Water deficit during critical growth stages (e.g., flowering, grain filling) limits turgor, reduces photosynthetic activity, and leads to flower drop and poor grain formation.

2. **Flooding and Waterlogging**
   Saturated soils hinder oxygen availability to roots, disrupt nutrient uptake, and encourage anaerobic microbial growth, causing root rot and plant death in crops like paddy and soybean.
3. **High Temperature Stress**
   Heat waves above optimal crop tolerance (>35°C for wheat during flowering) can denature enzymes, reduce pollen viability, and impair seed setting.
4. **Cold or Frost Events**
   Sudden drops in temperature can lead to freezing injury in rabi crops like mustard and potato, damaging cellular membranes and inhibiting metabolic function.
5. **Hailstorms and Strong Winds**
   These can cause physical injury to crops, lodging in cereals like wheat, and pod shattering in legumes, significantly reducing marketable yield.
6. **Soil Nutrient Deficiency**
   Deficiencies of macronutrients (e.g., N, P, K) and micronutrients (e.g., Zn, B, Fe) hinder metabolic activities such as chlorophyll synthesis and enzyme activation, reducing productivity.
7. **Soil Salinity**
   Excess salts in soil solution reduce osmotic potential, impairing water absorption and causing ion toxicity, particularly in salt-sensitive crops like pulses and fruits.
8. **Radiation Stress (UV-B and PAR imbalance)**
   Excessive solar radiation leads to oxidative stress in plants by generating reactive oxygen species, damaging photosynthetic apparatus and cellular DNA.
9. **Heavy Metal Contamination (e.g., Pb, Cd, As)**
   Accumulation of heavy metals from polluted irrigation water or industrial effluents interferes with enzymatic activities and induces oxidative damage, reducing plant vigor.
10. **Erratic Rainfall and Climate Variability**
    Changes in monsoon onset, duration, and intensity affect sowing dates, pollination success, and crop maturation cycles, leading to asynchronous crop development and losses.

Post-Harvest Losses:

Once the crop is harvested, the supply chain—encompassing handling, storage, transport, processing, and retail—becomes the new battleground.

Magnitude of Post-Harvest Losses - According to a 2022 report by NABARD and ICAR-CIPHET (Central Institute of Post-Harvest Engineering and Technology):

Table 1: Magnitude of Post-Harvest Losses

Crop	Estimated Loss (%)	Equivalent Loss (in ₹ Crores)
Cereals	4.3–6.1%	₹27,000+
Pulses	6.4%	₹7,000+
Fruits	5.8–18%	₹13,600+
Vegetables	6.9–13%	₹14,800+

Stage-wise Scientific Analysis (From Harvest to Market)

1. Harvesting Stage

Harvesting too early leads to immature produce with lower dry matter and storage resilience too late results in shattering (e.g., cereals), over-ripening, and quality deterioration. Manual or mechanical harvesting causes bruising, cuts, or broken grains/fruits, predisposing the produce to microbial invasion and accelerated respiration. Mechanical injury increases ethylene production, disrupting hormonal balance and hastening senescence. Damaged tissue releases sugars and amino acids, creating niches for pathogens like *Rhizopus*, *Penicillium*, and *Colletotrichum*.

2. Field Handling Stage

Delays in field collection allow produce to dehydrate or ferment under sun or rain. Contamination with soil, insects, and plant residues increases microbial load and post-harvest rot. Transpiration and evapotranspiration are uncontrolled in the field post-harvest, causing cellular water loss and wilting. Field heat (field heat = metabolic + solar heat) accelerates respiration rate, leading to depletion of stored carbohydrates and increased weight loss.

3. Threshing/Shelling and Primary Processing

Inefficient threshers/shellers break or crush grains/seeds (e.g., in pulses, maize, mustard), reducing market value. Manual processing leads to incomplete separation and unintentional spillage. Mechanical damage disrupts pericarp integrity, exposing the endosperm and embryo to oxidation, pest infestation (e.g., *Sitophilus oryzae*), and fungal colonization (*Aspergillus*, *Fusarium*). Cracked grains are also more susceptible to aflatoxin and ochratoxin contamination.

4. Drying Stage

Inadequate or uneven drying leads to high moisture retention, favoring microbial growth. Over drying makes grains brittle, increasing breakage during handling. Most fungi and bacteria thrive at moisture content >14% and relative humidity >65%. Uneven drying causes moisture migration within storage bags or bins, leading to localized hotspots and spoilage.

5. Grading and Sorting

Absence or improper grading leads to mixing of infected/damaged produce with healthy ones, spreading spoilage. Manual sorting is labor-intensive and inconsistent, leading to substandard quality control. Infestation by primary pests (*Callosobruchus maculatus*, *Trogoderma granarium*) spreads faster in mixed lots. Secondary microbial infections progress faster when ethylene-producing damaged units are in proximity.

6. Packaging Stage

Poor packaging materials (e.g., gunny bags) offer little protection from moisture, insects, and rodents. Compression and lack of aeration damage perishables like fruits and vegetables. Packaging affects the micro-atmosphere around the produce. Improper packaging causes accumulation of CO_2 and ethylene, leading to anaerobic respiration and spoilage. Oxygen depletion increases fermentation, off-flavors, and textural degradation.

7. Transportation

Unrefrigerated transport causes heat accumulation in perishables like tomato, banana, and leafy vegetables. Rough roads, overloading, and improper stacking cause bruising and spillage. Without cold chain logistics, metabolic activity and respiration continue unchecked, consuming nutrients and reducing shelf life. Bruising stimulates phenylpropanoid pathway, resulting in browning (due to polyphenol oxidase) and consumer rejection.

8. Storage and Warehousing

Improper storage temperature, RH, and ventilation encourage microbial and insect infestations. Rodent damage and theft also contribute to significant losses. Insects like *Tribolium castaneum* and *Plodia interpunctella* thrive in stored grains, causing not only quantitative losses but also qualitative degradation (increased uric acid, heat spots, off-odors). Accumulation of CO_2, temperature rise (>35°C), and high RH (>70%) cause grain germination, caking, and mycotoxin production.

9. Market Handling and Display

Exposure to sunlight, unregulated humidity, frequent handling, and absence of temperature control hasten perishability. Cross-contamination from infected produce leads to rapid spread of spoilage. Climacteric fruits like banana and mango undergo accelerated ripening due to ethylene accumulation. Increased microbial activity in unsanitary market conditions promotes cross-infection by *Botrytis*, *Erwinia*, and saprophytic fungi.

10. Delay in Sale or Processing

Gluts during harvest season or poor infrastructure delay market clearance, leading to rotting and rejection. For dairy, meat, and fresh produce, even a short delay outside optimal storage leads to rapid microbial spoilage. Post-harvest produce continues to be metabolically active. Any delay without refrigeration leads to nutrient breakdown, off-odors (due to lactic acid and acetic acid bacteria), and visual spoilage. In cereals, prolonged storage at >13% MC allows latent fungi to become active, reducing market acceptability.

Impact on Farmers and Consumers

Farmers:

- Reduced income due to spoilage and low prices at peak harvest times.
- Vulnerability to price shocks and post-harvest debt traps.

Consumers:

- Artificial inflation of food prices due to lower effective supply.
- Limited access to affordable, nutritious food, especially for the urban poor and rural landless laborers.

Government Interventions and policies

Pradhan Mantri Fasal Bima Yojana (PMFBY): To provide crop insurance against losses from natural calamities, pests, and diseases, thereby reducing the impact of pre-harvest losses.

Pradhan Mantri Krishi Sinchai Yojana (PMKSY): To improve irrigation efficiency and reduce crop stress from drought and water scarcity, minimizing abiotic losses.

National Food Security Mission (NFSM): To increase crop productivity and reduce yield gaps through better seeds, nutrients, and pest management.

Mission for Integrated Development of Horticulture (MIDH): To develop post-harvest infrastructure like cold chains and pack houses to reduce losses of fruits and vegetables

Conclusion:

India's food insecurity challenge is deeply intertwined with the inefficiencies of its agricultural system, particularly the vast losses before and after harvest. While food production continues to grow, addressing where and why we are losing food is the key to feeding every Indian. Through strategic investments, technology adoption, and policy reform, India has the potential to transform its food supply chain, ensure nutrition security, and uphold the dignity of its farmers.

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PREPARATION AND APPLICATION OF NEEM STICKS ACTIVATED CARBON FOR REMOVAL OF DYES

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Abstract:

The present study explores the adsorption performance of phosphoric-acid-activated carbon derived from neem sticks for the removal of 070 Cerulean Blue, Flexon Green and Ujala Violet Blue (a liquid fabric whitener) from aqueous solutions. Batch experiments were conducted by varying adsorbent dosages (0.4–2.4 g) and contact times (1, 2 and 12 hours). The results showed that removal efficiency increased with dosage and contact time, reaching up to 99% for Cerulean Blue, Flexon Green and Ujala violet blue at 12 hours contact time with dosage 2.4 g respectively. However, the equilibrium adsorption capacity (q_e) decreased with increasing dosage, from 70.42 to 12.87 mg/g for Cerulean Blue and from 68.96 to 16.26 mg/g for Flexon Green, primarily due to agglomeration and reduced surface availability. Adsorption kinetics followed the pseudo-second-order model, with high correlation coefficients (R^2 = 0.9999 for Cerulean Blue and 1.0000 for Flexon Green). The corresponding rate constants (k_2) increased with dosage, peaking at 2.0 g (0.1976 $g \cdot mg^{-1} \cdot hr^{-1}$ for Cerulean Blue and 0.1058 $g \cdot mg^{-1} \cdot hr^{-1}$ for Flexon Green), then slightly decreased at 2.4 g due to particle aglomeration. For Ujala, qt, q_e, and k_2 could not be determined due to the absence of a defined concentration in mg/L, as it is a liquid whitener. Instead, removal efficiency was assessed through absorbance measurements, which showed consistent improvement with increased dosage and time. From the results, it was found that, the neem-based activated carbon is an effective, low-cost and sustainable adsorbent for the removal of both synthetic dyes and liquid fabric whiteners from wastewater.

Keywords: Flexon Green, Ujala Violet, Cerulean Blue, Absorption and Neem Sticks.

Introduction:

The widespread use of synthetic dyes has grown alongside industrial sectors such as textiles, leather, cosmetics, paper and plastics. The dye-laden wastewater typically contains intense color, complex chemicals and low biodegradability, posing a major environmental risk (Liu, Zhang, & Wang, 2024). The dyeing process consumes large volumes of water and includes harmful substances like azo dyes, formaldehyde and heavy metals—many of which are not fully fixed to fabric and are released into the effluents (Saratale *et al.,* 2011). In areas with weak environmental controls, these untreated discharges degrade the aquatic ecosystems. Venkat

(2024) reports that, the dye runoff blocks sunlight, disrupting aquatic photosynthesis, harming fish, benthic life and destabilizing the food chains. Each year, around 800,000 tons of synthetic dyes are produced, with roughly 200,000 tons lost during processing and discharged into the environment (Vinayak, 2020). Azo dyes, in particular, degrade into carcinogenic aromatic amines that persist and bioaccumulate. These pollutants impact food security by contaminating fishery resources and agricultural land. When used for irrigation, dye-contaminated water alters the microbial diversity and suppresses the soil productivity (Zaharia & Suteu, 2012).

Human exposure through skin contact, inhalation or contaminated food and water has been linked to dermatitis, respiratory problems, organ damage, and cancer (Yusuf *et al.,* 2020). Conventional treatment methods like coagulation and flocculation are often ineffective for non-biodegradable dyes. Adsorption, by contrast, is a cost-effective and efficient approach, especially in resource-limited settings. Activated carbon is widely regarded as the most effective adsorbent due to its high surface area, porous nature and functional groups that support various adsorption mechanisms (Sillanpää *et al.,* 2013). Although commercial activated carbon has been in use since the 18th century later refined by Von Ostreijko through thermal and chemical activation (Bansal & Goyal, 2005) its high-cost limits application in developing regions. This challenge has led to growing interest in low-cost, eco-friendly adsorbents derived from agricultural residues and lignocellulosic biomass, supporting circular economy principles (Ioannidou & Zabaniotou, 2007). The present study focuses on the adsorption efficiency of phosphoric-acid-activated neem stick carbon produced through carbonization. The adsorbent is applied to remove three synthetic dyes Flexon Green, 070 Cerulean Blue, and Ujala Violet Blue from aqueous media.

Materials and Methodology

Preparation of Adsorbent

In the present study, neem (Azadirachta indica) sticks were collected from the JSS AHER campus and sun-dried. The sticks were crushed to 3 mm size approximately and oven-dried at 100 °C. The material was then soaked in 300 mL of 50% phosphoric acid (H_3PO_4) for 24 hours (El-Sayed *et al.,* 2014). The chemical activation was chosen for its lower temperature requirement, cost-efficiency and ability to produce high-surface-area, microporous carbon (Din *et al.,* 2017). After impregnation, the sample was carbonized at 400 °C for 1–2 hours in a muffle furnace to develop porosity (Rajan *et al.,* 2022). The sample was allowed to cool, washed with hot distilled water until the pH stabilized at 6.5 approximately (Saleem *et al.,* 2017), then the oven-dried and ground to ~150 µm. The resulting activated carbon was porous and suitable for adsorption and yield was calculated using the standard formula.

$$\text{Percentage Yield (\%)} = \frac{\text{Weight after carbonization}}{\text{Weight before carbonization}} \text{ x } 100$$

Experimental Set-up

A 300 mg/L aqueous solution of 070 Cerulean Blue and flexon green dye were prepared by dissolving 300 mg of each dye in 1 L of distilled water, while 4 mL of liquid Ujala was diluted in 1 L of distilled water. Then, 100 mL of each dye solution was treated with varying doses (0.4–2.4 g) of activated neem stick carbon and stirred at 150 rpm. Adsorption was monitored at 1, 2 and 12 hours, followed by filtration. Removal efficiency was calculated using:

$$\text{Removal Effiency (\%)} = \frac{A_o - A_t}{A_o} \text{ x } 100$$

Adsorption Capacity:

The adsorption capacity, expressed in mg/g, was used to evaluate the dye removal efficiency of the adsorbent. A fixed concentration of dye solution was treated with varying adsorbent dosages and subjected to different contact times (1, 2, and 12 hours). After agitation, the remaining dye concentration was measured using a UV-visible spectrophotometer. The adsorption capacity was calculated based on the difference between the initial and final dye concentrations.

$$q_t = \frac{C_o - C_e \text{ x } V}{m}$$

Where:

q_t = adsorption capacity (mg/g); C_o = initial dye concentration (mg/L)

C_e = final dye concentration (mg/L); V = volume of solution (L)

m = mass of an adsorbent (g)

Kinetic Analysis:

Adsorption kinetics was studied to understands how dye adsorb onto the adsorbent, the pseudo- second-order-kinetic model was applied due to its superior fit with experimental value. The linear form of the pseudo second order equation is:

$$\frac{t}{qt} = \frac{1}{k_2 q^2 e} + \frac{t}{q_e}$$

Where;

q_e = adsorption capacity at equilibrium (mg/g)

k_2 = pseudo – second order rate constant ($g.mg^{-1}.hr^{-1}$)

q_t = adsorption capacity at time t (mg/g)

To determine the q_e and k_2, a plot of t/qt versus t was constructed. From the linear plot:

The slope = $\frac{1}{q_e}$

The intercept = $\frac{1}{k_2 q^2 e}$

The coefficient of determination (R^2) was used to evaluate the model fit.

Result and Discussion:

From the experimental results, the following observations were presented as follows:

Absorbance Peak Analysis of Dye Samples

The UV spectra of the dye solutions were recorded from 200 to 800 nm to determine their maximum absorbance wavelengths (λ_{max}). From the results, it was showed that, 070 Cerulean Blue exhibited λ_{max} at 630 nm, Flexon Green at 600 nm, and Ujala Violet Blue at 556 nm. These values were used to monitor dye concentrations during treatment. The variation in λ_{max} reflects differences in chemical structure and chromophores.

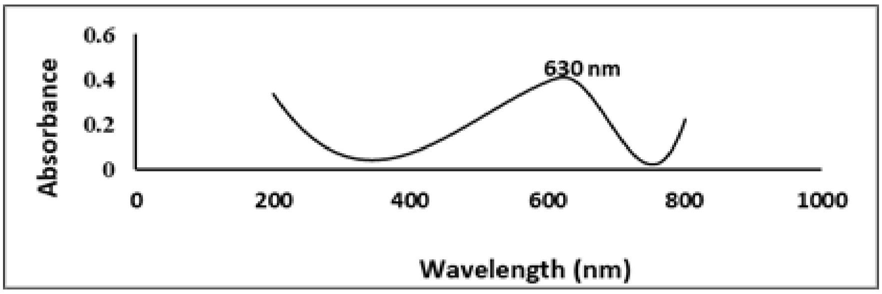

Fig. 1: Absorbance spectrum of 070 Cerulean Blue dye showing maximum peak at 630 nm

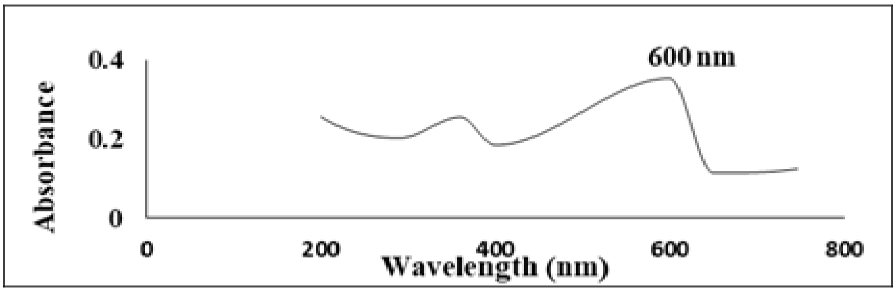

Fig. 2: Absorbance spectrum of Flexon green dye showing maximum peak at 600 nm

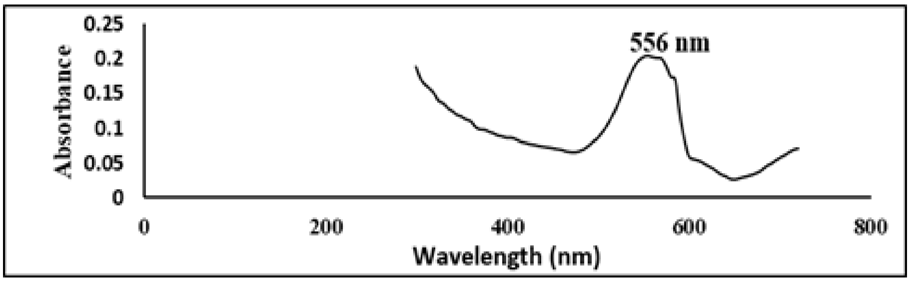

Fig. 3: Absorbance spectrum of Ujala violet blue showing maximum peak at 556 nm

Ultraviolet-Visible Spectrophotometer Analysis of dye removal by the Activated Carbon

1. 070 Cerulean blue dye

From the experimental results, it was found that, the removal efficiency of 070 cerulean blue dye was evaluated at a wavelength of 630 nm using neem stick activated carbon. The effect of varying adsorbent dosages (0.4, 0.8, 1.2, 1.6, 2, 2.4 g) and contact times (1, 2, 12) was studied in order to understand their influence on the dye adsorption.

Table 1: Removal Efficiency (%) of 070 cerulean blue dye at different dosages and contact times

Dosage (gram)	Removal Efficiency at 1 hour (%)	Removal Efficiency at 2 hours (%)	Removal Efficiency at 12 hours (%)
0.4	69.9	76	90.8
0.8	73.9	78.9	93
1.2	77	84	97
1.6	81	86.04	97.49
2	82	88.8	98.6
2.4	87.2	91	99

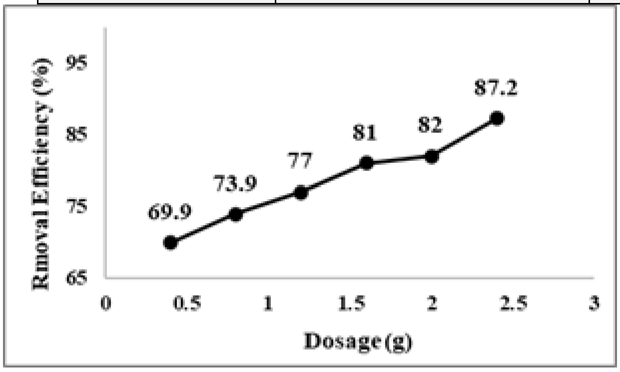

Fig. 4: Dosage vs removal efficiency

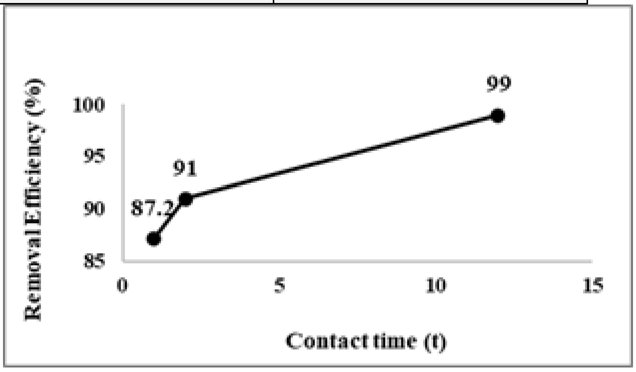

Fig. 5: Contact time vs removal efficiency

The removal efficiency of 070 Cerulean Blue increased with both adsorbent dosage and contact time, as illustrated in Figure 4 and Figure 5. With an increase in dosage from 0.4 g to 2.4 g, the removal efficiency improved from 69.9% to 87.2%, primarily due to the greater availability of the active adsorption sites (Ho, Y. S., & Mckay, G., 1999). However, beyond 2.0 g, the rate of increase became less significant, suggesting the possible site saturation or particle aggregation (Rao, R. A. K., & Kashifuddin, 2011). Similarly, the removal efficiency increased from 87.7% at 1 hour to 99% at 12 hours, indicating that, the prolonged contact time allows for more complete adsorption

Table 2: Adsorption Capacity

Dosage (gram)	1 hour (mg/g)	2 hours (mg/g)	12 hours (mg/g)
0.4	51.18	57	68.1
0.8	30.38	29.6	34.9
1.2	20.43	21	24.25
1.6	13.83	16.13	18.28
2	11	13.33	14.78
2.4	7.78	11.38	12.37

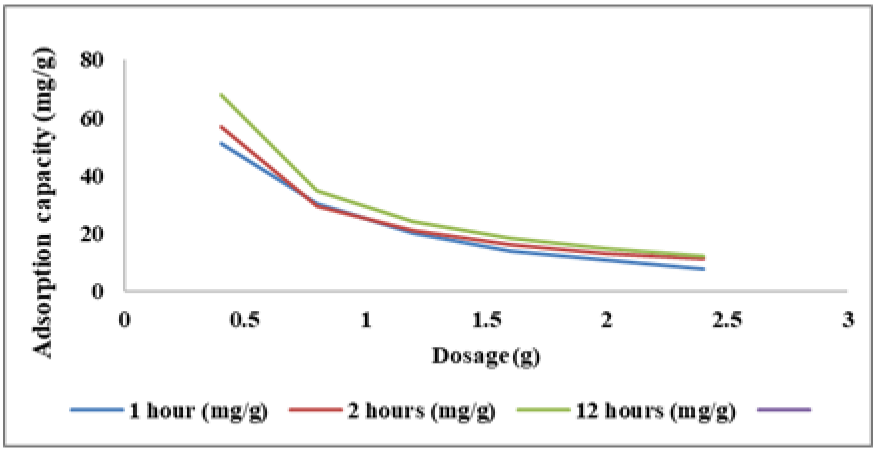

Figure 6: Adsorption Capacity vs dosage at 1, 2, 12 contact times.

With lower dosages, like 0.4 grams, it was observed that, the adsorption capacity (q_t) was at its peak, reaching 68.1 mg/g after a 12-hour mark as shown in figure 6, which demonstrates good discovery of the active sites. When moving towards the higher dosages, the adsorption capacity per gram reduced to 12.37 mg/g, because of the aggregation or overlapping of pores that were useful for the adsorption which lowered the effective surface area available (Kannan, N., & Sundaram, 2001).

Kinetic Study

In this study, the pseudo-second-order kinetic model was selected due to its superior fit with the experimental data. In comparison with the pseudo-first-order model, which showed a noticeable mismatch between the calculated and experimental adsorption capacities, the second-order model observed a better correlation and more accurate prediction of the equilibrium conditions.

Table 3: Kinetic Analysis (q_e, k^2, R^2)

Dosage (g)	q_e (mg/g)	k^2 (g. $mg^{-1}.hr^{-1}$)	R^2
0.4	70.42	0.0336	0.9999
0.8	35.71	0.0968	0.9998
1.2	24.81	0.1413	0.9999
1.6	18.8	0.1538	1
2	15.1	0.1976	0.999
2.4	12.87	0.16662	0.9999

As shown in figure 7, the pseudo-second-order rate constant (k_2) increased from 0.0336 to 0.1976 $g \cdot mg^{-1} \cdot hr^{-1}$ as adsorbent dosage increase from 0.4 g to 2.0 g, indicating the faster adsorption due to more available active sites. However, a slight drop to 0.1662 $g \cdot mg^{-1} \cdot hr^{-1}$ at 2.4 g suggests that, exceeding the optimal dosage may hinder the adsorption efficiency due to the particle agglomeration (Wate, S. R. *et al.,* 2007), diffusion limitations, or reduced mass transfer.

Meanwhile, Figure 8 shows a steady decrease in equilibrium adsorption capacity (q_e) from 70.42 mg/g at 0.4 g to 12.87 mg/g at 2.4 g, indicating that, although higher dosages may increase total dye removal, the adsorption efficiency per gram of adsorbent declines.

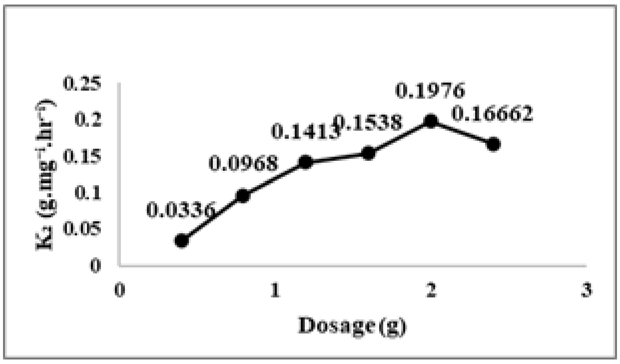

Fig. 7: Variation of k_2 with adsorbent dosage

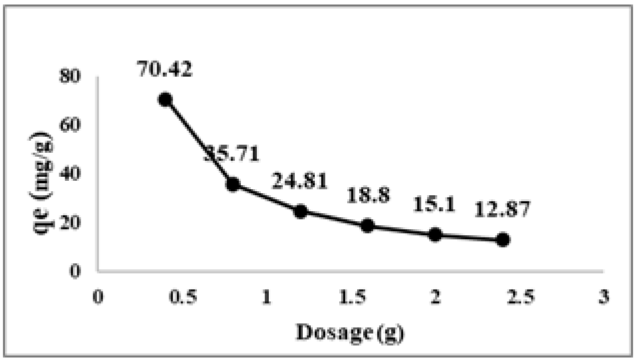

Fig. 8: q_e vs dosages

2. Flexon Green Dye

From the experimental results, the removal efficiency of Flexon green dye was evaluated at a wavelength of 600 nm using neem stick activated carbon. The effect of varying adsorbent dosages (0.4, 0.8, 1.2, 1.6, 2, 2.4 g) and contact times (1, 2, 12) was studied in order to understand their influence on the dye adsorption.

Table 4: Removal Efficiency (%) of 070 Flexon green dye at different dosages and contact times

Dosage (gram)	Removal Efficiency at 1 hour (%)	Removal Efficiency at 2 hours (%)	Removal Efficiency at 12 hours (%)
0.4	66.2	70.1	88.3
0.8	68	74.5	91.4
1.2	72.8	77	94
1.6	77.43	81	97.6
2	80.1	86.6	99.3
2.4	84	90	99

The dye removal efficiency increased steadily with the increase in adsorbent dosage, ranging from 66.2% at 0.4 g to 84% at 2.4 g, as shown in Figure 9. The figure 10 demonstrates that, contact time significantly influences the removal efficiency, with the values improving from 84% at 1 hour to 99% at 12 hours. The gradual increase indicates that, longer interaction time and higher dosages allows better diffusion of dye molecules onto the adsorbent surface, leading to the higher removal efficiency.

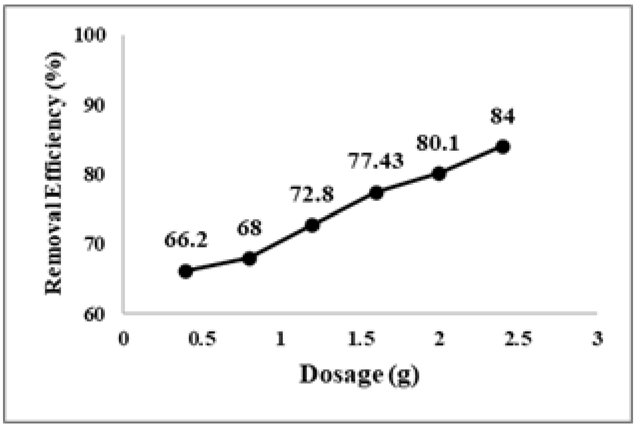

Fig. 9: Dosage vs removal efficiency

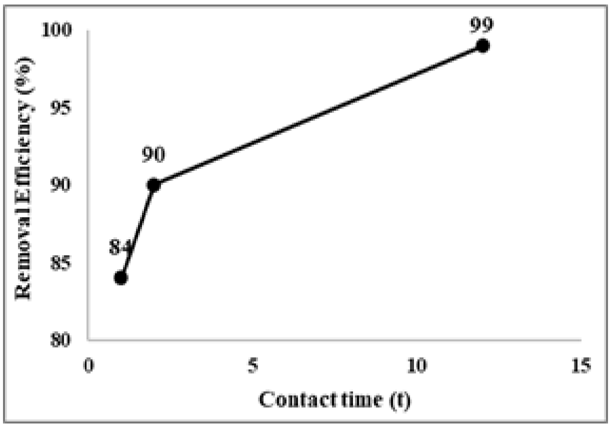

Fig. 10: Contact time vs removal efficiency

Table 5: Adsorption capacity

Dosage (gram)	1 hour (mg/g)	2 hours (mg/g)	12 hours (mg/g)
0.4	49.68	52.61	66.23
0.8	25.50	27.94	35.34
1.2	18.19	19.25	25.01
1.6	14.52	15.19	19.91
2	12.00	13	16.57
2.4	10.50	11.25	14.13

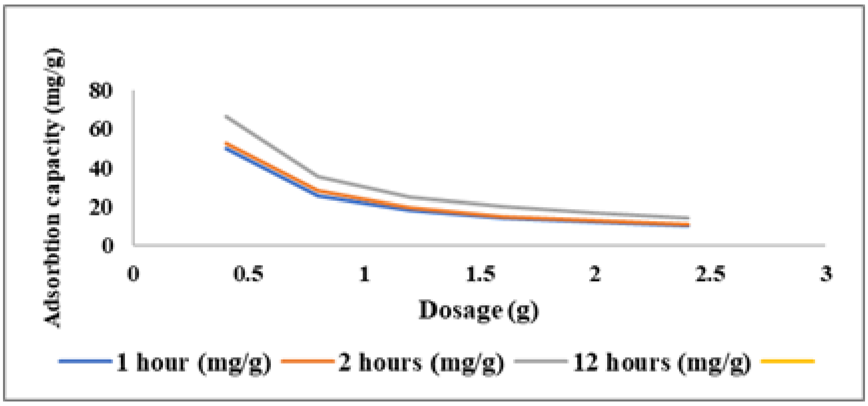

Fig. 11: Adsorption Capacity vs dosage at 1, 2, 12 contact times.

As shown in Figure 11, at contact time of 1, 2, and 12 hours, the maximum adsorption capacity (q_t) was seen at the lowest dosage, which was 0.4 g, where it peaked at 66.23 mg/g after 12 hours. This shows that, the fewer particles lead to better site utilization. With the increasing dosage, adsorption capacity per gram reduced to 14.13 mg/g, as a result of particle aggregation and overlapping the sites which decreased the surface area available for the dye to bind.

Kinetic Study

In this study, the pseudo-second-order kinetic model was selected due to its superior fit with the experimental data. Compared to the pseudo-first-order model, which showed a noticeable mismatch between the calculated and experimental adsorption capacities, the second-order model demonstrated a better correlation and more accurate prediction of equilibrium conditions.

Table 6: Kinetic Analysis (q_e, k^2, R^2)

Dosage (g)	q_e (mg/g)	k^2 (g. $mg^{-1}.hr^{-1}$)	R^2
0.4	68.96	0.0292	0.9999
0.8	36.9	0.0505	0.9997
1.2	26.17	0.0709	0.9998
1.6	20.8	0.0826	0.9998
2	17.3	0.1057	0.9999
2.4	16.26	0.0959	0.9999

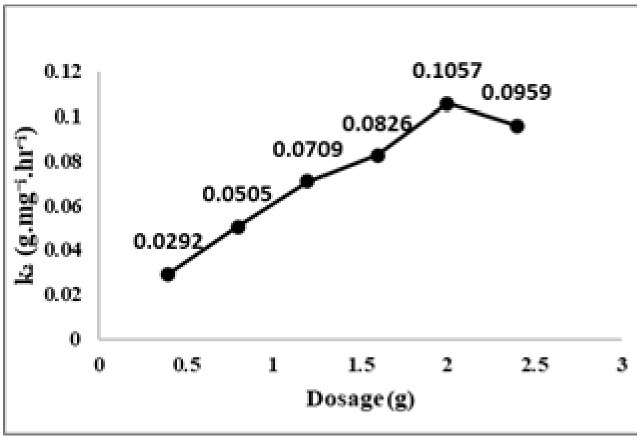

Fig. 12: Variation of k_2 with adsorbent dosage

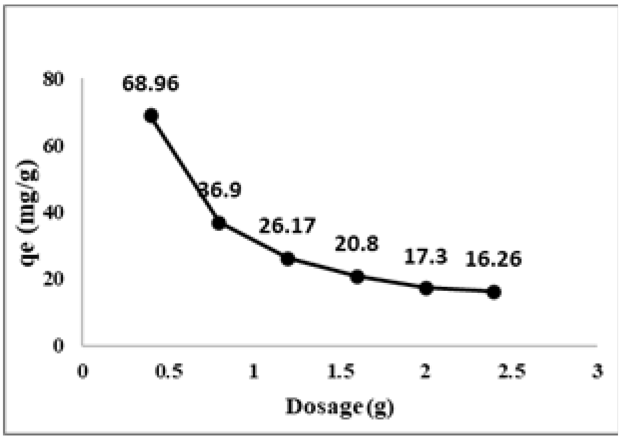

Fig. 13: q_e vs dosages

As shown in figure 12, the pseudo-second-order rate constant (k_2) increased from 0.0292 to 0.1058 $g{\cdot}mg^{-1}{\cdot}hr^{-1}$ as adsorbent dosage increase from 0.4 g to 2.0 g, suggesting the enhanced adsorption due to more available active sites. However, a slight decrease to 0.0959 $g{\cdot}mg^{-1}{\cdot}hr^{-1}$ at 2.4 g indicates the possible agglomeration and diffusion resistance. In contrast, Figure 13 shows a steady decline in the equilibrium adsorption capacity (q_e), from 68.96 mg/g at 0.4 g to 16.26 mg/g at 2.4 g, likely due to the site overlapping and reduced surface availability at higher dosages.

3. Ujala violet blue

In the present study, the removal efficiency of Ujala blue violet was evaluated at a wavelength of 556 nm using neem stick activated carbon. The effect of varying adsorbent dosages (0.4, 0.8, 1.2, 1.6, 2, 2.4 g) and contact times (1, 2, 12) was studied to understand their influence on dye adsorption.

Table 7: Removal Efficiency of Ujala violet blue at different dosage and contact time

Dosage (gram)	Removal Efficiency at 1 hour (%)	Removal Efficiency at 2 hours (%)	Removal Efficiency at 12 hours (%)
0.4	72.8	81.8	89.13
0.8	74.2	83.5	93.8
1.2	77	85	95
1.6	81.44	88.27	98.1
2	85.1	91	99.67
2.4	88	95.78	99

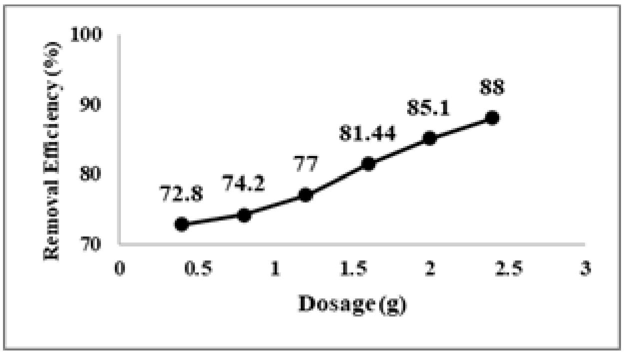

Fig. 14: Dosage vs removal efficiency

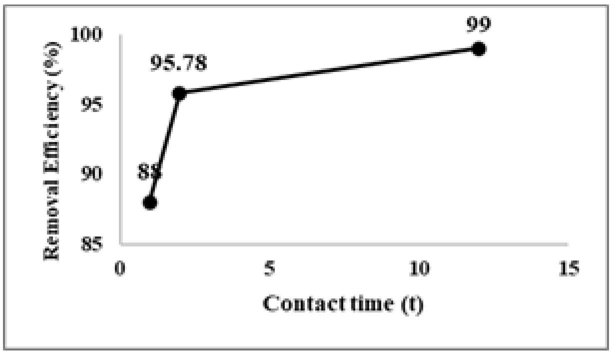

Fig. 15: Contact time vs removal efficiency

The removal efficiency of Ujala Violet Blue, being in liquid form, was evaluated based on the difference between initial and final absorbance readings. As depicted in Figure 14, an increasing trend in dye removal was observed with rising adsorbent dosages, ranging from 72.8% at 0.4 g to 88% at 2.4 g, indicating improved availability of active sites for adsorption. Similarly, Figure 15 shows that with extended contact time, the efficiency significantly increased from 88% at 1 hour to 99% at 12 hours.

Conclusion:

From the study it was confirmed that, the effectiveness of neem-stick-based activated carbon for removing synthetic dyes from water. Both dyes showed increased removal efficiency with higher dosages and longer contact times, Cerulean Blue increase from 69.9% (0.4 g, 1 hr) to 99% (2.4 g, 12 hrs), Flexon Green from 66.2% to 99%, and Ujala violet blue from 72.8% to 99% respectively**.** However, the adsorption capacity (qt and qe) decreased with the higher dosages due to the particle aggregation and site overlapping. For Cerulean Blue, q_e dropped from 70.42 mg/**g** (0.4 g) to 12.87 mg/g (2.4 g), and for Flexon Green from 68.96 mg/g to 16.26 mg/g. Adsorption followed the pseudo-second-order kinetic model**,** indicating chemisorption. Model fitting was excellent (R^2 = 0.9998–1.0000). The rate constant (k_2) increased with the dosage up to 2.0 g, then declined slightly. For Cerulean Blue, k_2 rose from 0.0336 to 0.1976 g·mg^{-1}·hr^{-1}**,** then dropped to 0.1662 g·mg^{-1}·hr^{-1}. Flexon Green showed a similar trend from 0.0292 to 0.1058 g·mg^{-1} then dropped to 0.0959 g·mg^{-1}·hr^{-1} at 2.4 g. Although the kinetic parameters couldn't be determined for Ujala Violet Blue due to its liquid form, visible removal confirmed its applicability. Overall, the neem stick activated carbon presents a low-cost, eco-friendly solution for dye-contaminated water treatment.

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IMPACT OF CLIMATE CHANGE ON SEED PRODUCTION AND SEED QUALITY PARAMETERS- REFER TO HEAT AND DROUGHT STRESS

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Abstract:

Climate change, characterized by increasing global temperatures and altered precipitation patterns, poses a significant threat to agricultural systems, particularly seed production. Climate change, manifested through rising global temperatures and erratic precipitation patterns, profoundly impacts seed production during reproductive stages, specifically concerning high temperature and drought stress. The altered climate conditions influence various critical aspects of seed development, including flowering, pollination, fertilization, and seed maturation. High temperatures during reproductive stages can disrupt pollen viability, impair pollen tube growth, and reduce stigma receptivity, leading to decreased seed set and impaired quality. Concurrently, drought stress intensifies the adverse effects, amplifying seed yield losses and compromising seed vigor. The intricate relationship between climate change, high temperature, drought, and their cumulative impact on seed production necessitates a deeper understanding to develop adaptive strategies, enhance resilience, and ensure sustainable crop production in a changing climate. Effect of temperature on pollen germination and pollen tube growth in longan in vivo and in vitro for this purpose first pollen germination was evaluated in vivo at three temperature regimes, showing the best performance at 23/24 ◦C. The effect of drought treatments on honey and wild bee attractivity to flowers of *Trigonella moabitica* during flowering stage by measuring the percentage of visitations. Climatic change is adversely affecting the seed production at various crop stages. there will be reduced growth and development of the plant due to the climatic change. The extreme temp and drought will manipulate the seed quality and quantity resulting in poor seed germination. These studies open a window to select the best cultivars for different temperatures and drought conditions.

Keywords: Climate Change, Seed Production, Seed Quality, Drought, Heat Stress.

Introduction:

Our planet, Earth, is uniquely known to support life in the solar system, with solar radiation serving as a vital energy source. Human endeavors like industrial activities, transportation, energy production, and deforestation lead to the emission of greenhouse gases. Since the Industrial Revolution, the concentration of these gases has significantly increased, resulting in a rise in global temperatures. Climate change has diverse and far-reaching consequences, as temperature fluctuations greatly impact life on Earth and the planet's physical processes. As the planet warms, sea levels are expected to rise due to the thermal expansion of water. Rising temperatures also cause the melting of ice stored in glaciers and polar regions, contributing to sea-level rise and increasing the risk of flooding and decreased river flow in the long term (Arunanondchai *et al.,* 2018). Additionally, climate change may alter water supplies, such as modifying the South Asian monsoon pattern (Noya *et al.,* 2018). Every day, the world faces the challenge of producing sufficient food for its growing population.

Climate change refers to the long-term alterations in a region's average weather patterns observed over time. It is characterized as a large-scale, long-term shift in the planet's weather patterns and average temperatures (IPCC, 2018). Current global climate models forecast a mean global temperature increase of 1.0-3.7 C by the end of the 21st century (IPCC, 2013). The majority of the warmest years since 1880, 9 out of 10, have occurred in the last decade (2000-2010), adversely impacting global food production (Mittler *et al.,* 2012). 13 out of the 15 warmest years have been in the past 15 years (2002-2017). India's annual mean temperature has risen by approximately 1.2 C since the start of the 20th century. The year 2016 recorded the highest annual mean temperature in India at 25.12 C. During the winter of 2016-17, the mean temperature was 2.95 C, the warmest in recorded history.

Climate change, as defined by the IPCC, is a change in the climate's state that can be identified by changes in its mean and/or variability, persisting for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or human activity. There are two main reasons for climate change:

1. Natural causes: These include volcanic eruptions, radiation, tectonic plate movement, and orbital variations. These activities can make an area's geographical condition harmful for life and raise the world's temperature, causing an imbalance in nature.
2. Anthropogenic intervention: Human activities like deforestation, using fossil fuel, industrial waste, and pollution have damaged the climate. Many plant and animal species have become extinct due to human activity.

Other impacts of climate change include changes in crop pest distribution and species that spread vector-borne diseases like malaria. Agriculture depends on climate factors like temperature, light, wind, rainfall, and solar radiation. Increases in temperature and carbon dioxide can increase crop yields in some places. However, nutrient levels, soil moisture, and water availability must also be met.

Climate change can cause severe losses and affect food safety during storage, for example, by changing populations of aflatoxin-producing fungi. Extreme weather events can damage infrastructure and affect storage and distribution. Climate change also affects pest and disease incidence, host-pathogen interactions, and insect ecology. Changes in droughts and floods can pose challenges for farmers and threaten food safety. The effects of climate change need to be considered along with other evolving factors that affect agricultural production, such as changes in farming practices and technology (Vaughan *et al.,* 2018).

In agriculture seed is the most basic and vital input in agriculture. Seed is the repository of the genetic potential of crop species, and continued use of quality seeds results in an increase in food production. In the last five decades, seed production in major field crops has increased by 1-3% per year due to continuous advancement in the field of plant breeding [Thakur and Sharma (2022)]. But Climate change poses several challenges tothe continued production of high-quality seed and impacts the seed industries because the seed industry is the cornerstone of global food security; food security depends on seed security. The global seed market is currently around US$ 66.9 billion. Domestically, the largest seed market isin the USA, followed by China, France, India, Brazil and Canada. Forty countries have domestic seed markets of US$ 100 million or greater, but others rely heavily on imports to supply their seed needs. The international seed market has tripled over the last three decades driven mainly by the evolution of multinational seed companies, the increased availability of F_1 hybrids, the protection of intellectual property, the increasing use of counter-season production, and the development of genetically engineered crops (FAO,2017).

India's population was 1.31 billion in 2018, with 67% residing in rural areas and the majority hasagriculture as their occupation. Although it contributes only 15% of GDP, the share of workers is about 55%. Major crops are rice, wheat, maize, coarse cereals, groundnut, cotton, sugarcane, fruits and vegetables. 60% of the cultivated area is rainfed as only 40% of the area is under irrigation. Rural poverty is 41% in 2017-18. Agriculture is a 'State Subject. In other words, the policies of provinces are also important. The seed must pass through there productive system, and climate change affects the sexual reproductive phase in plants for better seed production and quality. With this let's observe how climate change has an impact on seed production and quality.

Seed production in plants is influenced by climatic factors, which play a crucial role in determining the success of quality seed development. Some key climatic factors that influence seed production include temperature, relative humidity, solar radiation, precipitation, gas composition, and wind velocity.

1. Temperature: Temperature is a critical environmental factor that significantly influences crop development. Different crops have a specific temperature requirement for optimal growth because temperature affects various physiological and biological processes within the plants, such as germination, vegetative growth, photosynthesis, respiration, flowering, reproductive growth, pollen viability, pollination, seed development, and maturation, etc.

Each crop has a specific critical temperature point, such as the minimum, maximum, or optimum, which is called as Cardinal temperature. Minimum temperature is the lowest temperature for plant growth below which there is a significant reduction in growth and development. It can be for germination, photosynthesis, and other growth stages. Maximum temperature is the highest temperature behind which vital physiological processes can be disturbed due to the denaturation of enzymes as the plant experiences stress. Optimum temperature is the temperature range at which the plant experiences maximum growth rate development and physiological process. Based on this Cardinal temperature, we can select a suitable area for quality seed production. For example, broccoli requires 15 degrees optimum temperature for maximum growth whereas maize requires nearly 30-35 for good growth as depicted in the crop as you can see the different crops requires the different Cardinal temperatures for not only between the crop and within the crop also at various growth stages crop require the different temperature if any fluctuation is seen then plant efficiency will be reduced you can see this the table which is the defect in the temperature requirement. For maize crops, it requires a minimum of 10ºC and a maximum of 40ºC. Any range below and above this temperature will cause a severe decline in the growth rate. Similarly, during tasseling, if any fluctuation occurs it leads to abnormal tasseling during anthesis, failure in pollination, etc., which finally results in a decrease in seed yield and quality.

2. Gas Composition: Sunlight reaches the earth, and some energy is replicated back into space. This energy is absorbed and Re-radiated as heat because of the presence of greenhouse gases in the earth's atmosphere. Most of the heat then radiates in all directions, which results in the warming of the earth. Primary greenhouse gases include carbon dioxide, methane, nitrous acid, fluorinated gases, and water vapor, which are released due to the burning of fossil fuel, deforestation, and industrial applications such as air conditioners and electronics, etc, which have high global warming capacities. Global warming has a significant impact on agriculture by influencing climatic factors such as temperature changes, changing in the precipitation pattern, extending growing seasons, water scarcity and irrigation challenges, and extreme weather events like storms, cyclons, pests, and disease outbreaks. what changes in climate significantly impact seed production, affecting both the quality and quantity of seeds. High CO_2 results in an increase in the atmospheric temperature which further results in a decrease in yield.

3. Relative Humidity (RH): Moderately low relative humidity is required for the seed set in many crops provided with adequate soil moisture. For example, Seed set in wheat is high at 60% relative humidity compared to 80%. When water availability in the soil is not limited, high relative humidity causes poor flowering, and less relative humidity causes hard seed.

4. Rainfall: Moderately or adequate rainfall is suitable for the seed production excessive rainfall result in poor flowering, pollen wash out, activity of the pollination and less seed set. Not only this, it also results in a higher incidence of the disease, resulting in mold attack and seed discoloration. During the harvesting time, rain occurs in vitro germination occcurs, resulting in poor seed quality and quantity.

5. Solar radiation: The high solar radiation coupled with the high-temperature results in more heat stress, which causes pollen sterility.

6. Wind: Wind plays an important role in seed production, especially in wind-mediated cross-pollinated crops. Heavy wind may carry the Pollen, too, to prevent deposition on the stigma. Dry wind results in desiccated Pollen and low wind may not help properly move pollen. At maturity, heavy wind causes lodging and scattering of the seed.

Therefore, all these climatic factors should be at an optimum level for successful seed production in both quality and quantity, but during recent years, we have witnessed significant variations in the average weather conditions, which is called climatic change. climatic changes refer to the significant and long-term changes in the Earth climate caused by the increase in greenhouse gases in the earth's atmosphere.

High-temperature stress occurs when temperatures exceed a critical threshold, causing irreversible damage to plant growth and development (Singh, 1973). This stress disrupts germination, reduces photosynthesis efficiency, alters relative water content, and hampers protoplasmic movement. It also impairs material transport, decreases stability, affects hormone balance, and leads to poor seed quality and filling. The impact of high-temperature stress differs across crop stages. During the vegetative stage, it results in poor germination, increased seedling mortality, and reduced tiller count. At the reproductive stage, heat stress leads to reduced spikelet numbers, poor pollen viability, and impaired fertilization, ultimately reducing seed yield. At the grain filling stage, it causes reduced grain weight and increased chalkiness. The underlying causes of these negative effects include membrane damage, photosynthesis impairment, increased ROS production, phytohormone imbalance, and disrupted carbohydrate metabolism. This ultimately leads to reduced seed yield and quality. Notably, the reproductive stage is the most sensitive to heat stress.

Effect of High Temperature on Reproduction:

In this study, two crop conditions in **so** crop were compared: a control condition and a heat stress condition with a day temperature of 36°C and a night temperature of 26°C. The results showed that plants exposed to high temperatures exhibited abnormal style elongation and male sterility. The male sterility was associated with morphological alterations in sporophytic anther tissues, including the tapetum, epidermis, and endothecium. The most significant change was observed in the tapetum layer, which serves as nutritive tissue for microspore development. Deficits in tapetum tissue at high temperatures affected male gametogenesis, inducing male sterility.

Key Observations:

- Anthers from plants grown under control conditions showed normal development of endothecium, microscope, and tapetum.
- Anthers from plants grown at higher temperatures showed disintegrated microscope and tapetum.
- Pollen grains from plants grown under control conditions had densely stained cytoplasm and normal development.
- Pollen grains from plants grown at higher temperatures showed disintegrated cytoplasm and abnormal vacuole formation.

Scanning Electronic Micrograph Observations:

- Well-hydrated pollen grains with exins and tiny spinules were observed under control conditions.
- Non-hydrated pollen grains with tapetum debris and irregularly exins surface were observed under higher temperature exposure.

Tapetal cell degeneration in developing pollen is highly sensitive to heat stress, leading to premature degeneration of tapetal cells and programmed cell death of developing pollen. The mechanisms behind this are:

1. Increased Respiration and ROS Production: Pollen and tapetal cells contain a high number of mitochondria. Under heat stress, increased respiration leads to the production of more reactive oxygen species (ROS), causing damage to cellular components.
2. Premature Degeneration of Tapetum Cells: Heat stress causes premature degeneration of tapetum cells, reducing the delivery of carbohydrates and other compounds necessary for normal pollen development.
3. Reduced Nutrient Availability: The combination of reduced nutrient availability and increased respiration results in defective development of pollen grains.
4. Heat Shock Response: The unfolding of proteins can be mitigated by the heat shock response, controlled by heat shock factors. However, under high-temperature stress, the heat shock response is weak, insufficient to protect and refold proteins.
5. Microtubule Cytoskeleton Sensitivity: During cell division, microtubule cytoskeleton is sensitive to ROS. Heat stress affects the orientation of the spindle apparatus, leading to aberrant chromosomal behavior and subsequent failure of pollen development.

These factors collectively cause failure of pollen development under heat stress.

Key Effects of Heat Stress on Pollen Development:

- Premature Tapetal Cell Degeneration: Heat stress leads to premature degeneration of tapetal cells
- Increased ROS Production: Heat stress increases ROS production, damaging cellular components
- Reduced Nutrient Availability: Heat stress reduces nutrient availability for pollen development
- Defective Pollen Development: Heat stress leads to defective pollen development
- Failure of Pollen Development: Heat stress causes failure of pollen development

Stress (HT +WS) affecting pollen count and pollen germination

The combined stress of high temperature (HT) and water stress (WS) affects pollen count and pollen germination in rice. The specific conditions were:

- High temperature stress: 38°C day temperature and 29/21°C night temperature from one day of anthesis till four days continuously.
- Water stress: given 5 days before heading.

The pictorial illustration shows the effects of HT, WS, and combined stress (HT + WS) on pollen count and pollen germination. Two rice varieties were used: N22-19379: heat and drought tolerant Moroberekan: heat sensitive and drought tolerant.

Key Effects of Combined Stress (HT + WS):

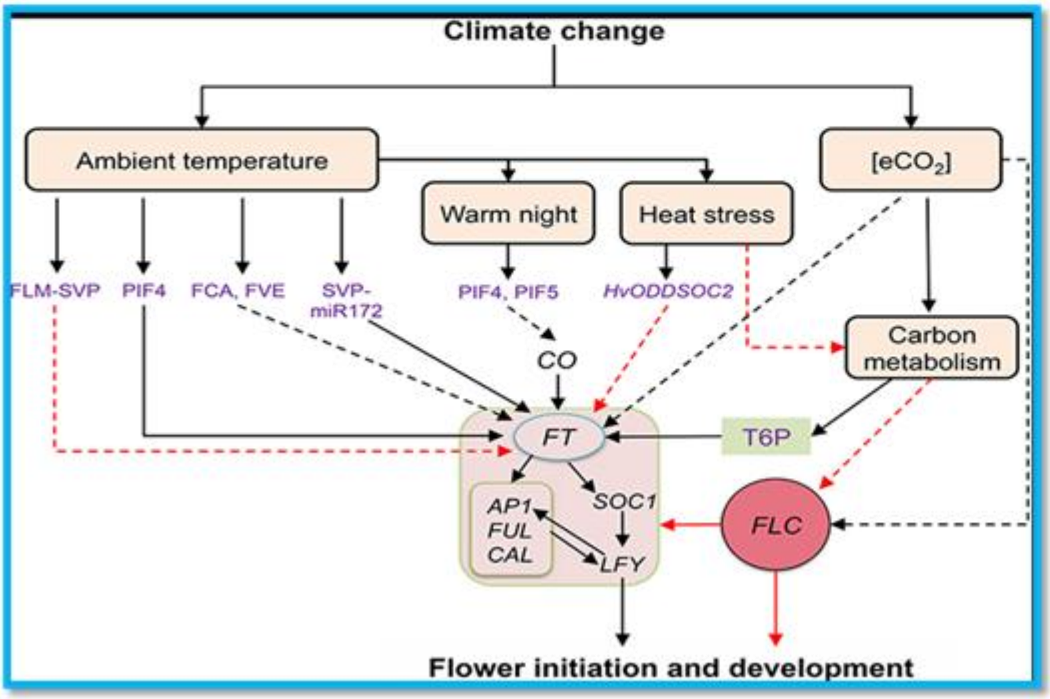
- Reduced Pollen Count: Combined stress reduces pollen count
- Reduced Pollen Germination: Combined stress reduces pollen germination
- Affected Spikelet Fertility: Combined stress affects spikelet fertility

High-Temperature-Induced Defects in tomato:

High-temperature-induced defects in tomato anther and pollen development occur when temperatures rise above optimal levels. Under control conditions (22 degrees for 12 hours), mild heat stress (30.5 degrees day temperature and 25.5 degrees night temperature) affects pollen viability. When grown under mild heat stress (32 degrees or 26 degrees), deformities like distance spacing between anther and twisting and greening of the tips occur. The frequency of these deformities increases with rising temperatures, reducing pollen viability. Cytological analysis reveals the presence of abnormal tissues similar to transmitting tissue in the anther. Ovule-like protrusions are found at the base of the anther, suggesting a partial conversion from anther to pistil due to heat stress.

Flowering Time

Flowering time is an important event in the plant lifecycle, modulated by environmental factors like photoperiod, light quality, vernalization, and growth temperature. A mild increase in growth temperature (from 23.8C to 27.8C) can induce flowering in Arabidopsis plants. FLOWERING LOCUS C suppresses thermal induction, while FLOWERING LOCUS M is a major-effect quantitative trait locus modulating thermosensitivity. Thermal induction acts upstream of the floral integrator FLOWERING LOCUS T and depends on the hormone gibberellin. Ambient temperature positively regulates FT by many genes but is negatively regulated by FLM-SVP. Changes in ambient temperature, like warmer nights and heat stress, interfere with flowering time. Warmer night temperatures induce early morning flowering by PIF4,5 genes. Heat stress disturbs carbon metabolism, sugar signaling, and flower repression genes. Co2 suppresses the action of flowering repressor genes and positively affects carbon metabolism and sugar signaling. Gene products involved in RNA splicing are specifically affected by thermal induction. Even small changes in temperature can act as cues for the induction of flowering (Zinn *et al.,* 2010).

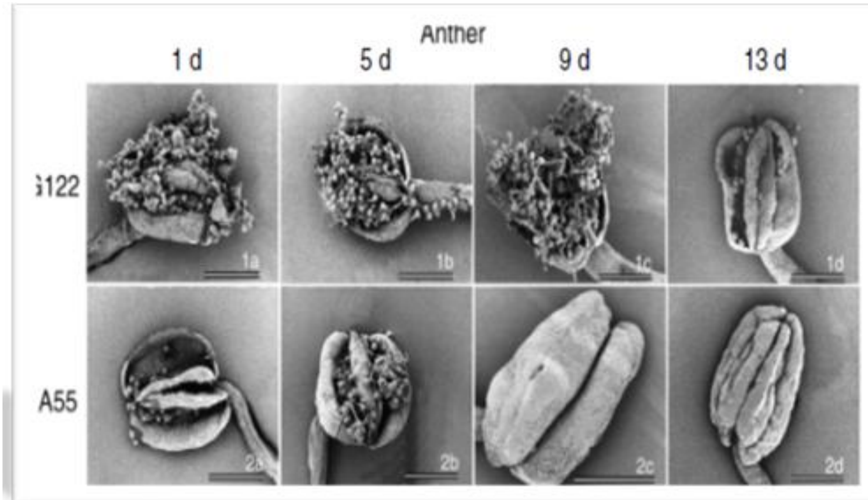


Pollen

High temperatures can wreak havoc on pollen development. When temperatures reach 32°C and 27°C during microsporogenesis in the P. vulgaris genotype, it affects the pollen exine structure, especially in heat-sensitive genotypes like A55. After 9 days of heat treatment, the anthers of A55 become indehiscent, and the exine structure is severely damaged. Even the anther itself collapses after just 4 days. The heat stress also impacts the pollen wall structure, reducing endothelial wall thickening and causing incomplete degeneration of the interocular septa. This results in flattened and collapsed microspores. The pollen cytoplasm is also affected, with the absence of one of the pollen wall layers. The secondary thickening of the endothelial layer is less developed, leading to reduced endothecial wall lignification and abnormal pollen morphology. In heat-tolerant genotypes like g122, the effects are less severe, but still noticeable. The pollen exine structure is affected after 24 hours of heat treatment. Overall, high temperatures during microsporogenesis can lead to reduced pollen viability, germinability, and fertility [1 2].

Key Effects of High Temperature on Pollen:

- Reduced Pollen Viability: High temperatures decrease pollen viability, making it less likely to fertilize
- Abnormal Pollen Morphology: Heat stress causes abnormal pollen shape and structure
- Indehiscent Anthers: High temperatures can prevent anther dehiscence, reducing pollen release
- Collapsed Microspores: Heat stress leads to flattened and collapsed microspores



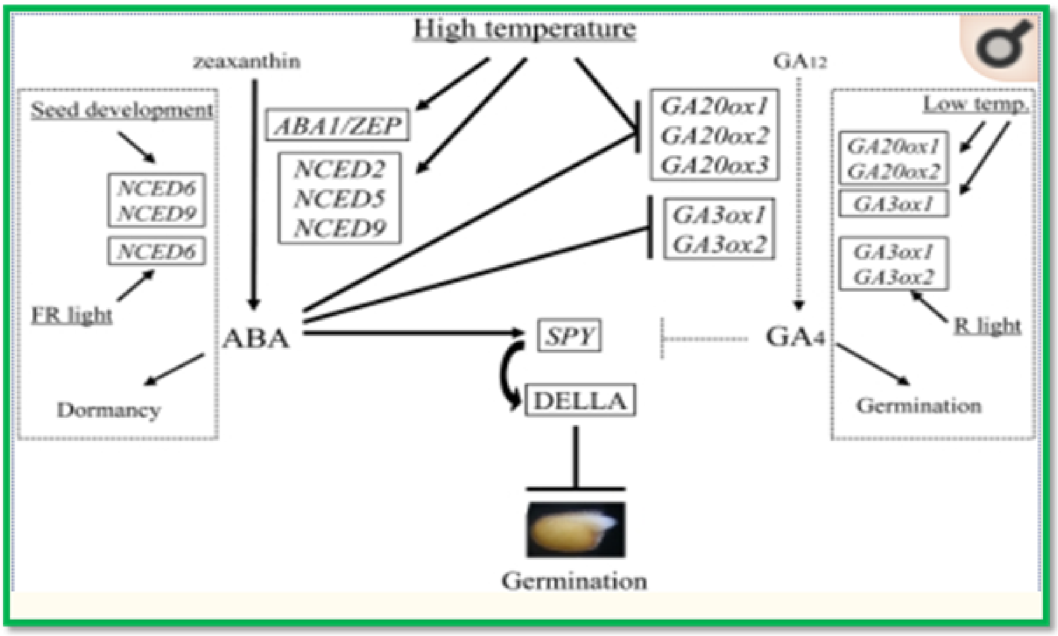
Seed Dormancy

Seed dormancy is a crucial adaptive mechanism that protects seeds from germinating prematurely under unfavorable conditions. Environmental factors like light, temperature, and water availability regulate seed dormancy. Phytohormonal pathways, particularly ABA and GA, play a key role in maintaining or releasing seed dormancy. High temperatures affect seed germination and dormancy by influencing ABA and GA, which have opposing effects. High temperatures induce the production of ABA synthesis genes (ABA 1/NCED), leading to increased ABA levels. This inhibits germination through Della protein and promotes dormancy through the SPY gene. Increased temperatures enhance the activity of Della protein, reducing germination, but don't affect its content. High temperatures also increase the expression of GA negative regulator genes (SPY) and suppress GA biosynthesis genes (GA20ox1, GA20ox2, GA20ox3, GA3ox1, and GA3ox2) indirectly through ABA.Some genes, like GA3oxo1 and

GA3oxo2, are directly affected by temperature increases. Decreased GA levels lead to reduced germination.

Key Effects of High Temperature on Seed Dormancy and Germination:

- Increased ABA: High temperatures induce ABA production, promoting dormancy
- Reduced GA: High temperatures suppress GA biosynthesis, reducing germination
- Della Protein Activation: High temperatures enhance Della protein activity, inhibiting germination
- SPY Gene Expression: High temperatures increase SPY gene expression, promoting dormancy



Drought:

- Drought conditions, characterized by low rainfall for an extended period, reduce soil water essential for plant growth. This drought stress negatively impacts flower pollination by:
- Decreasing viable pollen grains
- Reducing flower attractiveness to pollinators
- Decreasing nectar production

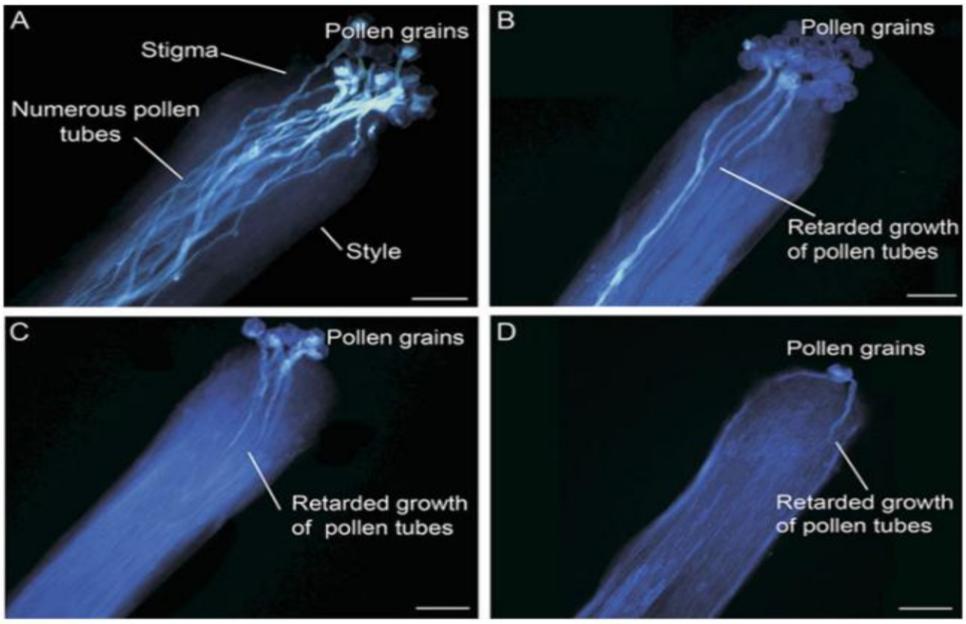
Consequently, crop seed set and yield are lowered. Drought stress affects crop yield by reducing grain yield and all yield components (Alqudah *et al.,* 2010). The reproductive stage is particularly sensitive to drought stress, which decreases viable pollen grains and pollinator attraction due to reduced nectar. This results in reduced seed quality. Drought stress also affects membrane integrity, leading to:

- Distorted membrane structure
- Drop in water potential
- Changes in CO2 fixative enzyme activity

- Negative impact on photosynthetic system 2 (cyclic photophosphorylation)

This leads to decreased stomatal conductance, reduced CO2/O2 ratio in chloroplasts, and ultimately, a decrease in photosynthetic rate.

In chickpea, the pistil is sensitive to drought stress. Water stress at three days before flowering and three days after flowering reduces flower size and anther bursting. Anthers of flowers in water-stressed plants did not burst when water potential decreased to -1.2 Mpa. The size of flowers near the tip of branches was reduced in water-stressed plants compared to well-watered plants. The viability of pollen under water-stressed and well-watered conditions shows that bright pollen grains are viable, while white-grey colored pollen grains have lost viability. Well-watered plants have more pollen grains, while water-stressed plants have more grey-colored and small pollen grains. Pollen tube development inside the style in chickpea shows that well-watered plants have good pollen growth reaching the ovary, but pollen from water-stressed plants has reduced pollen tube growth. Even if pollen tubes reach the ovary, drought stress during floral development negatively affects pollen germination and pollen tube growth. Commonly, reduced pollen growth in water-stressed plant stigma occurs when pollinated with both well-watered and water-stressed plant pollen. This suggests that flower abortion in chickpea is not only due to reduced pollen viability but also due to impairment of pistil functions under drought stress.



Pollination:

Pollen transfer from anther to the stigma of a flower is a crucial step in plant reproduction. Pollen grains are formed in the pollen sac, which is enclosed by a multilayered anther wall. For pollination to occur, the anther sac must open to release the pollen grains. High temperatures can affect the quantity and morphology of pollen, anther dehiscence, and pollen wall architecture. The chemical composition and metabolism of pollen are also impacted by high temperatures. High-temperature stress during gamete development can impair plant reproduction. Additionally, high temperatures and strong winds can cause desiccation of pollen or drying of the stigma, resulting in poor seed set and quality. The optimal temperature range for pollinator activity, particularly bees, is between 24-38°C. In some vegetables, high temperatures can inhibit the development of ovules.

Key Effects of High Temperature on Pollen and Pollination:

- Reduced Pollen Quantity: High temperatures affect pollen quantity
- Altered Pollen Morphology: High temperatures change pollen morphology
- Impaired Anther Dehiscence: High temperatures affect anther dehiscence
- Desiccation of Pollen: High temperatures and strong winds cause pollen desiccation
- Inhibited Ovule Development: High temperatures inhibit ovule development in some vegetables.

Drought stress affects pollination by bee visitation, leading to reduced crop yields. The percentage of honey bee and wild bee visitation is highest under well-watered conditions, but drastically reduces under moderate and drought stress conditions. This is due to reduced flower size, low nectar production, and reduced sucrose content, making flowers less attractive to bees under drought stress. As a result, the amount of pollen deposition on the stigma is reduced, leading to reduced seed set. Drought stress also affects pollen quality, such as reduced pollen weight and reduced pollen viability. This is because of reduced photosynthesis, resulting in reduced nutrient supply to reproductive organs. Insufficient food supply can cause pollen abortions. The percentage of non-viable pollen increases under drought stress compared to well-watered conditions, impairing seed yield and quality. Drought stress results in reduced number of pods per plant, reduced pod set percentage, reduced seed set per pod, reduced pod percentage, and reduced weight of seeds per pod. Due to reduced nutrient supply and poor pollination under drought conditions. Drought stress affects various pollination traits, including decreased availability of pollen, increased pollen sterility, reduced pollen tube germination and growth, reduced anther dehiscence, reduced flower size, and increased ovary abortion.

Key Effects of Drought Stress on Pollination and Seed Yield:

- Reduced Bee Visitation: Drought stress reduces bee visitation
- Reduced Pollen Quality: Drought stress reduces pollen weight and viability
- Reduced Seed Yield: Drought stress reduces seed yield and quality
- Impaired Pollination Traits: Drought stress affects various pollination traits

Conclusion:

Climate change (CC) is adversely affecting seed production (SP) at various crop stages. The key effects include: Reduced growth and development of plants due to climatic change. Changes in flowering duration and time, which can result in reduced quality and quantity of seeds, as well as reduced pollination visits. Reduced pollination, fertilization, and seed set. If rain occurs at harvesting, it can lead to in vitro germination. Extreme temperatures and drought can manipulate seed quality and quantity, resulting in poor seed germination.

Future Research Directions:

More research is needed to understand the impact of temperature and drought on seed production and seed quality. Developing varieties that can produce higher seed yields under adverse biotic and abiotic conditions is crucial. Identifying new seed production areas and novel seed quality enhancement techniques can help mitigate the effects of climate change.

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MICROPLASTICS IN TERRESTRIAL AND FRESHWATER ECOSYSTEMS: SOURCES, IMPACTS, DETECTION AND REMEDIATION STRATEGIES

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Abstract:

Microplastics have emerged as ubiquitous and persistent contaminants in soil and freshwater ecosystems, driven by escalating plastic production and insufficient waste management practices worldwide. These particles, ranging from 1 micrometer to 5 millimeters in size, originate from primary sources like personal care products as well as from the breakdown of larger plastic items. Their presence disrupts soil physical and chemical properties, impairs microbial community structure, and adversely affects plant growth and physiological functions. In aquatic environments, microplastics are ingested by a broad spectrum of organisms, leading to bioaccumulation, physiological stress, and altered trophic dynamics, with potential repercussions for ecosystem resilience. Human exposure through ingestion and inhalation raises critical health concerns due to microplastics capacity to carry toxic substances and induce inflammatory and oxidative responses. Advanced detection methods such as Attenuated Total Reflectance–Micro Fourier Transform Infrared Spectroscopy (ATR-μFTIR), Raman spectroscopy and pyrolysis Gas Chromatography–Mass Spectrometry (pyrolysis GC-MS) allow for accurate characterization of microplastics, but difficulties persist in standardizing procedures and detecting the smallest particles. Remediation strategies encompassing physical, chemical, and particularly biological approaches such as microbial biodegradation are emerging as promising avenues for mitigating microplastic pollution. However, further research is necessary to optimize their effectiveness and ensure scalability for real-world application. This chapter provides an in-depth examination of microplastic contamination in terrestrial and freshwater environments, detailing their sources, environmental and health implications, advanced detection methodologies, and current remediation techniques. It also highlights critical research gaps and underscores the need for interdisciplinary collaboration to develop innovative, sustainable, and globally applicable solutions to address the escalating challenges posed by microplastic pollution.

Introduction:

Plastics have been produced since 1950 and are used extensively due to their low cost, flexibility, durability, light weight, corrosion resistance and excellent water resistance [1]. After the invention of plastics, its production has increased dramatically [2]. In 2023 the global plastic production was 400 million metric tons and in India it was about 18 million metric tons. Global manufacturing of the plastic is growing 3% every year. Only 10% of the plastic waste produced is recycled, 14% incinerated and the rest are dumped into landfills [3,4]. In general, plastic wastes arises from sources such as bags, disposable containers, textile fibers, footwears, furniture and electronic gadgets. Plastics are classified into various types based on their size including macroplastics, mesoplastics, microplastics and nanoplastics (Table 1) [5]. Microplastics are tiny plastic particles in the size range of 1 µm to 5mm. Among plastic pollutants, microplastics have garnered increasing attention as a major environmental pollutant because of their persistence, ubiquity, and ability to infiltrate diverse ecosystems. Their small size facilitates ingestion by a wide range of organisms, raising concerns about physiological damage, toxicological effects, and bioaccumulation within food webs [6]. Moreover, microplastics can act as vectors for harmful chemicals and pathogens, compounding their environmental threat. The ecological risks posed by microplastics arise from multiple factors. Their small size facilitates ingestion by a wide range of organisms, from microscopic soil fauna to fish and other aquatic life. Ingestion can lead to physiological issues such as digestive blockage, impaired feeding, and internal tissue damage. Furthermore, microplastics may carry pollutants that are adsorbed, including heavy metals and persistent organic chemicals, potentially introducing toxins into organisms and magnifying adverse effects through bioaccumulation and trophic transfer [7]. These impacts ultimately threaten ecosystem stability, biodiversity, and the health of species, including humans, that depend on these environments. Given the complexity and breadth of microplastic pollution, comprehensive understanding of their sources, fate, ecological impacts, and removal strategies is essential [8]. This chapter provides a comprehensive overview of microplastic pollution in soil and freshwater ecosystems. It explores their sources, environmental and biological impacts, current detection and characterization methods, and emerging physical, chemical, and biological remediation strategies. By synthesizing current knowledge and identifying critical research gaps, this work aims to support effective management and mitigation of microplastic pollution in terrestrial and aquatic environments.

Table 1: Classification of microplastics according to their size

Type of Plastics (based on size)	Size Range
Nanoplastics	<1 µm
Microplastics	1 µm to 5 mm
Mesoplastics	5 mm to 25 mm
Macroplastics	>25 mm

Sources of Microplastics

Microplastics are smaller particles measuring between 1 µm to 5mm. Generally, microplastics can be classified into types according to their sources, primary and the secondary microplastics. The microplastics which are intentionally produced are known as primary microplastics while the secondary microplastics originate from the degradation of larger plastic debris. Primary microplastics are produced for various purposes including use in the skincare and personal care products such as face washes, facial scrubs, toothpastes, shampoos, moisturizers [6]. Fragmentation of larger plastic debris occurs due to various reasons such as sunlight, heat, radiation, physical abrasion and the presence of microorganisms or their enzymes. The entry of microplastics into the river occurs through various sources such as passage through waste water treatment plants, run off from agricultural lands and urban areas, fishing activities, storm water overflow events, human activities, industrial products or processes and incidental release. The important reason for microplastics in freshwater environments is inappropriate and inadequate waste management practices [9]. Microplastics enters the soil through municipal solid wastes, landfills, soil amendments, application of sewage sludge as fertilizer, composting, agricultural mulch, sewage irrigation, runoff from roads and atmospheric deposition [2].

Impacts of Microplastics on Soil and Plants

Microplastics have been widely detected in terrestrial environments, particularly in agricultural and urban soils [8]. Their increasing accumulation in soil ecosystems raises concerns regarding their interactions with plants, soil health, and associated biota. The presence of microplastics in soil was reported to alter the physical, chemical and biological properties of soil. Microplastics affects the soil porosity, structure, fertility, drainage, water holding capacity, soil aggregate stability, bulk properties, soil and hydraulic conductivity. It also disturbs the soil microbial community and crop yield quality. Microplastics are ingested by the soil organisms leading to bioaccumulation and biomagnification, gradually enters the food chain [2]. Plants are directly affected by microplastics present in the surrounding soil environment. Several studies have reported the inhibitory effects of microplastics on plant physiology and development. Experimental findings indicate that exposure to primary microplastics can adversely affect root elongation in plants such as *Lemna minor*, suggesting that microplastics may physically or chemically alter the root microenvironment. Microplastics in the rhizosphere may interfere with the uptake of essential nutrients and water, potentially leading to growth retardation and physiological stress. Some studies have indicated that microplastics may induce oxidative stress in plants, altering enzymatic activity and photosynthetic efficiency [8].

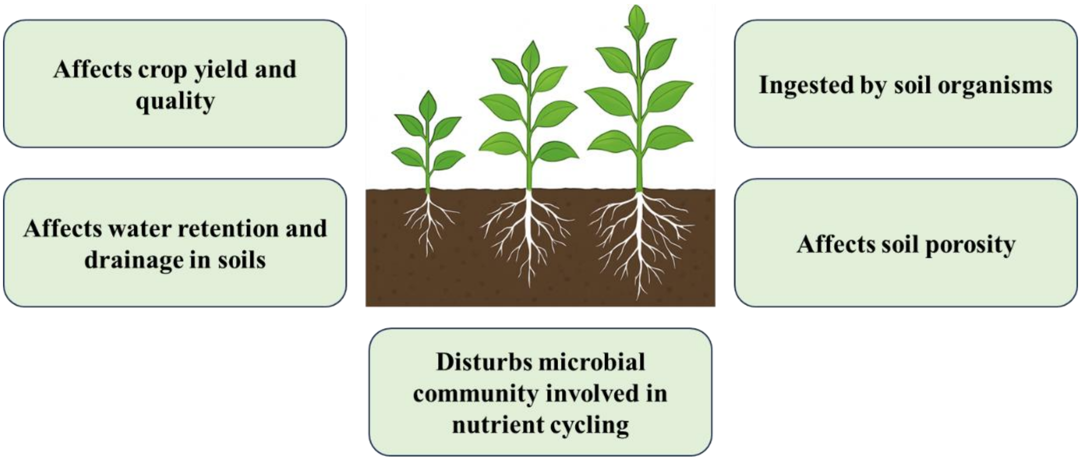

Fig. 1: Impacts of microplastics on soil

Impacts of Microplastics on Aquatic Biota

Microplastics represent a pervasive and complex environmental threat in aquatic systems. Due to their smaller size, microplastics can be easily ingested by a wide variety of aquatic organisms. Their resistance to degradation contributes to their long-term persistence in aquatic environments, enabling sustained interaction with aquatic biota. Aquatic organisms including zooplanktons, benthic vertebrates, fishes, bivalves and larger aquatic mammals, can ingest microplastics often mistaking them for food. and, in some cases, translocate to other tissues. Aquatic organisms exhibit a range of physiological and ecological responses to microplastic exposure, including digestive tract damage, growth inhibition, and bioaccumulation [10]. Accumulated microplastics can physically obstruct and damage digestive organs, inducing a false sense of satiety, leading to reduced food intake. Microplastics interfere with nutrient absorption and digestion, causing metabolic stress. Exposure to microplastics has been associated with reduced growth rates and compromised physiological conditions. In organisms such as the blue mussel (*Mytilus edulis*), Microplastics with diameters of 3.0 to 9.6 μm have been found in the hemolymph, suggesting their ability to cross biological barriers. In contrast, larger particles (>20 μm) are more likely to be excreted without tissue penetration. Repeated exposure can lead to bioaccumulation within tissues, potentially affecting long-term health and fitness. Through bioaccumulation and trophic transfer, microplastics can alter food web dynamics and reduce biodiversity, ultimately affecting ecosystem resilience. Microplastics also contribute to biomagnification as they travel through the food chain, progressively accumulating in higher trophic levels and ultimately posing risks to top predators, including humans [8].

Fig. 2: Biomagnification of microplastics along the food chain

Impacts of Microplastics on Human Health

The presence of microplastics in the environment is found to be highly toxic to various life forms including human beings, terrestrial organisms, aquatic organisms and plants [11]. Humans are exposed to microplastics through various routes such as ingestion, inhalation and thermal contact. The main way humans are exposed to microplastics is through ingestion. Ingestion of microplastics occurs via food packaging, drinking water, seafoods and salt contaminated with microplastics. Since microplastics are tiny particles, they float in the air and when we breathe in these particles enters our lungs [12]. The principal location of microplastic accumulation is the digestive tract. The severity of inflammatory bowel disease (IBD) is positively correlated with microplastic exposure, and they can alter the gut microbiome, disrupt intestinal barrier integrity, and trigger chronic inflammation. Moreover, inhaled microplastics can induce respiratory irritation, fibrosis, and potentially exacerbate conditions such as asthma and chronic obstructive pulmonary disease (COPD). Microplastics may translocate into the bloodstream and reach secondary organs, including the liver, spleen, and even the brain, where they can cause oxidative stress, cytotoxicity, and immune dysfunction. They also act as carriers of hazardous chemicals, heavy metals, and pathogenic microorganisms, amplifying their toxic effects and posing risks of endocrine disruption, reproductive toxicity, neurotoxicity, and genotoxicity. Continuous exposure raises concerns about bioaccumulation and long-term health consequences, including metabolic disorders and increased susceptibility to cancers [7].

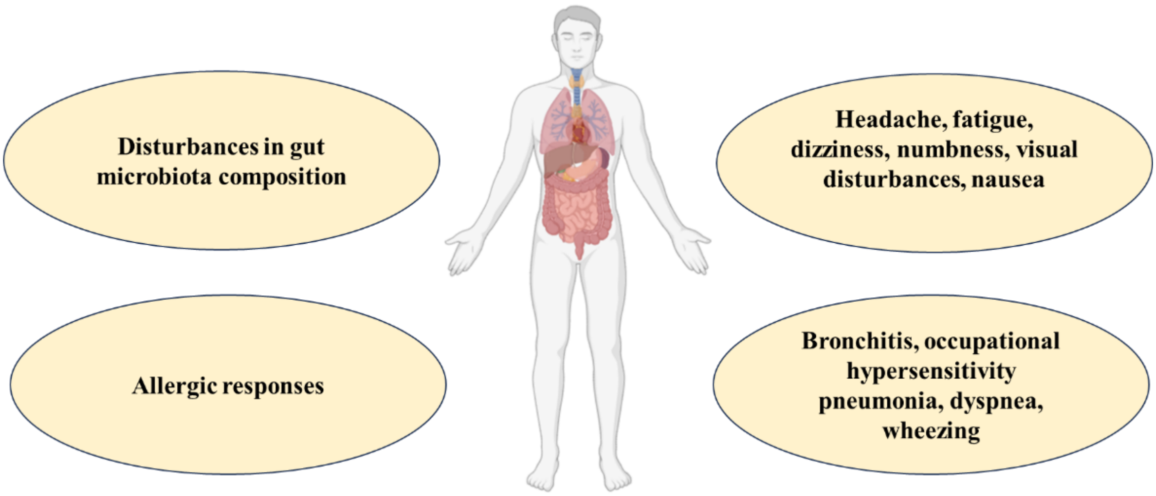

Fig. 3: Impacts of microplastics on human health

Methods to Isolate Microplastics from Soil and Freshwater Habitats

The isolation of microplastics from environmental matrices such as freshwater and soil requires precise sampling methods, separation from natural debris, and accurate identification techniques to ensure reliable analysis. In freshwater systems, surface or sub-surface samples from 0–18 cm depth can be collected using pumps, polycarbonate tubes, or buckets typically ranging from 0.3–25 L. These are filtered through fine mesh with pore sizes between 2.7–63 µm to capture small microplastics, including thin fibers [13]. To eliminate organic matter that may interfere with microplastic detection and identification, chemical digestion is commonly employed using oxidizing agents such as hydrogen peroxide (H_2O_2) and alkaline solutions like potassium hydroxide (KOH). These reagents effectively break down biological materials without degrading most synthetic polymers, thereby improving sample clarity and accuracy in subsequent analytical procedures [10].

Detection and Characterization of Microplastics

Identification and quantification of microplastics rely heavily on spectroscopic methods, considered the gold standard for polymer identification. Visual inspection and microscopic examination are the quick and easy way to understand about the surface properties of microplastics, but they have a high identification error rate and cannot identify microplastics less than 100 µm. Pyrolysis GCMS is a powerful method that breaks down plastics with heat to identify their composition, but it degrades the structure of the microplastics, also there is an increased possibility of misidentification because different microplastics may yield similar degradation products. Spectroscopic techniques like Fourier Transform Infrared Spectroscopy (FTIR) and Raman spectroscopy are commonly used for polymer identification [2]. For basic characterization, Scanning Electron Microscopy (SEM) coupled with Energy-Dispersive X-ray Spectroscopy (EDS/XEDS) is commonly employed to analyze the surface morphology and elemental composition of particles. While this method provides valuable insights into particle structure and the presence of inorganic elements, it cannot independently confirm the polymeric nature of microplastics and must be complemented with spectroscopic techniques for definitive identification [14]. ATR-µFTIR use both microscopy and spectroscopy to identify microplastics with high accuracy, without needing chemical treatment [15].

Analytical Techniques for the Assessment of Microplastics Biodegradation

A variety of analytical techniques are employed to evaluate microplastic biodegradation. Morphological and surface alterations can be examined using Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) [16]. High-Performance Gel Permeation Chromatography (HP-GPC) helps determine any significant changes in the molecular weight of the plastics. Changes in polymer crystallinity can be assessed through X-ray Diffraction (XRD). Gravimetric weight loss analysis provides insights into the percentage reduction in polymer mass. Gas Chromatography–Mass Spectrometry (GC-MS) is used to identify degradation metabolites, including bio-fragments and saturated linear alkanes, present in the culture medium. Additionally, FTIR detects specific polar functional groups, such as ester carbonyls and ketones, enabling quantification of oxidative degradation pathways [17].

Physical Approaches for Microplastic Removal

Physical remediation involves mechanical processes to separate or extract microplastics from contaminated environments. Techniques like filtration and sieving are widely used in wastewater treatment plants to trap microplastics using fine mesh filters. Sedimentation and flotation rely on density differences, where lighter particles float and heavier ones settle out. Magnetic separation is gaining attention by using surface-functionalized magnetic materials such as magnetic biochar to attract microplastics. Additionally, adsorption techniques using materials like activated carbon or biochar can trap microplastics on their porous surfaces, aiding in removal from water systems [17,18].

Chemical Approaches for Microplastic Removal

Chemical strategies aim to degrade or transform plastic polymers through specific reactions. Advanced Oxidation Processes (AOPs), including ozone treatment, UV radiation, or Fenton reactions, generate reactive oxygen species capable of breaking down plastic molecules. Chemical coagulation and flocculation help aggregate microplastics using coagulants like alum or ferric chloride, making them easier to remove through sedimentation or filtration. In some laboratory-scale approaches, solvent extraction or dissolution is applied to dissolve plastic selectively, though its environmental safety and scalability remain concerns [19].

Biological Approaches for Microplastic Removal

Biodegradation of microplastics is the process in which the microplastics are broken down by organisms or microorganisms or the enzymes produced by them. Biodegradation of microplastics can be studied under laboratory conditions by screening and isolating plastic degrading microorganisms from plastic polluted areas, followed by evaluating their degradation efficiency using standard analytical techniques. Plastics possess a carbon-carbon backbone structure, that serve as a carbon and energy source for the growth and reproduction of microorganisms. Utilization of plastics as a source of carbon and energy ultimately leads to the biodegradation of plastics [16]. One of the most promising strategies in biological remediation is microbial degradation, where specific strains of bacteria and fungi are capable of breaking down plastic polymers. These microbes colonize the plastic surface, forming a biofilm, and secrete extracellular enzymes that cleave the polymer chains. Notable plastic-degrading microorganisms include *Pseudomonas*, *Bacillus*, *Aspergillus*, and *Penicillium* species. For instance, *Ideonella sakaiensis* has been shown to degrade PET (polyethylene terephthalate) using enzymes like PETase and MHETase [20]. The effectiveness of microbial degradation depends on several factors such as the polymer type, surface area, bioavailability, and environmental conditions like pH, temperature, and oxygen levels. While microbial degradation of natural polymers (like starch or cellulose) is well-established, synthetic plastics like polyethylene (PE), polypropylene

(PP), and polystyrene (PS) degrade more slowly and require pretreatment or extended incubation periods [21].

Conclusion and Future Perspectives:

Future research on microplastic remediation should prioritize developing efficient, scalable, and environmentally sustainable technologies applicable across diverse soil and freshwater systems. Emphasis is needed on optimizing biological degradation processes, including identifying and engineering microbial strains and enzymes with enhanced plastic-degrading capabilities under varying environmental conditions. Additionally, integrating biological methods with physical and chemical treatments could improve overall removal efficiency and reduce secondary pollution. Research should also focus on understanding the fate and transformation of microplastics during remediation to ensure complete mineralization rather than partial breakdown into smaller particles. Assessing the ecological safety and long-term impacts of remediation agents and byproducts is critical. Translating laboratory successes to field-scale applications and developing cost-effective strategies suitable for real-world scenarios will be essential for effective mitigation of microplastic pollution.

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EFFECT OF SEED NANO-PRIMING ON ABIOTIC STRESS

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Introduction:

Presently, agricultural areas throughout the world face several obstacles due to fluctuations in climate, degradation in environment and usage of fertilizer and pesticide to meet the growing demand for food from the population (Pouratashi and Iravani, 2012). A new United Nation report claims that projection, the current the 7.6 billion people on the planet will grow to 8.5 billion and 9.8 billion by 2030 and 2050 respectively and 11.2 billion by 2100. Over half of food production must increase to fulfil the demands of the expanding global populace (Mittal *et al.,* 2020). This goal can only be achieved by combining technological intervention with new, upgraded management practices and regulations. The use of nanotechnology has transformed science and technology all around the world. Numerous agricultural uses are made possible by nanomaterials because of their special qualities. Nanomaterials can increase cropping systems' all things considered usage effectiveness with respect to inputs of agrochemicals (light, water, and pesticides) by providing a more efficient certain delivery method. By enhancing disease management, they can also reduce crop losses (Siddiqui *et al.,* 2015). Furthermore, crop stress management and agrochemical inefficiency were addressed by nanotechnology through the use of nano pesticides, nanosensors, and nano fertilizers (White and Torresdey, 2018). Since seeds are the primary and most vital component for crop establishment, the creation of more biotic and abiotic-resistant seeds can therefore address the problems of increased production and loss as a result of environmental limits. Seed priming provides long-term resistance to a range of plant stressors, such as salt, dehydration, and heavy metal toxicity, and is a state-of-the-art technique for boosting seed germination rates, crop yield, and seedling development. Using nanoparticles as priming agents, researchers have recently incorporated nanotechnology into standard seed priming methods to encourage the development of plants and production (Maroufi *et al.,* 2011). Nano-priming seeds can be used to accelerate both emergence of seedling and germination, which are the two primary aspects that define a plant's capacity to effectively establish itself under unfavourable conditions. Since seed nano-priming has been demonstrated to alter plant growth and development under both biotic and abiotic stresses, it is essential for preserving agriculture and boosting agricultural yields.

Role of Nanotechnology in Plants

The emerging field of nanotechnology has impacted every aspect of life and ignited a fresh revolution in science. Particles that are produced at nano scale and have one or more dimensions that are less than 100 nm are the basis of nanotechnology. Nanotechnology is likely to provide a new platform for achieving a dynamic equilibrium between farming output and sustainability of the environment. The agro-technological uprising has benefited from its ability to monitor a critical agricultural management process because of its modest size. Experts have also taken notice of its many potential benefits, which include increased food safety and quality, greater crop output and stress tolerance, soil nutrient absorption, less use of agricultural inputs, and more.

Seed Nano-Priming

Seed nano-priming is an efficient method that alters the seed metabolism and their signalling pathways to influence germination, establishment, and the lifecycle of plants. Numerous Researches has shown that many advantages of seed nano-priming, encompassing improved plant development and growth as well as increased nutritional status. While keeping the equilibrium between plant growth hormones and ROS, nano-priming can regulate biological processes. It is used to control physiology under abiotic stress, increase plant development and metabolism, and encourage synchrony in germination. Furthermore, it strengthens crops' biotic or abiotic stresses resistance, which lessens the need for fertilizers and pesticides. Numerous genes, including those related to plant stress tolerance, can be activated during germination by seed nano-priming, according to recent research. Initial results in the new area of seed priming for nanoparticle application have proven promising. Since many NPs include antimicrobial compounds that give them antibacterial properties, they can also be employed to preserve seeds. Furthermore, nano-priming may be used to focus on seed biofortification in order to improve food quality and production. After priming, nanoparticles go to and remain in the seed tissues. To promote plant growth and development, seed nano-priming uses metal, ceramic (metal oxides), carbon, and polymeric nanoparticles. Numerous studies suggest that metal oxide-derived nanoparticles may enhance physiology, seed germination, and seedling growth (Du *et al.,* 2017). Carbon-based NPs, like fullerene and carbon nanotubes, and metal-based NPs, like AgNPs, ZnONPs, AuNPs, ZnNPs, CuNPs, TiO_2NPs, FeNPs, FeS2NPs, MnNPs, Fe2O3, Si, CeO_2, FeO, and nZVI, have been used as priming agents in recent years to enhance crop plant stress tolerance, seed germination, and seedling growth (Mahakham *et al.,* 2017).

Mechanism of Seed Nano-Priming

Germination of seeds is the first and most important step in plantings to improve the quality of crops and yield. To guarantee the quality and output of agricultural plants, a range of techniques and treatments are applied prior to seeding. Seed priming was one of the fundamental methods that Heydecker first employed in 1973. In order for the seeds to sprout, priming entails partially wetting them with the solution, yet insufficient to let the radicle pierce the seed covering. Physical priming, nano-priming, hormonal priming, bio-priming, nutritional priming, hydro-priming, osmo-priming, and more sophisticated methods are the three categories under which a variety of priming approaches have been reported (Waqas *et al.,* 2019). Hydropriming, which includes soaking seeds in water before planting to speed up the germination processes, is the most widely used and cost-effective method. Bewley, (1997) and Taiz *et al.,* (2015) state that seed germination occurs in three stages: Due to low water potential, water movement Synthesis of proteins from the accessible DNA and RNAs in the apoplastic area, and mitochondrial repair, dry seeds imbibe water quickly in phase I; water imbibition decreases in phase II, reactivating metabolic activities such as protein synthesis and mRNA and promoting embryo expansion; and water uptake resumes in phase III, mobilizing stored food and causing radicle protrusion linked to cell elongation. Phases I and III of primed and non-primed seeds are identical, but phase II of primed seeds is prolonged by hydration, allowing for controlled water absorption and starting the metabolic activities that occur before germination (Rajjou *et al.,* 2012). Regulated water intake is the most crucial factor in phase II seed germination. Compared to phase III, environmental factors are more significant in this phase (Côme and Thévenot, 1982). After priming, seeds are dried and kept at their initial moisture content to maintain the priming treatment's efficacy and avoid seed degeneration (Varier *et al.,* 2010 and Ratikanta, 2011). Dehydration encourages the preservation of primed seeds; however, storage conditions and dehydration affect seed viability (Gurusinghe and Bradford, 2001). Multiple cellular activities, including the process of creating proteins and nucleic acids from scratch, the creation of ATP, the accumulation of phospholipids and sterols, the activation of the DNA repair system, and the antioxidant system, are triggered by successive rehydration during the sowing phase (Panda and Mondal, 2020).

Although the complete signalling and crosstalk of phytohormones in germination has not yet been well defined, researchers have found that the abscisic acid (ABA)/gibberellic acid (GA) balance ratio controls water uptake by changing the water potential threshold during germination (Rodriguezgacio *et al.,* 2009). Furthermore, PIP2, NIP1, TIP3, and TIP4 are among the genes in the aquaporin family that are regulated by ABA when seeds begin to germinate (Footitt *et al.,* 2019). Auxin's function, which in conjunction with ABA, facilitated the attachment to the seed coat of nanoparticles and their passage from the endosperm to the seed coat with respect to elongation of hypocotyl (Watahiki and Yamamoto, 1997). According to Guha *et al.,* (2018) the internalization of nanoparticles, which function in seeds as an exterior agent, triggers downstream routes of signaling and results in the build-up of ROS. By linking ABA and GA, this disrupts Dormancy of seeds in nano-primed seeds; however, for phytohormones other than ABA/GA, the movement of ROS influx between cells is unclear (Mahakham *et al.,* 2017). Nano-priming boosted the activity of α-amylase, a key component in the digestion of starch. Little is known about GA signalling factors and the crosstalk pathway involved in degradation of starch since GA regulates the induction and synthesis of the enzyme in nano-primed seeds (Man *et al.,* 2013 and Mahakham *et al.,* 2017).

Seed Nano-Priming Effect on Abiotic Stress

Nanoparticles can improve a plant's tolerance to environmental stresses by directly altering the metabolism of plants and seeds and stopping the creation of hormones. ROS generation, which are Participating in several metabolic processes, increases in tandem with storage proteins being mobilized and the quantity of phytohormones. NPs are capable of also enhanced the seed's ability to absorb water, which will increase the enzyme activity. Additionally, NPs lessen the quantity of excess ROS generated in the seed when subjected to abiotic stress by increasing the ability of enzymes like Superoxide dismutase, Catalase, and guaiacol-peroxidase to prevent seed cell damage. Reactive oxygen species (ROS), antioxidant content, germination rate, and metabolic capacity are all reduced if seeds are kept for a long time at low temperatures. Even at late stages, the application of Nanoparticles can improve germination and raise the reactive oxygen species (ROS) level in seedlings. The amount of ROS in seeds can be decreased by adding a variety of compounds to the biogenic Nanoparticles.

Heavy Metal Stress

Heavy metal stress is a major environmental issue that affects all living things and drastically lowers agricultural output (Irshad *et al.,* 2020 and Javaid, 2020). However, it appears that seed nano-priming increases plant tolerance to a number of metal toxicities. In addition to rapid germination, Si-primed wheat seeds demonstrated enhanced growth, biomass, and rate of photosynthesis, transpiration, and stomata conductance, amount of chlorophyll a and b and carotenoid content. It also had reduced levels of ROS, H_2O_2, EL, and malondialdehyde in cadmium-polluted soil, as well as improved antioxidative defense enzymes. The greatest reduction in Cd content was seen in the shoot (10–52%), roots (11–60%), and grain (12–75%) at a concentration of 1200 mg l^{-1} of Si NPs (Hussain *et al.,* 2019). Likewise, priming wheat seeds with zinc oxide (ZnO) and iron (Fe) nanoparticles improved development, the antioxidative defense system, and the toxicity of Cd while lowering Cd stress. This might be as a result of raising the zinc and iron content, which lessens the micronutrients' hidden hunger and, consequently, the buildup of Cd (Rizwan *et al.,* 2018). The ZIP family's iron transporters IRT1 and IRT2, and YSL15, YSL18, and YSL2 (YSL family) are the main ways that Cd is absorbed since it lacks a distinct transporter and is mostly associated with iron (Gao *et al.,* 2016). The study looked at the rice Fe transporters' inconsistent gene expression pattern. Under Cadmium stress, the genes OsIRT1 and OsYSL2 were significantly elevated, whereas the genes in nZVI and Cd-treated plants were significantly downregulated. Nonetheless, the control and ZVItreated plants showed the same pattern of expression (Guha *et al.,* 2020). Accordingly, Nano particles of copper produced biosynthesized in wheat improved growth and development of plant by lowering the quantity of Cr in the shoot and root, hence lowering Chromium stress and inhibiting Chromium transfer to other plant components (Noman *et al.,* 2020). Ragab and Saad-Allah (2020) investigated the effects of selenium on manganese-stressed *Helianthus annuus* (L.). Vitamin C, total flavonoid content, total phenolic compounds, CAT and SOD activity all increased in seedlings. By reducing oxidative stress and bolstering the antioxidative defense system, manganese toxicity is reduced. since a considerable drop in GSH activity may also facilitate the synthesis of chelating ligands.

Drought/Water Stress

Drought has a major impact on agricultural productivity and is one of the most important abiotic stressors in the globe. Unpredictable global climate change-induced irregular rainfall patterns are the main factor contributing to the global occurrence of drought stress on a regular basis (Lobell *et al.,* 2011). Water and various other elements were essential for plants. to survive. A lack of water in the soil has an impact on every aspect of plant development and growth. This loss of water affects the physiological and metabolic processes of plants (Sarker *et al.,* 2005, Sircelj *et al.,* 2005 and Silva *et al.,* 2009). Reduced agricultural yield is associated with a lack of water and nutrients. According to Poormohammad Kiani *et al.,* (2007) and Farooq *et al.,* (2009), drought mainly affects plant development by reducing the rate of cell division and water consumption effectiveness leaf growthand elongation of stem, reduced degradation of turgor pressure and enzymatic activity, decreased energy source and the growth of roots. Rai-Kalal *et al.,* (2021) discovered that SiO_2 nano-priming treatment lessens stress caused by drought in wheat plants by increasing the effectiveness of photosynthetic characteristics, such as more reaction centers that are active, greater absorbance, a mechanism of trapping and an enhanced rate of electron transfer. This is accomplished by maintaining biochemical equilibrium and reducing the inhibition of photosynthetic machinery brought on by stress, which eventually leads to an increase in biomass.

Salinity Stress

Salinity, sometimes referred to as salt stress, is the detrimental impact that excess minerals such as chloride ions (Cl^-) and sodium ions (Na+) have on plants (Munns, 2005). Salt stress reduces production, efficiency, and nutritional value of crops globally, making it a significant environmental issue for sustainable agriculture (Sharifi *et al.,* 2007). According to Jamil *et al.,* (2011), 20% of the global's arable land is already having a salt stress condition, and 50% of dry land is expected to become salinized by 2050. Numerous Researches has indicated that nano-priming helps plants mitigate the negative consequences of salt stress. Seedlings of *Lactuca sativa L.* stimulated with Silicon nanoparticles under salt stress showed salt tolerance by lowering malondialdehyde and H_2O_2 levels, boosting the enzymatic activity of antioxidants and enhancing germination properties. This led to a significant improvement in the seedlings' total plant tolerance (Alves Rde *et al.,* 2020). Additionally, the suppression of seedling development by various doses was reversed when nano-TiO_2 was used for *Paeonia suffruticosa* seed priming. While photosynthetic activity decreased, the 48-hour priming period increased germination indicators, antioxidant enzymatic activity (SOD, CAT, and peroxidase), the number of lateral roots, and the quantity of chlorophyll content. *Zea mays* L. seeds primed with 1000 mg l^{-1} nMPs (mango peel nanoparticles) at five distinct salinity levels (0, 2.5, 6.5, 9.5, and 12.5 dS m^{-1}) were investigated in a separate research. According to the findings, priming reversed the suppression of the vigor index, fresh and dried seedling weight, radicle and plumule length, and germination % (Elkhatib *et al.,* 2019). Increased cell proliferation in the seedling roots' apical meristem might be the cause of this (Farooq *et al.,* 2007). A similar result was observed for barley seedlings (*Hordeum vulgare* L.) in terms of the induction of nano-TiO2 against inhibition of germination and seedling development (Değer and Çevik, 2021). After priming-influenced seed imbibition with an increase in linoleic and linolenic acids under salinity stress, ZnONPs priming in Brassica napus changes the transcriptional level of expression of two genes, BnCAM and BnPER, this shows that the BnPER expression pattern and seed germination have improved (El-Badri *et al.,* 2021).

Conclusion:

The broad use of nanotechnology in agriculture is hampered by concerns about environmental safety and probable high costs, despite the fact that nanoparticles may increase plant stress tolerance. Nanopriming has demonstrated the unavoidable capacity to improve seed germination and seedling growth under abiotic stresses like as salt and drought. Based on the reviewed reports, we assume that the simulative effects of NMs are associated with increasing α-amylase activities, increasing soluble sugar contents, accelerating seed water uptake, and regulating the relative expression level of genes involved in ion equilibrium, antioxidant enzymes, and the ABA/GA ratio. Nanompriming can provide substantial advantages that reduce ecological risk and cost by using a modest dosage of NMs. Understanding the physico-chemical properties of the NMs and how they affect germination and the environment is crucial. Enhancing plant tolerance to abiotic stressors may be made easier by designing NMs with the best-fitting nanopriming characteristics, such as size and zeta potential. The seed coat structure varies among crop species. We assume that crop species with fewer layers of parenchyma cells and larger intracellular spaces may require a lower dosage of NMs to improve seed germination, whereas crop species with multiple layers of parenchyma cells and smaller intracellular spaces may require NMs with smaller sizes, a high zeta potential, and a higher dosage. NMs enter the seed through the intracellular spaces between the parenchyma cells.

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PRODUCTION OF ALTERNATIVE SOURCES OF BIOETHANOL FROM MAIZE GRAIN AND SUGARCANE

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Abstract:

Bioethanol, a renewable biofuel derived from fermentation of sugars in crops like maize and sugarcane, serves as a sustainable alternative to fossil fuels. Its production not only reduces greenhouse gas emissions but also promotes energy security and rural economic development. India has witnessed significant growth in bioethanol output, rising from 2057 million liters in 2013 to 6300 million liters in 2023, driven by ethanol blending policies and technological advancements. While first-generation bioethanol relies on food crops, second- and third-generation variants use agricultural residues and algae, offering improved sustainability. Despite progress, India faces challenges such as limited feedstock diversification, water-intensive sugarcane reliance, and supply-demand gaps. Notably, innovative approaches like tamarind pulp syrup (TPS) supplementation and enzymatic conversion of TrAPU maize seeds enhanced ethanol yield and efficiency. Additionally, among sugarcane top pretreatment methods, a mixture of glycerol, NaOH, and $FeCl_3$ showed the highest ethanol production (31.9 g/L). With continued support for second-generation technologies and regional capacity-building, bioethanol has the potential to significantly contribute to India's renewable energy transition and reduce reliance on fossil fuels.

Keywords: Bioethanol, Maize, Sugarcane, Production technology, Sustanability

Introduction:

Bioethanol, an alcohol produced by fermenting plant sugars, is a key renewable energy source that helps reduce carbon emissions and fossil fuel dependency. Maize (rich in starch) and sugarcane (rich in sucrose) are the primary feedstocks due to their high carbohydrate content and widespread availability.

Sugarcane-based ethanol, especially in Brazil, offers high energy yield per hectare, while maize dominates in countries like the U.S. Despite challenges such as land competition, water use, and energy balance concerns, technological advances are improving production efficiency and sustainability.

Bioethanol supports energy security, lowers greenhouse gas emissions, and benefits agricultural economies. This seminar discusses production processes, innovations, and sustainability challenges, emphasizing bioethanol's role in a greener energy future.

Biofuels:

Biofuels are renewable energy sources derived from organic materials such as plants, agricultural waste and even algae. They serve as alternatives to conventional fossil fuels like petroleum, coal and natural gas, offering a cleaner and more sustainable option for powering vehicles, generating electricity and providing heat. Biofuels are produced through biological processes like fermentation, anaerobic digestion and chemical reactions which making them part of the broader category of "biomass energy".

Biofuels are divided in two types:

1. **Bioethanol:** Bioethanol is a renewable biofuel made by fermenting sugars from crops like maize, sugarcane, wheat, and barley. It serves as a cleaner alternative to gasoline, used either pure or blended with fossil fuels for vehicle fuel.
2. **Biogas:** Biogas is a renewable energy produced via anaerobic digestion of organic waste like manure, food scraps, and sewage. It mainly contains methane and carbon dioxide, offering a clean, sustainable alternative to fossil fuels with environmental and economic benefits.

Comparison between Bioethanol and Petrol:

i. Sources:

- **Bioethanol**: A renewable biofuel made by fermenting sugars from crops like maize, sugarcane, and wheat.
- **Petrol**: A non-renewable fossil fuel obtained from crude oil through refining.

ii. Carbon Emissions:

- **Bioethanol**: Emits less CO_2 than petrol; the crops used absorb CO_2 during growth, contributing to a balanced carbon cycle.
- **Petrol**: Emits high levels of CO_2, SOx, and NOx, significantly contributing to air pollution and climate change.

iii. Energy Content:

- **Bioethanol**: Contains about 66% of the energy of petrol per litre, leading to lower fuel efficiency.
- **Petrol**: Higher energy content per litre, offering better fuel efficiency than bioethanol.

iv. Combustion:

- **Bioethanol**: Burns cleaner than petrol, emitting less CO, particulate matter, and unburnt hydrocarbons due to its high oxygen content.
- **Petrol**: Emits more pollutants from incomplete combustion, contributing to air pollution and health problems.

v. Environmental Impact:

- **Bioethanol**: Reduces reliance on fossil fuels and supports sustainable agriculture, but large-scale production may affect land use, water resources, and food security.
- **Petrol**: Causes major environmental damage through extraction and use, including oil spills, habitat loss, air pollution, and significant greenhouse gas emissions.

vi. Economic and Energy Security:

- **Bioethanol:** Can enhance energy security by reducing oil imports and supporting local economies, though large-scale production involves high infrastructure and processing costs.
- **Petrol:** Globally available but dominated by few exporters; subject to price volatility, posing risks to energy security for import-dependent nations.

Vii. Usage:

- **Bioethanol:** Commonly blended with petrol (e.g., E10, E85) and used in standard engines or flex-fuel vehicles with minimal modifications.
- **Petrol**: Still the dominant vehicle fuel globally, but its use is declining as biofuels and EVs gain popularity for environmental reasons.

viii. Cost:

- **Bioethanol**: More expensive to produce due to agricultural and processing costs, though subsidies can reduce the price.
- **Petrol**: Generally cheaper due to mature infrastructure, but prices are volatile and influenced by global oil markets.

World Bioethanol production: Global Bioethanol Production

Bioethanol, made from crops like maize and sugarcane, is a key renewable fuel. The U.S. (using corn) and Brazil (using sugarcane) lead production, with other countries like India and the EU expanding efforts. Used mainly as a petrol additive, it helps cut emissions. Growth in second-generation bioethanol from non-food biomass enhances sustainability and energy security.

India's Ethanol Status:

- 2009: India’s National Policy on Biofuels launched by the Ministry of New and Renewable Energy.

- 2013: Ethanol Blended Petrol (EBP) programme mandated 5% ethanol blending.
- 2018: Updated biofuel policy introduced to enhance adoption and awareness.
- 2022: Achieved 10% ethanol blending; target set for 20% blending by 2030.

But ethanol story in India has not fully succeeded due to several challenges, such as: Short fall in ethanol supplies, heavy water-intensive sugarcane, limited use of alternative feedstocks like maize or agricultural waste, insufficient blending and distribution infrastructure, fluctuating production costs, dependency on subsidies, and inconsistent government policies. Concerns over water and land usage further hinder progress.

Table 1: Ethanol demand and supply in India

Sl. No.	Year	Ethanol demand (crore liters)	Actual supply (crore liters)
1	2015-16	266.0	111.0
2	2016-17	280.0	65.5
3	2017-18	313.0	150.0
4	2018-19	329.0	189.6
5	2019-20	511.0	173.0
6	2020-21	371.0	302.3
7	2021-22	650	358.0
8	2022-23	800-900	400-500
9	2023-24	1000-1100	600-700
10	2024-25	**1350**	**1016**

The data from 2015-16 to 2024-25 highlights the trends in ethanol demand and supply in India. Ethanol demand has grown significantly, increasing from 266 crore liters in 2015-16 to 1350 crore liters in 2024-25. Actual supply has also improved during this period, rising from 111 crore liters to 1016 crore liters. the supply consistently falls short of the demand, creating a gap each year.

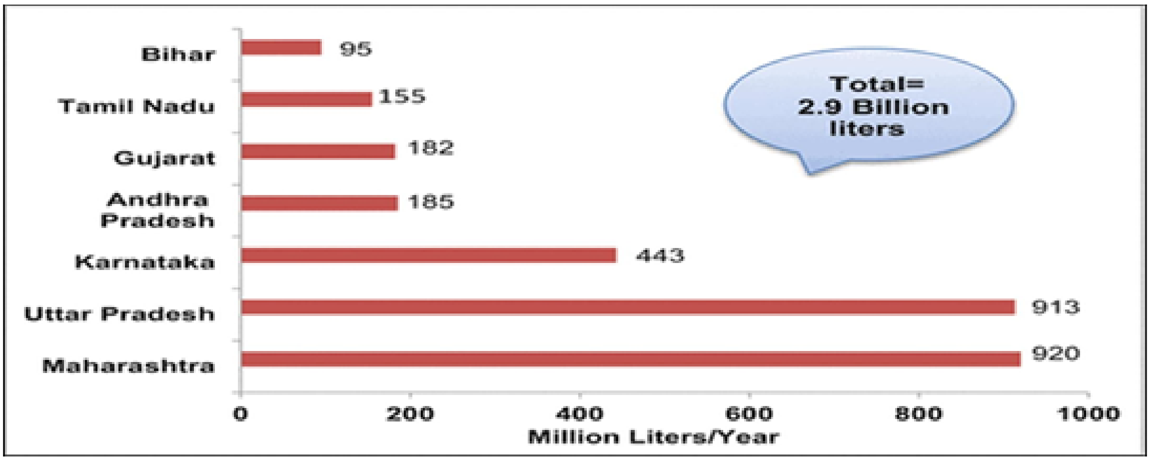

Fig 1. Production of bioethanol in India

State-wise Bioethanol Production in India (2022) India produced 2.9 billion liters of bioethanol in 2022. Maharashtra (920 M L) and Uttar Pradesh (913 M L) were top producers, driven by strong sugarcane cultivation. Karnataka (443 M L) ranked next, followed by Andhra Pradesh (185 M L) and Gujarat (182 M L). Tamil Nadu (155 M L) and Bihar (95 M L) contributed less, likely due to limited sugarcane or fewer production units. The data underscores the role of sugarcane-rich states in advancing India's bioethanol goals.

Commercial second-generation bioethanol refineries at India, among different states in India, Numaligarh refineries limited at Assam produced 187 kl day^{-1} which is highest producer, our state Karnataka Mangalore refineries petro-chemical limited produce 60 kl day^{-1} located at Davangere.

1. **First generation bioethanol (1G):** 1G bioethanol is produced from food crops like sugarcane, corn, wheat, and barley through fermentation and distillation. It uses established technology and supports agriculture, benefiting rural economies. However, it raises concerns over food security, land use, and sustainability due to its reliance on food crops and resource-intensive production. Despite a lower energy return, it is widely used in fuel blends like E10 and E85. Interest is growing in second- and third-generation bioethanol, which use non-food biomass for more sustainable production.
2. **Second generation bioethanol (2G):** 2G bioethanol is produced from non-food biomass such as agricultural and forestry residues, and energy crops like switchgrass. Unlike 1G bioethanol, it avoids food vs. fuel issues and promotes waste utilization. The process involves complex pretreatment and enzymatic hydrolysis to convert lignocellulosic material into fermentable sugars, followed by fermentation, distillation, and dehydration. Though more sustainable and potentially lower in emissions, 2G bioethanol faces challenges like high production costs, complex technology, and limited commercial scale. However, it holds strong promise for the future, with ongoing research aiming to improve efficiency and cost-effectiveness.
3. **Third generation bioethanol (3G):** 3G bioethanol is produced from algae (microalgae and macroalgae), avoiding food vs. fuel issues by using non-arable land and wastewater. Algae's high growth rate and CO_2 absorption make it a promising feedstock. Carbohydrates from algae are fermented into ethanol; lipids may also be used for biodiesel. While 3G bioethanol offers high yield potential and environmental benefits, it faces challenges like high production costs, technical complexity, and infrastructure needs. Continued research aims to make it a viable and sustainable future energy source.
4. **Fourth generation bioethanol (4G):** 4G bioethanol utilizes genetic engineering and synthetic biology to enhance ethanol production. Genetically modified microorganisms (e.g., bacteria, yeast, algae) are designed to ferment a wider range of substrates, including

industrial waste, for higher yields. It also explores integrated systems that combine bioethanol production with carbon capture**,** improving sustainability. Engineered feedstocks with enhanced traits can further boost efficiency. However, high R&D costs, technological complexity, and concerns over GMOs present major challenges. Despite this, 4G bioethanol offers promising potential for a highly efficient and low-emission biofuel future.

Raw Materials for Bioethanol Production

- Sugar-rich feedstocks: Sugarcane, sugar beet, sweet sorghum
- Starch-based feedstocks: Maize, wheat
- Lignocellulosic biomass: Agricultural residues, wood waste, fruit and vegetable waste

Steps in Bioethanol Production

1. **Feedstock Preparation**
   - **Harvesting**: Collection of raw materials (e.g., sugarcane, corn, residues, algae).
   - **Preprocessing**: Cleaning, grinding, or milling to prepare for conversion.
2. **Feedstock Conversion**
   - **1G Bioethanol**:
     - **Sugar Extraction** (e.g., from sugarcane).
     - **Starch Saccharification** (e.g., corn → sugars via enzymes).
   - **2G Bioethanol**:
     - **Pretreatment** of lignocellulosic biomass.
     - **Enzymatic Hydrolysis** to release sugars.
3. **Fermentation**: Microorganisms convert sugars into ethanol and CO_2 in fermentation tanks.
4. **Distillation**: Ethanol is separated from the fermented mixture.
5. **Dehydration**: Removal of residual water to produce anhydrous ethanol.
6. **Purification**: Ensures fuel-grade ethanol quality.
7. **Co-Product Handling**: Use of by-products (e.g., distiller's grains, bagasse) and waste management.
8. **Storage & Distribution**Ethanol stored in tanks and distributed for blending or direct use.

Types of Pretreatments for Bioethanol Production

1. **Physical Treatment**
   - *Methods: Grinding, milling, shredding, compression, microwaving, ultrasound*
   - *Purpose: Increase surface area and ease of enzymatic access*
   - *Pros: Simple and effective*
   - *Cons: High energy use and equipment costs*
2. **Chemical Treatment**
   - *Methods: Acid (e.g., H_2SO_4), alkaline (e.g., NaOH), organosolv, ozonolysis, ionic liquids*

- *Purpose: Break down lignin and hemicellulose to access cellulose*
- *Pros: Efficient sugar release*
- *Cons: Costly chemicals, waste management, specialized equipment*

3. **Physicochemical Treatment**
   - *Methods: Steam explosion, AFEX, hydrothermal treatment*
   - *Purpose: Combine heat/pressure with chemicals to disrupt biomass*
   - *Pros: Enhances sugar accessibility and yield*
   - *Cons: Expensive, requires high-tech setups*
4. **Biological Treatment**
   - *Methods: Use of fungi (e.g., white-rot), microbes, or enzymes*
   - *Purpose: Degrade lignin and improve cellulose accessibility*
   - *Pros: Eco-friendly, low energy input*
   - *Cons: Slower, longer processing time*

Enzymatic Hydrolysis in Bioethanol Production

Enzymatic hydrolysis is a key step in converting lignocellulosic biomass into fermentable sugars. It uses specific enzymes to break down:

- **Cellulose → Glucose** (by *cellulase enzymes*)
- **Hemicellulose → Various sugars** (by *hemicellulase enzymes*)

Advantages:

- High specificity and efficiency
- Milder operating conditions (lower temperature & pH)
- Fewer by-products and inhibitors

Challenges:

- Requires careful control of temperature, pH, and enzyme concentration
- Enzymes can be expensive; process optimization is crucial

Role:

Essential for releasing sugars for fermentation, improving bioethanol yield and process sustainability.

Fermentation Types in Bioethanol Production

1. **Simultaneous Saccharification and Fermentation (SSF):** Combines enzymatic hydrolysis and fermentation in one step. Increases efficiency, reduces sugar inhibition, and is cost-effective. Requires careful temperature optimization for enzymes and microbes.
2. **Simultaneous Saccharification and Co-Fermentation (SSCF):** Extends SSF by co-fermenting both hexose (glucose) and pentose (xylose) sugars. Enhances ethanol yield from lignocellulosic biomass. Efficient but needs precise control of enzyme and microbe performance.

3. **Separate Hydrolysis and Fermentation (SHF):** Hydrolysis and fermentation are done in separate stages, allowing optimal conditions for each. Offers better control but is time- and energy-intensive.
4. **Solid-State Fermentation (SSF):** Uses solid substrates (e.g., crop residues) with low moisture. Suitable for fungi-based enzyme production. Saves water and energy but needs strict control of moisture and aeration.

Bioethanol Separation and Purification (Condensed)

- **Distillation:** Ethanol is separated from the fermentation broth by heating. Vapors are condensed to get ~90 95% ethanol.
- **Azeotropic Distillation:** Breaks the ethanol-water azeotrope (~95.6%) using additives like benzene or cyclohexane to achieve >99.5% purity.
- **Dehydration (Molecular Sieves):** Porous materials selectively adsorb water, yielding ~99.7% pure fuel-grade ethanol.
- **Membrane Separation:** Energy-efficient methods like pervaporation or reverse osmosis purify ethanol by filtering water and impurities.
- **Other Methods:** Adsorption and solvent extraction can be used but are less common at large scales.

Advantages of bioethanol:

1. **Renewable:** Made from biomass like sugarcane and corn, bioethanol is sustainable and replenishable.
2. **Lower Emissions:** Burning bioethanol emits less CO_2, with partial offset by plant carbon uptake.
3. **Cleaner Combustion:** Releases fewer pollutants (SOx, NOx, particulates), improving air quality.
4. **Energy Security:** Reduces dependence on imported oil by using local feedstocks.
5. **Economic Boost:** Supports rural economies through jobs in farming and biofuel industries.
6. **Eco-Friendly:** Biodegradable and non-toxic, posing less risk to the environment.
7. **Fuel Blending:** Compatible with gasoline (e.g., E10, E85), reducing fossil fuel use.
8. **Fossil Fuel Conservation:** Decreases reliance on finite petroleum resources.
9. **Supports 2G/3G Technologies:** Encourages use of non-food biomass and algae, enhancing sustainability.

Applications of Bioethanol

1. **Laboratory Solvent:** Used as a solvent in chemical and biological laboratories.
2. **Preservation:** Applied in the preservation of biological specimens.
3. **Alcoholic Beverages:** Used in beverages like beer, wine, and brandy (in regulated forms).
4. **Fuel Blends:**

- o **Ethanol-Gasoline Blends**: E5G to E26G
- o **High Ethanol Blends**: E85G (85% ethanol + 15% gasoline)
- o **Ethanol-Diesel Blends**: E15D, E95D

5. **Power Generation:** Used as a thermal fuel in electricity production.
6. **Transport Fuel:** Serves as an alternative to gasoline in internal combustion engines.

Conclusion:

- The Bioethanol produced with supplementation of TPS (Tamarind pulp syrup) had a higher concentration of reducing sugar, bioethanol density and 8-9 per cent higher bioethanol quantity.
- Bioethanol assay demonstrated that a 40.2 per cent maize starch to ethanol conversion was achieved from the TrAPU maize seeds where the conversion efficiency was improved to reach 90.5 per cent when commercial amyloglucosidase was added after direct hydrolysis of TrAPU maize seeds.
- Among the various pretreatment methods for sugarcane tops, the combination of 6% glycerol, 5% NaOH, and 1% $FeCl_3$ yielded the highest ethanol production (31.9 g/L).

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INDIGENOUS LIVESTOCK MANAGEMENT FOR ENHANCING SOIL FERTILITY AND FARM PROFITABILITY IN ORGANIC AGRICULTURE

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Abstract:

Indigenous livestock management has long played a pivotal role in traditional farming systems, especially within organic agriculture, where sustainability, ecological balance, and resource efficiency are prioritized. This chapter explores the significance of integrating indigenous livestock into organic farming frameworks, emphasizing their multifaceted contributions to soil fertility enhancement and economic viability. Indigenous breeds, adapted to local climates and stress conditions, offer unique advantages such as disease resistance, low input needs, and compatibility with region-specific agroecological practices. Their dung and urine serve as vital raw materials for organic bio-inputs like compost, Panchagavya, Jeevamrut, and vermicompost, enriching soil health and microbial activity. Furthermore, the chapter discusses how incorporating livestock into mixed and integrated farming systems not only improves soil organic carbon and nutrient recycling but also provides diversified income sources through dairy, manure-based products, and biogas. While the benefits are substantial, the chapter also addresses challenges including breed conservation, institutional support, and market access. By drawing on both traditional wisdom and scientific validation, the chapter presents a holistic framework for harnessing indigenous livestock to promote sustainable soil fertility management and improve farm profitability within organic and climate-resilient agricultural paradigms.

Introduction:

The challenges posed by modern agriculture—including soil degradation, declining productivity, and climate vulnerability—have triggered a global reevaluation of farming systems. Among the most promising alternatives is the integration of indigenous livestock management within organic and sustainable agriculture**.** Traditional livestock systems, which have co-evolved with local ecosystems and communities over centuries, offer ecologically balanced solutions that modern, high-input systems often overlook.

In many parts of the world, especially in India and other developing nations, indigenous livestock breeds have formed the backbone of rural livelihoods and food systems. These animals—such as Gir, Sahiwal, Malnad Gidda (cattle); Murrah (buffalo); Jamunapari (goat); and

Kadaknath (poultry)—are not only resilient to local climatic and disease conditions but also well-adapted to thrive on native feed resources. Their by-products, including dung and urine, serve as essential components of organic soil amendments and natural fertilizers, forming a closed-loop system that enhances soil health without external inputs.

Organic farming relies heavily on ecological balance, nutrient cycling, and biological diversity. In this context, livestock are not just ancillary to crop production but rather central agents of sustainability. Indigenous livestock, with their low-maintenance needs and compatibility with traditional cropping systems, enable farmers to enhance soil fertility, reduce dependence on chemical inputs, and increase income through value-added animal products such as milk, ghee, manure-based fertilizers, and biogas.

Moreover, the integration of livestock in farming systems fosters agroecological resilience—a key requirement in the face of climate change. Animals contribute to carbon sequestration through improved pasture management and organic manure use, and they help farmers diversify risk by offering multiple streams of productivity.

However, despite these advantages, the widespread adoption of indigenous livestock-based organic farming faces several constraints. These include the erosion of traditional knowledge, decline in indigenous breed populations, lack of extension services, and limited policy support. Addressing these challenges is essential to realize the full potential of these systems.

This chapter aims to provide a comprehensive exploration of how indigenous livestock management can serve as a cornerstone of sustainable soil fertility and farm profitability**.** By examining biological, ecological, economic, and policy dimensions, this discussion seeks to inform researchers, practitioners, and policymakers about the untapped potential of livestock-integrated organic farming for building resilient, profitable, and regenerative agriculture systems.

Indigenous Breeds: Traits, Adaptation, and Utility

Indigenous livestock breeds are the outcome of centuries of natural and human selection under specific agroecological conditions. These animals have developed unique adaptive traits that allow them to thrive in harsh and variable environments, often with minimal inputs. Their genetic resilience, low maintenance costs, and multifunctional utility make them ideal for integration into organic and sustainable farming systems.

1. Distinctive Traits of Indigenous Breeds

Indigenous breeds are characterized by certain features that distinguish them from their exotic or crossbred counterparts. They generally possess:

A. **High disease and heat tolerance**, making them suitable for tropical and arid regions.
B. **Efficient feed conversion** even with low-quality or locally available fodder.
C. **Robust immune systems**, reducing the need for antibiotics or synthetic treatments.

D. **Longer productive lifespan** and low mortality rates.
E. **Multipurpose utility** – including draught power, milk, dung, urine, and cultural significance.

For example, the Sahiwal and Gir cattle are known for their heat resistance and steady milk yield, while the Malnad Gidda is prized for its adaptability in hilly terrain and nutrient-rich dung. Similarly, Kadaknath poultry offers meat high in iron and low in fat, gaining popularity among health-conscious consumers.

2. Climatic and Ecological Adaptation

One of the most compelling reasons to integrate indigenous livestock into organic systems is their ability to adapt to local climates and ecological pressures. These animals have evolved in synchrony with their environments, making them naturally suited to withstand:

A. Fluctuating temperatures and prolonged droughts
B. Endemic diseases and parasitic loads
C. Nutrient-scarce pastures or forest-based grazing

This adaptation reduces the need for external inputs such as concentrated feeds, chemical medications, and intensive housing—factors that often raise the cost and environmental burden of livestock management.

3. Socio-Economic and Cultural Relevance

Beyond their ecological value, indigenous breeds are closely woven into the socio-cultural fabric of many rural communities. Festivals, rituals, and agrarian lifestyles often center around these animals. This traditional bond fosters a stewardship ethic among farmers, motivating them to care for the animals in ways that align with ecological principles.

Economically, the use of indigenous livestock supports low-cost, self-reliant farming, especially important for smallholders. These animals enable farmers to produce manure, compost, milk, and value-added dairy products using internal farm resources, minimizing market dependency.

4. Role in Closed-Loop Organic Farming

Indigenous livestock are central to closed-loop systems, where waste becomes input. Their dung and urine are essential in preparing organic fertilizers such as:

A. Panchagavya – a fermented bio-tonic made from five cow by-products.
B. Jeevamrut – a microbial-rich liquid fertilizer.
C. Vermicompost – produced from dung as feedstock for earthworms.

Role of Indigenous Livestock in Soil Fertility Management

Indigenous livestock are not only valued for milk, meat, or labor but are also crucial for enhancing soil fertility through the organic inputs derived from their by-products. The integration of livestock waste into farming systems allows for nutrient recycling, minimizes external dependency, and enriches the soil's physical, chemical, and biological properties. This section discusses the traditional organic formulations derived from indigenous livestock and their scientifically validated roles in improving soil fertility.

1. Farmyard Manure (FYM)

Farmyard manure, a traditional and widely used soil amendment, is a decomposed mixture of cattle dung, urine-soaked bedding material, and crop residues. It contains essential macro- and micronutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium. Its regular application:

A. Improves soil structure by increasing porosity and water retention.
B. Encourages microbial diversity and enzymatic activity.
C. Enhances nutrient cycling and reduces nutrient leaching.

Indigenous cattle breeds, which are mostly stall-fed or grazed in low-input systems, produce dung that is richer in beneficial microbes compared to commercial crossbreeds, due to their natural, non-medicated diets.

2. Panchagavya: A Holistic Growth Enhancer

Panchagavya is a traditional fermented organic growth promoter made from five cow-derived ingredients—dung, urine, milk, curd, and ghee—often supplemented with sugarcane juice, tender coconut water, and ripe bananas. Originating in Vedic practices, Panchagavya is now gaining scientific validation for its role in:

A. Stimulating plant growth and flowering**.**
B. Enhancing soil microbial populations**,** particularly nitrogen-fixing and phosphate-solubilizing bacteria.
C. Suppressing soil-borne pathogens through natural antibiosis.

It acts as a biofertilizer, biopesticide, and bioenhancer in one formulation, making it an ideal input in resource-constrained organic systems.

3. Jeevamrut: A Microbial Inoculant

Jeevamrut is another indigenous input made from cow dung, cow urine, pulse flour, jaggery, and soil from bunds or forests. Unlike Panchagavya, which is more tonic-like, Jeevamrut primarily serves as a liquid microbial inoculant that:

A. Enhances the microbial biomass in the soil.
B. Accelerates the decomposition of organic matter.
C. Improves nutrient solubilization**,** especially of phosphorus and sulfur.

Its regular application leads to better root proliferation, higher crop yields, and increased resistance to pest and drought stress.

4. Vermicompost from Indigenous Livestock Dung

Dung from indigenous cattle is well-suited for vermicomposting due to its fibrous texture and balanced C:N ratio. When processed by earthworms (such as *Eisenia fetida*), it becomes a fine, humus-rich compost that:

A. Increases cation exchange capacity (CEC) of the soil.
B. Supplies plant growth-promoting hormones like auxins and cytokinins.
C. Improves nutrient retention and reduces erosion.

Farmers using vermicompost from indigenous livestock report higher yields, better taste in produce, and longer shelf life—factors linked directly to soil nutrient balance and microbial vitality.

5. Cow Urine as a Bio-Stimulant and Pesticide

Cow urine, often overlooked, is a powerful component in both soil enrichment and plant protection. It contains urea, uric acid, and a range of micronutrients and enzymes. Its uses include:

A. Acting as a foliar spray to promote vegetative growth.
B. Serving as a carrier medium in microbial biofertilizers.
C. Functioning as a natural pesticide, especially when mixed with neem extract or garlic-ginger pastes.

Recent studies have demonstrated cow urine's antibacterial and antifungal properties, supporting its use as a sustainable input in organic pest and nutrient management.

Integration of Livestock with Cropping Systems

Integrating indigenous livestock into mixed and integrated organic farming systems is a time-tested practice that enhances ecological sustainability, economic resilience, and on-farm resource efficiency. These integrated systems—where crops, livestock, trees, and even aquaculture are managed collectively—mirror natural ecosystems, minimizing waste and maximizing productivity. Indigenous livestock play a pivotal role in this integration, enabling nutrient recycling, reducing reliance on external inputs, and creating diversified income streams for smallholder farmers.

1. Understanding Integrated Organic Farming Systems (IOFS)

An Integrated Organic Farming System (IOFS) combines various agricultural enterprises such as crops, dairy, poultry, horticulture, aquaculture, and agroforestry on a single farm. The goal is to create a self-sustaining ecosystem that meets nutritional, economic, and environmental goals simultaneously.

In such systems:

A. Livestock waste nourishes crops.
B. Crop residues feed the animals.

C. Trees provide shade and fodder.
D. Legumes improve soil nitrogen for both crops and forage.

This circular relationship not only reduces input costs but also mitigates risks from market and climatic shocks.

2. Role of Indigenous Livestock in Resource Cycling

Indigenous livestock are integral to nutrient recycling and organic matter management. Their contributions include:

A. Manure and urine that enhance soil organic carbon and microbial health.
B. Body heat and trampling, which can aid composting in vermibeds or heap manure systems.
C. Grazing behavior**,** which maintains pasture health and contributes to carbon sequestration.

Because these animals are adapted to local conditions and feed sources, they utilize on-farm biomass efficiently**,** closing nutrient loops with minimal ecological footprint.

3. Livestock as a Source of Renewable Energy and Bio-inputs

In integrated systems, indigenous livestock also support renewable energy generation and eco-friendly input production:

A. Biogas units fueled by dung provide clean energy for cooking and lighting, reducing dependence on firewood or fossil fuels.
B. Slurry from biogas units becomes a nutrient-rich slurry that can be directly applied to fields or used in composting.
C. Manure-based pesticides and fungicides, such as cow dung slurry mixed with ash or neem extract, replace chemical agrochemicals.

This use of livestock in circular production systems reduces costs, lowers emissions, and supports carbon-neutral farming**.**

4. Income Diversification and Livelihood Security

Integrating livestock into farming systems ensures diversified income sources, which is crucial for economic resilience in uncertain climates and markets. A small farmer with indigenous cows may generate income from:

A. Sale of organic milk or ghee.
B. Manure-based products like vermicompost or Jeevamrut**.**
C. Handcrafted by-products such as dung cakes, gobar lamps, or organic fertilizers.
D. Small-scale dairy processing (e.g., curd, paneer) that adds local value.

This multi functionality contributes not only to household food security but also **to** employment opportunitie**s**, especially for women and elder family members.

5. Environmental and Climatic Benefits

By integrating indigenous livestock, farmers reduce their carbon footprint and increase ecological resilience. Benefits include:

A. Reduction in synthetic fertilizer and pesticide use, thereby lowering soil and water pollution.
B. Enhanced biodiversity, as livestock attract beneficial insects and microbes.
C. Improved soil structure and moisture retention, critical during droughts and erratic rainfall.

These features align well with the goals of climate-resilient and regenerative agriculture, which are now central to global food security discussions.

Livestock-Based Bio-Inputs in Organic Agriculture

Healthy soils are the cornerstone of sustainable agriculture. They are not inert media but dynamic ecosystems teeming with microbial life. These microbes—bacteria, fungi, actinomycetes, and protozoa—play essential roles in decomposing organic matter, fixing atmospheric nitrogen, solubilizing phosphorus, suppressing pathogens, and maintaining overall soil fertility. Indigenous livestock, through their waste products and the farming systems they support, contribute significantly to the enrichment of soil organic matter and microbial biodiversity. This section explores how livestock-based interventions stimulate biological activity and promote long-term soil health.

1. Livestock Manure: A Microbial Booster

Raw and composted manure from indigenous livestock provides a continuous influx of organic material rich in carbon compounds and microbial inoculants. Compared to synthetic fertilizers, livestock manure:

A. Increases microbial biomass carbon (MBC) and microbial respiration rates.
B. Acts as a substrate for decomposer fungi and beneficial bacteria.
C. Boosts populations of nitrogen-fixing bacteria (*Azospirillum*, *Rhizobium*) and phosphate-solubilizing microbes.

When properly composted, this manure leads to humus formation, stabilizing organic matter in the soil and enhancing its buffering capacity against pH and salinity fluctuations.

2. Compost and Vermicompost: Living Biofertilizers

Livestock-based compost and vermicompost harbor millions of microbes per gram, including *Trichoderma*, *Pseudomonas*, and *Bacillus* species. These organisms:

A. Aid in decomposition of crop residues and enhance nutrient availability.
B. Suppress soil-borne diseases through competition and antibiosis.
C. Improve root colonization and plant health via rhizosphere interactions.

Indigenous livestock dung—owing to its fibrous and undisturbed nature—forms an ideal base for composting, producing highly microbial-active compost that is rich in plant growth-promoting substances.

3. Liquid Bio-Inputs: Jeevamrut and Amrut Jal

Liquid formulations such as Jeevamrut (cow dung, urine, jaggery, gram flour, and soil) and Amrut Jal (fermented cow-based bio-tonic) are not only nutrient-rich but also biologically potent. These inputs:

A. Multiply native soil microflora, especially fungi and actinobacteria.
B. Increase enzymatic activity such as dehydrogenase, phosphatase, and urease.
C. Accelerate mineralization of nutrients, ensuring immediate uptake by plants.

Farmers report enhanced germination, faster growth, and resilience to stress after using these bio-inputs in seed treatment, foliar sprays, or soil drenching.

4. Soil Organic Carbon (SOC) Accumulation

A direct benefit of applying livestock waste is the improvement of soil organic carbon (SOC)**,** which is a key indicator of soil health and fertility. SOC influences:

A. Water retention and infiltration.
B. Cation exchange capacity (CEC) and nutrient holding**.**
C. Soil structure, reducing erosion and compaction.

Indigenous breeds raised under free-grazing or low-input systems contribute to SOC not only through manure but also through minimal stress on soil ecosystems, unlike confined or industrial livestock operations.

5. Enhancing Symbiotic Relationships

Livestock-based soil enrichment practices indirectly strengthen plant-microbe symbiosis, such as:

A. Mycorrhizal fungi enhancing phosphorus uptake.
B. Legume-Rhizobia nodulation for atmospheric nitrogen fixation.
C. Endophytes that colonize plant tissues and promote growth and immunity.

Economic Benefits of Indigenous Livestock Management

In the context of organic agriculture, where the emphasis is on sustainability, self-reliance, and natural resource conservation, economic viability becomes a crucial component. Farmers must not only sustain soil health and biodiversity but also maintain or increase profitability to ensure long-term livelihood security. Indigenous livestock, by virtue of their resilience, multifunctionality, and compatibility with organic principles, contribute significantly to the economic sustainability of farming households, particularly small and marginal ones. This section explores how managing indigenous livestock can optimize farm economics, reduce costs, and create new market opportunities.

1. Low Input Costs and Resource Self-Sufficiency

One of the most compelling advantages of indigenous livestock in organic systems is their low maintenance cost:

A. They thrive on locally available feed resources, such as crop residues, kitchen waste, and natural forage.
B. Require minimal medical intervention due to inherent disease resistance.
C. Do not need expensive housing or climate-controlled sheds, adapting well to local agro-climatic conditions.

This significantly reduces dependence on commercial feed, synthetic veterinary products, and fossil-fuel-driven infrastructure—allowing farmers to maintain operations with lower working capital.

2. Value Addition and Diversified Revenue Streams

Indigenous livestock contribute to multiple income streams, often from a single animal:

A. Milk and dairy products (curd, ghee, paneer) are in high demand, especially in urban organic markets.
B. Manure and compost can be packaged and sold as branded biofertilizers.
C. Urine-based biopesticides and Jeevamrut can be sold as eco-inputs to neighboring farms.
D. By-products such as cow dung cakes, vermiwash, and panchagavya are used in religious, cosmetic, and medicinal industries.

3. Market Premium for Organic and Indigenous Products

The growing consumer awareness about health and sustainability has created niche markets for organic animal products:

A. Milk from indigenous cows such as Gir, Sahiwal, or Red Sindhi is sought after for its A2 protein content.
B. Eggs, meat, and ghee from naturally raised animals fetch 20–40% higher prices in local and export markets.
C. Value-added manure products like vermicompost or cow dung-based potting mix are being sold online, creating e-commerce opportunities for smallholders.

4. Employment and Gender Empowerment

Indigenous livestock farming is inherently labor-intensive and inclusive, creating rural employment opportunities:

A. Women often manage feeding, milking, composting, and preparation of bio-inputs.
B. Youth are involved in marketing, delivery, and social media-based promotion of organic products.
C. Elderly members or those with limited mobility can contribute to small-scale dairy processing or vermicompost packaging.

5. Long-Term Economic Resilience

Though yield per animal may be lower than exotic breeds, indigenous livestock provide higher net returns over time due to:

A. Longer productive life spans.
B. Reduced treatment and maintenance costs.
C. Continuous availability of by-products useful in crop production.

Climate Resilience and Indigenous Livestock

Climate change presents one of the most pressing challenges to agriculture in the 21st century, marked by increased frequency of droughts, floods, extreme temperatures, and unpredictable rainfall. In this context, indigenous livestock integrated into organic farming systems emerge as a powerful tool to build both climate resilience **and** environmental sustainability. These systems mimic nature's nutrient loops, rely on ecological balance, and support farm-level adaptation strategies that reduce dependence on external inputs while strengthening the agroecosystem's capacity to bounce back from climatic shocks.

1. Adaptability of Indigenous Breeds to Climatic Extremes

Indigenous livestock breeds have evolved over generations in local climatic conditions, making them inherently resilient to heat stress, erratic rainfall, and fodder scarcity. Key adaptive traits include:

A. Heat tolerance through lighter skin, efficient sweating mechanisms, and lower metabolic heat production.
B. Drought resilience, as many breeds can survive on sparse vegetation and limited water.
C. Disease resistance, reducing vulnerability to climate-induced disease outbreaks.

For instance, breeds like Tharparkar**,** Malnad Gidda, and Kangayam continue to perform under climatic duress, unlike exotic breeds that often require costly interventions.

2. Mitigating Greenhouse Gas Emissions

Integrating indigenous livestock into organic systems contributes to GHG mitigation in several ways:

A. Avoidance of synthetic fertilizers by using livestock waste reduces nitrous oxide (N_2O) emissions, one of the most potent greenhouse gases.
B. Use of bio-digested slurry and composted manure decreases methane (CH_4) emissions compared to untreated dung.
C. Grazing-based systems sequester carbon in grasslands, enhancing soil organic carbon content over time.

3. Enhancing System-Level Resilience

By functioning as multifunctional components of agroecosystems, indigenous livestock help buffer the farm against climatic shocks:

A. During drought or crop failure, livestock becomes a fallback income source through milk, manure, or sale.
B. Mixed farming systems reduce dependence on any one input or product.
C. Integrated pest and disease management using livestock-based inputs creates resilient, self-regulating ecosystems.

In flood-prone or semi-arid zones, mobile indigenous livestock systems enable rotational grazing and resource flexibility that stationary crop systems lack.

4. Supporting Circular Economy and Waste Reduction

Indigenous livestock enable closed-loop nutrient cycling:

A. Dung and urine are returned to the soil as compost or liquid biofertilizers.
B. Fodder residues and crop waste are used as feed, minimizing on-farm waste.
C. Even urine, often discarded in conventional systems, is harnessed in biopesticide formulations.

This circular economy enhances farm resource efficiency, reduces reliance on external inputs, and aligns with nature's zero-waste principle.

5. Contribution to Biodiversity and Agroecological Balance

Grazing by indigenous livestock promotes floral diversity in pasturelands and disrupts weed dominance. Their interaction with landscapes helps:

A. Maintain pollinator populations, by preserving habitat diversity.
B. Reduce incidence of pest and disease cycles through natural manure application.
C. Encourage a mosaic of ecological niches, fostering beneficial microbes, insects, and earthworms.

Challenges in Indigenous Livestock Integration

Despite the benefits, several challenges hinder the widespread adoption of indigenous livestock in organic farming:

A. Breed conservation issues due to declining indigenous populations
B. Limited availability of quality livestock feed and healthcare
C. Inadequate veterinary and extension services
D. Lack of awareness and training among new-generation farmers
E. Market barriers for organic animal products

Additionally, youth are often reluctant to engage in animal rearing, viewing it as labor-intensive and less profitable compared to other vocations.

Policy and Institutional Framework

The Indian government, along with several NGOs and research institutions, has launched programs aimed at promoting indigenous livestock and organic farming:

A. **National Gokul Mission**: For the conservation and development of indigenous cattle breeds
B. **Rashtriya Gokul Gram**: Integrated villages focused on indigenous livestock improvement
C. **Paramparagat Krishi Vikas Yojana (PKVY)**: For organic farming promotion
D. **ICAR and NDDB programs**: Supporting research and training

Future Prospects and Research Priorities

Looking ahead, integrating indigenous livestock in organic systems can help transform agriculture into a more sustainable and equitable enterprise. Key future directions include:

A. Research on nutrient cycling and soil biology under livestock-based systems
B. Farmer-led innovations in bio-input preparation and application
C. Digital technologies to monitor animal health and soil conditions
D. Export opportunities for organic livestock products
E. Community-based breeding and marketing models

Conclusion:

Indigenous livestock management is not just a return to tradition—it represents a forward-looking, ecologically sound strategy for sustainable agriculture. By enhancing soil fertility, reducing input costs, and generating diversified income, it aligns perfectly with the goals of organic farming and climate-resilient food systems. With appropriate support and knowledge-sharing mechanisms, indigenous livestock can be powerful allies in building healthy soils, profitable farms, and empowered rural communities.

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WASTE WATER TREATMENT AND REUSE IN CROP PRODUCTION UNDER CLIMATE CHANGED CONDITION

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Abstract:

Climate change has intensified pressure on freshwater resources, necessitating alternative and sustainable water sources for agriculture. Wastewater, when adequately treated, presents a viable solution to address water scarcity and support crop production in water-stressed regions. This paper reviews the significance of wastewater treatment and its reuse in agriculture under changing climatic conditions. Advanced treatment technologies such as membrane filtration, constructed wetlands, and bioreactors ensure the safe removal of pathogens and harmful contaminants, making treated wastewater suitable for irrigation. Reusing wastewater not only conserves freshwater but also recycles nutrients such as nitrogen and phosphorus, enhancing soil fertility and crop yield. However, potential risks including heavy metal accumulation, salinity, and emerging contaminants require stringent monitoring and management. Integrating wastewater reuse with climate-smart agricultural practices offers a resilient pathway to ensure food security, environmental sustainability, and water resource management in a warming climate.

Keywords: Climate Change, Phytoremediation, Reuse, Waste Water, Wetland Construction

Introduction:

Water scarcity is a significant global issue primarily exacerbated by population pressure on freshwater sources, therefore wastewater reclamation or reuse is one of the most important necessities of the current scenario. Total water consumption worldwide for agriculture accounts 92 per cent. Out of which about 70 per cent of freshwater is used for irrigation (Anon., 2020), which comes from the rivers and underground water sources. The statistics shows serious concern for the countries facing water crisis. reported that 40 per cent of the global population is situated in heavy water stressed basins, which represents the water crisis for irrigation.

Therefore, wastewater reuse in agriculture is an ideal resource to replace freshwater use in agriculture.

Treated wastewater is generally applied for non-potable purposes, like agriculture, land, irrigation, groundwater recharge, golf course irrigation, vehicle washing, toilet flushes, firefighting, and building construction activities. It can also be used for cooling purposes in thermal power plants. At global level, treated wastewater irrigation supports agricultural yield and the livelihoods of millions of small holder farmers. Global reuse of treated wastewater for agricultural purposes shows wide variability ranging from 1.5 to 6.6 per cent. More than 10 per cent of the global population consumes agriculture-based products, which are cultivated by wastewater irrigation (Anon., 2006). Treated wastewater reuse has experienced very rapid growth and the volumes have been increased from 10 to 29 per cent per year in Europe, the USA, China, and up to 41 per cent in Australia. China stands out as the leading country in Asia for the reuse of wastewater with an estimated 1.3 M ha area including Vietnam, India, and Pakistan. Presently, it has been estimated that, only 37.6% of the urban wastewater in India is getting treated (Singh *et al.,* 2019). By utilizing 90 per cent of reclaimed water, Israel is the largest user of treated wastewater for agriculture land irrigation.

Wastewater reuse for crop irrigation showed several health concerns. Irrigation with the industrial wastewater either directly or mixing with domestic water showed higher risk. Risk factors are higher due to heavy metal and pathogens contamination because heavy metals are non-biodegradable and have a long biological half-life. It contains several toxic elements, *i.e.,* Cu, Cr, Mn, Fe, Pb, Zn and Ni (Mahfooz *et al.,* 2020). These heavy metals accumulate in topsoil and sourcing through plant roots; they enter the human and animal body through leafy vegetables consumption and inhalation of contaminated soils. Therefore, health risk assessment of such wastewater irrigation is important especially in adults. For this, an advanced wastewater treatment method should be applied before release of wastewater in the river, agriculture land and soils. Hence, alternate sources of water are required to use in agriculture due to population pressure on fresh water source.

What is Wastewater

Wastewater refers to any water that has been used and contaminated in various ways. It includes water from households (e.g., from toilets, sinks, showers), industries (e.g., from manufacturing processes) and agriculture (e.g., from irrigation or livestock operations). This water typically contains pollutants, organic matter, pathogens and sometimes harmful chemicals. Proper treatment of wastewater is essential to remove contaminants before it can be safely reused or discharged back into the environment.

- Wastewater is generated by domestic, sewage and industrial waste
- It is a potential source of essential nutrients required for crop production

- It is estimated that more than 15000 million liters of sewage water produced per day in India, in World more than 380 trillion liters and in Karnataka 3357 million liters
- Contribution of waste water to nutrient content is, 3.2 million tonnes of N, 1.4 million tonnes of P and 1.9 million tonnes of K per year

Water Availability and Demand

Every year on an average, India receives nearly 4000 BCM of water through rainfall, of which about 1999 BCM forms available water resources in rivers, lakes, reservoir, ground water and glaciers. However, the distribution of this quantity is not uniform across the country; apparently some river basins are acutely drought prone, while some are frequently devastated by flood. For example, the most flood prone basin of Brahmaputra and Barak, have an annual average water availability of 614 BCM, drains its major share into Bay of Bengal. At the same time, basins like Cauvery and East Flowing Rivers (EFR) between Pennar and Kanyakumari are facing water deficiency (Avinash Mishra and Arunlal K, 2022). On the other hand, India's development requirements grow at an optimistically positive rate. Population growth is also not an exception. The UN's population projection for India by 2050, which was relied upon by the NCIWRD while assessing the water demand for 2050, was 1500 million. But, we are about to cross this figure in 2030 itself. In addition, there is a surge in migration to urban centres leading substantial growth in urban water demand.

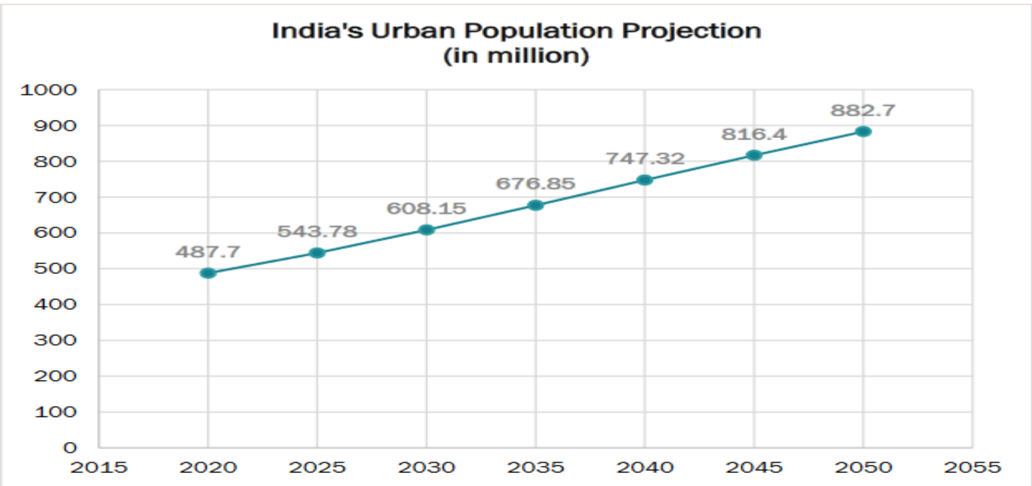

Figure 1: Projection of Indian Urban Population till 2050

(Anon., 2023)

The population projection data suggests that the wastewater generation will increase by about 75 per cent to 80 per cent in the next 25 years, which by volume works out to be 50000 MLD to 55000 MLD and thus taking the total estimated wastewater generation to 1.3 lakh MLD. At this rate, about 0.8 BCM of wastewater will be generated additionally every year, and thus the total annual wastewater volume is expected to reach close to 48 BCM by 2050. This volume is about 3.5 times the existing installed treatment capacity, which testifies the necessity of scaling up of treatment capacity, robust system for wastewater collection, and a well-accepted framework for reusing the treated wastewater (TWW) (Table 1 & Fig. 1).

Table 1: Estimated wastewater generation till 2050 in India

Year	Projected urban population (million)	Estimated wastewater generation (MLD)	Annually generated quantity (BCM)
2025	543.78	80479.44	29.37
2030	608.15	90006.20	32.85
2035	676.85	100173.80	36.56
2040	747.32	110603.36	40.37
2045	816.40	120827.20	44.10
2050	882.70	130639.60	47.68

(Anon., 2023)

What is wastewater treatment

Wastewater treatment is the process of converting wastewater into water that is no longer suitable for its original purpose due to contamination into an effluent that can be either returned to the water cycle with minimal environmental impact or reused. This treatment process involves physical, chemical and biological processes to remove contaminants and pollutants from wastewater, making it safe for discharge or reuse.

Processes Involved in Wastewater Treatment:

1. **Preliminary Treatment:** This involves screening to remove large objects such as sticks, rags and plastics, followed by grit removal to eliminate sand, gravel and other heavy solids.
2. **Primary Treatment:** Wastewater enters a sedimentation tank where heavy solids settle to the bottom as sludge, while oils and grease float to the surface and are skimmed off. This process removes about 60% of suspended solids and 30-40% of biochemical oxygen demand (BOD).
3. **Secondary Treatment:** The remaining wastewater undergoes biological treatment, where microorganisms break down organic matter. This can be done in activated sludge systems, trickling filters, or other biological reactors. Secondary treatment removes more than 90% of suspended solids and BOD.

Global Water Reuse

- Human being
- Agricultural irrigation
- Industrial and urban applications
- Tourism

- Ground water recharge
- Building construction
- Algae growth
- Aquaculture
- Animal production

Source of Wastewater

1. **Point source of water pollution:** refers to contaminants that enter a water body or way from a single identifiable source is called as point source of water pollution. *e.g.,* Industries, landfill sites, oil transport pipelines, distillery spent wash act.
2. **Non-point source of water pollution:** refers to different contamination that does not originate from single identifiable source is called as non-point source of water pollution. *e.g.,* Farming activities, urban and infrastructure developments, mining activities, nutrient and urban runoff act.

Ways to Treat Waste Water

1. **Bioremediation:** Microbial bioremediation is an eco-friendly natural cleaning process enhanced with specialized equipment.

❖ This wastewater management method removes contaminants from soil and groundwater that industrial processes produce. Using microorganisms to decompose contaminants, bioremediation is an economical way to reduce pollution and keep groundwater clean.

The benefits of bioremediation include the following:

Bioremediation can effectively clean these contaminants from groundwater and soil. The benefits of bioremediation include the following:

- An eco-friendly solution
- In situ application
- Quick turnaround time
- Minimal equipment requirement
- Positive reputation

- Cost-effectiveness
- Decreased liability
- Energy efficiency
- Official approval

Factors affecting the Bioremediation

1. Concentration of the contaminant
2. Nutrient availability
3. Surfactants enhancers of bioavailability
4. Characteristics of the contaminated soil
    a. pH
    b. Temperature
    c. Oxygen availability

2. Phytoremediation: Phytoremediation basically refers to the use of plants and associated soil microbes to reduce the concentrations or toxic effects of contaminants in the environment.

Benefits of phytoremediation

- Environmentally friendly
- Cost-effective
- Large-scale applicability
- Prevents spreading of contaminants
- Soil improvement
- Sustainable
- Reduces environmental exposure
- Minimal disruption
- Long-term solution

Drawbacks of phytoremediation

- Time-consuming
- Limited plant species
- Depth limitations
- Climate and site-specific
- Contaminant transfer
- Biomass disposal
- Seasonal variations
- Land use limitations
- Genetic variability
- Lack of public acceptance

Table 2: Most commonly used microorganisms for wastewater treatment

S.N	Species	Effects
Algae		
1	*Ascophyllum nodosum*	Effective against Pb, Ni, Cu, Cd and Zn
2	*Spirogyra sp.*	Effective against Cr, Cu, Fe, Mn and Zn
3	*Scenedesmus sp.*	Removal of Cd and Cu, detoxification of cyanide from wastewater.
4	*Scenedesmus abundans*	Removal of nitrogen, phosphorus, and other inorganic compounds from industrial wastewater
5	*Botryococcus braunii*	Eliminates Cu, Cd, Co, and Zn from polluted water, applied in the treatment of hypersaline wastewater
6	*Dunaliella salina*	Removes Methylene Blue dye from wastewater.
7	*Sargassum muticum*	Removal of lead (II), N, P and detoxification of cyanide from wastewater
8	*Chlorella sp*	-
Fungi		
1	*Aspergillus fumigates*	Effective removal of Pd
2	*Bjerkandera adusta*	Effective in wastewater decolourisation and detoxification
3	*Phanerochaete chrysosporium*	Degrade several aromatic compounds
4	*Trametes versicolor*	Wastewater decolourisation, humic acid removal from industrial wastewater
5	*Rhizopus arrhizus*	Bio sorption of heavy metals
6	*Fusarium flocciferum*	Absorption of Ni(II) and Cd(II) from wastewater
7	*Penicillium chrysogenum*	Absorption of Cd(II) from wastewater
Bacteria		
1	*Pseudomonas veronii*	Effective removal of Cd, Zn and Cu
2	*Sphingomonas sp.*	Degrades naphthalene-2-sulphonate (a building block of azo dyes) present in contaminated water
3	*Paenibacillus azoreducens*	Colour removal from wastewater with 98% efficiency
4	*Pseudomonas luteola*	Decolouration of wastewater
5	*Bacillus subitlis*	Reduction of TOC
6	*Bacillus laterosponus*	Reduction of TOC
7	*Pseudomonas aeruginosa*	Reduction of TOC
8	*Methylobacterium Organophilum*	Removal of Cu and Pb from wastewater
9	*Herminiimonas arsenicoxydans*	Arsenic absorption in wastewater
Yeast		
1	*Candida tropicalis*	Effective removal of Cd, Cr, Cu, Ni and Zn

(Kesari *et al.,* 2021)

Table 3: Most commonly used plant species for phytoremediation

S.N	**Common Name**	**Plant Species**	**Effects**
1	Bamboo	*Bambus volgaris*	Reduction of BOD, COD, TSS and heavy metals from wastewater and most commonly used one
		Dendrocalamus strictus	
2	Poplar	*Populous destoids*	Reduction of heavy metals from wastewater
3	Willow	*Salix sp.*	-
4	Mulberry	*Morus alba*	-
5	Eucalyptus	*Eucalyptus cinerea*	Only used in non-cultivable area
		Eucalyptus gunnii	
6	Common rush	*Juncus effusus L.*	Reduction of BOD, COD, TSS, nitrogen, phosphate and fecal coliforms
7	Grey club-rush	*Scirpus validus L.*	-
8	Broadleaf cattail	*Typha latifolia L.*	-
9	Fairy moss	*Azolla californiana*	Reduction of turbidity BOD, COD and TSS
10	Chinese celery	*Oenanthe javanica*	Influences dissolved oxygen, pH and temperature wastewater purification and nutrient uptake
11	marsh pennywort	*Hydrocotyle vulgaris*	Removal of total nitrogen and NH_4– nitrogen
12	Swamp morning	*Ipomoea aquatica*	-
13	Water hyacinth	*Eichornia crassipes*	Reduction of ammonia, nitrate BOD, COD, TSS, turbidity and heavy metals
14	Para grass	*Brachiaria mutica*	-
15	Wild sorghum	*Sorghastrum mutans*	-

(Kesari *et al.,* 2021)

Process of Phytoremediation

- **Phytovolatilization:** Phytovolatilization involves the uptake of contaminants by plant roots and its conversion to a gaseous state and release into the atmosphere. This process is driven by the evapotranspiration of plants.
- **Phytodegradation**: Phytodegradation involves the degradation of organic contaminants directly, through the release of enzymes from roots, or through metabolic activities within

plant tissues. In phytodegradation organic contaminants are taken up by roots and metabolized in plant tissues to less toxic substances.

- **Phytoextraction:** Phytoextraction uses the ability of plants to accumulate contaminants in the aboveground, harvestable biomass. This process involves repeated harvesting of the biomass in order to lower the concentration of contaminants in the soil.
- **Phytostabilization:** Phytostabilization aims to retain contaminants in the soil and prevent further dispersal. Contaminants can be stabilized in the roots or within the rhizosphere.
- **Phytostimulation:** is the enhancement of soil microbial activity for the degradation of organic contaminants, typically by organisms that associate with roots. This process occurs within the rhizosphere, which is the layer of soil that surrounds the roots.
- **Rhizofiltration:** Rhizofiltration is a form of phytoremediation that involves filtering contaminated groundwater, surface water, and wastewater through a mass of roots to remove toxic substances or excess nutrients. Both absorption and adsorption of the contaminants on the root takes place during the process.

3. Wetland Construction: Constructed wetlands (CWs) are engineered systems that have been designed and constructed to utilize the natural processes involving wetland vegetation, soils and the associated microbial assemblages to assist in treating wastewaters.

Salient features of wetland construction:

- ❖ Cost efficient in terms of construction, operations and maintenance
- ❖ Effectively treats wastewater from human waste, agricultural runoff, storm water and some metals or pollutants from mining and industry
- ❖ Uses technology that is simple to understand and manage
- ❖ Low energy consumption required for operations
- ❖ Prepares water for reuse
- ❖ Assists in maintaining groundwater and surface water levels
- ❖ Contributes to environmental protection by providing a habitat for plants and animals
- ❖ Acts as a means of water storage
- ❖ Pleasing natural aesthetics

In general, there are three types of wetland construction

1. **Surface flow constructed wetlands**

Surface flow constructed wetlands appear similar to natural swamp area's in which plants are rooted in a submerged layer of sand or gravel.

- ❖ Aeration of the sediment takes place by the unique property of helophyte plants which act as oxygen pumps providing dissolved oxygen with their roots to a wide variety of microorganisms.

- ❖ We apply surface flow constructed wetlands generally when flow rates are highly unpredictable (run-off from roads) and when anaerobic pre-treatment in a septic tank or bio digester is not required, this is because of the odour nuisance it would cause.
- ❖ The design is mainly dependent on spatial limitations, ambient temperatures, matrix characteristics and organic and hydraulic load.

2. Vertical flow constructed wetlands

- ❖ The desire to further reduce the size of constructed wetlands led to the development of vertical flow constructed wetlands.
- ❖ Anaerobic pre treated wastewater coming from a septic tank or bio digester is intermitted pumped on top of the constructed wetland.
- ❖ By trickling down the wastewater effectively sucks air in the constructed wetland whenever the pump stops, forcing aeration of the rhizosphere.
- ❖ This increases the aeration capacity up to approximately twenty times compared to horizontal subsurface flow constructed wetlands.
- ❖ Apart from that no short circuit flows are possible and due to lower levels of oxygen deeper in the matrix nitrate is removed under anoxic conditions.
- ❖ We can, for instance, adjust the level of the aquifer and the depth of the matrix as design parameters.

3. Horizontal subsurface flow constructed wetlands

- ❖ This type of constructed wetland is most commonly used for aerobic post treatment of domestic wastewater and can take a higher hydraulic load than a surface flow constructed wetland.
- ❖ In order to dissolve solid organic matter anaerobic pre-treatment in a septic tank or bio digester is required.
- ❖ A thick layer of gravel above the aquifer holds a layer of stagnant air and prevents odour nuisance in the vicinity.
- ❖ Aeration takes place as in surface flow constructed wetlands.
- ❖ The wastewater is however forced to pass thorough the matrix ensuring intensive contact between wastewater and bacteria in the rhizosphere (root zone of the plants).
- ❖ In this manner all wastewater is treated as no short circuit flow is possible.
- ❖ Horizontal subsurface flow constructed wetlands, when accurately designed, provide an extremely reliable low cost aerobic post treatment solution which is applicable all over the world.

Table 4: Heavy metals concentration and their permissible limits (FAO standards) for agricultural use of sewage water

Heavy metals	**Untreated sewage water**	**Treated sewage water**	**Permissible limit mg l^{-1} (FAO, 1985)**
	Concentration (mg l^{-1})		
Cobalt	0.004	0.001	0.05
Lead	NT	NT	-
Arsenic	0.004	0.002	0.10
Boron	0.035	0.017	0.20
Nickel	0.004	0.004	0.10
Chromium	NT	NT	-

Table 5: Microorganism content for agricultural use of sewage water

Water	**Untreated sewage water**	**Treated sewage water**	**Normal water**
Actinomycetes (10^2)	132	10	4
Fungi (10^3)	37	15	8
Bacteria (10^5)	29	17	12
E. coli (10^5)	5	0	0
Salmonella (10^2)	0	0	0

(Sachin, 2019)

Untreated sewage water content higher beneficial microorganisms along with it content higher harmful microorganisms that is *E coil.* By using of untreated sewage water for irrigation E coli enters in food chain and it cause health problems so treated sewage water is better for irrigation as compared to untreated sewage water due it contents harmful microbes (Table 5).

Domestic wastewater are higher chemical properties and microbial load followed by treated wastewater as compared to fresh water. Therefore, treated wastewater is better for irrigation point of view as compared to domestic wastewater (Table 6).

Application of treated domestic wastewater improve tomato growth, yield and quality parameter, soil physical, chemical and biological accept soil porosity and permeability this is due to the accumulation of suspended materials on the soil surface. They also stated that wastewater irrigation would increase ESP and clogging of the soil porosity (Table 8).

Table 6: Properties of different sources of water

S.N	Parameters	Domestic waste water	Treated waste water	Fresh water
1	pH	7.37	7.4	7.31
2	EC (dS/m)	1.23	1.1	0.71
3	TSS (mg/l)	442	326	-
4	BOD (mg/l)	350	251	-
5	COD (mg/l)	490	380	-
6	Total N (mg/l)	17.5	15.1	1.65
7	Total P (mg/l)	13.8	12.4	0.13
8	Total K (mg/l)	0.75	0.52	0.11
Microbial analysis (CFC/ml)				
1	Actinomycetes	3.5×10^3	2.1×10^3	-
2	Fungi	2.1×10^3	1.3×10^3	-
3	Bacteria	2.7×10^3	1.8×10^3	-
4	*E. coli*	5.3×10^4	3.1×10^4	-

(Rahul, 2016)

Table 7: Properties of raw and treated spent wash

S.N	Properties	Raw spent wash	Treated spent wash
1	pH	4.80	8.59
2	EC (dS/m)	>30	19.9
3	BOD (mg/l)	45,000	5,400
4	COD (mg/l)	1,00,000	14,000
5	Colour	Dark brown	Light in colour
6	N (%)	1.54	0.12
7	P (%)	1.08	0.06
8	K (%)	2.95	1

(Rahul, 2016)

Table 8: Effect of treated domestic wastewater on soil properties, growth, yield and quality parameter of tomato

Soil properties		Tomato crop parameters	Increase	Decrease
1	Soil fertility	Crop yield	↑↑	
2	Porosity and permeability	Crop growth	↑	↓
3	Nutrient content	Fruit quality	↑↑	
4	pH	Fruit flesh/firmness	↑↑	
5	Organic matter	Size of fruits	↑↑	
6	Total organic carbon	Size of leaves	↑↑	
7	Heavy metal concentration	Microbial Contamination	↑↑	
8	Soil water retention capacity	Presence of E-Coli	↑↑	
9	Microbial contamination	Heavy metal concentration	↑↑	
10	Electrical conductivity	Titratable acidity	↑↑	
11	Bulk density	Vitamin C	↑↑	

(Sagar *et al.,* 2023)

Table 9: Different categories of water

Category	Source of water	Usages in agriculture
Green water	Soil moisture and water inside plants	Used by plants, particularly forest, grassland and dryland agriculture, 50% of total water resource
Fossil water	Ground water	Agricultural and domestic use
Blue water	Water of sea, rivers and canals	Used for irrigation
Grey water	Waste water of bathrooms, kitchen and washbasins	Potential for use in crop production, good for kitchen garden and lawn irrigation
Black water	Industrial waste and domestic sewage	Potential for use in crop production, after treating water for removal of heavy metals and pathogens
Virtual water	Used in producing grains or animal products	Export-import of food grain or animal products causing indirectly export-import of this water, future importance

What is Wastewater Reuse

The U.S Environmental Protection Agency (EPA) defines wastewater reuse as, "using wastewater or reclaimed water from one application for another application. A common type of reclaimed from municipal wastewater (sewage)"

Reasons for Wastewater Reuse

The most common reasons for establishing a wastewater reuse program is to identify new water sources for increased water demand and to find economical ways to meet increasingly more stringent discharge standards and it also content essential macro and micro nutrients it reduces the usage of chemical fertilizer, improve soil fertility, increase crop yield, reduces the cost of cultivation and increase farmer net income.

Types of Reuse

1. **Non-Potable Reuse:**
   - Urban Irrigation:
   - Agricultural Irrigation:
   - Industrial Uses:
   - Toilet Flushing:
2. **Potable Reuse**:
   - Direct Potable Reuse (DPR)
   - Indirect Potable Reuse (IPR)
3. **Environmental Reuse**:
   - Environmental Enhancement
   - Groundwater Recharge

Advantages and disadvantages of wastewater reuse

Advantages

1. Conservation of freshwater
2. Nutrient supply
3. Improved soil health
4. Cost savings
5. Drought resilience
6. Environmental benefits
7. Crop diversity and rotation
8. Energy conservation
10. Community support
11. Adaptation to climate change
12. Public health considerations

Disadvantages

1. Health risks
2. Salinity and soil quality issues
3. Accumulation of heavy metals and chemicals
4. Water quality variability
5. Legal and liability issues

6. Public perception and social acceptance
7. Potential for pathogen transmission
8. Impact on crop quality and market acceptance
9. Environmental concerns
10. Infrastructure and operational costs

How to Manage Poor Quality Water

1. Blending of water: canal water mix with bore well water
2. Cyclic application of irrigation water: first fresh water application followed by poor water application (1:1)
3. Soil dilution: the crops that are irrigated by alternate source of water one-time good quality water and second time poor quality water so that dilution occurs in the root zone and sequential application in which the water source is change during the season according to specific salt tolerant of crop at each growth stage.
4. Selecting of resistance crop and genotype: salt resistance genotypes and economic part of the plant should be above the ground part.
5. Follow suitable method of irrigation: e.g., drip irrigation suitable for saline water application
6. Use poor quality water in agroforestry and alternative land use planning

Conclusion:

The treatment and reuse of wastewater in crop production present a sustainable solution to address the growing challenges of water scarcity, especially in arid and semi-arid regions. When properly treated, wastewater serves as a valuable source of both water and nutrients, reducing dependence on freshwater resources and synthetic fertilizers. However, its safe application requires adherence to quality standards, regular monitoring, and adoption of appropriate treatment technologies to mitigate risks associated with pathogens, heavy metals, and chemical contaminants. Integrating treated wastewater into agricultural practices not only enhances water use efficiency and crop productivity but also supports environmental conservation and circular economy goals. Therefore, promoting awareness, policy support, and infrastructure development for wastewater reuse in agriculture is crucial for achieving long-term food and water security.

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CLIMATE-RESILIENT AGRICULTURAL PRACTICES FOR RISK MITIGATION IN ORGANIC FARMING

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Abstract:

Climate change has emerged as a major threat to global food security, posing significant risks to agricultural productivity and rural livelihoods. Extreme weather events, unpredictable rainfall patterns, rising temperatures, and increasing pest pressures challenge conventional farming systems, especially in developing regions. Organic farming, with its emphasis on ecological balance, soil health, and biodiversity, offers a robust framework for building resilience in agriculture. This chapter explores the concept and principles of climate-resilient agriculture (CRA), focusing on its integration within organic farming systems. It provides an in-depth examination of adaptive strategies, indigenous practices, technological innovations, and policy frameworks that collectively mitigate climate risks while promoting sustainable food systems. The chapter also includes case studies, challenges, and future directions, making it an essential reference for researchers, practitioners, and policymakers.

1. Introduction:

The global agricultural sector is increasingly affected by climate change, which manifests in rising temperatures, erratic precipitation patterns, frequent droughts, floods, and a rise in pest and disease outbreaks. These climate-related disturbances jeopardize the stability and productivity of agricultural systems, particularly those that are resource-poor or dependent on natural rainfall. According to the Intergovernmental Panel on Climate Change (IPCC), agricultural productivity could decline by up to 30% in many parts of the world by 2050 due to climate-induced stresses.

In response to this growing threat, the concept of climate-resilient agriculture (CRA) has emerged as a vital component of sustainable development. CRA refers to a holistic approach that enables farming systems to anticipate, absorb, adapt to, and recover from climate shocks and stresses. It includes adaptive capacity building, livelihood diversification, risk management, and ecological restoration.

Concurrently, organic farming presents itself as a powerful ally in the pursuit of resilience. Unlike conventional agriculture, which often relies heavily on external chemical inputs and monocultures, organic systems emphasize the health of ecosystems and the sustainability of resources. Organic agriculture is based on principles such as soil fertility enhancement, biodiversity promotion, ecological balance, and the reduction of environmental pollution.

Integrating CRA strategies with organic farming practices holds immense potential for creating robust, adaptable, and sustainable farming systems. The convergence of traditional knowledge with modern scientific innovations, supported by policy and institutional frameworks, can lead to significant advancements in building climate resilience in agriculture. This chapter investigates the multifaceted relationship between climate resilience and organic farming, aiming to provide comprehensive insights into their integration and implementation. It outlines core principles, adaptive practices, technological innovations, and policy instruments necessary to build robust farming systems capable of withstanding climate variability. The importance of stakeholder engagement, especially among farming communities, policymakers, and researchers, is also emphasized, highlighting the need for participatory and inclusive approaches to sustainable development.

2. Understanding Climate-Resilient Agriculture (CRA)

2.1 Definition and Objectives

Climate-Resilient Agriculture (CRA) refers to farming strategies designed to maintain or enhance productivity and sustainability in the face of climate variability. It seeks to improve the adaptive capacity of agricultural systems, reduce vulnerabilities, and increase carbon sequestration by promoting ecologically sustainable and socially inclusive practices. CRA focuses on transforming agricultural systems to make them more robust and flexible in the face of adverse climatic conditions. This involves the adoption of sustainable land management practices, diversification of crops and income sources, early warning systems, and improved access to climate information and resources.

2.2 Key Principles of CRA 2 Key Principles of CRA

1. **Diversity and Redundancy**: Promoting agricultural biodiversity, including crop diversification, mixed farming systems, and agroforestry, enhances the capacity of farming systems to absorb shocks and maintain productivity. Redundancy ensures that if one component fails due to climate stress, others can compensate.
2. **Efficient Resource Use**: Utilizing resources such as water, soil, and nutrients in an efficient manner helps ensure sustainability. This includes the use of precision farming techniques, micro-irrigation, and renewable energy to optimize input use and minimize waste.
3. **Adaptability and Flexibility**: Building flexible systems that can rapidly adjust to climate signals—such as changing planting dates or crop varieties—allows farmers to remain productive in the face of uncertainty. It also involves institutional flexibility to adopt evolving scientific and policy tools.

4. **Integration of Traditional and Scientific Knowledge**: Local knowledge systems have evolved to cope with specific climate risks. Integrating these with modern research and innovations allows the development of region-specific, culturally appropriate solutions that are more likely to be adopted by communities.
5. **Community Empowerment and Participation**: Climate resilience is strengthened when local communities are involved in decision-making, planning, and implementation. Empowering farmers with knowledge, tools, and rights builds ownership and fosters long-term commitment to sustainable practices.
6. **Systemic and Landscape-Level Approaches**: Rather than focusing solely on individual farms, CRA promotes landscape-level planning, which includes forests, watersheds, and ecosystems to enhance the resilience of entire agroecological zones.
7. **Risk Anticipation and Management**: Early warning systems, crop insurance schemes, and climate forecasting tools help farmers anticipate and prepare for climatic extremes, reducing losses and improving recovery.
8. **Equity and Inclusivity**: CRA recognizes the differentiated impacts of climate change on vulnerable groups such as smallholders, women, and indigenous communities. Ensuring their inclusion in policy and practice enhances overall system resilience.

3. Role of Organic Farming in Climate Resilience

3.1 Soil Health and Fertility Organic farming techniques focus on enhancing soil health through the use of compost, green manure, and crop rotation. These practices increase the soil organic matter content, improve its structure, and enhance water-holding capacity. Healthy soils are better able to retain nutrients and moisture during periods of drought or heavy rainfall, making them more resilient to climate extremes.

3.2 Biodiversity Conservation Organic farms are typically more diverse than conventional ones. By cultivating multiple crops and maintaining hedgerows, cover crops, and natural habitats, organic farmers support beneficial insects and natural pest control mechanisms. Biodiversity acts as a buffer against the spread of pests and diseases, contributing to system stability during climatic disruptions.

3.3 Reduction in Greenhouse Gas Emissions Organic farming avoids the use of synthetic fertilizers and pesticides, which are energy-intensive to produce and apply. As a result, organic systems tend to emit fewer greenhouse gases, particularly nitrous oxide. Additionally, the carbon sequestration potential of organic soils is higher, helping mitigate climate change.

3.4 Sustainable Water Management Practices such as mulching, contour plowing, and rainwater harvesting help organic farms manage water resources more efficiently. These methods reduce water loss, prevent runoff, and increase groundwater recharge, ensuring that crops can survive periods of low rainfall.

(ISBN: 978-81-991070-3-8)

4. Climate-Resilient Practices in Organic Farming

Climate-Resilient Practices in Organic Farming

Organic farming inherently promotes ecological sustainability, resource efficiency, and biodiversity—all of which make it a natural ally in building resilience to climate change. By focusing on soil health, eliminating synthetic inputs, and preserving traditional knowledge systems, organic farming offers a robust framework for climate-resilient agriculture. The following climate-resilient practices have been widely adopted and promoted within organic farming systems:

1. Agroforestry and Intercropping

Agroforestry involves integrating trees and shrubs into agricultural landscapes, often alongside annual or perennial crops. This practice contributes to climate resilience by:

A. Reducing wind speed and evapotranspiration, creating a microclimate favorable to crops.
B. Enhancing water infiltration and preventing erosion through deep-rooted tree systems.
C. Providing diversified income sources (timber, fruits, fodder, medicinal plants).
D. Sequestering carbon, thereby contributing to climate change mitigation.

Intercropping, or growing two or more crops in proximity, stabilizes yields under unpredictable weather by distributing risk across species. It enhances nutrient cycling, discourages pests, and improves land-use efficiency.

2. Conservation Tillage and Mulching

Reduced or zero tillage practices minimize soil disturbance, maintain soil structure, and improve organic matter retention. Combined with organic mulching—the application of straw, leaves, or composted biomass on soil surfaces—these methods:

A. Improve moisture retention and reduce evaporation.
B. Moderate soil temperature fluctuations.
C. Suppress weed growth naturally.
D. Protect against soil erosion from heavy rains or wind.

Together, these enhance the soil's ability to buffer against climate extremes like drought and floods.

3. Use of Drought- and Heat-Tolerant Varieties

Organic farmers often rely on traditional and indigenous crop varieties that are naturally adapted to local conditions. These varieties typically:

A. Have deeper root systems for water extraction.
B. Exhibit resilience to high temperatures and erratic rainfall.
C. Require fewer external inputs.

Community seed banks and on-farm seed saving promote access to these resilient varieties and preserve local biodiversity, ensuring that farmers are not dependent on costly commercial seeds.

4. Green Manuring and Cover Cropping

Planting green manures (e.g., legumes like sunn hemp or dhaincha) and cover crops during off-seasons:

A. Adds organic nitrogen to the soil through biological fixation.
B. Protects the soil from erosion and nutrient leaching.
C. Enhances soil microbial diversity and organic carbon content.
D. Suppresses weed growth.

These practices prepare the field for the next cropping season with improved fertility and resilience.

5. Organic Soil Amendments (Composting, Biochar, Vermicomposting)

Soil fertility and moisture retention are critical in climate-stressed environments. Organic amendments such as:

A. **Compost**: Enhances soil organic matter, water retention, and microbial activity.
B. **Vermicompost**: Rich in plant growth hormones and nutrients, improving soil structure.
C. **Biochar**: Charcoal-like substance that improves soil aeration, nutrient retention, and carbon sequestration.

These inputs make soil systems more resilient to temperature and moisture extremes while reducing reliance on external chemical fertilizers.

6. Integrated Pest and Disease Management (IPDM)

Pest outbreaks are increasingly common due to climate shifts. Organic systems manage this risk using IPDM strategies, including:

A. Crop rotation and trap cropping to break pest cycles.
B. Biological control agents (e.g., ladybugs, parasitic wasps).
C. Botanical pesticides such as neem or garlic extracts.
D. Habitat manipulation like hedgerows to attract natural predators.

Such practices reduce vulnerability to pest pressure while maintaining ecosystem balance.

7. Water Harvesting and Efficient Irrigation

Water scarcity is one of the most pressing climate-related challenges. Organic farmers often implement:

A. Rainwater harvesting systems (e.g., farm ponds, rooftop collection).
B. Contour bunding and trenching to slow runoff and promote infiltration.
C. Drip and sprinkler irrigation systems to maximize water use efficiency.

These ensure water availability during dry spells and protect crops from moisture stress.

8. Crop Diversification and Mixed Cropping

Depending on a single crop makes farming systems vulnerable to failure under climate stress. Organic farmers employ crop diversification strategies such as:

A. Polycultures that include cereals, legumes, vegetables, and fruits.
B. Livestock integration to recycle nutrients and diversify income.
C. Staggered planting to spread climatic risk across time and space.

This approach minimizes the chances of total crop failure and enhances food and economic security.

9. Renewable Energy Integration

Many organic farms are beginning to integrate solar panels**,** biogas units, and wind turbines to power irrigation pumps, processing units, and lighting systems. These not only reduce carbon footprints but also enhance energy independence, which is crucial during climate-induced power disruptions.

10. Community-Based Resilience Initiatives

Organic farming often thrives within cooperatives and self-help groups, which foster knowledge sharing, access to inputs, and collective marketing. These networks:

A. Facilitate early warning dissemination and climate forecasting.
B. Enable group-based risk-sharing mechanisms like community crop insurance.
C. Promote farmer-led experimentation with climate-resilient technologies.

Such community engagement amplifies resilience at the landscape level.

5. Indigenous Knowledge and Traditional Practices

5.1 Examples from Indian Agriculture

A. **Zabo Farming (Nagaland)**: A centuries-old practice that integrates livestock, forest, and crop farming to manage water and nutrients.
B. **Bamboo Drip Irrigation (Meghalaya)**: An ingenious method of transporting water to fields using bamboo channels.
C. **Sacred Groves and Crop Calendars**: Cultural practices that maintain biodiversity and guide planting schedules based on traditional ecological knowledge.

5.2 Role in Enhancing Resilience Indigenous practices often evolve through generations of trial and error, making them well-adapted to local conditions. They preserve genetic diversity, use low-cost inputs, and are usually environmentally friendly. These attributes enhance the resilience of farming systems and complement modern climate adaptation strategies.

6. Technological Innovations Supporting CRA

6.1 ICT Tools and Mobile Apps Information and Communication Technology (ICT) tools are increasingly used in agriculture to provide real-time weather updates, pest alerts, market prices, and best practice guides. Mobile apps enable farmers to make data-driven decisions that enhance climate resilience.

6.2 Climate-Smart Sensors and Monitoring Tools Advanced tools such as soil moisture sensors, drone-based imaging, and automated weather stations allow farmers to monitor field conditions accurately. These innovations facilitate timely interventions and resource-efficient farming.

6.3 Biotechnological Interventions Biotechnology contributes to the development of crop varieties that are drought-tolerant, pest-resistant, and nutrient-efficient. It also aids in the production of biofertilizers and biopesticides that support organic farming systems.

7. Policy and Institutional Support

7.1 International Frameworks

A. **UNFCCC (United Nations Framework Convention on Climate Change)**: Supports climate adaptation and mitigation in agriculture.
B. **SDGs (Sustainable Development Goals)**: Goal 2 (Zero Hunger) and Goal 13 (Climate Action) emphasize the role of sustainable agriculture.
C. **Paris Agreement**: Encourages countries to enhance climate resilience in key sectors including agriculture.

7.2 Indian Government Initiatives

A. **National Mission for Sustainable Agriculture (NMSA)**: Focuses on climate adaptation and sustainable resource management.
B. **Paramparagat Krishi Vikas Yojana (PKVY)**: Promotes organic farming through participatory guarantee systems.
C. **Climate Resilient Villages**: A model approach to integrate adaptive practices at the community level.

7.3 Need for Policy Integration There is a critical need to align agricultural policies with climate and environmental goals. Integrating organic agriculture promotion with climate resilience objectives ensures a unified, efficient, and impactful strategy.

8. Case Studies

8.1 Sikkim: Fully Organic State Sikkim became the first fully organic state in India in 2016. This transformation led to improved soil health, increased biodiversity, and enhanced farmer incomes. The state's policies support training, certification, and market access, demonstrating the potential of integrated organic and climate-resilient agriculture.

8.2 Andhra Pradesh: Community-Managed Natural Farming (CMNF) This initiative involves training farmers in agroecological methods that reduce input costs and improve soil fertility. Farmers report better yields and greater resilience to drought, illustrating the power of community-led approaches in building sustainable farming systems.

9. Challenges and Limitations

A. **Limited Awareness and Training**: Many farmers are unaware of CRA practices or lack access to training resources.
B. **Infrastructure and Certification Barriers**: Organic certification can be time-consuming and costly, and rural areas often lack the necessary infrastructure.

C. **Yield Gaps and Market Access**: Organic farms may initially produce lower yields, and farmers often struggle to find reliable markets.

D. **Policy Fragmentation**: Lack of coordination between climate, agriculture, and rural development policies hampers effective implementation.

10. Future Directions

A. **Strengthen Research-Extension Linkages**: Improve information flow between research institutions and farming communities.

B. **Promote Farmer-Led Innovation**: Encourage participatory technology development and knowledge sharing.

C. **Foster International Cooperation**: Share successful models and technologies across borders.

D. **Develop Resilience Metrics**: Create tools and indicators to measure the effectiveness of climate-resilient practices.

Conclusion:

Climate-resilient agricultural practices, particularly when integrated with the principles of organic farming, represent a powerful approach to safeguarding food systems against the increasing threats of climate change. This chapter has provided a holistic overview of how ecological, social, technological, and institutional strategies can work in concert to promote adaptive and sustainable agriculture. With adequate support, knowledge exchange, and participatory frameworks, farmers can become both stewards of the environment and architects of resilience.

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Advances in Soil and Water Research

ISBN: 978-81-991070-3-8

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Bhumi Publishing

ISBN 978-81-991070-3-8

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