ISBN: 978-93-47587-71-9

RESEARCH AND REVIEWS IN AGRICULTURE, HORTICULTURE AND ANIMAL HUSBANDRY

Editors:
Dr. Narender Mohan
Dr. Anuj Kumar
Dr. Pooja Verma
Dr. Brijesh Kumar

BHUMI PUBLISHING, INDIA
FIRST EDITION: DECEMBER 2025

Research and Reviews in Agriculture, Horticulture and Animal Husbandry

(ISBN: 978-93-47587-71-9)

DOI: https://doi.org/10.5281/zenodo.18112652

Editors

Dr. Narender Mohan

ICAR–Indian Institute of Wheat and Barley Research (IIWBR), Karnal, Haryana

Dr. Anuj Kumar

ICAR–Indian Institute of Wheat and Barley Research (IIWBR), Karnal, Haryana

Dr. Pooja Verma

ICAR–Indian Institute of Wheat & Barley Research (ICAR-IIWBR), Karnal, Haryana

Dr. Brijesh Kumar

Department of Soil Science, Dr. Rajendra Prasad Central Agricultural University, Pusa (Samastipur), Bihar

Bhumi Publishing

December 2025

Title: Research and Reviews in Agriculture, Horticulture and Animal Husbandry

Editors: Dr. Narender Mohan, Dr. Anuj Kumar, Dr. Pooja Verma, Dr. Brijesh Kumar

First Edition: December 2025

ISBN: 978-93-47587-71-9

DOI: https://doi.org/10.5281/zenodo.18112652

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

Agriculture, horticulture, and animal husbandry form the backbone of global food security, rural livelihoods, and sustainable development. In an era marked by climate change, population growth, resource limitations, and technological transformation, these sectors are undergoing rapid and multidimensional change. The present book, *Research and Reviews in Agriculture, Horticulture and Animal Husbandry*, is conceived as a comprehensive scholarly platform that captures contemporary research trends, critical reviews, and innovative practices across these interrelated domains.

This volume brings together contributions from researchers, academicians, scientists, and practitioners who are actively engaged in advancing agricultural productivity, horticultural innovation, and livestock sustainability. The chapters address a wide spectrum of themes, including crop improvement, soil and water management, precision farming, protected cultivation, post-harvest technologies, animal nutrition, breeding strategies, disease management, and the application of biotechnology and digital tools in agri-animal systems. Emphasis has also been placed on sustainability, climate-resilient practices, integrated farming systems, and farmer-centric approaches that bridge the gap between research and field-level application.

The book aims to serve as a valuable reference for undergraduate and postgraduate students, researchers, extension professionals, policymakers, and industry stakeholders. By presenting both fundamental concepts and advanced research insights, it encourages interdisciplinary thinking and fosters a holistic understanding of agriculture, horticulture, and animal husbandry as interconnected components of a resilient food system. Each chapter has been carefully reviewed to ensure scientific rigor, clarity, and relevance to current and future challenges.

We sincerely acknowledge the efforts of all contributing authors for sharing their expertise and research findings, as well as the reviewers for their critical evaluations and constructive suggestions. We also extend our gratitude to the publisher for their support in bringing this scholarly work to fruition. It is our hope that this book will stimulate further research, inspire innovation, and contribute meaningfully to the sustainable advancement of agricultural and allied sciences.

- Editors

TABLE OF CONTENT

ADVANCES IN NUTRITIONAL APPROACHES FOR ENHANCING GROWTH PERFORMANCE AND MILK PRODUCTION IN GOATS

C. S. Chaudhari*, Shiwani Singh, S. D. Jagadale and N. R. Karambele

Department of Animal Nutrition,

Mumbai Veterinary College, Parel-12

*Corresponding author E-mail: chaudhari.charudatta@gmail.com

Introduction:

Goat farming holds an increasingly important position in global livestock production, contributing significantly to food security, rural livelihoods and climate resilient agriculture. Goats are well adapted to diverse and harsh agro ecological zones, making them vital for communities in Asia, Africa and the Mediterranean regions where resource limitations restrict the productivity of other ruminants (Boyazoglu & Morand Fehr, 2001). In India, goats represent one of the largest livestock populations and act as a financial safety net for landless and marginal farmers due to their low maintenance cost, higher reproductive rate and steady market demand (Singh *et al.,* 2023). Goat milk, in particular, is gaining increasing recognition because of its digestibility, therapeutic value and suitability for individuals with cow milk allergies (Park *et al.,* 2007). The rising health consciousness among consumers has further expanded the interest in goat milk based functional foods and nutraceuticals (Kalyankar *et al.,* 2022).

Nutritional management plays a fundamental role in enhancing growth performance, reproductive efficiency, immunity and milk production in goats. Adequate nutrition supports optimal rumen microbial activity, efficient nutrient utilization and improved metabolic functioning, which are essential for achieving the desired productive and reproductive milestones (Assad & El Shazly, 2024). Early life nutrition particularly influences long term productivity, while proper feeding during gestation and early lactation ensures healthy kids, reduced kidding complications and sustained milk yield (Santos *et al.,* 2018). With the increasing commercialization of goat farming and growing consumer demand for high quality milk and meat, adopting science based feeding strategies has become crucial for maximizing profitability and ensuring animal welfare (Singh *et al.,* 2023).

The demand for goat meat and milk is steadily rising in many developing regions due to population growth, urban dietary shifts and preference for lean, easily digestible animal protein sources (Devendra, 2013). Despite their adaptability, goats face significant nutritional challenges, especially in extensive and semi intensive systems where feed availability fluctuates seasonally and the quality of forages often remains suboptimal (Assad & El Shazly, 2024). Mineral deficiencies, heat stress, high parasite load and limited access to concentrate supplementation further reduce productive potential in such systems (McDowell *et al.,* 1993). These challenges vary widely across intensive, semi intensive and extensive production systems, making balanced and species specific nutritional planning essential for achieving optimal growth and milk performance in goats (Devendra, 2013).

2.1 Basics of Goat Nutrition

Goats are highly adaptable small ruminants with unique digestive characteristics that allow them to efficiently utilize a wide variety of feed resources, including shrubs, tree leaves and browse species. Their digestive system consists of the rumen, reticulum, omasum and abomasum, similar to cattle and sheep, but with certain anatomical and physiological differences that influence nutrient digestion (Devendra & Burns, 1983). Goats possess a relatively larger reticulorumen capacity compared to their body size, enabling them to process fibrous feeds while maintaining higher feed intake on a metabolic body weight basis (Lu, 1988).

One distinguishing feature of goats is their selective feeding behavior. They prefer browsing over grazing and often choose leaves, twigs and higher quality plant parts, which results in better voluntary intake and enhanced digestibility of diets rich in secondary plant metabolites (Silanikove, 2000). Compared to sheep, goats exhibit more efficient detoxification of tannin rich forages and improved nitrogen recycling, contributing to superior adaptability in resource poor environments (Huston *et al.,* 1986). Cattle, in contrast, rely heavily on grasses and have lower tolerance for lignified browse, making goats more efficient in semi arid and hilly ecosystems.

Rumen fermentation patterns in goats also differ slightly from other ruminants, with greater propionate production when fed high quality browse diets, which supports better energy utilization (Silanikove, 2000). These unique digestive characteristics make goat nutrition highly flexible, allowing the use of diverse feedstuffs for sustaining growth, reproduction and milk production.

2.2 Nutrient Requirements of Different Categories of Goats

Nutrient requirements vary widely among goats depending on age, physiological stage, gender and production level. Kids require high quality, easily digestible nutrients during early growth to support rapid tissue development and rumen maturation. Colostrum feeding within the first 2 hours is critical for passive immunity, followed by milk and early introduction of creep feed to encourage rumen development (Santos *et al.,* 2018). Growing kids (3-9 months) need balanced energy and protein supply to achieve target body weights and optimal feed conversion efficiency.

Lactating does have the highest nutrient demands due to milk synthesis, which requires substantial amounts of energy, protein and minerals. According to ICAR (2023), nutrient intake increases proportionally with milk yield, fat percentage and body weight. In early lactation, energy dense diets prevent excessive body weight loss, while mid and late lactation feeding aims to maintain yield and replenish body reserves.

Pregnant does, especially during the last 6 8 weeks of gestation, require increased nutrient density to support fetal growth and udder development. Undernutrition during this period may lead to low birth weight, weak kids and increased peripartum complications (Devendra, 2013). Breeding bucks also require balanced rations with adequate protein (10 12%) and minerals such as zinc and selenium to maintain libido, semen quality and overall reproductive performance (Mahgoub *et al.,* 2016).

Goats maintained in semi-intensive or grazing systems often experience nutrient deficiencies due to seasonal fluctuations in forage quality. Supplemental feeding with concentrates, mineral mixtures and high-quality roughages is essential for meeting the ICAR 2023 standards across all physiological stages.

2.3 Macro and Micro Nutrient Requirements

Energy

Energy is the most limiting nutrient in goat nutrition and is primarily supplied through carbohydrates and fats. Energy requirements increase substantially during growth, late gestation and lactation due to higher metabolic demands. Insufficient energy intake reduces weight gain, milk yield and reproductive efficiency (NRC, 2007). Goats typically require 0.90-1.3 kg total digestible nutrients (TDN)/day depending on size and production level, as per ICAR (2023).

Protein

Protein is essential for muscle synthesis, fetal development and milk protein production. Rumen degradable protein (RDP) supports microbial growth, while undegraded dietary protein (UDP) contributes to metabolizable protein supply. Kids require 14-18% CP, whereas lactating does produce high milk volumes may require 12-14% CP (ICAR, 2023). Protein deficiency results in stunted growth and reduced milk yield (Silanikove, 2000).

Fiber

Fiber maintains rumen health, stabilizes fermentation and prevents acidosis. Goats efficiently digest moderate fiber levels due to their browsing habits. Diets containing 18-25% crude fiber support optimal rumen function (Lu, 1988).

Minerals

Minerals such as Ca, P, Cu, Zn, Co, I and Se are critical for metabolic functions, skeletal development, reproduction and immunity. Calcium and phosphorus are required in a 2:1 ratio, while trace minerals like copper and selenium support enzyme activity and disease resistance (McDowell *et al.,* 1993). Deficiencies can lead to reproductive failures and poor growth.

Water

Water intake affects feed intake, rumen fermentation, digestion and thermoregulation. Goats require 3-7 liters/day depending on temperature, physiological state and diet composition (Devendra, 2013).

Table 1: Nutrient Requirements of Goats According to ICAR (2023)

Category	Body Weight (kg)	CP (%)	TDN (%)	Ca (g/day)	P (g/day)
Kids (0 3 months)	5-10	16-18	65-68	4-5	3-4
Growers (3 9 months)	10-20	14-16	60-65	5-6	4-5
Pregnant Does (Late Gestation)	30-45	12-14	65-70	6-7	4-6
Lactating Does (1 2 L/day)	30-45	12-14	68-72	7-9	6-7
Breeding Bucks	35-50	10-12	60-65	6-7	4-5

3. Nutritional Management for Optimal Growth:

3.1 Feeding of Kids

Early life nutrition is a major determinant of lifetime productivity in goats, influencing growth rate, immunity, rumen development and survival. The most critical component of neonatal feeding is adequate colostrum intake within the first few hours after birth. Kid goats should receive at least 10% of their body weight in colostrum within the first 12 hours to ensure passive transfer of immunoglobulins and to provide essential nutrients, growth factors and antimicrobial peptides (Santos *et al.,* 2018). The absorption efficiency of immunoglobulins declines rapidly after birth, making timely feeding essential for achieving optimal immune protection (Besser & Gay, 1994). Beyond immunity, colostrum also provides higher energy and protein content than mature milk, which supports thermoregulation and early growth (McCoy *et al.,* 2019).

After the first 3-5 days, kids can be transitioned to whole milk or high-quality milk replacers. Natural milk remains the gold standard, supplying superior nutrient density and biological components. However, milk replacers formulated with 22-24% crude protein and 20-25% fat can serve as effective alternatives in commercial operations, reducing dependence on dam's milk and enabling early breeding of does (Bastholm *et al.,* 2017). Plant protein-based replacers should be avoided in early life due to lower digestibility and higher allergenic potential compared to dairy based replacers (Park *et al.,* 2007). Consistent feeding schedules, proper sanitation and correct mixing of replacers are essential to avoid digestive disturbances such as diarrhea.

Early introduction of creep feed is crucial for promoting rumen development. Creep feed can be offered from 10-15 days of age to stimulate papillae growth and encourage microbial colonization (Lu, 1988). High quality creep feeds typically contain 16-18% crude protein, easily fermentable carbohydrates and a balanced mineral vitamin premix. The presence of small amounts of fiber enhances rumination behavior and accelerates rumen maturation (Silanikove, 2000). Kids provided with creep feed exhibit higher weaning weights, better post weaning growth and improved feed efficiency compared to those raised solely on milk and forage (Soryal *et al.,* 2013). Weaning should be gradual and typically occurs at 8-12 weeks when kids consume 200-250 g/day of creep feed.

3.2 Feeding of Growing Goats

Growing goats (3-9 months) require balanced energy and protein intake to support muscle accretion, skeletal development and metabolic growth. Energy is a primary driver of growth and insufficient supply leads to reduced feed intake and poor weight gain. Diets for growers should provide 60-65% TDN depending on breed and growth targets (ICAR, 2023). Energy rich ingredients such as maize, barley, sorghum and good quality forages help maintain optimal growth trajectories. Overfeeding of energy, however, may predispose goats to excessive fat deposition and reduced future reproductive efficiency, particularly in replacement does (Devendra, 2013).

Protein plays a central role in tissue synthesis and is often second only to energy in limiting optimal growth. Growing goats generally require 14-16% crude protein, with a balanced combination of rumen degradable protein (RDP) and undegradable dietary protein (UDP) (NRC, 2007). Bypass (protected) protein sources such as heat treated soybean meal, formaldehyde treated groundnut cake and commercial bypass protein supplements help improve metabolizable protein supply, especially where low quality forages dominate the diet (Mahgoub *et al.,* 2016). These supplements improve muscle development, enhance average daily gain and support better immune function.

Mineral mixture supplementation is essential during the growing phase due to rapid bone development and high metabolic activity. Trace minerals like zinc, copper, selenium and cobalt support enzyme function, immunity and hormonal regulation (McDowell *et al.,* 1993). In many

Indian production systems, forages often fail to provide adequate minerals, making supplementation necessary to prevent deficiencies such as zinc responsive dermatitis, anemia and reduced immunity (Devendra & Burns, 1983).

Feed conversion efficiency (FCE) is a key indicator of productivity in growing goats. High energy, moderately high protein diets combined with adequate mineral supplementation improve FCE significantly (Huston *et al.,* 1986). Goats raised under semi intensive systems often show better FCE compared to extensive systems due to improved feed quality and reduced energy expenditure on grazing. Introducing high quality cultivated forages such as lucerne, cowpea and hybrid Napier improves nutrient supply and enhances digestibility (Silanikove, 2000). Regular monitoring of growth rates and body condition scoring help adjust diets to avoid under or overfeeding.

Implementing structured feeding strategies during the growing phase ensures that goats reach ideal market weights, supports reproductive development in future breeding stock and enhances lifetime productivity. Integrating creep feeding, balanced rations, bypass proteins and mineral supplementation remain fundamental to optimizing growth performance in goats across production systems.

4. Nutritional Management for Milk Production

4.1 Nutrient Requirements for Lactating Does

Lactation represents the most nutritionally demanding phase in a doe's production cycle, as nutrients are required simultaneously for milk synthesis, maintenance, metabolic functioning and in many cases, recovery of body reserves lost during early lactation. Energy is the primary limiting nutrient during this period and there is a well established positive relationship between dietary energy density and milk yield. High producing lactating goats require energy dense rations with 65-72% total digestible nutrients (TDN), depending on body weight and level of milk output (ICAR, 2023). Diets supplying insufficient energy leads to negative energy balance, mobilization of body fat, reduced milk yield and increased susceptibility to metabolic disorders such as ketosis (Silanikove, 2000).

Energy density strongly influences milk yield because energy supports glucose production, the primary precursor for lactose synthesis. Since lactose regulates milk volume by controlling osmotic pressure, inadequate energy directly reduces milk quantity (Pulina *et al.,* 2006). Incorporation of high energy ingredients such as maize, barley, bypass fats and good quality forages increases energy availability and helps maintain persistency of lactation (NRC, 2007). Goats generally exhibit better feed efficiency than sheep and cattle when fed high energy diets due to their superior ability to digest fibrous and browse based feeds (Lu, 1988).

Protein is equally essential in determining milk production potential. Lactating does require 12- 14% crude protein in the total ration, with an adequate balance of rumen degradable protein (RDP) and undegradable dietary protein (UDP) (ICAR, 2023). Microbial protein synthesized in the rumen provides the majority of amino acids, but when milk yield is high or dietary energy is limiting, microbial protein alone becomes insufficient (Pulina *et al.,* 2006). Supplementation with bypass protein sources such as heat treated soybean meal, formaldehyde treated groundnut cake, or commercial protected protein improves metabolizable protein supply and enhances milk yield and composition (Mahgoub *et al.,* 2016).

Amino acids such as methionine and lysine are specifically limiting in lactating goats. Methionine influences milk fat synthesis and overall milk protein concentration, while lysine directly supports casein formation (Pfeil *et al.,* 2015). Supplementation with rumen protected forms of these amino acids has been shown to improve milk yield and enhance protein percentage in goat milk, particularly under intensive production systems (Park *et al.,* 2007). Minerals such as Ca, P, Mg and trace elements (Zn, Cu, Se) are also critical during lactation for metabolic functions, rumen microbial activity and maintenance of mammary health (McDowell *et al.,* 1993). Water intake is another determinant of milk yield, as goats require 4-6 liters/day or more depending on temperature and milk output.

Thus, nutrient requirements for lactating does are multifactorial and closely tied to milk yield potential, body condition and management system. Optimal supply of energy, protein, amino acids, minerals and water is fundamental to sustaining high and persistent lactation.

4.2 Effect of Nutrition on Milk Quantity and Quality

Nutrition plays a decisive role not only in determining milk volume but also its compositional quality, including milk fat, protein, lactose and solids not fat (SNF). Milk composition in goats is highly influenced by forage quality, concentrate level, type of carbohydrates, fat supplementation and mineral status (Park *et al.,* 2007).

Milk Fat

Milk fat is the most variable component of goat milk and is highly responsive to dietary changes. Diets rich in fiber, particularly physically effective neutral detergent fiber (peNDF), support acetate production in the rumen, which is the principal precursor for de novo fatty acid synthesis (Silanikove, 2000). Poor quality roughage, low fiber diets, or excessive concentrate feeding reduces rumen pH, suppresses fiber digesting microbes and decreases acetate production, resulting in lower milk fat percentage (Lu, 1988). Supplementation with bypass fats increases energy density and milk fat yield without affecting rumen fermentation. Additionally, oilseeds such as sunflower or linseed, when fed in controlled quantities, improve milk fat quality by increasing unsaturated fatty acid content (Nudda *et al.,* 2006).

Milk Protein

Milk protein concentration is influenced largely by dietary protein quality, metabolizable protein supply and amino acid balance. High quality RDP supports microbial protein synthesis, while UDP contributes directly to amino acid absorption. Diets containing adequate levels of bypass protein enhance milk protein percentage, particularly casein, which is vital for cheese making quality (Mahgoub *et al.,* 2016). Amino acids such as lysine and methionine play regulatory roles in protein synthesis at the mammary gland level (Pfeil *et al.,* 2015). Energy protein synchrony is essential; if energy is limiting, amino acids are deaminated and used as an energy source rather than directed toward milk protein formation.

Lactose

Lactose is the least variable component of goat milk, but it is highly sensitive to dietary energy intake. Lactose synthesis requires glucose and inadequate energy reduces glucose availability, subsequently reducing lactose concentration and milk yield (Sanz Sampelayo *et al.,* 2002). High energy diets with readily fermentable carbohydrates improve lactose synthesis and support higher milk volumes. Conversely, metabolic stress or poor quality roughages reduce lactose concentration and milk yield.

SNF (Solids Not Fat)

SNF includes protein, lactose, minerals and water soluble vitamins. Its concentration is influenced by dietary protein supply, mineral balance and energy intake. A deficiency in any of these components reduces SNF content, affecting milk processing quality and market value (Park *et al.,* 2007). Adequate mineral supplementation, particularly calcium, phosphorus and zinc, helps maintain optimal SNF levels and supports mammary gland functioning (McDowell *et al.,* 1993).

Overall, balanced nutrition enhances both milk quantity and its compositional quality. High quality forages combined with balanced concentrates, adequate bypass nutrients and proper mineral nutrition contribute to higher and more consistent milk performance in goats.

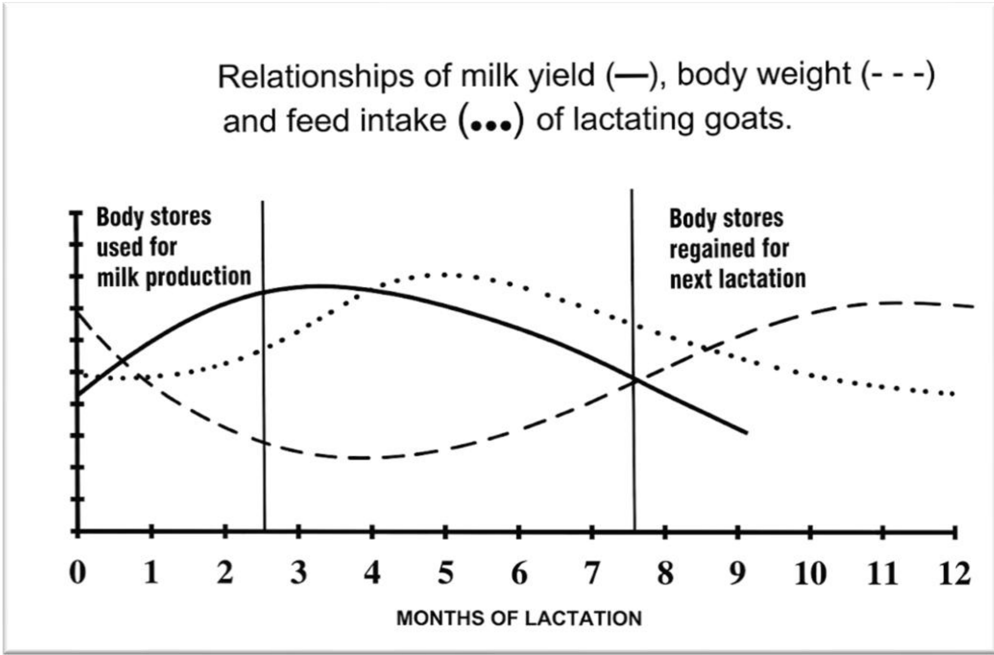


Figure 1: Lactation curve of goat, (Gafsi *et. al,* 2024)

4.3 Phase Wise Feeding During Lactation

Lactation in goats is typically divided into three physiological stages-early lactation, peak lactation and mid to late lactation. Each phase requires specific nutritional strategies aligned with milk production curve, body condition score (BCS) and metabolic demand.

Early Lactation (0-6 weeks)

Early lactation is characterized by a rapid increase in milk yield and a tendency for does to enter negative energy balance. Feed intake lags behind the rising milk production, leading to mobilization of body fat and protein reserves (Silanikove, 2000). Diets in this phase should be energy dense, containing 68-72% TDN, supported by high quality roughage and adequate concentrate supplementation. Inclusion of bypass fats and bypass protein helps meet the high demand for energy and amino acids (NRC, 2007). The protein level should be around 14-16% with adequate metabolizable protein supply. Methionine and lysine supplementation during this phase enhances milk protein and supports udder health (Pfeil *et al.,* 2015). Adequate minerals and vitamins, especially Ca, P, Mg, Zn and Se, are essential to prevent metabolic disorders such as hypocalcemia and ketosis.

Peak Lactation (6-10 weeks)

Peak lactation represents the highest milk yield period, where the does nutrient requirements are maximal. The focus during this phase is to maintain peak yield and prevent excessive loss of body condition. High quality forages combined with 1-1.5 kg/day concentrates containing 12-14% CP are recommended (ICAR, 2023). Rumen protected fat and protein supplements enhance energy and amino acid availability. Maintaining rumen health is critical; adequate fiber in the form of chopped green fodder or dry fodder prevents ruminal acidosis (Lu, 1988). Water intake must be unrestricted as water availability directly affects milk output.

Mid and Late Lactation (10-24 weeks)

Milk yield gradually declines in mid to late lactation and nutrient requirements decrease accordingly. The aim in this phase is to maintain milk persistency while restoring body reserves lost during early lactation (Devendra, 2013). Diets can be adjusted to moderate energy levels (65- 68% TDN) with protein content reduced to 12-14%. Concentrate feeding may be gradually reduced depending on milk output. Adequate mineral supplementation remains essential to maintain milk quality and reproductive readiness. Goats in late lactation should be fed to achieve an optimal BCS of 2.5-3 before breeding (Mahgoub *et al.,* 2016). High quality forages such as lucerne, cowpea fodder and hybrid Napier can support both maintenance and moderate production levels.

Phase wise feeding ensures that lactating goats maintain productive efficiency throughout the lactation cycle, supporting milk yield, udder health, body condition and reproductive performance. Well structured feeding programs reduce metabolic stress, enhance lactation persistency and ultimately improve profitability in dairy goat systems.

5.1 Use of Probiotics to Enhance Milk Productivity in Goats

Probiotics have emerged as an important nutritional strategy in dairy goat production due to their positive effects on rumen fermentation, nutrient digestibility, immune function and overall lactation performance. Probiotics defined as live microorganisms that confer health benefits when administered in adequate amounts commonly include *Lactobacillus*, *Bifidobacterium*, *Bacillus* and beneficial yeasts such as *Saccharomyces cerevisiae* (FAO/WHO, 2020). Their increasing use in small ruminant nutrition reflects a shift toward sustainable feeding practices that enhance production without relying heavily on antibiotics or synthetic additives.

In lactating goats, probiotics significantly influence rumen microbial ecology, improving the breakdown of fiber and enhancing volatile fatty acid production, particularly acetate and propionate. These fermentation end products are key substrates for milk fat and lactose synthesis, thereby supporting higher milk yield and improved milk composition (Zhang *et al.,* 2022). Yeast based probiotics, particularly *Saccharomyces cerevisiae*, stabilize rumen pH, increase cellulolytic bacterial populations and reduce lactic acid accumulation, resulting in better dry matter intake (DMI) and milk output under both intensive and semi intensive systems (Elghandour *et al.,* 2020).

Recent studies have linked probiotic supplementation with enhanced milk quality parameters, including increased fat, protein and solids not fat (SNF) levels. This improvement is partly attributed to increased nutrient absorption and better amino acid availability for mammary gland metabolism (Abdelrahman *et al.,* 2021). Some strains such as *Lactobacillus plantarum* and *Bacillus subtilis* enhance immune function in lactating does, reducing subclinical mastitis incidence and improving udder health, which indirectly contributes to more consistent milk yield (Gao *et al.,* 2023). Improved immunity also reduces oxidative stress, which is associated with decreased milk production during periods of heat stress or metabolic strain.

Probiotics may also enhance feed efficiency by increasing microbial protein synthesis in the rumen. Higher microbial protein flow to the small intestine supports amino acid availability for milk protein synthesis, leading to improved casein concentration and overall milk protein percentage. This is particularly important in dairy goats due to the high value of goat milk cheese, which depends heavily on protein quality (Elghandour *et al.,* 2020).

Furthermore, trials conducted in hot climatic regions have demonstrated that probiotics help mitigate heat stress related production losses by improving rumen stability and reducing physiological markers of stress (Gao *et al.,* 2023). As goats are often reared under extensive or semi intensive conditions in tropical climates, probiotics offer a practical method to enhance resilience while boosting milk productivity.

Probiotics represent a promising nutritional tool for improving milk yield, composition, feed efficiency and resilience in lactating goats. Their role in promoting rumen health, enhancing immunity and stabilizing physiological functions makes them a valuable component in modern, sustainable dairy goat nutrition programs.

5.2 Phytogenic and Herbal Additives for Optimum Growth and Milk Production

Phytogenic and herbal feed additives have gained increasing attention in dairy goat nutrition due to their natural origin, safety and multifunctional benefits. These plant derived substances such as essential oils, tannin rich forages, saponins and aromatic herbs possess antimicrobial, antioxidant and rumen modulating properties that contribute to improved growth performance and lactation efficiency (Patra, 2011). Their use aligns with the global movement toward reducing antibiotic use and enhancing sustainable livestock production.

In lactating goats, phytogenic additives enhance rumen fermentation by selectively inhibiting pathogenic or excessive ammonia producing bacteria while promoting beneficial microbial species. Essential oils from oregano, thyme and cinnamon have been shown to increase propionate production and reduce methane emission, improving the efficiency of energy utilization for milk synthesis (Calsamiglia *et al.,* 2007). Increased propionate availability directly supports glucose synthesis in the liver, enhancing lactose formation and thereby improving milk volume. At the same time, better fiber digestion associated with herbal additives contributes to higher acetate production, which aids in milk fat synthesis.

Plant extracts such as fenugreek (*Trigonella foenum graecum*) and moringa (*Moringa oleifera*) have demonstrated galactagogue effects, improving both milk yield and milk components. Studies report that moringa leaf supplementation enhances milk fat, protein and solids not fat due to its high nutrient density, antioxidant capacity and rich amino acid profile (Nouman *et al.,* 2014). Similarly, fenugreek seeds stimulate appetite, improve rumen environment and support higher milk production by modulating hormonal pathways linked to lactogenesis (Tibin *et al.,* 2019).

Herbal additives also contribute to improved growth performance in young and growing goats. Saponin rich plants such as *Yucca schidigera* reduce rumen ammonia levels and enhance microbial protein synthesis, leading to improved average daily gain and feed efficiency (Patra, 2011). Tannin containing plants such as quebracho, when supplemented at optimal levels, reduce protein degradation in the rumen and increase the availability of amino acids for tissue and milk protein synthesis (Calsamiglia *et al.,* 2007).

5.3 Nano Minerals and Their Role in Optimal Growth and Milk Production

Nano-minerals have emerged as a novel and efficient approach to mineral supplementation in ruminants, including goats, due to their enhanced bioavailability, higher surface area, and improved absorption compared to conventional inorganic or organic mineral forms. Nano-sized mineral particles (1–100 nm) exhibit higher reactivity and stability, enabling better interaction with the gastrointestinal tract and rumen microbiome, thereby improving growth performance, immune function, and milk productivity (Yatoo *et al.,* 2021). Among nano-minerals, nano-zinc, nano-selenium, nano-copper, and nano-iron are the most widely studied for their roles in small ruminant nutrition.

Nano-zinc is critical for enzymatic activity, keratin synthesis, immunity, and reproductive performance. Supplementation of nano-zinc has been shown to improve average daily gain, feed conversion efficiency, and udder health in goats by enhancing epithelial integrity and immune responses (Elshahawy & Ahmed, 2019). It also plays a role in milk synthesis by improving rumen fermentation, stabilizing microbial populations, and supporting protein metabolism. Improved zinc bioavailability has been associated with higher milk protein and SNF content, likely due to enhanced amino acid utilization and mammary gland function.

Nano-selenium is an essential component of glutathione peroxidase, a major antioxidant enzyme. It reduces oxidative stress in lactating does, improving metabolic efficiency and supporting higher milk yield and quality (Wang *et al.,* 2020). Nano-selenium also enhances reproductive performance, immunity, and overall health, contributing indirectly to improved growth and lactation persistency. Its higher absorption efficiency compared to sodium selenite results in improved antioxidant status in both does and offspring.

Nano-copper plays a central role in hemoglobin synthesis, connective tissue formation, and immune modulation. In goats, nano-copper supplementation improves growth rate and immune function while reducing susceptibility to parasitic and bacterial infections (Abdelnour *et al.,* 2023). Enhanced copper bioavailability also promotes more efficient rumen microbial activity and better fiber digestion, contributing to improved energy utilization for milk production. Similarly, nano-iron enhances erythropoiesis, oxygen transport, and metabolic activity. In young goats, nano-iron supplementation supports growth, hematological parameters, and immunity, promoting better early-life performance (Yatoo *et al.,* 2021).

5.4 Agro Industrial byproducts

Agro industrial by products represent valuable, cost-effective feed resources that can significantly enhance growth and milk production in goats when used strategically. These byproducts—such as oilseed cakes, cereal brans, molasses, distillers' dried grains, fruit pomace, and sugarcane bagasse—offer high nutrient density and help address seasonal feed shortages common in tropical production systems. Their incorporation into goat diets improves feed efficiency, reduces feeding costs, and promotes sustainability in livestock farming (Gemeda & Hassen, 2015).

Oilseed cakes such as groundnut cake, soybean meal, cottonseed cake, and sunflower cake are rich in protein and serve as excellent supplements for growing and lactating goats. These protein rich by products enhance microbial fermentation, improve rumen nitrogen balance, and support higher milk protein synthesis, especially when used alongside low quality roughages (Khan *et al.,* 2020). Cottonseed cake and sunflower cake also supply moderate fat levels, increasing dietary energy density an important aspect for high yielding dairy goats.

Cereal by products like wheat bran and rice bran are widely available energy and fiber sources with favorable palatability. Wheat bran enhances rumen function by providing fermentable fiber and vitamins, while rice bran contributes essential fatty acids that may improve milk fat and overall milk quality (Bampidis & Robinson, 2006). Molasses serves as a readily fermentable carbohydrate source that enhances rumen microbial growth, increases feed intake, and improves digestibility making it particularly useful in diets based on crop residues.

Distillers' dried grains with solubles (DDGS), a byproduct of ethanol production, have gained attention due to their high protein and energy content. Supplementing DDGS in goat diets has demonstrated improvements in average daily gain and milk yield due to enhanced rumen fermentation and amino acid supply (Zhang *et al.,* 2019). Fruit by products such as citrus pulp and apple pomace offer fermentable fiber, pectin, and energy, often improving milk yield and affecting milk flavor positively when fed in controlled amounts.

5.5 Yeast Culture and Enzymes in Optimal Growth and Milk Production

Yeast cultures and exogenous enzymes have become increasingly important feed additives in dairy goat nutrition due to their ability to enhance rumen fermentation, improve nutrient digestibility and support higher growth and milk production. Yeast products particularly *Saccharomyces cerevisiae* are widely used to stabilize rumen pH, stimulate beneficial microbial populations and enhance fiber digestion (Morsy *et al.,* 2021). They function by scavenging oxygen in the rumen, creating a more favorable anaerobic environment that promotes cellulolytic bacterial activity. This results in increased production of volatile fatty acids, especially acetate and propionate, which are key precursors for milk fat and lactose synthesis, respectively (Saleem *et al.,* 2020).

In lactating goats, supplementation with yeast culture has been shown to improve dry matter intake, increase milk yield and enhance milk composition. Recent studies highlight improvements in milk fat and protein percentages due to enhanced nutrient availability and improved microbial protein synthesis (Maamouri *et al.,* 2022). Yeast culture also boosts immune function and reduces oxidative stress, which is particularly beneficial under heat stress or intensive production systems, ultimately supporting sustained lactation and animal health (Alhidary *et al.,* 2023).

Exogenous enzymes such as cellulases, xylanases, proteases and amylases act synergistically with the rumen microbiota to break down complex feed components. Enzyme supplementation increases the digestibility of fiber, starch and protein, resulting in improved feed conversion efficiency and higher average daily gain in growing goats (Kholif *et al.,* 2018). Improved fiber degradation increases rumen turnover, enhancing voluntary feed intake and energy supply for productive functions. In lactating does, enzyme treated diets have been associated with increased milk yield due to improved availability of nutrients essential for mammary gland metabolism (Maamouri *et al.,* 2022).

Furthermore, combining yeast culture with fibrolytic enzymes has shown additive benefits by simultaneously enhancing microbial activity and hydrolyzing complex fiber fractions, leading to improved nutrient absorption and higher metabolic efficiency. This dual supplementation strategy is increasingly recommended in high producing dairy goats for optimizing growth, rumen health and milk production.

Overall, yeast cultures and exogenous enzymes offer a sustainable and effective approach for improving growth performance, rumen stability, nutrient digestibility and milk production in goats, making them valuable components of precision nutrition programs.

5.6 Bypass Fat and Bypass Protein for Optimal Growth and Milk Production

Bypass fat and bypass protein have become essential components of precision feeding strategies in dairy goats, particularly in systems aiming for high growth rates and sustained milk production. These supplements are designed to resist degradation in the rumen and supply nutrients directly to the small intestine, thereby improving nutrient efficiency and supporting metabolic functions critical during high demand phases such as early lactation and rapid growth (NRC, 2007).

Bypass Fat

Bypass fat, also known as rumen protected fat, increases dietary energy density without negatively affecting rumen fermentation. This is particularly important during early lactation, when does experience negative energy balance due to rapid increases in milk yield. Supplementing 3-5% bypass fat has been shown to improve dry matter intake, enhance energy availability and increase milk yield and milk fat percentage (Khan *et al.,* 2020). Bypass fats also reduce body tissue mobilization, thereby lowering the risk of ketosis and improving reproductive performance postpartum. Recent studies report that calcium salts of long chain fatty acids enhance the supply of essential fatty acids to the mammary gland, improving the fatty acid profile of goat milk (Adeyemi *et al.,* 2021).

Bypass Protein

Bypass protein (rumen undegradable protein, RUP) ensures that a greater proportion of dietary amino acids escapes rumen degradation and becomes available for absorption in the intestine. This is particularly valuable for high yielding goats, in which microbial protein synthesis alone cannot meet amino acid requirements. Supplementing bypass protein sources such as heat treated soybean meal, formaldehyde treated groundnut cake, or commercial RUP blends has been shown to enhance milk yield, increase milk protein percentage and improve body condition in lactating does (Abdalla *et al.,* 2022).

In growing goats, bypass protein supplementation improves muscle accretion, growth rate and feed efficiency due to better availability of essential amino acids such as lysine and methionine, which are critical for lean tissue development (Mahgoub *et al.,* 2016). The improved amino acid supply also enhances immune function and overall metabolic efficiency.

Combined Benefits

The combined use of bypass fat and bypass protein has a synergistic effect, supplying adequate energy and amino acids for optimal growth and lactation persistency. This nutritional strategy is particularly beneficial under intensive and semi intensive systems, where higher productivity demands more precise nutrient targeting.

5.7 Precision Feeding Tools for Optimal Growth and Milk Production

Precision feeding tools are increasingly used in dairy goat systems to optimize nutrient delivery, enhance production efficiency and reduce metabolic stress. These tools rely on accurate assessment of nutrient requirements, feed intake and physiological status, enabling producers to tailor diets that match the animal's exact stage of growth or lactation. One of the foundational tools in precision nutrition is Body Condition Scoring (BCS). Regular BCS monitoring helps identify under conditioned or over conditioned goats, allowing timely dietary adjustments to maintain an optimal score of 2.5-3.0 for lactating does and replacement stock (Musa *et al.,* 2020). Maintaining proper BCS improves reproductive performance, milk yield and longevity.

Another essential tool is Dry Matter Intake (DMI) estimation, as intake largely determines nutrient supply. Predictive models incorporating body weight, stage of lactation and forage quality are increasingly used to estimate DMI and optimize ration formulation (Tedeschi & Fox, 2020). Accurate DMI estimation prevents both underfeeding and overfeeding, supporting consistent milk production and efficient feed utilization.

Modern precision nutrition also incorporates nutrient modeling systems such as CNCPS Small Ruminants and ICAR based feeding standards, which allow more accurate prediction of energy, protein and mineral requirements under varying environmental and management conditions (Cannas *et al.,* 2019).

Additionally, emerging technologies such as automated weighing systems, milk meters and rumen sensors provide real time data on growth patterns, feed efficiency, rumen pH and physiological stress. These insights help producers make evidence based adjustments to feeding strategies, ultimately enhancing both growth performance and milk output (Neethirajan, 2021).

6. Nutritional Challenges in Goat Production

Goat production systems across tropical and subtropical regions frequently face significant nutritional challenges that hinder growth, reproduction and milk productivity. These challenges are often interlinked with environmental constraints, forage availability and health status, making nutritional management a complex task. Four major issues affecting goat nutrition include mineral deficiencies, seasonal feed scarcity, parasite load and heat stress.

6.1 Mineral Deficiencies

Mineral imbalances are among the most widespread nutritional constraints in goat systems, especially in regions where soil mineral profiles are poor. Deficiencies of copper, zinc, cobalt and selenium are particularly common and impact metabolic functions, immune competence, growth and reproductive performance (McDowell *et al.,* 1993). Copper deficiency can lead to anemia, poor coat condition, reduced fertility and impaired rumen microbial activity. Zinc deficiency affects keratin formation, hoof health and epithelial integrity, making goats more susceptible to mastitis and infections (Elghandour *et al.,* 2020). Selenium deficiency, meanwhile, weakens antioxidant defense mechanisms and increases the risk of retained placenta, weak kids and lowered milk yield (Wang *et al.,* 2020).

Mineral deficiencies often go unnoticed due to subclinical symptoms, yet even mild deficits can significantly reduce feed utilization efficiency and milk composition. Supplementation with mineral mixtures, chelated minerals, or more efficient nano mineral forms is therefore essential for maintaining optimal productivity, particularly during late gestation and early lactation.

6.2 Seasonal Feed Scarcity

In many developing countries, goat production is closely tied to rain fed forage systems. During dry seasons, forage availability declines sharply and what remains is often lignified, nutrient poor and deficient in protein and vitamins. This scarcity leads to reduced dry matter intake, weight loss, stunted growth in kids and decreased milk output in lactating does (Devendra, 2013).

Seasonal fluctuations reduce rumen microbial efficiency due to lower fermentable substrates, resulting in poor digestion and metabolic stress. Strategies such as fodder conservation (silage, hay), cultivation of drought tolerant forages like sorghum and cowpea and supplementation with concentrates or non-conventional feeds (tree leaves, agro industrial by products) are critical to bridging the nutritional gap. Integrating browse species such as subabul and moringa also helps sustain nutrition during lean periods.

6.3 Parasite Load and Impact on Nutrition

Internal and external parasites pose a major constraint on nutrient utilization in goats. Gastrointestinal nematodes such as *Haemonchus contortus* cause blood loss, protein depletion and anemia, severely reducing growth rate, milk production and reproductive efficiency (Hoste *et al.,* 2018). Parasite infestation increases metabolic demands while simultaneously reducing feed intake and nutrient absorption. The combined effect leads to poor feed conversion efficiency and stunted performance.

Parasitic load is often highest during humid seasons, when larvae proliferate on pasture. Strategic deworming, rotational grazing and supplementation with tannin rich plants like quebracho or sericea lespedeza have been shown to reduce parasite burden and improve nutrient availability (Patra, 2020). Improved protein and mineral nutrition also enhance immune resilience, allowing goats to better withstand parasitic challenges.

6.4 Heat Stress and Summer Feeding Strategies

Heat stress is an increasingly significant challenge due to rising temperatures associated with climate change. Goats exposed to high ambient heat exhibit reduced feed intake, altered rumen function, elevated respiration rate and increased oxidative stress, all of which impair growth and lactation (Gao *et al.,* 2023). Heat stress reduces rumen microbial activity and shifts fermentation toward less efficient pathways, lowering production of volatile fatty acids essential for milk synthesis.

Feeding strategies to mitigate heat stress include providing high quality, energy dense diets that compensate for reduced intake, increasing dietary fat up to 5% for additional energy and offering easily digestible forages. Ensuring adequate water availability and supplementing electrolytes such as sodium, potassium and bicarbonate help maintain hydration and rumen buffering capacity. Probiotic and yeast supplementation has been shown to stabilize rumen pH and improve performance under heat stress conditions (Alhidary *et al.,* 2023). Shade provision, cooling systems and feeding during cooler times of the day also improve feed intake and nutrient utilization.

Conclusion:

Nutritional management in goats is a multi-dimensional task that demands both scientific understanding and practical adaptability. As this chapter highlights, optimum growth and sustained milk production are not the outcomes of a single feeding practice, but of a coordinated approach that begins as early as colostrum intake and continues through each physiological stage of the animal's life cycle. Goats are remarkably resilient animals, yet their productivity depends heavily on how well their nutritional needs are met in the context of changing environments, seasonal feed variations, and production demands. Nutrient requirements, feeding strategies, and phase-wise lactation management shows that targeted nutrition can significantly improve animal performance. Incorporating advances such as probiotics, nano-minerals, herbal additives, yeast cultures, and precision feeding tools enables producers to fine tune diets with greater accuracy than ever before. Likewise, the use of agro-industrial by-products offers an economical and sustainable way to bridge nutritional gaps without compromising milk quality or growth. Challenges such as mineral deficiencies, parasite pressure, heat stress, and feed scarcity remind us that nutritional planning must remain flexible and responsive. No single feeding programme fits all situations; instead, successful goat production relies on continuous observation, timely adjustments, and an understanding of how nutrition interacts with health and management.

Ultimately, improving goat productivity is not just about increasing numbers it is about supporting healthier animals, strengthening rural livelihoods, and moving toward more sustainable livestock systems. With informed nutritional interventions and evolving scientific tools, the potential for better growth, higher milk yields, and improved overall performance in goats is both achievable and promising.

References:

1. Abdalla, E. B., Sharaf, H. A., & El-Sherbiny, M. (2022). Effect of rumen undegradable protein supplementation on milk performance in dairy goats. *Small Ruminant Research, 214*, 106722.
2. Abdelnour, S. A., Abd El-Hack, M. E., Khafaga, A. F., & Arif, M. (2023). Nano-copper as a novel feed additive: Impacts on ruminant health and production. *Animal Biotechnology, 34*(2), 330–341.
3. Abdelrahman, M. M., Alhidary, I. A., & Gado, H. (2021). Influence of probiotic supplementation on milk yield and composition in goats. *Small Ruminant Research, 198*, 106352.
4. Adeyemi, K. D., Sazili, A. Q., & Samsudin, A. A. (2021). Calcium salts of fatty acids and their role in ruminant lactation performance. *Animals, 11*(3), 756.
5. Alhidary, I. A., Abdelrahman, M. M., & Gado, H. (2023). Yeast culture supplementation improves performance and immune response in heat-stressed goats. *Journal of Applied Animal Research, 51*(1), 234–242.
6. Assad, F., & El-Shazly, H. (2024). Nutrient utilization and requirements in sheep and goats. *Journal of Veterinary and Animal Nutrition, 12*(1), 1–15.
7. Bampidis, V., & Robinson, P. H. (2006). Citrus by-products as ruminant feeds: A review. *Animal Feed Science and Technology, 128*(3–4), 175–217.
8. Bastholm, S. K., *et al.* (2017). Growth and health of goat kids fed milk replacers versus natural milk. *Journal of Dairy Science, 100*(5), 3501–3512.
9. Besser, T. E., & Gay, C. C. (1994). The importance of colostrum to the health of the neonatal calf. *Veterinary Clinics of North America, 10*(1), 107–117.
10. Boyazoglu, J., & Morand-Fehr, P. (2001). Mediterranean dairy sheep and goat products and their quality—A critical review. *Small Ruminant Research, 40*(1), 1–11.

11. Calsamiglia, S., Busquet, M., Cardozo, P. W., Castillejos, L., & Ferret, A. (2007). Essential oils as modifiers of rumen microbial fermentation. *Journal of Dairy Science, 90*(6), 2580–2595.
12. Cannas, A., Tedeschi, L. O., Fox, D. G., & Pell, A. N. (2019). The Small Ruminant Nutrition System: A tool for precision feeding. *Small Ruminant Research, 180*, 45–52.
13. Devendra, C. (2013). Investments on goats for securing livelihoods in developing countries. *Asian Journal of Agriculture and Development, 10*(2), 1–18.
14. Devendra, C., & Burns, M. (1983). *Goat production in the tropics*. Commonwealth Agricultural Bureaux.
15. Elghandour, M. M. Y., *et al.* (2020). Probiotics in ruminant nutrition: Interactions, benefits, and modes of action. *Animal Feed Science and Technology, 267*, 114554.
16. Elshahawy, I. I., & Ahmed, A. M. (2019). Effects of dietary nano-zinc supplementation on growth performance and health status of goats. *Small Ruminant Research, 177*, 147–154.
17. FAO/WHO. (2020). *Guidelines for the evaluation of probiotics in food*. Food and Agriculture Organization of the United Nations.
18. Gafsi, N., Martin, O., Bidan, F., Grimard, B., & Puillet, L. (2024). Diversity of performance patterns in dairy goats: Multi-scale analysis of lactation curves. *Peer Community Journal, 4*, e85.
19. Gao, Y., Zhang, X., & Li, H. (2023). Dietary probiotics improve production performance, rumen fermentation, and antioxidant capacity in lactating goats. *Journal of Dairy Science, 106*(4), 2451–2464.
20. Gemeda, B. S., & Hassen, A. (2015). Supplementing agro-industrial byproducts to improve feed utilization and performance in ruminants. *Livestock Research for Rural Development, 27*(12), 1–10.
21. Goetsch, A. L., & Sheep & Goat Extension. (n.d.). Goat early lactation: Feed intake, body weight, and milk yield relationships. *Goat Extension*.
22. Hoste, H., Torres-Acosta, J. F. J., & Sandoval-Castro, C. (2018). Nutrition–parasite interactions in goats. *Veterinary Parasitology, 253*, 59–67.
23. Huston, J. E., Taylor, C. A., & Brooks, T. D. (1986). Grazing systems and stocking rates for sheep, goats, and cattle on rangeland. *Journal of Animal Science, 62*(1), 59–66.
24. ICAR. (2023). *Nutrient requirements of goats*. Indian Council of Agricultural Research, New Delhi.
25. Kalyankar, S. D., *et al.* (2022). Nutritional and nutraceutical properties of goat milk for human health. *CABI Reviews, 17*, 1–12.

26. Khan, N. A., Habib, G., & Ullah, G. (2020). Rumen-protected fat supplementation and its impact on milk yield and composition in dairy goats. *Journal of Dairy Science, 103*(7), 6571–6580.
27. Kholif, A. E., Gouda, G. A., & Olafadehan, O. A. (2018). Dietary enzyme addition for improving nutrient utilization and lactational performance in goats. *Animal Feed Science and Technology, 245*, 131–138.
28. Lu, C. D. (1988). Grazing behavior and diet selection of goats. *Journal of Dairy Science, 71*(5), 1348–1354.
29. Maamouri, O., Rekhis, J., & Ben Salem, H. (2022). Effects of dietary yeast and enzymes on milk production and rumen fermentation in dairy goats. *Small Ruminant Research, 209*, 106636.
30. Mahgoub, O., Kadim, I. T., & Al-Saqry, N. M. (2016). Effects of nutritional status on reproductive performance of bucks. *Small Ruminant Research, 136*, 76–82.
31. McCoy, G., *et al.* (2019). Colostrum composition and immune development in neonatal ruminants. *Livestock Science, 226*, 122–129.
32. McDowell, L. R., Conrad, J. H., Ellis, G. L., & Loosli, J. K. (1993). *Mineral deficiencies in ruminants*. University of Florida Press.
33. Morsy, T. A., Hassan, A. A., & Elghandour, M. M. Y. (2021). Yeast probiotics and their impacts on rumen fermentation and productivity in ruminants. *Frontiers in Veterinary Science, 8*, 645432.
34. Musa, H. H., *et al.* (2020). Body condition scoring as a tool for improving productivity and welfare in small ruminants. *Livestock Science, 238*, 104030.
35. Neethirajan, S. (2021). Precision livestock farming technologies for small ruminants. *Sensors, 21*(17), 5922.
36. NRC. (2007). *Nutrient requirements of small ruminants: Sheep, goats, cervids, and New World camelids*. National Academies Press.
37. Nouman, W., *et al.* (2014). Potential of *Moringa oleifera* L. as livestock fodder crop: A review. *Turkish Journal of Agriculture and Forestry, 38*(1), 1–14.
38. Nudda, A., *et al.* (2006). Dairy goat feeding and milk composition: Effects of diet on fatty acid profile. *Small Ruminant Research, 62*(3), 187–192.
39. Park, Y. W., *et al.* (2007). Functional and nutritional characteristics of goat milk. *Small Ruminant Research, 68*(1–2), 88–113.

40. Patra, A. K. (2011). Effects of essential oils and phytogenic feed additives on rumen fermentation and performance of ruminants. *Animal Feed Science and Technology, 168*(2–4), 189–198.
41. Patra, A. K. (2020). Plant secondary metabolites for controlling gastrointestinal nematodes in ruminants. *Journal of Animal Physiology and Animal Nutrition, 104*(2), 531–545.
42. Pfeil, R. M., *et al.* (2015). Methionine and lysine supplementation in dairy goats. *Journal of Dairy Science, 98*(6), 4070–4080.
43. Pulina, G., *et al.* (2006). Energy and protein requirements of lactating goats. *Livestock Science, 104*, 1–7.
44. Sanz Sampelayo, M. R., *et al.* (2002). Relationships between nutrition and milk composition in goats. *Journal of Dairy Science, 85*(2), 440–445.
45. Santos, D. O., Silva, L. M., & Lima, G. F. (2018). Effects of nutritional management on reproductive performance in goats. *Journal of Animal Physiology and Animal Nutrition, 102*(3), 667–678.
46. Saleem, A. M., Zanouny, A. I., & El-Medany, S. A. (2020). Influence of yeast culture on nutrient digestibility and lactation performance in goats. *Veterinary World, 13*(5), 1042–1048.
47. Silanikove, N. (2000). The physiological basis of adaptation in goats to harsh environments. *Small Ruminant Research, 35*(3), 181–193.
48. Singh, M. K., Singh, S. K., & Chauhan, M. S. (2023). Exploring potential of goat-based dairy farming in India and way forward. *Indian Journal of Animal Sciences, 93*(3), 243–250.
49. Soryal, K., *et al.* (2013). Influence of creep feeding on growth and carcass traits in dairy goat kids. *Journal of Applied Animal Research, 41*(3), 292–298.
50. Tedeschi, L. O., & Fox, D. G. (2020). Predicting dry matter intake for precision feeding of small ruminants. *Journal of Animal Science, 98*(5), skaa129.
51. Wang, Y., Liu, Q., & Guo, Y. (2020). Nano-selenium supplementation enhances antioxidant status and milk performance in lactating goats. *Journal of Dairy Science, 103*(9), 8562–8571.
52. Yatoo, M. I., Saxena, A., Gopalakrishnan, A., & Pal, A. (2021). Nanotechnology-based interventions in animal nutrition and production. *Veterinary World, 14*(3), 743–753.
53. Zhang, Q., Liu, S., & Wang, Y. (2022). Effects of multi-strain probiotics on milk performance and rumen fermentation in dairy goats. *Animals, 12*(18), 2345.

ASSESSING CLONAL PROPAGATED PLANTS PERFORMANCE UNDER INCREASING GREENHOUSE GAS CONCENTRATIONS IN DEVELOPING ECONOMIES

Manoj N. S*[1], Vivek M S[2] and Abhishek Belli M[3]

[1]Department of Genetics and Plant Breeding,

[2]Department of Soil Science and Agricultural Chemistry,

[3]Department of Crop Physiology,

University of Agricultural Sciences, GKVK, Bangalore 560065

*Corresponding author E-mail: nsmanoj330@gmail.com

Abstract:

The continued increase in greenhouse gases including CO_2, CH_4 and N_2O has intensified global warming, with global temperatures climbing to around 1.3 °C above pre-industrial levels as of 2024. Rising greenhouse gas (GHG) concentrations like CO_2, CH_4 and N_2O have spurred unprecedented global warming at ~1.3 °C above pre-industrial in 2024. This climate shift is significantly affecting tropical agriculture, where resources are limited. Crops propagated through clonal methods including sugarcane, banana, cassava and potato generally exhibit high heterozygosity. Clonally propagated crops, many of which are polyploid, play a crucial role in food and non-food production systems across developing regions. They can exhibit remarkable plasticity *via* resource-sharing, epigenetic memory symbioses and potentially by buffering stress. Yet, the combined effects of elevated CO_2 and other GHG driven stresses on clonal plant physiology and yield are poorly quantified in tropical systems. Here we review how rising CO_2, CH_4 and N_2O alter plant growth with emphasis on clonal traits such as resource allocation, stomatal adjustment, carbohydrate partitioning and gene regulation. Key knowledge gaps include scarce CO_2-enrichment data and limited understanding of clonal epigenetics. Finally, we outline strategies in genomics, biotechnology and climate-smart agronomy to leverage clonal adaptability for resilient agriculture in developing economies.

Keywords: Clonal Propagation, Climate Change, Polyploid Crops and Greenhouse Gases

1. Introduction:

Greenhouse gas concentrations have risen sharply, with atmospheric CO_2 now at ~425 ppm (increasing by ≈1.3 ppm per year), while methane (~1934 ppb) and nitrous oxide (~339 ppb) have reached record highs. This continuous rise in GHGs has led to global warming and altered precipitation (NOAL, 2025). In developing regions, such changes already depress crop yields *via* heat stress, drought and erratic rains. Notably, lower latitude food producing areas have seen yield declines tied to recent warming, exacerbating food insecurity where resources are limited (IPCC, 2022).

Clonal propagation is widespread in tropical agriculture. Staple crops like sugarcane, banana, cassava and potato are grown vegetatively to preserve high yield hybrids. These polyploid crops maintain high heterozygosity, along with substantial genetic variability and hybrid vigor, through clonal reproduction. Vegetatively propagated potato, sugarcane and banana play a crucial role in global food supply and harbor the genetic potential to meet nutritional needs (Sakthivel *et al.* 2025). Clonal plants can also share resources among connected ramets such as stolons, rhizomes and tubers, effectively buffering spatial heterogeneity (De Souza *et al.* 2008). These features include high genetic diversity, resource integration and stress memory suggest clonal crops may exhibit unique adaptability under climate change. It is therefore vital to study how elevated GHGs level especially CO_2 interact with abiotic stress in clonal species. High CO_2 can boost photosynthesis which is called CO_2 fertilization effect but also shifts plant water use and nutrient balance. Simultaneous stressors such as heat, drought and salinity may trigger epigenetic adaptations in asexually propagated plants. Understanding these mechanisms is especially important in tropical developing economies, where agriculture faces climate variability, resource constraints and limited access to advanced technology. Many countries lack FACE (Free Air Carbon Dioxide Enrichment chambers) and controlled facilities to test crops under future CO_2 scenarios and breeding programs for clonals are under resourced. This chapter addresses these gaps by integrating global and field-based findings on clonal plant responses to rising GHGs, focusing on tropical case studies and implications for climate-resilient cultivation.

2. Greenhouse Gas Trends and Agricultural Implications

Atmospheric greenhouse gases continue to rise, with carbon dioxide, the primary contributor increasing from about 280 ppm in the pre-industrial era to roughly 425 ppm by 2025. Likewise, methane has climbed from around 1,890 ppb in 2000 to about 1,934 ppb in 2025 and nitrous oxide has increased from roughly 316 ppb to 339 ppb over the same period, reaching record highs. These rising concentrations trap more heat, contributing to a global surface temperature anomaly of +1.29 °C in 2024 compared with the 20th-century average an increase that set new temperature records across every continent (NOAA 2025). According to the IPCC WGII, even the current level of warming is already undermining food security through rising temperatures and altered rainfall patterns. Looking ahead, developing regions in the tropics and subtropics are projected to face disproportionately severe impacts, including more frequent droughts and floods, as well as emerging pest pressures (IPCC, 2022).

For agriculture, higher CO_2 has mixed effects. It can enhance photosynthesis and water-use efficiency in C_3 crops, but it also intensifies heat stress and may reduce crop quality. Models project that further warming will increasingly push tropical crops beyond their optimal temperatures. Moreover, shifts in monsoon patterns and soil moisture cycles disrupt planting schedules and soil nutrient dynamics. For example, in South Asia rising variability is projected to lower wheat and rice yields, exacerbating food shortages. African maize and sorghum are similarly vulnerable to drought intensification, while Central and South America may face more intense hurricanes and dry spells. In short, GHG driven climate change alters temperature and rainfall regimes and thus exerts major pressure on tropical farming systems.

3. Plant Clonal Systems: Structure and Ecological Roles

Clonal reproduction involves vegetative propagation of genetically identical modules (ramets) that often remain physiologically connected. This allows resource integration: for instance, water and nutrients absorbed by one ramet can be shared with others in poorer patches. Clonal growth helps plants cope with environmental heterogeneity by translocating resources from richer to poorer locations. Such integration can enhance survival in drought or nutrient poor conditions. Clonal plants also avoid the energy and risk of seed germination, persisting through bulbs, tubers, rhizomes or suckers even when the aboveground parts die back (Xiao *et al.* 2023).

Adaptive advantages:

Connected ramets can also divide labor for example, some may forage for water in drier patches while others focus on photosynthesis in sunnier areas thereby, enhancing the efficiency and performance of the entire clonal plant system. Polyploid clonal crops often have high genetic redundancy and heterozygosity, which buffer stress. High heterozygosity and genetic variability make polyploids more vigorous with greater stress-buffering capacity. Vegetative propagation also fixes heterozygous genomes intact, passing on beneficial trait combinations. Moreover, clonal plants can carry epigenetic memories of stress into new ramets. Together, these traits let clones exploit stable niches and recover from localized disturbances effectively (Gonzalez *et al.* 2018).

Sugarcane (*Saccharum spp.*), a C_4 grass, is a prime example of how clonal polyploid plants combine physiological and genetic advantages to thrive under variable conditions. It is propagated by stem cuttings or ratooning. As a polyploid grass, sugarcane has efficient photosynthesis and extensive root systems. It stores large amounts of carbon in biomass and can tolerate intermittent floods, but is sensitive to extreme heat. Breeding new sugarcane varieties is difficult due to its complex genome, so farmers rely on clonal propagation to preserve elite hybrids (Gonzalez *et al.* 2018).

In addition to sugarcane, tropical banana (*Musa spp.)* is a sterile triploid grown entirely by suckers or tissue culture. Cassava (*Manihot esculenta*) and potato (*Solanum tuberosum*) reproduce via cuttings or tubers, multiplying identical clones. Even many grasses used for pastures or turf spread via stolons/rhizomes (e.g. Bermuda grass, Kentucky bluegrass) and are effectively clonal. Non food clonal plants share these traits. In all cases, clonal propagation maintains uniform crop quality and allows rapid expansion of well-adapted genotypes, but it also means that a single stress like disease and drought can affect entire clonal stands (Sakthivel *et al.* 2025).

In banana, clonal propagation ensures uniform fruit bunches each season. However, it also restricts genetic variation in plantations. Many disease outbreaks (*e.g.,* Fusarium wilt) have devastated banana monocultures. Therefore, there is need to breed or engineer climate-resistant banana clones due to increasing heat and moisture stress.

Overall, clonal systems are ecologically versatile, they combine rapid vegetative spread with genetic advantages from polyploidy. These attributes confer stress tolerance (e.g. drought or low nutrients) not easily achieved in seed-propagated crops. Understanding how clonal structure influences stress response is key to leveraging these crops under climate change.

4. Physiological and Molecular Adaptation Mechanisms

a) CO_2 fertilization and photosynthesis:

Elevated CO_2 often enhances photosynthesis and biomass production in many clonal crops, particularly those using the C_3 pathway. Globally, plant photosynthesis rose by roughly 12 per cent between 1982 and 2020 as atmospheric CO_2 increased. Controlled experiments show that several clonally propagated C_3 crops such as cassava typically gained about 12 to 14 per cent yield when exposed to CO_2 concentrations near 550 ppm.

Clonally propagated grasses used for fodder, many of which are maintained through vegetative divisions or stolons, exhibit similar growth stimulation. Although C_4 clonal crops are generally less sensitive, some still show notable responses under very high CO_2. For example, a long-term chamber experiment demonstrated that sugarcane, a clonally propagated C_4 species, exhibited ~30 per cent higher photosynthetic rates and ~40 per cent greater total biomass at ~720 ppm CO_2 compared to ambient conditions, along with a ~29 per cent increase in sucrose content. These findings indicate that clonal crops whether C_3 or C_4 can experience measurable gains in growth and productivity as CO_2 continues to rise (De Souza *et al.* 2008).

b) Stomatal and water-use adjustments:

High CO_2 typically causes partial stomatal closure, reducing transpiration. In the sugarcane study, stomatal conductance fell ~37 per cent and transpiration ~32 per cent under elevated CO_2, boosting intrinsic water-use efficiency by ~62 per cent. Many plants under CO_2 enrichment cut water loss by 5 to 20 per cent through stomatal closure. For drought-prone tropics, this water-saving response is beneficial. Clonal plants often exploit this by shifting carbon allocation to roots, a meta-analysis found elevated CO_2 increased above-ground plant growth by ~21 per cent and below ground through roots/tubers by ~28 per cent. This means clonal crops may invest extra CO_2-derived carbon into storage organs e.g. cassava roots, potato tubers or deeper roots, further improving drought resilience.

c) Carbohydrate partitioning:

Elevated CO_2 can alter how plants distribute assimilates. Many studies saw more carbon sent to roots and stems. This can enhance stress tolerance: for example, more root biomass improves access to deep water or soil nutrients. In cassava, higher CO_2 resulted in significantly larger storage roots for several cultivars. In FACE experiment found that at ~600 ppm CO_2, African cassava cultivars had 33 to 86 per cent greater storage root biomass than controls. This demonstrates that clonal root crops stand to gain yield under rising CO_2, potentially offsetting some heat/drought losses (De souza *et al.* 2008)

d) Epigenetic memory:

Clonal plants can remember past stresses via epigenetic changes. When sexually reproducing plants go through meiosis, many stress-induced epigenetic marks like DNA methylation, histone changes reset. Clones bypass meiosis, so heritable epigenetic modifications persist across ramets. In *Trifolium repens*, drought in one generation induced DNA methylation changes that carried over to subsequent clonal offspring. This suggests clonal crops may inherit a preconditioned stress response state. Environmentally induced epigenetic change can be better maintained in clonal than sexual generations, potentially enabling rapid adaptation in clonal lineages. Thus, epigenetic regulation could allow clones to acclimate across seasons. However, documented phenotypic effects of such memory remain limited and more research is needed on molecular mechanisms in crops. (Gonzalez *et al.* 2018)

e) Rhizosphere interactions:

Elevated CO_2 often increases root exudation of sugars and other organics, which can enrich the soil microbiome. Many clonal roots form symbioses with mycorrhizal fungi and nitrogen-fixing bacteria. Under high CO_2, these symbionts receive more carbon and can enhance plant nutrition and stress tolerance. For example, inoculation of drought-stressed clonal seedlings

(*Cinnamomum migao*) with arbuscular mycorrhizal fungi dramatically improved plant water status and nutrient uptake. The mycorrhizal trees under drought had higher biomass and leaf N/P levels than non-inoculated ones. Such symbiotic benefits likely extend to agricultural clones with well-colonized sugarcane or cassava may sustain better growth under combined CO_2 enrichment and water stress. In general, reinforcing beneficial soil microbes and mycorrhizae is an important mechanism by which clonal plants maintain productivity in changing environments (Xiao *et al.* 2018).

5. Case Studies from Developing Economies

a) India – Sugarcane:

India's tropics grow extensive sugarcane plantations by ratooning, making it a key study system. Indian research using CO_2 enriched chambers has shown that sugarcane still benefits from higher CO_2, despite being C_4. It was found that under ~600 to700 ppm CO_2, sugarcane stalk height, leaf area and juice yield increased by 10 to 15 per cent. In open-top chamber experiments likewise showed 30 per cent higher photosynthesis and 40 per cent more biomass at ~720 ppm (De souza *et al.* 2008). However, heat stress above ~30 to 32 °C can negate some gains. Overall, these studies suggest Indian sugarcane yields may rise slightly with CO_2, but further warming and water scarcity remain threats. Breeding efforts now focus on clones combining CO_2 responsiveness with heat tolerance.

b) Africa – Cassava:

Cassava dominates many African diets and is propagated by stem cuttings. In deep-rooted cassava plants, they tolerate drought better than cereals. It's reported that cassava thrives in poor soils and resists drought more effectively than maize or rice (Gonzalez *et al.* 2018). The major FACE study at Illinois, using African cultivars demonstrated large yield benefits from CO_2: storage-root biomass increased 33 to 86 per cent at ~600 ppm CO_2 (Vera *et al.* 2023). This implies cassava plantations in sub-Saharan Africa could gain substantial yield from CO_2 fertilization. Still, African cassava faces high temperatures and pest pressures; heat above 40 °C can impair tuber formation. In practice, cassava's plasticity (e.g. altering growth cycles under stress) and clonal uniformity make it a key climate-resilient crop. Programs in Nigeria and DR Congo are now screening cassava clones for both CO_2 responsiveness and heat tolerance.

c) Southeast Asia – Banana:

In tropical Asia, commercial bananas are largely clonal Cavendish varieties. Tissue-culture nurseries produce uniform planting material. Climate change such as temperature swings and irregular monsoons is harming banana production. A systematic review notes that climate and stressors like drought and flooding already constrain banana yield and calls for more climate-adaptation research. Elevated CO_2 effects on banana have been less studied; however, as a C_3 plant with large leaves, bananas likely increase biomass under CO_2 but also need more water. One concern is that uniform clonal stands can suffer synchronized failure under extreme events. Hence in Southeast Asia, scientists are exploring new banana cultivars often hybrids or GM with stress-tolerance traits. Tissue-culture propagation will be critical to deploy any improved clones.

d) Comparative outcomes:

Overall, clonal crops show varied responses. Indian sugarcane (C_4) has modest CO_2 gain but high temperature tolerance if bred. African cassava (C_3) appears to benefit strongly from CO_2 and withstand drought, making it relatively robust. Asian bananas (C_3) may gain in biomass but suffer heat/disease. Field indicators such as photosynthesis rate, biomass, WUE and carbohydrate allocation consistently reflect CO_2 benefits. Stress indicators such as leaf temperature, water potential and chlorophyll fluorescence show that well-colonized clones e.g. with mycorrhizae fare better under combined CO_2 and drought. These case studies illustrate that clonal propagation can be an advantage under elevated GHG, but only if accompanied by adaptive management. (Xiao *et al.* 2023)

6. Challenges and Knowledge Gaps

Despite the promise of clonal resilience, major knowledge gaps persist. First, data scarcity most CO_2 enrichment studies focus on temperate C_3 crops. There are few FACE experiments on tropical clonals. Notably, the cassava trial was done in Illinois rather than Africa and many regions lack even chamber facilities. Second, molecular mechanisms remain poorly resolved. The complex polyploid genomes of clones resist conventional genetic study. The role of epigenetics in clonal stress memory is only beginning to be documented; we lack broad data on how epigenetic marks translate to agronomic traits. Third, technology gaps: many developing regions cannot afford or maintain high-tech labs or breeding programs. There are few clonal-breeding initiatives for climate traits. Even molecular tools like CRISPR face regulatory and infrastructure hurdles in these countries. Lastly, ecological complexity is a challenge: CO_2 interacts with nutrient cycles and biotic factors like pests and diseases in unpredictable ways. For example, higher CO_2 can alter weed crop dynamics and soil pathogens, but these effects are understudied in clonals.

We lack region-specific experimental evidence on clonal crops under future GHG scenarios and the underlying biology is only partially understood. Addressing these gaps will require building research capacity e.g. establishing FACE sites in the tropics and fostering interdisciplinary studies linking physiology, genetics and socioeconomics.

7. Future Prospects and Climate-Resilient Strategies

a) Biotechnology and breeding:

Advances in genomics offer hope for clonal crop improvement. New sequencing and editing tools can target stress-resistance genes even in complex genomes. CRISPR/Cas platforms can be used to engineer climate-resilient traits in potato, banana and sugarcane. Gene editing can introduce novel alleles or tweak regulatory sequences in clonals without altering heterozygosity. Marker-assisted selection and genomic selection, although underused in clonals, can accelerate breeding for heat/drought tolerance. Exploiting epigenetic variation is another frontier if we can identify stable stress-memory marks, breeders might select clones with beneficial epigenetic profiles (Sakthivel *et al.* 2025).

b) Climate-smart agronomy:

Carbon-smart agriculture in clonal cropping systems includes enhancing soil carbon e.g. via cover crops or biochar, improving irrigation efficiency and diversifying cropping systems. IPCC highlights measure like building soil organic matter, controlling erosion and using heat/drought-tolerant varieties as key adaptations. In smallholder contexts, agroforestry like intercropping clones with trees can buffer microclimate and improve resilience. For example, shade trees in cacao or banana plantations help reduce heat stress. Integrated pest management will be vital, as pests often expand with warming. Carbon farming credits or similar incentives could encourage practices that sequester more carbon while boosting clonal crop health.

c) Policy and collaboration:

Achieving these strategies requires international support. South Asian analysts recommend investing in climate services and infrastructure e.g. flood control, irrigation and in climate-resilient crop development. Global R&D networks CGIAR and CABI, etc. should prioritize clonally propagated staples and their wild relatives. Capacity building training local scientists and farmers in new technologies is essential. Public private partnerships can help deploy improved clones, tissue culture labs and seed systems at scale. In summary, combining cutting-edge biotechnology with traditional knowledge (local landraces and agroecological wisdom) will create a "carbon-smart" framework suited to clonal agriculture.

Conclusion:

Clonal propagation offers a unique resilience pathway in a changing climate. Clonal crops genetic diversity, resource-sharing ability and potential for stress memory make them well-suited to cope with higher CO_2 and associated stresses. However, harnessing this resilience requires more research and action. Developing countries must strengthen their research infrastructure and adopt advanced breeding tools for clonals. Integrating genomics, epigenetics and beneficial microbiomes with climate-smart practices can help sustain clonal crop productivity. Ultimately, maintaining food security and ecological stability under rising GHGs will depend on leveraging every asset including clonal adaptability available to farmers in the tropics and beyond.

References:

1. Abdoussalami, A., Checkina, M. L., & Hossain, M. N. (2023). Climate change and its impacts on banana production: A systematic analysis. *Environment, Development and Sustainability*, 25, 12217–12246.
2. Amelework, A. B., Bairu, M. W., Maema, O., Venter, S. L., & Laing, M. (2021). Adoption and promotion of resilient crops for climate risk mitigation: A case analysis of cassava in South Africa. *Frontiers in Sustainable Food Systems*, 5, 617783.
3. De Souza, A. P., Gaspar, M., Ulian, E. C., Waclawovsky, A. J., Nishiyama, M. Y & Dos Santos, R. V., (2008). Elevated CO_2 increases photosynthesis, biomass and productivity and modifies gene expression in sugarcane. *Plant, Cell & Environment,* 31(8), 1116–1127. DOI:10.1111/j.1365-3040.2008.01822.
4. Intergovernmental Panel on Climate Change. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Cambridge University Press.ipcc.ch
5. IPCC. (2022). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels.
6. Misra, V., Yadav and A. K., & Srivastava, A., (2019). Can sugarcane cope with increasing atmospheric CO_2 concentration? *Australian Journal of Crop Science*, 13(5), 780–784.
7. National Centers for Environmental Information (NOAA). (2025). State of the Climate: Global Climate Report for 2024. https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202413.
8. National Oceanic and Atmospheric Administration (NOAA). (2025). Trends in Mauna Loa CO_2. NOAA/ESRL Global Monitoring Laboratory. https://gml.noaa.gov/ccgg/trends/ gml.noaa.gov
9. Rendina-González, A. P., Preite, V., Verhoeven, K. J. F., & Latzel, V. (2018). Transgenerational effects and epigenetic memory in the clonal plant *Trifolium repens*. *Frontiers in Plant Science*, 9, 1677. DOI:10.3389/fpls.2018.01677
10. Ruiz-Vera, U. M., Balikian, R., Larson, T. H., & Ort, D. R. (2023). Evaluation of the effects of elevated CO_2 concentrations on the growth of cassava storage roots by destructive harvests and ground penetrating radar scanning approaches. *Plant, Cell & Environment,* 46(1), 93–105. DOI:10.1111/pce.14474

11. Sakthivel, S. K., Vennapusa, A. R., & Melmaiee, K. (2025). Enhancing quality and climate resilient traits in vegetatively propagated polyploids: transgenic and genome editing advancements, challenges and future directions. *Frontiers in Genetics*, 16, 1599242.
12. UNDP. (2025). Climate-Smart Agriculture: How agriculture can adapt to reduce GHG emissions. United Nations Development Programme.
13. World Bank. (2016). Climate-Smart Agriculture: A Global Sourcebook. World Bank.
14. Xiao, X., Liao, X., Yan, Q., Xie, Y., Chen, J., & Liang, G. (2023). Arbuscular mycorrhizal fungi improve the growth, water status and nutrient uptake of *Cinnamomum migao* under drought stress and recovery. *Journal of Fungi*, 9(3), 321.
15. Yang, P., Huang, L., & He, S. (2023). Adaptive strategies employed by clonal plants in heterogeneous patches. *Forests,* 14(8), 1648.

BIOPLASTICS AS A TOOL FOR SUSTAINABLE ANIMAL HUSBANDRY AND FARM WASTE MANAGEMENT

Rinkal Sundriyal[1] and Karan Bharat Jain*[2]

[1]Animal Husbandry Department, Uttarakhand 246275

[2]Wildlife Institute of India, Dehradun, Uttarakhand 248001

*Corresponding author E-mail: kbj2312@gmail.com

Abstract:

With rapid industrialization and intensification of livestock production systems, the demand for packaging, storage, and disposable materials in animal husbandry has increased substantially, leading to widespread reliance on petroleum-based plastics. These materials are largely single-use in nature and persist in the environment for prolonged periods, causing contamination of soil, water, fodder, and animal habitats. Such persistence poses significant risks to livestock health, farm hygiene, and the safety of animal-derived products. As the global focus shifts toward sustainability, now a necessity rather than a choice, the continued dependence on petroleum-based plastics has become increasingly incompatible with sustainable animal husbandry practices. Consequently, the exploration of environmentally sound alternatives is imperative. Bioplastics, derived from renewable plant and animal sources, represent a promising substitute due to their improved degradability and reduced environmental footprint. This review critically summarizes the types of bioplastics, their biological sources, advantages and limitations, current market status, recent research advancements, and future prospects, with particular emphasis on their potential applications within animal husbandry and allied sectors.

Keywords: Petroleum-Based Plastics, Bioplastics, Animal Husbandry, Microalgae, Sustainable Agriculture, Bioeconomy

Introduction:

It cannot be ethically or practically justified to manufacture billions of plastic products that are used briefly yet persist in the environment for centuries, posing serious challenges to animal husbandry and livestock-based production systems. Plastics have infiltrated every component of the agro-ecosystem, from fodder, drinking water, and housing materials to livestock products such as milk, meat, fish, and even common salt consumed by animals and humans alike. Air and water bodies have effectively become global dumping grounds, with approximately 8 million plastic pieces entering oceans daily, resulting in the death of nearly 1 lakh marine animals and turtles and about 1 million seabirds each year. Such contamination directly threatens fisheries and aquaculture, which form integral allied sectors of animal husbandry. In 1950, a global population of 2.5 billion generated around 1.5 million tons of plastic waste, which escalated to 3-20 million tons by 2016 with a population of 7 billion, and this figure is projected to double by 2034 (Clair, 2023). The concept of a plastic-free Earth is therefore not merely an environmental ideal but a commitment essential for safeguarding animal health, livestock productivity, and ecosystem sustainability. Although plastic cannot be entirely eliminated from animal husbandry practices, its substitution with sustainable alternatives is imperative.

Bioplastics, derived from renewable resources, present a viable solution for reducing plastic-related risks in livestock production systems. These materials can be produced from plant sources such as sugarcane (Wu, 2011), corn (Marichelvam *et al.,* 2019), soybean (Paetau *et al.,* 1994; Salmoral *et al.,* 2000), canola (Zhang *et al.,* 2018), wood (Singh and Mohanty, 2007), vegetable fats and oils (Kale *et al.,* 2019; Parada *et al.,* 2019), castor beans (Godoy *et al.,* 2009), jackfruit (Rajakumari and Muthu, 2018), and potato (Soomaree, 2016; Arikan and Bilgen, 2019), as well as from algae (Yap *et al.,* 2023), natural gas (Piemonte, 2011; Oliver *et al.,* 2024), waste newspapers (Gaurav *et al.,* 2018), and animal slaughterhouse by-products, including fats and feathers (Degli *et al.,* 2021). The utilization of animal-derived waste materials for bioplastic production supports circular bioeconomy approaches within animal husbandry, promoting waste valorization while reducing environmental contamination.

Bioplastics may be biodegradable, bio-based, or both. The term biodegradable refers to the end-of-life degradation process, whereas bio-based denotes the renewable biological origin of the material. Biodegradable bioplastics are those that can be completely decomposed within a few months by microorganisms such as bacteria, fungi, and algae into carbon dioxide, methane, biomass, and inorganic compounds. Compostable bioplastics represent a specific category that degrades into nutrient-rich biomass without releasing toxic residues, thereby offering particular relevance for farm waste management systems (Song *et al.,* 2009). While all compostable materials are biodegradable, not all biodegradable materials are compostable, as some may release harmful substances during degradation. Polylactic acid (PLA) is a commonly cited example of a compostable bioplastic with potential applications in animal husbandry, including feed packaging, veterinary disposables, and farm hygiene products.

History

Early plastics used by humans were primarily derived from natural, bio-based polymers such as natural rubber and cellulose-based materials including Parkesine, Celluloid, and Cellophane. In 1897, Galalith, produced from milk-derived casein, represented one of the earliest animal-based bioplastics, demonstrating the potential of livestock by-products in material development. In 1926, Maurice Lemoigne reported the first microbial bioplastic, polyhydroxybutyrate (PHB), synthesized by *Bacillus megaterium* (Rothman and Ryan, 2023). Commercial bioplastics advanced with the introduction of Rilsan (Polyamide-11) in 1947, followed by the development of polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and plasticized starches in the 1990s (Lackner, 2000).

The invention of synthetic plastics began with John Wesley Hyatt's cellulose-based polymer in 1869 and expanded rapidly after Leo Baekeland's development of Bakelite in 1907, particularly during World War II (Rothman and Ryan, 2023). Although plastics initially reduced pressure on wildlife resources, their uncontrolled expansion over time has led to widespread environmental contamination, adversely affecting livestock health, farm ecosystems, and sustainable animal husbandry, thereby transforming plastics into a major environmental threat (Muneer *et al.,* 2021).

Sources of Bioplastics

A wide range of natural resources can be utilized for bioplastic synthesis, with production methods varying according to the source, although the basic chemical structure and functional properties remain largely similar. Starch-based bioplastics are produced from renewable biomass containing vegetable starch and glycerol, where long polymer chains are formed by heating starch sources such as corn with biomass-derived glycerine. Bioplastics are available in several forms, including starch-based plastics, polyhydroxybutyrates (PHBs) synthesized by glucose-utilizing bacteria, polyamide-11 derived from natural oils, and polylactic acid (PLA) composed of repeating $(C_3H_4O_2)_n$ units. Among these, PLA is the most widely used due to its ease of production, achieved by fermenting dextrose obtained from corn into lactic acid (Ward and Wyllie, 2019).

In the context of animal husbandry, food waste and slaughterhouse by-products such as blood, fats, and intestinal residues represent valuable raw materials for bioplastic synthesis, supporting waste valorization and circular bioeconomy principles (Umesh *et al.,* 2023). Microalgae have also emerged as a promising source for bioplastics, either through the formation of composite materials by blending algal biomass with polymers or through intracellular production of biopolymers such as PHBs and starch, followed by extraction and processing (Hempel *et al.,* 2011; Jafari-Sales *et al.,* 2017).

Classification of Bioplastics

1. Cellulose-based Bioplastics: They are produced using cellulose esters and cellulose derivatives. Example- Cellulose acetate

2. Starch-based Bioplastics: They are derived from starch obtained from plant sources like corn, potato, etc. Example- Polylactic acid (PLA), Polyhydroxyalkanoates (PHA), Polybutylene adipate terephthalate, Polycaprolactone, etc.
3. Protein-based Bioplastics: They are synthesized by using protein sources like casein, milk, wheat gluten, etc.
4. Aliphatic Polyesters: It includes a collection of bio-based polyesters. Example- PHB (Poly-3-hydroxybutyrate), PHA (Polyhydroxyalkanoates), PHV (Polyhydroxyvalerate), PLA (Polylactic acid), Polyamide II, etc.
5. Organic Polyethylene: They are synthesized from the fermentation of raw agricultural materials like sugar cane and corn (Jafari-Sales *et al.,* 2017).

It's necessary to keep in mind that not all bioplastics are biodegradable like Bio-Polyethylene Terephthalate (Bio-PET), Bio-PE, PA. But they can be recycled like petroleum-based plastics. Even many bioplastics need special facilities to get degraded. If they once entered landfills, then they will take 10 to 1000 years to break down (Zinn, 2024).

Another classification can be as follows:

1. Conventional plastics- Are fossil fuel (non-renewable resources) based and non-biodegradable. Example- Polyethylene (PE), Polypropylene (PP), Acrylonitrile Butadiene (ABS), etc.
2. Bio-based but non-biodegradable Bioplastics- Include Bio-Polyethylene (Bio-PE), Bio-Polyethylene terephthalate (Bio-PET).
3. Bio-based and biodegradable Bioplastics- Include PLA, PHA, and other plant-based cellulose compounds.
4. Oil-based and biodegradable Bioplastics- Include Polybutylene succinate (PBS) and Polycaprolactone (PCL) (Nandakumar, 2024).

Current Trends

At present, the share of bio-based plastics in the emerging bioeconomy exceeds that of biodegradable plastics. Nevertheless, biodegradable plastics have shown substantial growth, with increased application expected over the next five years in non-packaging sectors such as textiles, agriculture, horticulture, and transport (Hofer, 2021), all of which are closely linked to animal husbandry and allied farming systems. Public perception also supports this transition; a national survey of 2,518 Australians revealed that 58% were unaware of any potential negative environmental impacts of bioplastics, while 68% expressed a desire for their increased use. Notably, 62% of respondents indicated they would dispose of bioplastic products in recycling bins, suggesting a growing bioplastic stream within waste management systems (Ramesh *et al.,* 2020).

Major multinational companies, including Coca-Cola, have begun adopting bio-based plastics in packaging and have committed to increasing bioplastic use. In parallel, research institutions and start-ups are developing innovative alternatives, such as Full Cycle Bioplastics (California), which produces PHA from plant residues for manufacturing bags, containers, and cutlery. Additionally, Michigan State University has explored cost-effective bioplastic production using cyanobacteria that continuously generate sugars through photosynthesis. These sugars are consumed by plastic-producing bacteria, offering a reusable and sustainable system that reduces dependence on conventional agricultural feedstocks (Philp *et al.,* 2013).

Future Scopes

A major limitation of conventional plastics lies in their inefficient waste management, particularly within agricultural and animal husbandry systems where plastic residues contaminate soil, water, and fodder. Therefore, materials that degrade rapidly in natural environments are urgently required. According to international standards set by the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM), a material is considered biodegradable if it completely degrades within 56 days in aquatic environments and within two years in soil (Dilkes-Hoffman *et al.,* 2019).

Bioplastics represent a sustainable alternative not only for the packaging industry but also for broader applications relevant to animal husbandry, including feed packaging, farm disposables, and veterinary materials. For instance, synergistic blends of polylactic acid (PLA) and polycaprolactone (PCL) have been developed as fully biodegradable substitutes for conventional petroleum-based plastics (Narancic *et al.,* 2018).

Moreover, bioplastic production offers significant socioeconomic benefits by generating employment opportunities, particularly in rural and agriculture-based sectors. The use of starch, lignin (a by-product of the paper industry), and other plant-derived materials can reduce production costs while supporting agro-industrial integration, thereby contributing to sustainable livestock production systems and rural livelihoods (Ramesh *et al.,* 2020).

Pros and Cons of Bioplastics

Bioplastics offer several advantages over petroleum-based plastics, particularly within animal husbandry and allied agricultural systems. They reduce dependence on non-renewable fossil resources, lower greenhouse gas emissions, and help minimize persistent plastic waste in farm environments (Zinn, 2024). Owing to their lightweight nature and potential reusability, bioplastics can effectively replace single-use plastics commonly employed in feed packaging, veterinary disposables, and farm operations, thereby improving environmental hygiene and animal welfare.

However, bioplastics are not entirely free from environmental drawbacks. The cultivation of crops used as raw materials often involves intensive use of fertilizers and agrochemicals, which may contribute to soil acidification, nutrient imbalance, and environmental degradation if not managed sustainably (Muthusamy and Pramasivam, 2019). Such impacts must be carefully considered, particularly in regions where agriculture and livestock production coexist closely.

Ultimately, the responsibility for mitigating plastic pollution lies with human society. Bioplastics derived from food waste, vegetable residues, slaughterhouse by-products, and microalgae represent promising alternatives for reducing plastic load in animal husbandry systems. Nevertheless, excessive or indiscriminate use of bioplastics may also pose future environmental challenges (Narancic *et al.,* 2018). As the complete elimination of plastics is presently unrealistic, their judicious and need-based use, supported by sustainable production practices, remains the most viable approach for protecting ecosystems and ensuring long-term sustainability in animal husbandry.

Conclusion:

The replacement of petroleum-based plastics with bioplastics has the potential to provide substantial environmental benefits and support sustainable animal husbandry systems. One of the most pressing challenges associated with conventional plastics is ineffective waste management, as these materials persist in the environment for extended periods and adversely affect soil, water, fodder, and animal health. Bioplastics offer a sustainable alternative by enabling improved degradability, thereby reducing long-term environmental accumulation. Incremental changes in daily practices, such as adopting plant- and bio-based products, can collectively mitigate the severity of future environmental impacts. This transition requires active participation not only from industries but also from individuals. Moreover, bioplastics present significant opportunities for rural employment, agro-industrial development, and value addition to agricultural and livestock by-products, while also demonstrating growing potential in biomedical and veterinary applications. Together, these advantages position bioplastics as a key component in advancing a resilient, sustainable, and environmentally responsible future for animal husbandry and allied sectors.

References:

1. Arıkan, E. B., & Bilgen, H. D. (2019). Production of bioplastic from potato peel waste and investigation of its biodegradability. *International Advanced Researches and Engineering Journal*, *3*(2), 93-97.

2. Clair, J. S. (2023). Sleep Now in the Fire: The Year in Climate. *CounterPunch*.
3. Degli Esposti, M., Morselli, D., Fava, F., Bertin, L., Cavani, F., Viaggi, D., & Fabbri, P. (2021). The role of biotechnology in the transition from plastics to bioplastics: An opportunity to reconnect global growth with sustainability. *FEBS open bio*, *11*(4), 967-983.
4. Dilkes-Hoffman, L., Ashworth, P., Laycock, B., Pratt, S., & Lant, P. (2019). Public attitudes towards bioplastics-knowledge, perception and end-of-life management. *Resources, Conservation and Recycling*, *151*, 104479.
5. Gaurav, S. V. S. A. S., & Mishra, D. A. (2018). Bioplastic: A Better Alternative to Plastics from Waste Paper. *International Journal for Scientific Research & Development*, *6*(2), 3626-3628.
6. Godoy, M. G., Gutarra, M. L., Maciel, F. M., Felix, S. P., Bevilaqua, J. V., Machado, O. L., & Freire, D. M. (2009). Use of a low-cost methodology for biodetoxification of castor bean waste and lipase production. Enzyme and microbial technology, 44(5), 317-322.
7. Hempel, F., Bozarth, A. S., Lindenkamp, N., Klingl, A., Zauner, S., Linne, U., Steinbuchel, A., & Maier, U. G. (2011). Microalgae as bioreactors for bioplastic production. *Microbial cell factories*, *10*(1), 81-87.
8. Hofer, K. (2021). Ethical issues related to recycling of German plastics in Asia.
9. Jafari-Sales, A., Shahniani, A. R., & Bagherizadeh, Y. (2017). Bioplastics and the environment. *Electronic Journal of Biology*, *13*(3), 274-279.
10. Kale, R. D., Jadhav, N. C., & Pal, S. (2019). Fabrication of green composites based on rice bran oil and anhydride cross-linkers. *Iranian Polymer Journal*, *28*(6), 471-482.
11. Lackner, M. (2000). Bioplastics. *Kirk-Othmer Encyclopedia of Chemical Technology*, 1-41.
12. Marichelvam, M. K., Jawaid, M., & Asim, M. (2019). Corn and rice starch-based bio-plastics as alternative packaging materials. *Fibers*, *7*(4), 32-46.
13. Muneer, F., Hussain, S., Sidra-tul-Muntaha, M. R., & Nadeem, H. (2021). Plastics versus bioplastics. *Degradation of Plastics*, *99*, 193-237.
14. Muthusamy, M. S., & Pramasivam, S. (2019). Bioplastics-An eco-friendly alternative to petrochemical plastics. *Current world environment*, *14*(1), 49-60.
15. Nandakumar, A. (2023). Bioplastics Classification and Properties. In *Second and Third Generation Bioplastics*, 15-28.
16. Narancic, T., Verstichel, S., Reddy Chaganti, S., Morales-Gamez, L., Kenny, S. T., De Wilde, B., Padamati, R. B., & O’Connor, K. E. (2018). Biodegradable plastic blends create

new possibilities for end-of-life management of plastics but they are not a panacea for plastic pollution. *Environmental science & technology*, *52*(18), 10441-10452.

17. Oliver, I., Martinez-Perez, N., Fullana, A., & Conesa, J. A. (2024). Impact of bioplastic design on biodigestion treatment. *Sustainability*, *16*(16), 7167-7180.
18. Paetau, I., Chen, C. Z., & Jane, J. L. (1994). Biodegradable plastic made from soybean products. 1. Effect of preparation and processing on mechanical properties and water absorption. *Industrial & engineering chemistry research*, *33*(7), 1821-1827.
19. Parada Hernandez, N. L., Bahu, J. O., Schiavon, M. I. R., Bonon, A. J., Benites, C. I., Jardini, A. L., Filho, R. M., & Wolf Maciel, M. R. (2019). (Epoxidized castor oil-citric acid) copolyester as a candidate polymer for biomedical applications. *Journal of Polymer Research*, *26*(6), 149-158.
20. Philp, J. C., Bartsev, A., Ritchie, R. J., Baucher, M. A., & Guy, K. (2013). Bioplastics science from a policy vantage point. *New biotechnology*, *30*(6), 635-646.
21. Piemonte, V. (2011). Bioplastic wastes: the best final disposition for energy saving. *Journal of Polymers and the Environment*, *19*(4), 988-994.
22. Rajakumari, M., & Muthu selvi, V. (2018). Production of starch based biodegradable plastic from jackfruit seed flour (Artocarpus heterophyllus). *Int J Curr Adv Res*, *7*, 9382-9385.
23. Ramesh, S., Shaiju, P., & O'Connor, K. E. (2020). Bio-based and biodegradable polymers-State-of-the-art, challenges and emerging trends. *Current Opinion in Green and Sustainable Chemistry*, *21*, 75-81.
24. Rothman, R., & Ryan, A. J. (2023). The history and future of plastics. *Plastic pollution in the global ocean*, *1*, 21-46.
25. Salmoral, E. M., Gonzalez, M. E., & Mariscal, M. P. (2000). Biodegradable plastic made from bean products. *Industrial Crops and Products*, *11*(2-3), 217-225.
26. Singh, S., & Mohanty, A. K. (2007). Wood fiber reinforced bacterial bioplastic composites: Fabrication and performance evaluation. *Composites Science and Technology*, *67*(9), 1753-1763.
27. Song, J. H., Murphy, R. J., Narayan, R., & Davies, G. B. H. (2009). Biodegradable and compostable alternatives to conventional plastics. *Philosophical transactions of the royal society B: Biological sciences*, *364*(1526), 2127-2139.
28. Soomaree, K. (2016). Production of potato starch-based bioplastic. *Chemical and Environmental Engineering*, 86.

29. Umesh, M., Sarojini, S., Choudhury, D. D., Santhosh, A. S., & Kariyadan, S. (2023). Food waste valorization for bioplastic production. *Waste valorization for value-added products*, *1*, 216-256.
30. Ward, A. M., & Wyllie, G. R. (2019). Bioplastics in the General Chemistry Laboratory: Building a semester-long research experience. *Journal of Chemical Education*, *96*(4), 668-676.
31. Wu, C. S. (2011). Performance and biodegradability of a maleated polyester bioplastic/recycled sugarcane bagasse system. *Journal of Applied Polymer Science*, *121*(1), 427-435.
32. Yap, X. Y., Gew, L. T., Khalid, M., & Yow, Y. Y. (2023). Algae-based bioplastic for packaging: a decade of development and challenges (2010-2020). *Journal of Polymers and the Environment*, *31*(3), 833-851.
33. Zhang, Y., Liu, Q., & Rempel, C. (2018). Processing and characteristics of canola protein-based biodegradable packaging: A review. *Critical Reviews in Food Science and Nutrition*, *58*(3), 475-485.
34. Zinn, M. (2024). More than PHB-the PHAmily of Copolymers: Justifications for Broader Use and Summary of Biodegradation Facts on Polyhydroxyalkanoates (PHA)-A Review. *Chemical and Biochemical Engineering Quarterly*, *38*(4), 265-291.

TRIBAL FARMER ADOPTS INTEGRATED FARMING SYSTEM AT KHAG, DISTRICT BUDGAM, UT OF J&K – RE-AFFIRMS FAITH IN AGRICULTURE SYSTEMS THROUGH SKUAST-K LED EXTENSION

Bhinish Shakeel, Bilal A Lone, Mir Nadeem Hassan, Vaseem Yousuf, Ambreen Nabi, Sabia Akhter, Shazia Ramzan and Khurshid Zargar

Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir (SKUAST-K), Srinagar, Jammu and Kashmir

*Corresponding author E-mail: bhinishshakeel@skuastkashmir.ac.in

The current chapter is a narrative of an entrepreneur, Mr. Mudasir Ahmad Dar, who has carved a niche for himself in the field of agriculture through adoption of Integrated Farming System in the Tribal region of District Budgam. He has exemplified a working model of Integrated Farming System in a short span of time dovetailing benefits of various government assistance in order to maximize yield and productivity per unit area through intensification and diversification of crops with integration of allied agri-based enterprises**.** He has been hand-held by Krishi Vigyan Kendra - Budgam along with residents of Shonglipora, Khag, a far-off Tribal region in District Budgam. Krishi Vigyan Kendras Budgam, operating as District resource centre for dissemination of scientific technology on agriculture and allied sciences, since its inception in 2013, has been constantly endeavouring to train and support rural entrepreneurs to upscale their skill sets. A Research conducted by Harvard University, the Carnegie Foundation and Stanford Research Centre suggests that 85% of job success comes from having well-developed soft and people skills, and only 15% of job success is contingent on technical skills and knowledge (hard skills).

Introduction:

Rural entrepreneurship is not only important as a means of generating employment opportunities in the rural areas with low capital cost and raising the real income of the people, but also its contribution to the development of agriculture and urban industries Building capacity of Rural Agri-prenuers are a promising solution for unemployment, migration, economic disparity, reduce poverty, development of rural areas and backward regions. Most of the rural populace is associated with agriculture and allied activities as pedigree occupation. However, to be commercially viable, these units need to sharpen their skill sets to thrive as a successful venture.

India is home to about 700 tribal groups with a population of 104 million, as per 2011 census. This indigenous people constitute the second largest tribal population in the world after Africa. Tribal population of Jammu & Kashmir is among the nascent Tribal Groups joining the main stream of planned development, to which they have brought a distinct and colourful cultural variety. Their economy is closely linked with the forests and they are living a substandard life because of their primitive mode of livelihood.

Majority of them are placed below the poverty line, possessing meagre assets and are exclusively dependent on wages, forest produce and farming, that too in a traditional way which leads to non remunerative returns. The peculiar aspect of tribals of our state is their scattered population who inhabit the difficult and remote geographic terrains which poses a severe threat to their speedy development.

In J&K state the following communities have been declared as scheduled tribes 1. Balti, 2. Beda, 3. Bot, Bota, 4. Brokpa, Drokpa, Dard, Shin, 5. Changpa, Garran, 6. Mon, 8. Purigpa, 9. Gujjar, 10. Bakerwal, 11. Gaddi and 12. Sippi.

Factors enabling favourable Agri-Development in Tribal Areas (SWOT Analysis)

Strengths:

1. Traditional knowledge: Tribal farmers in India possess traditional knowledge and skills related to farming and agriculture, which have been passed down from generation to generation.
2. Local varieties of crops: Tribal farmers cultivate a variety of crops that are well-suited to the local agro-climatic conditions and have high nutritional value.
3. Sustainable farming practices: Tribal farmers have a deep understanding of the local ecosystem and practice sustainable farming methods, which help to conserve natural resources and maintain the ecological balance.
4. Strong community ties: Tribal communities in India have a strong sense of community and social cohesion, which enables them to work together towards a common goal.

Weaknesses:

1. Limited access to resources: Tribal farmers in India often have limited access to resources such as land, water, credit, and infrastructure.
2. Many tribal areas in India lack basic infrastructure such as roads, electricity, and storage facilities, which makes it difficult to transport and store agricultural produce.
3. Low levels of education: Tribal farmers often have low levels of education and may lack the skills and knowledge required to take advantage of new technologies and market opportunities.

4. Vulnerability to climate change: Tribal farmers are often located in remote areas and are particularly vulnerable to the impacts of climate change, such as droughts, floods, and crop failures.

Opportunities:

1. Government support: The Indian government has launched several schemes and programs to support tribal farming, such as the Integrated Tribal Development Program and the Tribal Sub-Plan.
2. Growing demand for organic produce: There is a growing demand for organic produce in India and abroad, which presents an opportunity for tribal farmers to increase their income.
3. Value addition: Tribal farmers can add value to their agricultural produce by processing and packaging it, which can lead to higher profits and better market access.
4. Tourism: Tribal areas in India are known for their unique culture and traditions, which can attract tourists and provide an additional source of income for tribal farmers.

Threats:

1. Land acquisition: Tribal farmers in India are often at risk of losing their land to large-scale development projects such as mining, dams, and highways.
2. Market competition: Tribal farmers face competition from larger farmers and agribusinesses, which have greater access to resources and market information.
3. Changing dietary habits: Changing dietary habits and preferences among consumers may lead to a decline in demand for traditional crops grown by tribal farmers.
4. 4. Climate change: Climate change poses a significant threat to tribal farming in India, as it can lead to crop failures, loss of livestock, and damage to infrastructure.

Extension Outreach and Initiatives

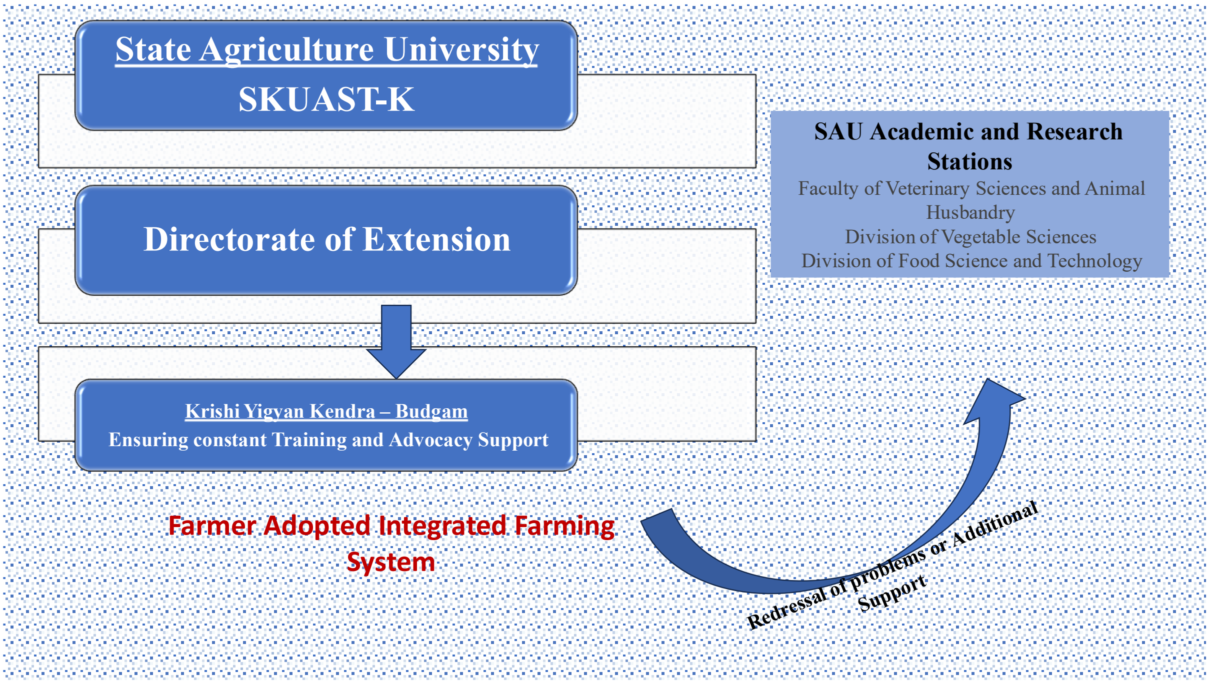
Khag is a tehsil (since 2008) in Beerwah Sub-district of Budgam which is approximately 20 km from Budgam and 35 km from District Srinagar. It is connected to Mazhama Railway Station (19km) with closest airport as Srinagar International Airport (55 km). Resident of village, Drang, the entrepreneur initiated the experiment a year ago with vegetable production under protected conditions (polyhouse), production of field crops and sheep rearing. As part of initiatives under the University outreach for progressive farmers led through the Directorate of Extension, a high value vegetable production was initiated under a high-tech polyhouse following a proper package-of-practice including INM, IDM and IPM etc as instructed by Krishi Vigyan Kendra Budgam. Adherence to Package of Practice laid down by SKUAST-K and availing Government Schemes of Assistance through Line Departments. IFS model of the farmer combines various compatible enterprises such as crops (field crops, horticultural crops).

Resource utilization of resources efficiently is critical for sustainable development. It is only through judicious use of resources and inter-linking the enterprises, a farmer can ensure productivity, profitability, livelihood creation, conservation of natural resources and maintenance of sustainable ecosystem

Technologies Addressed

Integrated farming system is a sustainable agricultural system that integrates livestock, crop production, fish, poultry, tree crops, plantation crops and other systems that benefit each other. It is based on the concept that 'there is no waste' and 'waste is only a misplaced resource' which means waste from one component becomes an input for another part of the system. • IFS approach is considered to be the most powerful tool for enhancing profitability of farming systems especially for small and marginal farmers to make them bountiful.

Mudasir Ahmad has aptly adopted the IFS and in this journey of the IFS, favorable collaborations between Line Departments, KVK and FVSc and AH, SKUAST-K that have yielded fruitful results. Capacity Building Programme on Wool and Pelt Processing in collaboration with Division of LPT, FVSc and AH, SKUAST-K, Capacity Building Programme Value Addition of Milk, in collaboration of LPM, FVSc and AH, SKUAST-K and Skill Training for Rural Youth on Protected Cultivation of Vegetable Crops have all aided this process of transformation of a Profitable IFS enterprise in a Tribal Area.



Model of operations and extension support

Impact of the Venture:

Quantitative Outcomes:

Sr. No.	Crop	Area (in Kanal)/No	Production (in Qtl)	Gross Income	Net income	B:C Ratio
Field Crops						
01	Oats	2.0	2.0	12400	9400	3.13
02	Rice	13	49	122500	76500	1.66
03	Rajma	3.0	2.0	30000	24000	4.00
Horticulture Crops						
04	Onion	0.5	1.0	2800	2000	2.50
05	Garlic	1	5.0	35000	24000	2.18
06	Apple	12	360	476000	300000	2.27
07	Walnut	45 plants	7.5	150000	120000	4.00
08	Vegetable cultivation under protected conditions (tomato, Cucumber, cherry & Capsicum	1	10	100000	700000	2.50
Livestock						
09	Cows	02	80000 ltrs	320000	230000	2.40
10	Sheep	20	@10000/sheep	200000	145000	2.63

The Krishi Vigyan Kendra – Budgam, further extended support to mobilise dairy farmers of the region for assemblage into a Dairy Cooperative for facilitate milk sales. Dairy farmers of the region (Khag, Nasrpura, Trapei, Shonglipora, Bathipora, Sitaharan, Drang) were mobilised after successive mobilisation drives in the community into a Farmers Producer Organisation, The Khag Kissan Farmer Producer organization cooperative Ltd. Drung Khag sponsored by NABARD. Mudasir Ahmad Dar is constantly endeavouring for mobilizing farmers into the FPO, business planning, market linkages and other allied activities of the FPO as its Chief Execution Officer. The FPO has already generated assets like Automatic Milk Collection Unit (AMCU), Wool Shearing Machines and Wool Weighing Scales availing Government Assistance under Holistic Agriculture Development Plan that rolled out in 2022 as a massive UT Government Initiative for upheaval of agriculture and allied sector in Jammu and Kashmir. A vehicle worth 12 lakhs has also been purchased for milk supply has also been purchased for milk distribution.

Output: Asset Generation

Details	Assistance	Status
Bulk Milk Cooler	Holistic Agriculture Development Plan	06 No.
Automated Milk Collection Units	-do-	04 No.
Wool Weighing Scale	-do-	5 Quintal (02 No.) 2 Quintal (01 No.)
Wool Shearing Machine	-do-	03 No.
Fat Analyser	-do-	02 No.
Van	-	01 No

KVK Budgam Team mobilising Dairy Farmers

Activities under Dairy, Sheep Rearing and Vegetable cultivation

Visuals supporting Activities under Vegetable Production, Dairy FPO and Wool Shearing

Impact of the Endeavor

- Building faith in agriculture as a promising livelihood option in times when most agricultural land is being rampantly diverted to non-agricultural uses.
- Leading by example and becoming leader of sorts, encouraging local youth to emulate the experience
- Fostering a collaboration between Line Departments, NGOs, KVK and other resource centres of SKUAST-K
- Improving the standard of living through maximizing the total net returns and provide more employment, minimizing the risk and uncertainties
- Skill development through various trainings programs undertaken at KVK Budgam SKUAST-K.

Challenges Faced:

Marketability: The Division of Vegetable Science facilitated marketability of the farmers produce by providing an authorised market for sale of potato.

Under Production: Vegetable production was enhanced through awareness cum training programmes by KVK Budgam, SKUAST-K and scientific/technical advice from scientists of KVK Budgam has led to optimum production of vegetable crops and seedling for sale thereof.

Challenges faced in milk production are highly perishable commodity with an unsure market. They are currently negotiating with the leading local Dairy Corporate, Khyber Agro for a sustained rate (Rs 42 per litre) instead of Rs 39 per litre.

Conclusion:

Mr. Mudasir Ahmad Dar is the emerging face of an educated agri-prenuer. He has marked his presence in the field by taking the lead and consolidating activities as a commercial unit. He has a mention worthy turnover of Rs. 60 lacs in a short span of time dovetailing horticulture and dairy farming. Having tasted success through sheer hard work, Mr. Mudasir inspires to take his venture to newer heights. He now intends to explore opportunities in value addition of vegetables and preservation of milk through canning/bottling, deep freezing of mutton etc. His journey is a testament that motivation to embrace agri-based livelihood seeking Government schemes and State Agri-Universitys support can transform rural economies into sustainable agri-economies.

CHALLENGES AND LEARNINGS FROM FARMERS PRODUCER'S ORGANISATIONS IN DISTRICT BUDGAM, UT OF J&K – A CASE STUDY OF VEGETABLE BASED FPOS SPONSORED BY NCDC

Bhinish Shakeel*, Bilal A. Lone, Vaseem Yousuf, Mir Nadeem Hassan, Uzma Bashir, Asima Amin, Shabeena Majid, Shazia Ramzan, Khurshid A Zargar, Sabiya Akhter, Ambreen Nabi, Shabir A. Ganie, Kavita Rani, Afsa I. Nehvi and Iram Farooq

Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir (SKUAST-K), Srinagar, Jammu and Kashmir

*Corresponding author E-mail: bhinishshakeel@skuastkashmir.ac.in

Abstract:

The rhetoric on Farmers Producers Organisation as an assemblage of farming community has been gaining a lot of popularity off-late. The Farmer Producer Organizations (FPOs) are essentially meant to strengthen small and marginal farmers with an end-to-end support and service including provide small farmers with end-to-end support and services, including technical assistance, marketing, processing, and cultivation inputs. The core philosophy is to raise the standard of these farmers by facilitating their income. FPOs which are formed as Farmer Producer Companies (FPCs) allow members to access financial and other input services. To compete in market, FPOs must be competent with other companies and competitors in the market, and they have a tremendous potential to capture future food retails not only in India but throughout the world. Keeping this in view an attempt has been made in this book chapter to highlight various constraints related to the growth, performance, and challenges of FPOs along with strategies to make them more effective in the present context. The major constraints found based on the review are poor Human resource management – inter-personal relationships between Board Members/Members, absence of empathy and compassion for common betterment, rivalry among Board Members, Difficult and tedious process of securing Operational Certificates (Seed/Fertilizer/Pesticide etc) lack of exposure to other successful endeavors.

Keywords: Farmers Producers Organisations, Challenges, Jammu and Kashmir.

Introduction

In the paradigm of development, the Government of India generated a Central Sector Scheme for the people associated with agriculture – a sector contributing to 18.2% of the nation's GDP, titled "Formation and Promotion of 10,000 Farmer Produce Organizations (FPOs)" with major focus on upheaval of farming community. A well-defined strategy and committed resources the Scheme are set-out to formulate 10,000 new FPOs in the country with budgetary provision of Rs 6865 crore.

At the core of formation of each FPO, that are to be developed in produce clusters, wherein agricultural and horticultural produces are grown / cultivated for leveraging economies of scale and improving market access for members. "One District One Product" cluster to promote specialization and better processing, marketing, branding & export. Under this Central Sector Scheme with funding from Government of India, formation & Promotion of FPOs are to be done through the Implementing Agencies (IAs). Presently 09 Implementing Agencies (IAs) have been finalized for formation and promotion of FPOs viz. Small Farmers Agri-Business Consortium (SFAC), National Cooperative Development Corporation (NCDC), National Bank for Agriculture and Rural Development (NABARD), National Agricultural Cooperative Marketing Federation of India (NAFED), North Eastern Regional Agricultural Marketing Corporation Limited (NERAMAC), Tamil Nadu-Small Farmers Agri-Business Consortium (TN-SFAC), Small Farmers Agri-Business Consortium Haryana (SFACH), Watershed Development Department (WDD)- Karnataka & Foundation for Development of Rural Value Chains (FDRVC)- Ministry of Rural Development (MoRD).

The Implementing Agencies (IAs) engage Cluster Based Business Organizations (CBBOs) to aggregate, register & provide professional handholding support to each FPO for a period of 5 years. CBBOs have been empanelled & engaged by IAs. CBBOs operate as an end-to-end knowledge for all issues related to FPO promotion. During 2020-21, a total of 2200 FPO produce clusters were allocated for formation of FPOs, which also include specialized FPO produce clusters such as 100 FPOs for Organic, 100 FPOs for Oil seeds etc. Of these, 369 FPOs are targeted for 115 aspirational districts in the country. Additionally, NAFED would form the specialized FPOs which should necessarily be forwardly linked to the market, agri-value chain, etc. NAFED will provide market and value chain linkages to the FPOs formed by other Implementing Agencies. NAFED has formed & registered 05 Honey FPOs during current year in Uttar Pradesh, Madhya Pradesh, Rajasthan, Bihar & West Bengal.

FPOs are earmarked to provide financial assistance upto Rs 18.00 lakh per FPO for a period of 03 years. In addition to this, provision has been made for matching equity grant upto Rs. 2,000 per farmer member of FPO with a limit of Rs. 15.00 lakh per FPO and a credit guarantee facility upto Rs. 2 crore of project loan per FPO from eligible lending institution to ensure institutional credit accessibility to FPOs.

At district level, a District Level Monitoring Committee (D-MC) is constituted under the Chairmanship of District Collector/ CEO/ ZillaParishad with representatives of different related departments and experts for overall coordination & monitoring the implementation of scheme in the district including the suggestion for potential produce cluster & development

At National level, National Project Management Agency (NPMA) as a professional organization has been engaged for providing overall project guidance, coordination, compilation of information relating to FPOs, maintenance of MIS and monitoring purpose.

There are well defined training structures in the scheme and the institutions like Bankers Institute of Rural Development (BIRD), Lucknow and Laxman Rao Inamdar National Academy for Co-operative Research & Development (LINAC), Gurugram have been chosen as the lead training institutes for capacity development & trainings of FPOs. Training & skill development modules have been developed to further strengthen the FPOs also through CBBOs.

Formation & promotion of FPOs is the best foot forward to convert Krishi into Atmanirbhar Krishi. This will enhance cost effective production and productivity and higher net incomes to the member of the FPO. Also improve rural economy and create job opportunities for rural youths in villages itself.

FPOs formulated under NCDC at the Krishi Vigyan Kendra – Budgam

In the year 2022, KVK-Budgam was empanelled as Cluster Based Business Operations by the NCDC to formulate two vegetable and mushroom based FPOs in the District. After subsequent community mobilisation through awareness programmes in the District, the Kendra succeeded in assembling farmers in Block Budgam and Bagat-e-Kanipora (B.K.pora) as Sheikh ul Alam and Umeed Ki Kiran respectively in Feb 2022.

Indicator	Umeed Ki Kiran Farmer Producer Cooperative Ltd	Sheikh Ul Alam Farmer Producer Cooperative Ltd
No. of Farmer Members	114	136
Equity Grant recieved 1st Tranche	2.05 Lakh (Received)	1.66 Lakh (Received)
Management Cost Availed/ Applied for	1st Tranche: 3.66 Lakh (Received)	1st tranche: 3.48 Lakh (Received) 2nd trenche:2.95 lakhs (Applied)
Registered on e-NAM portal	Yes	Yes
Office Bearer Appointed	Yes	Yes
Status	Functional	Functional

Sr. No	Indicator	Number
1.	Farmers Mobilised	234
2.	Women Farmer Mobilised	110
3.	Average Farmer in each FPO	117
4.	Average Women Farmer in each FPO	55

Technologies Addressed through Extension Outreach

As part of handholding to these FPOs, KVK Budgam has been rendering Extension Outreach Services to these Farmers through community mobilisation for FPO membership, short-duration Training and Awareness Programmes on Protected Cultivation of Vegetables, Nursery Raising of Vegetable Crops as Profitable Venture, Scientific Cultivation of Exotic Vegetables, Pollination Management in Cucurbitaceous Crops.

Similarly, several Schools on Fruit and Vegetable Processing, Dhingri Mushroom Cultivation, Hybrid Seed Production in Vegetable Crops, Packaging, Labelling and Licensing in Processed Fruits and Vegetables. All these aspects are dealt with practical demonstrations and exposure visits in line with Principles of Extension for effective learning. In prevailing competitive times

Apart from these the farmers have been hand-held for Packaging and labelling in processed fruits and vegetables to sharpen their repertoire of generic skills required to deal with exhibitions at regional and National Level.

Community Mobilisation

General Body Meeting

Trainings and Schools

Exhibition at Annual Seed Mela SKUAST-K

Products generated by FPO

Introduced Pared and Peeled vegetables for home delivery (Order based) in vicinity

Challenges Faced by FPOs at Budgam

Despite growing popularity of FPOs for strengthening farmers group at the grass-roots some bottlenecks have been identified while

Sr. No.	Issues	Possible Solution
1.	Tough eligibility criteria for Seed/Fertilizer License.	The FPOs need to avail a barrage of licenses to be a commercially viable group. The Board of Directors and the member FPO may or may not be science graduates. There is a need for relaxation in eligibility criteria to obtain Seed/Fertilizer/Pesticide license to facilitate preliminary formalities for execution of FPO. Also, there is no waiver in registration fee for these groups.
2.	Tedious Process of Registration for Licenses	For execution of FPO, there are certain licenses that are laid down under the guidelines to obtain TIN, PAN, GST, Seed/Fertiliser/Pesticide, E-NAM, ONDC, fssai, APEDA, Mandi license. It is a cumbersome and tedious process.
3.	Conflict of interest among Board of Directors	Rivalry among members to achieve key positions in the organization and challenging each other for key positions in the group have been observed. Often the members are reluctant to give valid input in operations to CEO and other members with the view that those who are monetary remunerated must be ones who must be solely accountable for operations.
4.	Non-inclusion of Local Elected Leaders	The Board members are farmers representative from the region of FPO. CEO and Accountant appointed for business operations may or may not be from the same geographical area. Non-inclusion of Local Elected Leader in the FPO which could act as a facilitator in case of conflict in the group.
5.	Lack of Exposure and professional management and among FPO Members	Most members of FPO are illiterate or semi-literate. Education, not to be viewed only as functional literacy, broadens the horizons of an individual. In absence of exposure to Co-operatives, Best-Practice FPOs in other areas that can be emulated, the FPOs do not have a heads-up as to how to lead, develop a stronghold, develop a niche with some innovative service, to sustain as a farmers collective. Lack of cohesion between FPO Members has also been observed. More often they are not privy on various activities of FPO.

6.	Absence of Skill Sets in Board of Directors/Members of FPO	As already stated, the farmers are illiterate and are not equipped with skill sets, particularly Soft Skill Sets that could groom them in handling inter-personal dynamics with members. Moreso, the members are inept to deal with technology, particularly Information Communication Technology. (ICT)

The same constraints and issues have been reported in the Maharashtra, Osmanabad District in 2019 where members reported non-inclusion of local leaders in FPCs, lack of coordination for different group activities, lack of support from the government department after the establishment of FPCs, political affiliation of members, companies have limited access to banks, inadequate profit to individual members and village-level workers not providing enough information about all schemes related to FPCs.

A study conducted by Navaneetham *et al.* (2019) on Analysis of constraints for performance improvement of FPCs in Tamil Nadu revealed that capturing the market for selling the produce was the biggest constraint and farmers were unable to raise funds from farmers.

Similarly, in a Strategy Paper for promotion of 10,000 Farmer Producer Organisations (FPOs), by SFAC (2019) some challenges faced in the promotion of FPOs are, difficulty and delay in the mobilisation of farmers, limited organisational and management capacity of FPOs, need for incubation and handholding support to FPOs, membership base of an FPO, policy level challenges, limited capability to autonomously invest in primary/ secondary processing, storage and custom hiring facilities, and inability of FPOs to access institutional credit sans collateral.

Poor professional management, shortage of working capital, inability to access loans from financial institutions, unawareness of producer-members, insufficient directions and vision from the Board of Directors and poor infrastructure facilities were major hurdles for better performance of Producer Organizations as revealed in a study on socio-economic impacts on members of FPO in the plains region of Chhattisgarh reported by Prishila Kujur *et al.* (2019)

Verma *et al.* (2021) conducted a study on Constraints perceived by the members and non-members towards the functioning of FPO-AKPCL in Kannauj District of Uttar Pradesh. The results revealed that inadequate storage facilities, shortage of transportation facilities, lack of grading and packaging skills, rivalry among members to achieve key positions in the organization, and challenging each other for key positions in the group were the significant constraints faced by the member farmers.

According to Chauhan *et al.* (2021), the constraints associated with the functioning of Farmer Producer Organisations (FPOs) were undeveloped storage facilities, undeveloped processing facilities, lack of computer knowledge due to which they are unable to derive benefits of the available ICT tools, lack of awareness about packaging, lack of labour available during harvesting, lack of sufficient finance, lack of skilled labour in harvesting, processing, fluctuation of price every year, lack of proper market information, involvement of middlemen and lack of proper infrastructure. The study was conducted in Cooch Bihar district of West Bengal by collecting primary data from 100 FPO members.

Conclusion:

Despite major thrust of government on formation of FPOs by Government as a launch-pad for small and marginal farmers socio-economic development, the FPOs are far from achieving this goal in view of the challenges mentioned in this narrative. There is a need for intensive rigorous capacity building in terms of strengthening these groups in terms of Human Resource (Role clarity, inter-personal dynamics, ownership, collective responsibility etc). Trainings at KVKs and other centres needs to be supplemented strongly with Exposure Visits to Model FPOs for cross-learning as would give some food for thought to emulate in their own region. All the support to FPOs must be sustained rigorously till it achieves it logical conclusion of an economically viable farmers collective.

References:

1. Chauhan, K., Adhikary, A., & Pradhan, K. (2021). Identification of constraints associated with farmers' producer organisations (FPOs). *International Journal of Current Microbiology and Applied Sciences, 10*(1), 1859–1864.
2. Chopade, S. L., Kapse, P. S., & Dhulgand, V. G. (2019). Constraints faced by the members of farmer producer company. *International Journal of Current Microbiology and Applied Sciences, 8*(8), 2358–2361.
3. Kujur, P., Gauraha, A. K., & Netam, O. K. (2019). The socio-economic impact of farmer producer organizations in Chhattisgarh plains. *Journal of Entomology and Zoology Studies, 7*(6), 1104–1106.
4. Navaneetham, B., Mahendran, K., & Sivakumar, S. D. (2019). Analysis of constraints for performance improvement of FPCs in Tamil Nadu. *International Journal of Farm Sciences, 9*(2), 12–18.
5. SFAC. (2019). *Strategy paper for promotion of 10,000 farmer producer organisations (FPOs)*. Small Farmers' Agribusiness Consortium, New Delhi.
6. Verma, A. K., Singh, V. K., Asha, K., Dubey, S. K., & Verma, A. P. (2021). Constraints perceived by the members and non-members towards functioning of FPO-AKPCL in Kannauj District of Uttar Pradesh. *Economic Affairs, 66*(2), 335–341.

BALANCED FERTILIZATION STRATEGIES FOR WHEAT: LINKING PHYSIOLOGICAL TRAITS, YIELD, AND SOIL HEALTH

Megha Vishwakarma

Shri Vaishnav Institute of Agriculture,

Shri Vaishnav Vidyapeeth Vishwavidyalaya, Indore (M.P.), India

Corresponding author E-mail: meghavishwakarma007@gmail.com

Abstract:

Wheat *(Triticum aestivum* L.) is a major cereal crop whose productivity in India, including Madhya Pradesh, remains below global standards due to nutrient imbalances and declining soil fertility. This review highlights the effects of different nutrient sources and NPK levels on wheat growth, yield, and soil health. Studies indicate that integrated nutrient management (INM), combining chemical fertilisers with organic amendments such as farmyard manure, vermicompost, and biofertilizers, significantly enhances chlorophyll content, SPAD values, leaf area index, dry matter accumulation, and yield attributes. INM also improves nutrient uptake, nutrient use efficiency, and the chemical and biological properties of soil, including organic carbon content, available macronutrients, and micronutrient availability. These findings underscore that balanced application of inorganic and organic nutrients is essential for sustainable wheat production, optimising yield potential, and maintaining soil fertility.

Keywords: NPK, Integrated Nutrient Management, Soil Fertility, Organic Amendments, Biofertilizers

Introduction:

Wheat *(Triticum aestivum* L.) is the third most produced cereal globally, serving as a staple food for millions. In India, it is cultivated over 30.42 million hectares, yielding 92.29 million tonnes annually, with an average productivity of 3034 kg ha^{-1}. In Madhya Pradesh, wheat occupies 5.91 million hectares with a production of 17.69 million tonnes and a productivity of 2993 kg ha^{-1} (Anonymous, 2018). However, wheat productivity in India and Madhya Pradesh (~3 t ha^{-1}) remains lower than in countries like China and Mexico (~5 t ha^{-1}). Achieving sustainable productivity of 5 t ha^{-1} requires maintaining good soil health and optimizing the use of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K).

Wheat hybrids producing around 5 t ha^{-1} can remove significant amounts of nutrients from the soil, including 110 kg N, 15 kg P, 129 kg K, 5 kg S, 2 kg Fe, 2 kg Mn, 200 g Zn, and 150 g B ha^{-1}. Despite this, farmers primarily apply N fertilizers (mainly urea), often neglecting P and K, which leads to nutrient imbalances, soil fertility decline, and reduced productivity (Rai, 2006). Current recommended doses of NPK are often insufficient to achieve optimum yields due to emerging deficiencies of other nutrients and deteriorating soil conditions. Moreover, soil fertility ratings used by testing laboratories have remained largely unchanged for over fifty years, rendering previous "optimal" recommendations suboptimal. Increasing NPK doses from 100% to 150% has been shown to further enhance productivity (Singh, 2016).

Nitrogen is a key component of chlorophyll and regulates numerous aspects of plant metabolism, root growth, and nutrient uptake (Sinclair and Horie, 1989). Phosphorus plays a vital role in photosynthesis, respiration, energy storage, and cell division (Bakhsh *et al.,* 2008), while potassium is essential for photosynthesis and transport of photosynthates to storage organs. Wheat is typically cultivated with adequate nitrogen to achieve high yields, making nitrogen content a reliable indicator of plant nutritional status. Leaf chlorophyll content, which correlates with nitrogen content, serves as an important tool to monitor crop nutrition and guide fertilizers management. Although the relationship between leaf chlorophyll content and overall photosynthetic canopy is well-documented, limited information exists on the vertical distribution of chlorophyll and nitrogen within the plant canopy (Ciganda *et al.,* 2008).

Chlorophyll content reflects the photosynthetic efficiency and overall metabolic activity of the plant. Nutrient deficiencies can impair chlorophyll synthesis, reducing growth and yield. Adequate nutrient availability through fertilizers promotes vigorous foliage, enhanced meristematic activity, and higher synthesis of photo-assimilates, leading to increased chlorophyll content and improved wheat productivity (Ullah *et al.,* 2018). Proper use of fertilizers in appropriate forms and amounts is critical to maximise these benefits.

Maintaining soil health through organic and biological resources is a cost-effective strategy to sustain productivity. However, nutrient release from organic sources may not synchronise with crop demand, and N utilization under organic treatments can be as low as 30% compared to 60–80% under inorganic fertilizers. Organic inputs such as farmyard manure, crop residues, and biofertilizers improve soil organic carbon, N use efficiency, and crop productivity but are limited by low nutrient content.

Integrated nutrient management (INM) combines organic and inorganic sources, enhancing nutrient use efficiency, crop yield, and soil health while reducing dependency on chemical fertilizers (Dejene and Lemlem, 2012). Organic inputs build soil organic matter, improve cation exchange capacity, support soil structure, and enhance moisture retention, whereas inorganic fertilizers provide readily available nutrients during peak crop demand. Thus, effective crop nutrition requires balancing soil fertility management with timely nutrient supply through both organic and inorganic sources.

The optimization of NPK management and the interactions between nutrient sources and levels remain central to achieving sustained wheat production, cost-effective cultivation, and improved soil health. Keeping in view the above discussion, a comprehensive review of earlier scientific investigations has been presented to elucidate the effects of nutrient management practices on growth, chlorophyll content, yield and soil health of wheat.

2.1 Effect of Different Sources of Nutrients and Levels of NPK on SPAD and Chlorophyll Content of Wheat

Several studies have demonstrated the positive influence of nutrient sources and NPK levels on SPAD values and chlorophyll content in wheat. Costa *et al.* (2001) reported that SPAD values increased with higher nitrogen fertilization (0, 85, 170, and 225 kg ha^{-1}) and plant age. Kumar (2004) observed that applying 100-75-50 kg NPK ha^{-1} or the same NPK dose combined with 10 t ha^{-1} of farmyard manure (FYM) significantly enhanced total chlorophyll content to 1.95 mg g^{-1} and 2.26 mg g^{-1} at 60 DAS, respectively. Bojović and Stojanović (2005) reported significant increases in chlorophyll a, b, and total chlorophyll with 150-80-100 kg N ha^{-1}. Szeles (2007) found SPAD values increased with nitrogen levels, achieving maximum yields at 120-90-106 kg NPK ha^{-1}. Tranavičienė *et al.* (2007) observed enhanced chlorophyll levels with 150-80-120 kg NPK ha^{-1} compared to 90-80-120 kg NPK ha^{-1}. Organic amendments also improved chlorophyll content. Jan and Boswal (2015) reported that FYM + biofertilizer (BF) increased SPAD to 39.50 and chlorophyll a, b, and total chlorophyll to 1.41, 0.34, and 1.82 mg g^{-1}, respectively. Jat *et al.* (2015) recorded the highest SPAD of 36.53 at 60 DAS with 120-60-60 kg NPK ha^{-1}. Similarly, Kumar (2015) reported increased SPAD values with 120-60-60 kg NPK ha^{-1} and 30 kg N ha^{-1} through vermicompost, reaching 41.76 and 40.44 at 60 DAS. Al-Erwy *et al.* (2016) observed 50–67% increases in chlorophyll a and 14.8–42.6% in chlorophyll b with 100–250 kg N ha^{-1}. Sandhu (2016) reported the highest SPAD values with 50-25-12 kg NPK ha^{-1} combined with 50% N from FYM at different growth stages. Al Amin *et al.* (2017) demonstrated enhanced SPAD with combinations of chemical fertilizer, vermicompost, and FYM. Khalifa *et al.* (2018), Saharan *et al.* (2018), and Fiorentin (2019) similarly reported significant increases in SPAD and chlorophyll content with higher NPK levels, combined with organic amendments and biofertilizers.

2.2 Effect of Different Sources of Nutrients and Levels of NPK on Leaf Area Index (LAI) and Dry Matter Accumulation of Wheat

Nutrient management significantly influenced the leaf area index (LAI) of wheat. Dhaka and Gill (2007) found that applying 120 kg N + 40 kg P_2O_5 ha^{-1} increased LAI at harvest by 29.8%, 14.3%, and 5.3% compared to lower N and P levels. Rehman (2010) observed a maximum LAI of 2.46 with 45 t FYM ha^{-1} in sandy loam soil. Kaushik *et al.* (2012) reported that combining 3 t ha^{-1} vermicompost (VC) with 100% RDF, Azospirillum, and PSB significantly increased LAI to 2.47, 3.47, and 3.88 at 30, 60, and 90 DAS, respectively. Sandhu (2016), Kakraliya (2017), Gawali and Unni (2018), Kaur *et al.* (2018), Verma *et al.* (2018), and Maurya *et al.* (2019) all observed higher LAI values with integrated nutrient management, combining inorganic fertilizers with organic amendments and biofertilizers, highlighting improved canopy development and photosynthetic potential.

Dry matter accumulation (DMA) increased significantly with higher NPK doses and organic amendments. Chaturvedi (2006) reported DMA of 14.65 and 14.45 t ha^{-1} with 125-26-100 kg NPK ha^{-1} during 2003 and 2004, respectively. Devi *et al.* (2011) found that 100% RDF + 1 t VC + PSB increased DMA to 683.47 g m^{-2}. Kaushik *et al.* (2012) observed maximum DMA with 3 t VC + 100% RDF + Azospirillum + PSB at 30, 60, and 90 DAS. Neelam *et al.* (2015), Chopra *et al.* (2016), Sandhu (2016), Kakraliya (2017), Kaur *et al.* (2018), and Saharan *et al.* (2018) consistently reported higher DMA with the combined application of inorganic and organic fertilizers emphasizing the synergistic effect of integrated nutrient management on biomass accumulation in wheat.

2.3 Effect of Different Sources of Nutrients and Levels of NPK on Yield, Yield Attributes and nutrient Use Efficiency of Wheat

Nutrient management strongly influenced wheat yield and its components. Chaturvedi (2006) reported higher plant height, tillers, grains per spike, 1000-grain weight, and grain yield with 125-26-100 kg NPK ha^{-1}. Channabasanagowda *et al.* (2007) found improved growth and yield with 50% VC + 50% FYM. Malghani *et al.* (2010), Ali *et al.* (2011), Davari *et al.* (2012), Kaushik *et al.* (2012), Rehman (2014), Desai *et al.* (2015), Verma *et al.* (2015), Chopra *et al.* (2016), Mohan *et al.* (2018), Saharan *et al.* (2018), Ullah (2018), Borse *et al.* (2019), and Parewa *et al.* (2019) similarly reported significant increases in tiller number, spike length, grains per spike, test weight, grain yield, and straw yield with NPK combined with organic amendments and biofertilizers.

These findings collectively indicate that integrated nutrient management, combining optimized NPK levels with organic sources and biofertilizers, enhances wheat chlorophyll content, LAI, dry matter accumulation, and ultimately yield, confirming the importance of balanced nutrient management for sustainable wheat production.

The effect of different nutrient sources and NPK levels on wheat has been widely studied. Ishaq *et al.* (2001) observed that application of 180-60-75 kg ha^{-1} NPK in loamy soil significantly increased nitrogen, phosphorus, and potassium content in wheat grain at the tillering stage. Gopinath *et al.* (2008) reported that 150 kg N through FYM and 150 kg N through vermicompost in silty clay loam soil enhanced grain P and K content. Similarly, Davari *et al.* (2012) found that combinations of vermicompost, rice residues, and biofertilizers maximized N, P, and K content in wheat grain. Ram *et al.* (2014) reported that integrated applications of NPK with FYM, green manure, and biofertilizers improved nutrient content in both grain and straw. High levels of NPK also significantly enhanced wheat nutrient content, as shown by Rakshit *et al.* (2015) and Rekaby *et al.* (2016). Argal *et al.* (2017) and Gawali and Unni (2018) demonstrated that integrated nutrient management—including RDF, FYM, PSB, and $ZnSO_4$—significantly increased N, P, and K content at various growth stages.

Regarding nutrient uptake, Chaturvedi *et al.* (2006) reported that 125-26-100 kg ha^{-1} NPK significantly increased N and P uptake by wheat grain compared to the control. Studies by Tripathi *et al.* (2007), Devi *et al.* (2011), Davari *et al.* (2012), and Sharma (2013) further confirmed that NPK in combination with FYM, vermicompost, PSB, and microbial inoculants maximized NPK uptake in grain and straw. Similarly, Ram *et al.* (2014), Jat *et al.* (2015), Rakshit *et al.* (2015), Rekaby *et al.* (2016), Singh *et al.* (2016), Gawali and Unni (2018), Borse *et al.* (2019), and Surve *et al.* (2019) observed that nutrient uptake increased significantly with integrated nutrient management or higher NPK levels.

Nutrient use efficiency is also influenced by nutrient sources. Al Amin (2017), Kakralia *et al.* (2017), Kumar and Mukhopadhyay (2017), Sarwar *et al.* (2018), Chuan *et al.* (2019), and Dobocha *et al.* (2019) reported that integrated applications of FYM, vermicompost, and microbial inoculants, along with 100% or higher RDF, improved agronomic efficiency, apparent N recovery, partial factor productivity, and physiological efficiency.

2.4 Effect of Different Sources of Nutrients and Levels of NPK on Soil Chemical And Biological Properties

Chemical properties of soil are likewise affected by nutrient sources. Yaduvanshi (2003), Saha *et al.* (2010), Devi *et al.* (2011), Katkar *et al.* (2011), Gudadhe *et al.* (2015), Mohammadi *et al.* (2015), Meshram *et al.* (2016), Elankavi (2017), Wailare and Kesarwani (2017), and Gawali and Unni (2018) reported that the addition of FYM, vermicompost, or organic sources with NPK improved soil organic carbon and available N, P, and K, while soil pH was either slightly reduced or maintained at favorable levels.

The availability of micronutrients in soil is also enhanced by organic and integrated nutrient management. Dhaliwal *et al.* (2010), Sur *et al.* (2010), Walia *et al.* (2010), Rutkowska *et al.* (2014), Shahid *et al.* (2015), Saha *et al.* (2019), and Parven *et al.* (2020) demonstrated that FYM, vermicompost, and NPK applications increased the availability of Zn, Cu, Fe, and Mn in the soil compared to NPK alone.

Soil biological properties are also positively influenced by integrated nutrient management. Okur *et al.* (2009), Chakraborty *et al.* (2010), Venkatesh *et al.* (2012), Benbi *et al.* (2015), Ghosh *et al.* (2012), Bahadur *et al.* (2012), Dubey *et al.* (2014), Sathish *et al.* (2016), Meshram *et al.* (2016), Bharadwaj *et al.* (2019), and Alam *et al.* (2020) reported that combined application of FYM, compost, and NPK increased microbial biomass carbon, dehydrogenase activity, populations of Azotobacter and PSB, as well as carbon fractions (labile and non-labile) and total organic carbon.

Overall, these studies collectively demonstrate that integrated nutrient management, involving chemical fertilizers combined with organic sources and microbial inoculants, significantly enhances wheat nutrient content, uptake, and use efficiency, and improves both the chemical and biological properties of soil.

Conclusion:

Integrated nutrient management, combining optimised NPK levels with organic sources and biofertilizers, consistently improves wheat physiological parameters, nutrient uptake, and yield. Organic amendments enhance soil organic carbon, microbial activity, and micronutrient availability, while inorganic fertilizers supply nutrients in readily available forms during peak crop demand. The synergistic effects of INM not only maximize grain and straw production but also maintain long-term soil fertility, highlighting its critical role in achieving sustainable wheat productivity. Proper management of both nutrient sources and levels is therefore essential to enhance wheat growth, yield, and overall soil health in regions like Madhya Pradesh.

References:

1. Al Amin, M., Hasanuzzaman, M., & Roy, T. S. (2017). Effects of different sources of nutrients and levels of NPK on the growth and yield of wheat. *Journal of Agriculture and Ecology*, 4(1), 12–21.
2. Al-Erwy, A. S., Al-Toukhy, A. A., & Bafeel, S. O. (2016). Effect of nitrogen levels on chlorophyll content and yield of wheat *(Triticum aestivum* L.). *International Journal of Plant & Soil Science*, 10(6), 1–9.
3. Anonymous. (2018). *Agricultural Statistics at a Glance 2018*. Directorate of Economics and Statistics, Department of Agriculture, Cooperation and Farmers Welfare, Ministry of Agriculture & Farmers Welfare, Government of India.
4. Bakhsh, I., Khan, M. S., Khan, M. Q., & Jaffar, M. (2008). Effect of various levels of phosphorus on the yield and yield components of wheat. *Journal of Agricultural Research*, 46(1), 33–40.

5. Bojović, B., & Stojanović, J. (2005). Chlorophyll and carotenoid content in wheat cultivars as a function of nitrogen nutrition. *Archives of Biological Sciences*, 57(4), 283–290.
6. Chaturvedi, I. (2006). Effects of integrated nutrient management on growth, yield and economics of wheat (*Triticum aestivum* L.). *Indian Journal of Agronomy*, 51(4), 285–288.
7. Ciganda, V., Gitelson, A., & Schepers, J. (2008). Vertical profile of chlorophyll in maize canopy: Its detection and implication on total canopy chlorophyll estimation. *Remote Sensing of Environment*, 112(10), 3536–3547.
8. Davari, M. R., Sharma, S. N., & Mirzakhani, M. (2012). The effect of combinations of organic materials and biofertilizers on soybean-wheat cropping system. *Applied and Environmental Soil Science*, 2012, Article 507167.
9. Dejene, M., & Lemlem, M. (2012). Integrated nutrient management for sustainable crop production and soil health. *Journal of Biology, Agriculture and Healthcare*, 2(5), 110–124.
10. Dhaka, A. K., & Gill, M. S. (2007). Effect of nitrogen and phosphorus on growth and yield of wheat. *Indian Journal of Agronomy*, 52(2), 120–123.
11. Dhaliwal, S. S., Sadana, U. S., & Walia, S. S. (2010). Direct and residual effect of organic and inorganic sources of micronutrients on yield and their availability in soil under rice-wheat system. *Journal of the Indian Society of Soil Science*, 58(2), 209–213.
12. Gawali, A. S., & Unni, S. (2018). Impact of integrated nutrient management on soil health and productivity of wheat. *International Journal of Chemical Studies*, 6(3), 2050–2055.
13. Jan, A., & Boswal, M. V. (2015). Effect of organic and inorganic fertilizers on chlorophyll content and yield of wheat (*Triticum aestivum* L.). *Indian Journal of Agricultural Research*, 49(5), 450–454.
14. Jat, G., Majumdar, S. P., & Jat, M. L. (2015). Influence of nitrogen and phosphorus levels on nutrient uptake, yield and quality of wheat. *Journal of Soil and Water Conservation*, 14(1), 51–56.
15. Kaushik, M. K., Vyas, A. K., & Singh, P. (2012). Effect of integrated nutrient management on growth and yield of wheat. *Indian Journal of Agronomy*, 57(2), 143–148.
16. Kumar, A. (2004). Effect of integrated nutrient management on the chlorophyll content and yield of wheat. *Journal of Wheat Research*, 2(1), 45–48.
17. Kumar, P. (2015). Response of wheat to integrated nutrient management in North-Western Himalayas. *Journal of Crop and Weed*, 11(2), 125–129.
18. Rai, R. K. (2006). *Nutrient management in wheat: Problems and prospects*. Indian Agricultural Research Institute (IARI) Technical Bulletin.

19. Saha, J. K., *et al.* (2010). Long-term effect of FYM and NPK on soil organic carbon and availability of nutrients in a Vertisol. *Journal of the Indian Society of Soil Science*, 58(4), 400–405.
20. Saharan, V., *et al.* (2018). Role of biofertilizers and organic manures in sustainable wheat production. *International Journal of Current Microbiology and Applied Sciences*, 7(2), 1540–1547.
21. Sandhu, S. S. (2016). Integrated nutrient management in wheat (*Triticum aestivum* L.) under irrigated conditions. *International Journal of Agriculture, Environment and Biotechnology*, 9(4), 565–571.
22. Sinclair, T. R., & Horie, T. (1989). Leaf nitrogen, photosynthesis, and crop radiation use efficiency: A review. *Crop Science*, 29(1), 90–98.
23. Singh, J. (2016). Optimization of NPK doses for enhancing wheat productivity in Madhya Pradesh. *Indian Journal of Soils*, 14(2), 88–94.
24. Ullah, A., *et al.* (2018). Integrated nutrient management for improving wheat productivity. *Journal of Plant Nutrition*, 41(11), 1435–1444.
25. Yaduvanshi, N. P. S. (2003). Substitution of inorganic fertilizers by organic manures and residues in rice–wheat systems in alkali soils. *Experimental Agriculture*, 39(1), 61–68.

CHLOROPHYLL FLUORESCENCE: A TOOL TO MONITOR PHYSIOLOGICAL STATUS OF PLANTS UNDER ABIOTIC STRESS CONDITIONS

Lakshmi S

Department of Crop Physiology,

Adhiparasakthi Horticultural College, G.B. Nagar, Kalavai 632506, Tamil Nadu, India

Corresponding author E-mail: lakshmisubramaniyanl@gmail.com

Abstract:

Photosynthesis is the fundamental physiological process that sustains plant growth and ecosystem productivity. Any disruption in photosynthetic efficiency caused by abiotic stresses such as drought, heat, salinity, nutrient deficiency, heavy metal toxicity, ozone, and ultraviolet radiation directly affects plant performance and crop yield. Chlorophyll fluorescence has emerged as one of the most powerful, rapid, non-invasive, and sensitive techniques for probing the functional integrity of the photosynthetic apparatus, particularly Photosystem II (PSII). Because fluorescence emission is closely linked to photochemical efficiency, heat dissipation, and electron transport dynamics, changes in fluorescence parameters provide early and reliable indicators of stress-induced damage well before visible symptoms appear. This chapter comprehensively reviews the theoretical basis of chlorophyll fluorescence, fluorescence induction kinetics, the Kautsky effect, OJIP transients, and pulse-amplitude-modulated (PAM) fluorometry. Special emphasis is placed on the application of fluorescence techniques to assess plant physiological status under major abiotic stresses. The chapter highlights how specific fluorescence parameters such as F_0, F_m, F_v/F_m, ΦPSII, non-photochemical quenching, and performance index (PI) respond to different stress conditions. The integration of chlorophyll fluorescence with plant stress physiology offers a valuable bioindicator framework from single leaves to ecosystems and contributes significantly to crop improvement strategies under changing climatic conditions.

Keywords: Photosynthesis, Chlorophyll Fluorescence, Abiotic Stress, Photosystem II, PAM Fluorometry, OJIP Transients, Crop Productivity

Introduction:

Photosynthesis is the most important physio-biochemical process on Earth, forming the basis of life by converting solar energy into chemical energy stored in organic compounds. Green plants, algae, and cyanobacteria uniquely possess the ability to utilize light energy to reduce carbon dioxide into carbohydrates, a process that requires assimilatory power in the form of ATP and NADPH generated during the light reactions of photosynthesis. Chlorophyll pigments, particularly chlorophyll *a*, play a central role in capturing light energy and driving photochemical reactions within the thylakoid membranes of chloroplasts. During the late twentieth century, significant progress in photosynthesis research was achieved through the development of modern optical techniques that allow the non-destructive investigation of photosynthetic processes at multiple organizational levels, ranging from thylakoid membranes to whole plant canopies (Baker, 2008). Among these techniques, chlorophyll fluorescence has emerged as a particularly powerful tool for studying photochemical and non-photochemical processes associated with PSII (Maxwell and Johnson, 2000). Chlorophyll fluorescence is the red to far-red light re-emitted by chlorophyll molecules after the absorption of photosynthetically active radiation (400–700 nm). Although fluorescence accounts for only a small fraction (approximately 0.5–10%) of absorbed energy, its yield is highly sensitive to changes in photosynthetic efficiency, making it an excellent probe of plant physiological status (Krause and Weis, 1991).

Abiotic stresses represent one of the major limitations to global crop productivity. Unlike animals, plants are sessile organisms and cannot escape unfavourable environmental conditions. Instead, they rely on complex physiological, biochemical, and molecular mechanisms to perceive stress signals, transduce them, and mount adaptive responses (Lichtenthaler, 1998). Since chloroplasts are both the site of photosynthesis and a major source of reactive oxygen species, they function as primary sensors of abiotic stress (Brestic and Zivcak, 2013). Consequently, stress-induced alterations in photosynthesis are rapidly reflected in chlorophyll fluorescence signals.

Chlorophyll Fluorescence: Definition and Biophysical Basis

Chlorophyll fluorescence is defined as the red to far-red radiation emitted by photosynthetic tissues when illuminated with light in the 400–700 nm range (McCree, 1971). Blue and red wavelengths are absorbed more efficiently by chlorophyll than green light, resulting in higher excitation of PSII reaction centers (Porcar-Castell *et al.,* 2014).

The fate of absorbed light energy in PSII follows three competing pathways:

1. Photochemistry, where energy is used to drive electron transport
2. Heat dissipation, known as non-photochemical quenching
3. Fluorescence emission, the re-radiation of excess energy

Any increase in the efficiency of one pathway leads to a decrease in the yield of the other two (Kalaji *et al.,* 2016). Therefore, fluorescence yield increases when photochemistry is inhibited or when heat dissipation mechanisms are insufficient, making fluorescence a sensitive indicator of stress-induced dysfunction.

Kautsky Effect and Fluorescence Induction

The relationship between photosynthesis and fluorescence was first demonstrated by Kautsky and Hirsch (1931), who observed a characteristic fluorescence transient when dark-adapted leaves were illuminated. This transient consists of an initial rapid rise in fluorescence followed by a slower decline to a steady-state level, corresponding to the induction of photosynthesis. The initial rise is attributed to the reduction of QA, the primary quinone electron acceptor of PSII, leading to closure of reaction centers and increased fluorescence emission. The subsequent decline reflects the activation of photochemical and non-photochemical quenching processes as carbon fixation and energy dissipation mechanisms become fully operational (Rohacek *et al.,* 2008).

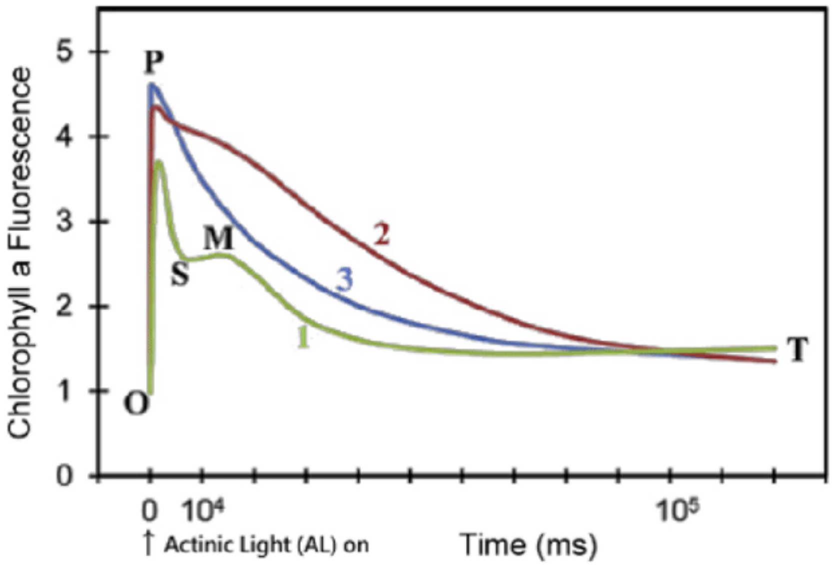


Figure 1:. Kautsky Effect

OJIP Fluorescence Transient and JIP-Test

The fast fluorescence induction curve, known as the OJIP transient, reflects the sequential reduction of electron acceptors in the photosynthetic electron transport chain. The O–J phase corresponds to the reduction of QA, the J–I phase to the reduction of plastoquinone and cytochrome b6f, and the I–P phase to the reduction of PSI acceptors (Strasser *et al.,* 2004). Stress conditions such as heat, drought, and nutrient deficiency often induce additional features such as the K-band, which indicates damage to the oxygen-evolving complex (Guha 2013).

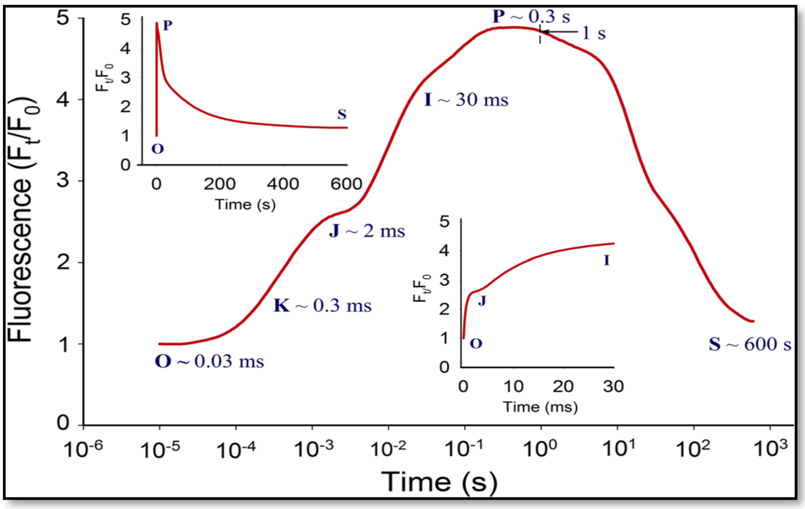


Figure 2: OJIP Fluorescence Induction Curve

PAM Fluorometry and Saturation Pulse Method

Pulse-amplitude-modulated (PAM) fluorometry allows the separation of photochemical and non-photochemical quenching by using weak measuring light and short saturating pulses (Maxwell and Johnson, 2000). Key fluorescence parameters derived from PAM measurements include F_0, F_m, F_v/F_m, ΦPSII, qP, and NPQ, which collectively describe PSII efficiency under dark- and light-adapted conditions.

Chlorophyll Fluorescence Parameters and Their Significance

- **F_0**: Minimal fluorescence (all PSII reaction centers open)
- **F_m**: Maximal fluorescence (all PSII reaction centers closed)
- **F_v/F_m**: Maximum quantum efficiency of PSII
- **ΦPSII ($\Delta F/F_m'$)**: Effective quantum yield under light
- **NPQ**: Non-photochemical quenching
- **PI**: Performance index reflecting overall photosynthetic vitality

A decline in F_v/F_m from the optimal value (~0.83) is widely used as an indicator of photoinhibition and stress (Baker, 2008).

Abiotic Stress and Photosynthetic Vulnerability

Abiotic stress is defined as any non-living environmental factor that restricts plant growth or disrupts normal metabolic functioning. Common abiotic stresses include drought, temperature extremes, salinity, nutrient deficiency, heavy metal toxicity, ozone exposure, and ultraviolet radiation. Although plants have evolved multiple protective and acclimatory mechanisms, severe or prolonged stress can overwhelm these defenses, leading to oxidative damage, photoinhibition, and reduced productivity.

The chloroplast is a primary target of abiotic stress because it is:

1. A major site of light-driven redox reactions
2. A source of reactive oxygen species (ROS)
3. Highly dependent on membrane integrity and enzyme coordination

Under stress, an imbalance arises between the generation of excitation energy and its utilization for photochemistry. Excess excitation energy must be dissipated safely to avoid irreversible damage to PSII. Chlorophyll fluorescence parameters provide quantitative insights into this imbalance and into the efficiency of stress-induced photoprotective responses (Murata *et al.,* 2007).

Chlorophyll Fluorescence Responses to Abiotic Stresses

Heat Stress

Heat stress destabilizes protein–pigment complexes in the thylakoid membrane, particularly affecting PSII due to its thermolabile oxygen-evolving complex (OEC). One of the earliest detectable symptoms of heat stress is an increase in minimal fluorescence (F_o), indicating partial inactivation or disconnection of PSII reaction centers (Allakhverdiev *et al.,* 1997). A concomitant decrease in maximal fluorescence (F_m) reflects impaired charge separation and energy trapping efficiency (Mathur *et al.,* 2014). Fast fluorescence induction curves reveal the appearance of a pronounced K-band at approximately 300 µs, which is widely regarded as a diagnostic feature of heat-induced OEC damage (Strasser *et al.,* 2004; Brestic *et al.,* 2013). Genotypic differences in the temperature threshold for K-band appearance have been exploited for screening heat-tolerant crop varieties (Kalaji *et al.,* 2017; Farhad *et al.,* 2023).

Fluorescence Signatures

Heat stress typically induces:

- An increase in minimal fluorescence (F_o), indicating partial inactivation or disconnection of PSII reaction centers
- A decrease in maximal fluorescence (F_m) due to damage to chlorophyll–protein complexes
- A reduction in F_v/F_m, reflecting photoinhibition
- Appearance of the K-band in OJIP transients, diagnostic of OEC dysfunction

Cold Stress

Low temperature stress restricts enzyme kinetics, slows electron transport, and increases excitation pressure on PSII, particularly when combined with high irradiance. Fluorescence studies demonstrate that cold-sensitive species exhibit a decline in ΦPSII and an increase in NPQ, reflecting enhanced energy dissipation to prevent photodamage (Wei *et al.,* 2022). Cold-tolerant species maintain higher PSII connectivity and show smaller changes in F_v/F_m and PI, indicating efficient photoprotective mechanisms. The JIP-test has proven valuable in distinguishing chilling tolerance based on reaction center density and electron transport probabilities (Zhang *et al.,* 2024).

Fluorescence Signatures

Cold stress results in:

- Decreased ΦPSII (effective quantum yield)
- Reduced electron transport rate (ETR)
- Enhanced non-photochemical quenching as a protective response

Cold-tolerant species or acclimated plants exhibit relatively stable F_v/F_m values and more efficient thermal energy dissipation.

Drought Stress

Drought stress affects photosynthesis in a stepwise manner. Under moderate drought, stomatal closure limits CO_2 availability, whereas severe or prolonged drought results in metabolic impairment and structural damage to the photosynthetic apparatus (Yan *et al.,* 2024). Chlorophyll fluorescence studies show that PSII is relatively resistant to mild water deficit but becomes increasingly affected under severe drought. OJIP analysis frequently reveals the appearance of both L- and K-bands under drought conditions, indicating reduced PSII connectivity and partial OEC inhibition (Guha *et al.,* 2013). The performance index (PI) has emerged as one of the most sensitive parameters for drought screening and correlates strongly with yield performance under water-limited conditions.

Fluorescence Signatures

Chlorophyll fluorescence responses to drought include:

- Decline in ΦPSII and ETR
- Increase in NPQ, reflecting enhanced thermal dissipation
- Reduction in performance index (PI), a highly sensitive indicator of drought stress
- Appearance of L- and K-bands in OJIP curves, indicating altered PSII connectivity and donor-side limitations

Recent evidence demonstrates that drought-tolerant genotypes maintain higher PSII stability and exhibit smaller reductions in PI during stress, supporting the use of fluorescence for drought screening (Chen *et al.,* 2021).

Salinity Stress

Salinity stress combines osmotic stress with ion toxicity, leading to reduced water uptake and disruption of thylakoid membrane organization. Fluorescence parameters typically reveal a reduction in F_v/F_m, ΦPSII, and PI, accompanied by increased NPQ, reflecting enhanced thermal dissipation of excess energy (Mousavi *et al.,* 2022). OJIP transients indicate that salinity stress affects both donor and acceptor sides of PSII, although damage is often more pronounced at the donor side. Chlorophyll fluorescence has also been used to differentiate between osmotic and ionic components of salt stress (Hammami 2024).

Fluorescence Signatures

Under salinity stress:

- F_v/F_m declines due to photoinhibition
- NPQ increases, indicating enhanced energy dissipation
- Electron transport efficiency beyond QA is reduced
- PI decreases sharply under prolonged salinity

Halophytes and salt-tolerant cultivars sustain higher photochemical efficiency by maintaining better ion compartmentalization and antioxidant capacity (Akhter *et al.,* 2021).

Nutrient Deficiency Stress

Nutrient limitations disrupt photosynthetic metabolism by altering pigment composition, enzyme activity, and energy transfer processes. Nitrogen deficiency reduces chlorophyll content and reaction center density, leading to decreased absorption and trapping efficiency (Latifinia and Eisvand 2022). Phosphorus deficiency impairs ATP synthesis and NADPH regeneration, reducing electron transport efficiency and carboxylation capacity (Foyer and Spencer, 1986). Potassium deficiency affects thylakoid pH regulation and enzyme activation, leading to reductions in F_v/F_m and PI. JIP-test parameters provide an integrated view of these nutrient-specific limitations (Chen *et al.,* 2024).

Fluorescence Signatures

Nutrient deficiency causes:

- Decreased chlorophyll content and absorption capacity
- Reduced RC/CS (reaction centers per cross section)
- Lower PI and ΦPSII

Heavy Metal Stress

Heavy metals such as cadmium and lead exert strong inhibitory effects on PSII by disrupting both donor-side and acceptor-side reactions. Cadmium inhibits OEC activity and electron transfer between QA and QB, leading to enhanced NPQ and reduced photochemical efficiency (Hachani *et al.,* 2021). Lead stress induces structural damage to thylakoid membranes, reduces chlorophyll synthesis, and causes characteristic K-band formation in OJIP transients.

Chlorophyll fluorescence parameters therefore serve as sensitive indicators of heavy-metal toxicity before visible symptoms occur.

Fluorescence Signatures

Heavy metal stress leads to:

- Reduced photochemical efficiency
- Increased thermal dissipation
- Lower density of active reaction centers
- Altered OJIP kinetics indicating donor- and acceptor-side inhibition

Recent fluorescence-based studies demonstrate that tolerant plants activate antioxidant and chelation mechanisms, which partially restore PSII efficiency (Qureshi *et al.,* 2024).

Ozone Stress

Tropospheric ozone enters leaves through stomata and generates reactive oxygen species in the apoplast, triggering oxidative damage and premature senescence. Ozone exposure reduces PSII efficiency by decreasing excitation capture and increasing excitation pressure, as indicated by increased F_0 and reduced F_v/F_m (Gao *et al.,* 2022). Fluorescence imaging has revealed spatial heterogeneity in ozone damage, particularly under acute exposure, providing insights into within-leaf variability of stress responses (Gupta *et al.,* 2023).

UV-B Radiation Stress

UV-B radiation directly damages PSII core proteins, especially D1 and D2, leading to impaired electron transport and photoinhibition. Chlorophyll fluorescence studies show that reductions in F_v/F_m and ΦPSII are reliable indicators of UV-B sensitivity, while tolerant genotypes exhibit efficient repair mechanisms (Janeeshma, *et al.,* 2023).

Fluorescence Signatures

Ozone and UV stress cause:

- Reduced F_v/F_m
- Increased F_0, indicating PSII deactivation
- Spatial heterogeneity in fluorescence across leaf surfaces

Chlorophyll fluorescence imaging has been particularly effective in detecting localized ozone and UV damage before visible symptoms appear (Guidi 2019).

Applications of Chlorophyll Fluorescence

- Non-destructive monitoring of photosynthesis
- Early detection of abiotic stress
- Screening stress-tolerant genotypes
- Crop phenotyping and precision agriculture

- Ecosystem and climate change studies

Conclusion:

Chlorophyll fluorescence has proven to be a powerful, sensitive, and non-destructive tool for assessing the functional status of the photosynthetic apparatus under abiotic stress conditions. Because photosynthesis is among the earliest physiological processes affected by environmental constraints, changes in fluorescence parameters provide early and reliable indicators of stress-induced damage, often before visible symptoms appear. The close relationship between fluorescence emission, photochemical efficiency, and heat dissipation enables detailed insights into energy partitioning within Photosystem II. Different abiotic stresses, including heat, cold, drought, salinity, nutrient deficiency, heavy metal toxicity, ozone, and ultraviolet radiation, affect photosynthesis through distinct mechanisms; however, they ultimately disrupt electron transport and energy balance in the chloroplast. These disruptions are reflected in characteristic changes in fluorescence parameters such as F_0, F_m, F_v/F_m, ΦPSII, non-photochemical quenching, and performance index. Analysis of fluorescence induction kinetics, particularly OJIP transients, further enhances the ability to diagnose stress-specific damage to the photosynthetic machinery.

Beyond its diagnostic value, chlorophyll fluorescence has significant applications in plant breeding, stress physiology, and crop management. The technique enables rapid screening of stress tolerance, supports high-throughput phenotyping, and contributes to improved understanding of plant acclimation and adaptation strategies. When integrated with complementary physiological and biochemical measurements, chlorophyll fluorescence offers a comprehensive framework for evaluating plant performance under adverse environments. Overall, its versatility and scalability make chlorophyll fluorescence an indispensable approach for advancing sustainable agriculture and plant resilience under changing climatic conditions.

References:

1. Baker, N. R. (2008). Chlorophyll fluorescence: a probe of photosynthesis in vivo. *Annu. Rev. Plant Biol.*, *59*, 89-113.
2. Maxwell, K., & Johnson, G. N. (2000). Practical guide to fluorescence. Journal of Experimental Botany, 51, 659–668.
3. Krause, G. H., & Weis, E. (1991). Chlorophyll fluorescence and photosynthesis. Annual Review of Plant Physiology, 42, 313–349.
4. Lichtenthaler, H. K., & Schweiger, J. (1998). Cell wall bound ferulic acid, the major substance of the blue-green fluorescence emission of plants. Journal of Plant Physiology, 152(2-3), 272-282.

5. Brestic, M., & Zivcak, M. (2013). PSII fluorescence techniques for measurement of drought and high temperature stress signal in crop plants: protocols and applications. In Molecular stress physiology of plants (pp. 87-131). India: Springer India.
6. McCree, K. J. (1971). The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. *Agricultural Meteorology*, *9*, 191-216.
7. Porcar-Castell, A., *et al.* (2014). Fluorescence review. *New Phytologist, 201*, 1–20.
8. Kalaji, H. M., Jajoo, A., Oukarroum, A., Brestic, M., Zivcak, M., Samborska, I. A., ... & Ladle, R. J. (2016). Chlorophyll a fluorescence as a tool to monitor physiological status of plants under abiotic stress conditions. *Acta physiologiae plantarum*, *38*(4), 102.
9. Kautsky, H., & Hirsch, A. (1931). Fluorescence of chlorophyll. *Naturwissenschaften, 19*, 964.
10. Rohacek, K., Soukupova, J., & Bartak, M. (2008). Chlorophyll fluorescence: a wonderful tool to study plant physiology and plant stress. *Plant Cell Compartments-Selected Topics. Research Signpost, Kerala, India*, *41*, 104.
11. Strasser, R. J., Tsimilli-Michael, M., & Srivastava, A. (2004). Analysis of the chlorophyll a fluorescence transient. In Chlorophyll a fluorescence: a signature of photosynthesis (pp. 321-362). Dordrecht: Springer Netherlands.
12. Guha, (2013). K-band as drought indicator. *Plant Physiology and Biochemistry, 69*, 204–210.
13. Murata, N., Takahashi, S., Nishiyama, Y., & Allakhverdiev, S. I. (2007). Photoinhibition of photosystem II under environmental stress. *Biochimica et Biophysica Acta (BBA)-Bioenergetics*, *1767*(6), 414-421.
14. Allakhverdiev, S. I., Kreslavski, V. D., Fomina, I. R., Los, D. A., Klimov, V. V., Mimuro, M., ... & Carpentier, R. (2012). Inactivation and repair of photosynthetic machinery under heat stress. *Photosynthesis: overviews on recent progress and future perspective. IK International Publishing House Pvt. Ltd., New Delhi*, 189.
15. Mathur, S., Agrawal, D., & Jajoo, A. (2014). Photosynthesis: response to high temperature stress. *Journal of photochemistry and photobiology B: Biology*, *137*, 116-126.
16. Brestic, M., Zivcak, M., Olsovska, K., Kalaji, H. M., Shao, H., & Hakeem, K. R. (2013). Heat signaling and stress responses in photosynthesis. In *Plant signaling: Understanding the molecular crosstalk* (pp. 241-256). New Delhi: Springer India.
17. Kalaji, M. H., Goltsev, V. N., Żuk-Gołaszewska, K., Zivcak, M., & Brestic, M. (2017). *Chlorophyll fluorescence: understanding crop performance—basics and applications*. CRC Press.

18. Farhad, M., Kumar, U., Tomar, V., Bhati, P. K., Krishnan J, N., Barek, V., ... & Hossain, A. (2023). Heat stress in wheat: a global challenge to feed billions in the current era of the changing climate. *Frontiers in Sustainable Food Systems*, *7*, 1203721.
19. Wei, Y., Chen, H., Wang, L., Zhao, Q., Wang, D., & Zhang, T. (2022). Cold acclimation alleviates cold stress-induced PSII inhibition and oxidative damage in tobacco leaves. *Plant Signaling & Behavior*, *17*(1), 2013638.
20. Zhang, J., Tang, C., Xie, J., Li, J., Zhang, X., & Wang, C. (2024). Exogenous strigolactones alleviate low-temperature stress in peppers seedlings by reducing the degree of photoinhibition. *BMC Plant Biology*, *24*(1), 907.
21. Yan, W., Lu, Y., Guo, L., Liu, Y., Li, M., Zhang, B., ... & Huo, J. (2024). Effects of drought stress on photosynthesis and chlorophyll fluorescence in blue honeysuckle. *Plants*, *13*(15), 2115.
22. Chen, J., Liu, X., Du, S., Ma, Y., & Liu, L. (2021). Effects of drought on the relationship between photosynthesis and chlorophyll fluorescence for maize. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *14*, 11148-11161.
23. Mousavi, S. S., Karami, A., & Maggi, F. (2022). Photosynthesis and chlorophyll fluorescence of Iranian licorice (*Glycyrrhiza glabra* L.) accessions under salinity stress. *Frontiers in Plant Science*, *13*, 984944.
24. Akhter, M. S., Noreen, S., Mahmood, S., Athar, H. U. R., Ashraf, M., Alsahli, A. A., & Ahmad, P. (2021). Influence of salinity stress on PSII in barley (*Hordeum vulgare* L.) genotypes, probed by chlorophyll-a fluorescence. *Journal of King Saud University-Science*, *33*(1), 101239.
25. Latifinia, E., & Eisvand, H. R. (2022). Soybean physiological properties and grain quality responses to nutrients, and predicting nutrient deficiency using chlorophyll fluorescence. *Journal of Soil Science and Plant Nutrition*, *22*(2), 1942-1954.
26. Chen, L. H., Xu, M., Cheng, Z., & Yang, L. T. (2024). Effects of nitrogen deficiency on the photosynthesis, chlorophyll a fluorescence, antioxidant system, and sulfur compounds in Oryza sativa. *International Journal of Molecular Sciences*, *25*(19), 10409.
27. Hachani, C., Lamhamedi, M. S., Zine El Abidine, A., Abassi, M., Khasa, D. P., & Béjaoui, Z. (2021). Water relations, gas exchange, chlorophyll fluorescence and electrolyte leakage of ectomycorrhizal *Pinus halepensis* seedlings in response to multi-heavy metal stresses (Pb, Zn, Cd). *Microorganisms*, *10*(1), 57.
28. Abdullaev, F., Pirogova, P., Vodeneev, V., & Sherstneva, O. (2024). Chlorophyll fluorescence in wheat breeding for heat and drought tolerance. *Plants*, *13*(19), 2778.

29. Gao, Y., Liu, Y., Chen, B., Tao, Y., Cui, C., Wen, Y., ... & Yuan, X. (2022). Response of fluorescence and chlorophyll physiological characteristics of typical urban trees to ozone stress. *Atmosphere*, *13*(11), 1885.
30. Gupta, A., Yadav, D. S., Agrawal, S. B., & Agrawal, M. (2023). Individual effects of high temperature and tropospheric ozone on tomato: a review. *Journal of Plant Growth Regulation*, *42*(3), 1421-1443.
31. Moustaka, J., & Moustakas, M. (2023). Early-stage detection of biotic and abiotic stress on plants by chlorophyll fluorescence imaging analysis. Biosensors, 13(8), 796.
32. Janeeshma, E., Johnson, R., Amritha, M. S., Noble, L., Aswathi, K. R., Telesiński, A., ... & Puthur, J. T. (2022). Modulations in chlorophyll a fluorescence based on intensity and spectral variations of light. *International Journal of Molecular Sciences*, *23*(10), 5599.
33. Guidi, L. (2019). Chlorophyll fluorescence imaging under ozone stress. *Environmental Pollution, 249*, 996–1005.
34. Hammami, Z. (2024). Salinity tolerance assessment using chlorophyll fluorescence. *Frontiers in Plant Science, 15*, 1324388.

ZINC NANOSENSORS IN PRECISION AGRICULTURE AND SOIL MONITORING

Priya Sharma[1] and Gharsiram*[2]

[1]Department of Agronomy, Junagadh Agricultural University, Junagadh (Gujarat) – 362001

[2]LSRC College of Agriculture Mandawa, Jhunjhunu, SKRAU, Bikaner 333001

*Corresponding author E-mail: loona161@gmail.com

Abstract:

The rapid advancement of nanotechnology has created new opportunities in precision agriculture, particularly in soil health monitoring and crop management. Zinc-based nanosensors have emerged as viable technologies due to their distinct physicochemical features, biocompatibility, and low cost. This chapter investigates the construction, mechanisms, applications, benefits, and problems of zinc nanosensors in precision agriculture, with a focus on their usage for real-time soil monitoring and nutrient management. Applications extend to monitoring fertilizers, herbicides, early disease diagnosis and heavy metal stress mitigation, while promoting sustainable farming through efficient resource use and reduced environmental impact.

Keywords: Nanotechnology, Zinc Nanosensors, Precision Agriculture, Soil Health Monitoring, Sustainable Farming

Introduction:

Agriculture has entered a new era, characterized by data-driven, accurate, and highly efficient processes. This change, also known as precision agriculture, focusses on optimizing crop management at the field level by employing modern technologies to monitor, observe, and respond to both inter- and intra-field variability. Precision agriculture increases crop yields, conserves resources, and promotes environmental sustainability by adjusting agricultural operations to the unique needs of different areas within a field.

Soil health monitoring is a vital component of this method. Assessing and monitoring soil health and quality is critical for making educated decisions about agricultural management, environmental protection, and land use planning (Bai *et al.,* 2018). Traditional soil testing procedures, on the other hand, are generally time-consuming, labour-intensive, and do not provide the resolution required for precision farming. Furthermore, the geographical and temporal variability of soil parameters makes it difficult to collect representative samples and track soil health in real time (Rodrigo-Comino, 2018).

In this context, nanotechnology has emerged as a game changer, enabling a new generation of agricultural sensors and diagnostic gadgets. Zinc-based nanosensors have received a lot of attention because of their unique qualities, such as high sensitivity, selectivity, environmental compatibility, and low cost. These nanosensors provide remarkable precision in real-time monitoring of soil characteristics, allowing farmers to make prompt and targeted interventions. As a result, zinc nanosensors are becoming increasingly important in modern precision agriculture tactics that aim to boost productivity while maintaining environmental stewardship.

Nanosensors

A sensor is a tool that helps determine the signal obtained from a stimuli, vibration, heat, or motion in the environment and sends the information back to the computer processor for processing. These are the gadgets used extensively in daily life; one such example is a tactile sensor that is sensitive to touch, such as lift buttons, or lamps or lights that are turned on and off by sensing the touch (Denizli*et al.,* 2022).

A nanosensor is a sensor that is built in nanoscale dimensions with the primary goal of producing data on an atomic level and transmitting data that can be easily analysed. Nanosensors have several advantages, including a compact size that requires less power to operate, great sensitivity, and better specificity than current sensors (Lim and Ramakrishnan, 2006).

Nanosensors are of varies types –

1. Metallic Nanoparticles (NPs)
2. Magnetic
3. Quantum dots
4. Graphene
5. Carbon Nanotubes
6. Nanocomposites

Nanosensors enable real-time sensing techniques, are cost-effective, and have a very short response time, making them superior to traditional techniques like as chromatography and spectroscopy. Nanosensors can aid precision farming by delivering critical information regarding required data, allowing farmers to save resources and increase productivity (Panpatte*et al.,* 2016). Nanosensors aid in delivering information on the best time for each phase of agriculture, such as watering plants, applying pesticides, and harvesting crops, based on the physiological conditions of the soil and climate of a given area. They can aid in the treatment of plant disease before symptoms develop on the plant, hence promoting crop health.

They also treat the illness in a specific location rather than the entire plant, allowing us to use only the necessaryamount of pesticides/insecticides, eliminating residual pesticides while keeping the plant healthy. Nanosensors are also effective for assessing soil water tension and can be used in conjunction with an autonomous irrigation controller. This helps us manage irrigation based on soil moisture. Otherwise, farmers will have difficulty managing their irrigation systems.

Structure of Nanosensor

Nanosensors are advanced devices that detect and respond to physical and chemical changes on the nanoscale. Their construction consists of a sensing element, a transducer, and a readout mechanism, all of which play an important role in the sensor's operation. The sensing element is frequently built of nanomaterials, such as carbon nanotubes, nanoparticles, or nanowires, which have a large surface area and unique features at the nanoscale, increasing sensitivity and selectivity. These materials can interact with certain analytes, such as gases, chemicals, or biomolecules, causing observable changes in electrical, optical, or thermal properties.

The transducer turns these changes into a readable signal, which may be electrical, optical, or mechanical, depending on the application. The combination of nanomaterials and microfabrication processes enables the miniaturization of the entire sensor structure, resulting in tiny, portable devices. This miniaturization not only enables real-time monitoring of ambient conditions, biological systems, and chemical processes, but it also expands the possibilities for integration into a wide range of applications, from healthcare diagnostics to environmental monitoring (Liyakat&Liyakat, 2024).

Zinc Nanoparticles-Based Sensors

Metal NPs (MNPs) are considered to be a significant class of nanomaterial due to their facile synthesis, large surface area, high catalytic activity, and selectivity (Wang and Gu, 2015) and cost effectiveness also.

Zinc is classified as a semiconductor material with a wide bandgap (3 eV) and also as a piezoelectric material (Chaari and Matoussi, 2017). Zinc nanostructures and oxides are recognized as good materials due to their unique features, which include great thermal, chemical, physical, and photochemical stability as well as high biocompatibility. It also has optical transmittance, ease of synthesis, strong analytical performance, and outstanding sensitivity, as well as significant stability at physiological pH (Kołodziejczak-Radzimska, T. Jesionowski., 2014; Wang, 2004). In addition to these qualities, zinc nanoparticles (ZnNPs) have good electrocatalytic behaviour, with effective electron transport, a large electrochemical coupling constant, and radiation absorption properties, making them a versatile material (Mahmud *et al.,* 2017; Makino *et al.,* 2005).

Recent Developments in Zinc Nanosensors

1. Detection of Residual Fertilizers

Chemical fertilizers have grown increasingly important in recent years due to a 100-fold increase in global demand over the previous 50 years, with use of chemical fertilizers 30% to 50% higher than that of natural fertilizers (Khan and Hanjra, 2009;Galloway *et al.,* 2008). However, because to its rapid adoption, it has serious environmental consequences, including water pollution, soil contamination, ozone layer depletion, the introduction of poisons into food products, and the greenhouse effect (Riva *et al.,* 2016). As a result, monitoring and enhancing its utilization are becoming increasingly important in agriculture. Researchers have developed ammonia and urea sensors based on ZnO NP and Pt-coated Al-doped ZnO NP.

To detect urea, ZnO was adsorbed on an electrospun nanofiber of polyamide 6 (PA6) and polypyrrole (PPy) and then placed on FTO (Migliorini *et al.,* 2018). The nanofiber matrix demonstrated good urease enzyme immobilization, with great selectivity against urea and a detection limit of 0.011 mg/dL. On the other hand, the effect of doping on ZnO NP was investigated (Chen *et al.,* 2018). Pt nanoparticles were deposited onto the Al-doped-ZnO layer to improve ammonia sensing. The result of Pt was seen, and the detected ammonia level was 1 ppm NH_3/air. The device responded quickly in 24 seconds, followed by a recovery time of 4 seconds.

2. Nutrient Monitoring

Zinc nanosensors have emerged as promising tools for real-time and precise monitoring of soil nutrients, a critical component of sustainable and efficient precision agriculture. Among the various nutrients, macronutrients like nitrogen (N), phosphorus (P) and potassium (K), are of particular interest, alongside micronutrients such as zinc (Zn) itself, whose deficiency can significantly limit crop productivity.

Zinc oxide (ZnO) nanoparticles, especially when combined with multi-walled carbon nanotubes (MWCNTs), have been utilized to create impedance-based sensors capable of detecting soil potassium levels. These sensors exhibit a linear impedance response to potassium concentrations ranging from 5 to 25 mM, with a high correlation coefficient (R^2 = 0.957), facilitating real-time soil nutrient monitoring (Kumar *et al.,* 2021). Zinc nanoparticles significantly influence soil biochemical processes by enhancing enzymatic activities such as urease and phosphatase, which are key indicators of soil nutrient status. The improved microbial activity facilitates nutrient mineralization and availability (Raliya and Tarafdar, 2013). Metal oxide nanoparticle-based sensors, such as ZnO and SnO_2, have been used for detecting potassium ions (K^+), with a detection range of 0.1 to 100 mM (Huang *et al.,* 2019).

The combination of zinc-based nanosensors with artificial intelligence (AI) has led to the development of mobile soil analysis systems. These systems utilize colorimetric paper sensors and AI algorithms to provide real-time, on-the-spot soil nutrient analysis, enhancing decision-making in precision agriculture (da Silva *et al.,* 2022).

3. Heavy Metal Stress Mitigation

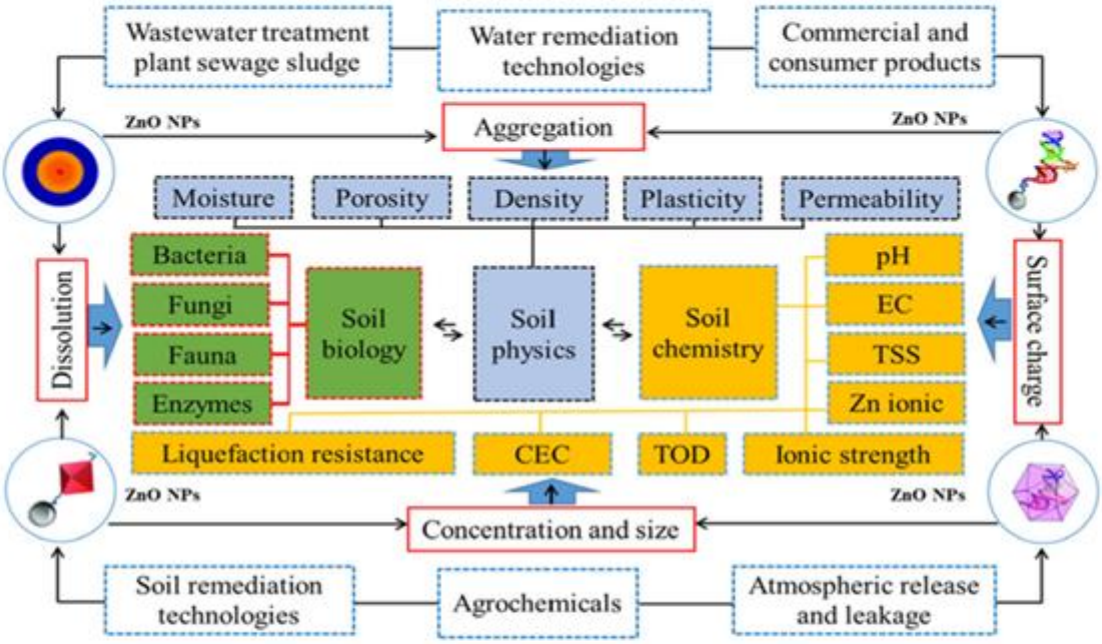


Figure 1: Schematic diagram summarizing the pathways that controlling the transport of the ZnO NPs into the soil. Also, the behavior of the ZnO NPs in soil including aggregation, dissolution, and stability. Moreover, the potential impact of ZnO NPs on the physio-chemical and biological properties of soil. CEC, TSS, EC, and TOD denote cation exchange capacity, total soluble salts, electrical conductivity, and total oxidant demand (Source: Sheteiwy*et al.,* 2021)

Studies have shown that biosynthesized ZnO NPs can mitigate arsenic stress in crops like mungbean by enhancing antioxidant enzyme activities and reducing arsenic accumulation (Rani *et al.,* 2023). A study demonstrated that ZnO NPs alleviated oxidative stress in *Leucaena leucocephala* seedlings exposed to cadmium (Cd) and lead (Pb). The treatment enhanced photosynthetic pigments and antioxidant enzyme activities while reducing lipid peroxidation, indicating improved plant health under heavy metal stress (Venkatachalam *et al.,* 2017). Research on rice (*Oryza sativa* L.) revealed that combining ZnO NPs with beneficial bacteria (*Bacillus cereus* and *Lysinibacillusmacroides*) reduced the uptake of heavy metals like Pb and

Cu. This synergistic approach enhanced plant growth and decreased heavy metal accumulation in plant tissues (Akhtar *et al.,* 2021). Foliar application of ZnO NPs in wheat under cadmium stress conditions improved plant growth, photosynthesis, and grain yield. The treatment also reduced cadmium accumulation in grains, highlighting the potential of ZnO NPs in enhancing crop productivity under heavy metal stress (Zhou *et al.,* 2021).

Application of ZnO NPs in rice cultivation decreased arsenic accumulation in shoots and roots. The treatment not only mitigated arsenic toxicity but also promoted plant growth, suggesting ZnO NPs as a viable strategy for managing arsenic-contaminated soils (Yan *et al.,* 2021).

4. Soil pH and Salinity Sensing

Application of ZnO NPs has been observed to influence soil pH levels. In a study, ZnO NPs increased soil pH, especially when combined with rice-straw-derived biochar, indicating their potential in managing soil acidity (Shemawar*et al.,* 2021).ZnO NPs have been effective in mitigating salt stress in tomato plants by promoting mineral uptake, enhancing chlorophyll content, and reducing oxidative stress markers, thus improving plant resilience in saline soils (Ahmed *et al.,* 2024). High concentrations of ZnO NPs altered soil properties by increasing pH and decreasing redox potential, which can affect nutrient cycles and microbial communities, emphasizing the importance of monitoring application levels (Zhang *et al.,* 2024).

Table 1: Examples of Zn nanoparticles-based sensors for soil monitoring (Parameswari *et al.,* 2024)

Sensor type	Nanomaterial used	Working Principle
Conductometric sensors	Zinc Oxide Nanorods	Change in conductivity of ZnO nanorods upon interaction with nitrate and ammonium ions
Conductometric sensors	Zinc Oxide Nanorods	Change in conductivity of ZnO nanorods in response to pH
Electrochemical sensor	Metal oxide Nanoparticles (*e.g.*, SnO_2, ZnO)	Redox reactions at the electrode-electrolyte interface upon interaction with CO_2, CH_4 and N_2O for greenhouse gas sensing in soil.
Surface Acoustic Wave sensor	Zinc oxide nanorods	Change in acoustic wave propagation due to gas adsorption (*e.g.*, CO_2, CH_4 and N_2O) for greenhouse gas sensing in soil.

5. Plant Disease Diagnosis

Plant pathogenic illnesses or diseases can be discovered using a variety of imaging, spectroscopy, and conjugate imaging and spectroscopy methods (Li *et al.,* 2020). Most likely, the role of diagnostic techniques is to achieve rapid, early, sensitive, simple, in situ, reliable, and automated high throughput identification and quantification of the causative agent, allowing the extent of virulence to be determined before the disease's actual visual symptoms appear (Khiyami*et al.,* 2014). Nanomaterial-based sensor technologies offer adaptable and diversified sensing platforms or methodologies for elucidating/quantifying single or many analytes (Giraldo *et al.,* 2019) and can aid in the early, quick, and sensitive detection of plant pathogens (Kumar and Arora, 2020). In response to a pathogen attack, the plant produces a wide range of signal molecules. Few abundant and signature signal molecules, such as specific enzymes, gaseous molecules (*e.g.,* nitrous oxide, volatile organic compounds), reactive oxygen species, secretory compounds such as oxylipins, and the expression of a critical gene (pathogenesis-related proteins-PRPs, PAMPs), can be effectively used as key biomarkers for the development of nanobiosensor platforms (Li *et al.,* 2020).

Early and sensitive detection (detection limit of 25 μg mL^{-1}) of plant pathogenic *Fusarium oxysporum* has been reported through the use of 3-Mercaptopropionicacid-functionalized CdSe/ZnS QD in a fluorescence-based assay (Rispail*et al.,* 2014). Khansili*et al.* (2020) created a colorimetric sensor utilising a composite of curcumin and ZnO NPs to detect aflatoxin B1. The sensor showed a colour change from red to yellow and had a detection limit of 11 μg/kg, which was validated by HPLC data. Zinc-derived nanomaterials (nanoparticles/composites) at low working concentrations can kill spores or inhibit spore germination (sporostatic/sporicidal activities), as well as inhibit the vegetative mycelial growth of filamentous fungal plant pathogens. For example, treatment with ZnO NPs (3 mM L^{-1}) resulted in a significant decrease in fungal growth of *B. cinerea* and *P. expansum* (He *et al.,* 2011). *Peronospora tabacina* spore germination was totally suppressed by Zn NPs, ZnO NPs, and $ZnCl_2$ soluble salt at doses of 15-20 mg L^{-1}(Wagner *et al.,* 2016). A comparable electrochemical DNA biosensor involving ZnO nanoparticles-chitosan membrane-doped gold electrode was developed to conveniently identify *Trichoderma harzianum* biocontrol fungus (Siddiquee*et al.,* 2014)

6. Soil Moisture and Humidity

The microsensor was tested at humidity levels ranging from 40% to 90%, as well as with varying moisture contents of bentonite and red soil. The sensor has been proved to be highly stable, give repeatable data, and respond quickly (Patil *et al.,* 2017). Another group created a sensor utilising SWCNT/ZnO NP and chitosan composite. Because of its swelling effect, chitosan contributed to improving the composite's moisture resistance. The gadget demonstrated high reversibility and yielded good results (Dai *et al.,* 2019).

Plant growth status changes can be monitored using a multimodal flexible sensor system that use stacked $ZnIn_2S_4$ (ZIS) nanosheets as the sensing medium. A flexible sensor based on zinc oxide thin semiconductor (ZIS) was used to measure light and humidity levels near the leaves or in the area where plant transpiration occurs. Plant dehydration can be measured by examining the opening and shutting of their stomata, which signal relative humidity levels (Lu *et al.,* 2020).

7. Herbicides Sensing

The electrochemical sensor for molinate herbicide was investigated by fabricating a sensor based on the carbon paste incorporated with ZnO NP. The device demonstrated exceptional results such as voltammetric response compared to the nascent electrode, better sensitivity, and selectivity (Shetti*et al.,* 2019).

8. Pesticides Sensing

ZnO NPs have demonstrated significant insecticidal effects against the fall armyworm, *Spodoptera frugiperda*. Exposure led to increased mortality, developmental deformities, reduced oviposition, and decreased egg hatchability, indicating their potential as an eco-friendly alternative to conventional pesticides (Pittarate*et al.,* 2021). Combining ZnO NPs with neonicotinoid pesticides like thiamethoxam enhanced insecticidal efficacy against pests such as *Spodoptera litura* and *Aphis gossypii*. This synergy resulted in higher mortality rates and allowed for reduced pesticide dosages (Elmasry, 2021).ZnO NPs improved the effectiveness of thiamethoxam by inducing oxidative stress in pests, leading to increased mortality, developmental delays, and reduced reproductive capacity in *Spodoptera litura*(Jameel *et al.,* 2020).

Potential Challenges and Future Prospects

Even while high-performance nanosensors exhibit encouraging developments, there are still obstacles to overcome before they may be actively incorporated into the agricultural industry. In real-world situations where weather variables could impact sensing ability, nanosensors have not yet been evaluated. Nanosensor manufacturers must work closely with regulatory bodies to assess on-site sensor performance in a variety of unique situations, especially with regard to safety protocols. Actually, for a safe and sustainable agriculture, the inherent safety concerns with the use of nanosensors with crops need to be carefully addressed. To confirm the impacts of the use and disposal of nanomaterials on ecosystems, analytical techniques must be created. For real-time in-vivo research, more work is still needed to create light, wearable, and flexible nanosensors with smooth integrated contacts with living plants. The potential of useful applications in concurrently monitoring multiple plant growth parameters will be presented by the new design and miniaturization of the multi-sensing platform (Tong *et al.,* 2023).

Conclusion:

Zinc-based nanosensors represent a significant advancement in the field of precision agriculture and soil monitoring. Their unique physicochemical properties—such as high surface area, photostability, and biocompatibility—enable efficient detection of key soil parameters, including nutrient levels, pH, moisture, and salinity. These nanosensors provide real-time, accurate data that can be used to make informed decisions regarding fertilizer application, irrigation scheduling, and overall crop management. Such precision reduces resource waste, enhances crop yields, and minimizes environmental degradation.

In addition to monitoring soil health, zinc nanoparticles also exhibit antimicrobial and stress-mitigating properties that contribute to improved plant resilience under biotic and abiotic stress conditions. Their integration into smart sensing platforms enables continuous field-level diagnostics, supporting sustainable farming practices. The use of biosynthesized zinc oxide nanoparticles further aligns with eco-friendly approaches, reducing dependence on synthetic chemicals.

However, challenges remain regarding the environmental fate, long-term toxicity, and regulatory frameworks surrounding nanotechnology in agriculture. Future research should focus on optimizing sensor design, ensuring safety, and promoting scalable deployment for field applications. Overall, zinc nanosensors offer a transformative tool for advancing precision agriculture, supporting global food security, and promoting environmentally sustainable farming systems. Their continued development holds great promise for modernizing agricultural practices in the era of climate change.

References:

1. Ahmed, M., Marrez, D. A., Rizk, R., Zedan, M., Hamid, D. A., Decsi, K., Kovacs, G. P., & Toth, Z. (2024). The influence of zinc oxide nanoparticles and salt stress on the morphological and some biochemical characteristics of *Solanum lycopersicum* L. plants. *Plants, 13*(10), 1418.
2. Akhtar, N., Khan, S., Rehman, S. U., Rehman, Z. U., Khatoon, A., Rha, E. S., & Jamil, M. (2021). Synergistic effects of zinc oxide nanoparticles and bacteria reduce heavy metals toxicity in rice (*Oryza sativa* L.). *Plant Toxics, 9*(5), 113.

3. Akshay Kumar, A., Naveen Kumar, S. K., Aniley, A. A., Fernandez, R. E., & Bhansali, S. (2019). Hydrothermal growth of zinc oxide (ZnO) nanorods on screen-printed IDEs for pH measurement application. *Journal of The Electrochemical Society, 166*, B3264.
4. Bai, Z., Caspari, T., Gonzalez, M. R., Batjes, N. H., Mäder, P., Bünemann, E. K., De Goede, R., Brussaard, L., Xu, M., Ferreira, C. S. S., & Reintam, E. (2018). Effects of agricultural management practices on soil quality: A review of long-term experiments for Europe and China. *Agriculture, Ecosystems & Environment, 265*, 1–7.
5. Chaari, M., & Matoussi, A. (2017). Electrical conduction and dielectric studies of ZnO pellets. *Physica B, 407*, 3441–3447.
6. Chen, H. I., Chi, C. Y., Chen, W. C., Liu, I. P., Chang, C. H., Chou, T. C., et al. (2018). Ammonia sensing characteristic of a Pt nanoparticle/aluminum-doped zinc oxide sensor. *Sensors and Actuators B: Chemical, 267*, 145–154.
7. da Silva, A. F., Ohta, R. L., Azpiroz, J. T., Fereira, M. E., Marçal, D. V., Botelho, A., Coppola, T., et al. (2022). Artificial intelligence enables mobile soil analysis for sustainable agriculture. *Applied Physics*, 1–35.
8. Dai, H., Feng, N., Li, J., Zhang, J., & Li, W. (2019). Chemiresistive humidity sensor based on chitosan/zinc oxide/single-walled carbon nanotube composite film. *Sensors and Actuators B: Chemical, 283*, 786–792.
9. Denizli, A., Nguyen, T. A., Rajendran, S., Yasin, G., & Nadda, A. K. (2022). *Nanosensors for smart agriculture*. Elsevier.
10. Elmasry, N. S. (2021). Efficacy of zinc oxide nanoparticle adding to two neonicotinoids pesticides against *Spodoptera litura* and *Aphis gossypii*. *Egyptian Academic Journal of Biological Sciences, 13*(1), 209–215.
11. Fraceto, L. F., Grillo, R., de Medeiros, G. A., Scognamiglio, V., Rea, G., & Bartolucci, C. (2016). Nanotechnology in agriculture: Which innovation potential does it have? *Frontiers in Environmental Science, 4*, 20.
12. Galloway, J. N., Townsend, A. R., Erisman, J. W., Bekunda, M., Cai, Z., Freney, J. R., et al. (2008). Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science, 320*, 889–892.
13. Giraldo, J. P., Wu, H., Newkirk, G. M., & Kruss, S. (2019). Nanobiotechnology approaches for engineering smart plant sensors. *Nature Nanotechnology, 14*, 541–553.
14. He, L., Liu, Y., Mustapha, A., & Lin, M. (2011). Antifungal activity of zinc oxide nanoparticles against *Botrytis cinerea* and *Penicillium expansum*. *Microbiological Research, 166*, 207–215.

15. Huang, X., Dong, F., Xiang, D., Zhang, X., & Zhang, L. (2019). Ultrasensitive and selective nonenzymatic glucose detection based on Au@Pt core-shell nanoparticles decorated graphene. *Sensors and Actuators B: Chemical, 279*, 227–233.
16. Jameel, M., Shoeb, M., Khan, M. T., Ullah, R., Mobin, M., Farooqi, M. K., & Adnan, S. Y. (2020). Enhanced insecticidal activity of thiamethoxam by zinc oxide nanoparticles: A novel nanotechnology approach for pest control. *ACS Omega, 5*(3), 1607–1615.
17. Khan, S., & Hanjra, M. A. (2009). Footprints of water and energy inputs in food production: Global perspectives. *Food Policy, 34*, 130–140.
18. Khansili, N., Rattu, G., Kumar, A., & Krishna, P. M. (2020). Development of colorimetric sensor with zinc oxide nanoparticles for rapid detection of aflatoxin B1 in rice. *Materials Today: Proceedings, 21*, 1846–1855.
19. Khiyami, M. A., Almoammar, H., Awad, Y. M., & Alghuthaymi, M. A. (2014). Plant pathogen nanodiagnostic techniques: Forthcoming changes. *Biotechnology Equipment, 28*, 775–785.
20. Kołodziejczak-Radzimska, T., & Jesionowski, T. (2014). Zinc oxide—from synthesis to application: A review. *Materials, 7*, 2833–2881.
21. Kumar, A. A., Kumar, S. K. N., & Fernandez, R. E. (2021). Real-time sensing of soil potassium levels using zinc oxide–multiwall carbon nanotube-based sensors. *IEEE Transactions on Nanobioscience, 20*(1), 50–56.
22. Kumar, V., & Arora, K. (2020). Trends in nano-inspired biosensors for plants. *Materials Science for Energy Technologies, 3*, 255–273.
23. Li, Z., Yu, T., Paul, R., Fan, J., Yang, Y., & Wei, Q. (2020). Agricultural nanodiagnostics for plant diseases: Recent advances and challenges. *Nanoscale Advances*.
24. Lim, T.-C., & Ramakrishna, S. (2006). A conceptual review of nanosensors. *Zeitschrift für Naturforschung A, 61*, 402–412.
25. Liyakat, K. S. S., & Liyakat, K. K. S. (2024). Nanosensors in agriculture field: A study. *International Journal of Applied Nanotechnology, 10*(2), 12–22.
26. Lu, Y., Xu, K., Zhang, L., Deguchi, M., Shishido, H., Arie, T., Pan, R., Hayashi, A., Shen, L., Akita, S., & Takei, K. (2020). Multimodal plant healthcare flexible sensor system. *ACS Nano, 14*(9), 10966–10975.
27. Mahmud, M. A., Elumalai, N. K., Upama, M. B., Wang, D., Chan, K. H., Wright, M., et al. (2017). Low-temperature processed ZnO thin film as electron transport layer for efficient perovskite solar cells. *Solar Energy Materials and Solar Cells, 159*, 251–264.

28. Makino, T., Segawa, Y., Tsukazaki, A., Ohtomo, A., & Kawasaki, M. (2005). Electron transport in ZnO thin films. *Applied Physics Letters, 87*, 022101.
29. Migliorini, F. L., Sanfelice, R. C., Mercante, L. A., Andre, R. S., Mattoso, L. H. C., & Correa, D. S. (2018). Urea impedimetric biosensing using electrospun nanofibers modified with zinc oxide nanoparticles. *Applied Surface Science, 443*, 18–23.
30. Panpatte, D. G., Jhala, Y. K., Shelat, H. N., & Vyas, R. V. (2016). Nanoparticles: The next generation technology for sustainable agriculture. In *Microbial inoculants in sustainable agricultural productivity* (pp. 289–300).
31. Parameswari, P., Belagalla, N., Singh, B. V., Abhishek, G. J., Rajesh, G. M., Katiyar, D., Hazarika, B., & Paul, S. (2024). Nanotechnology-based sensors for real-time monitoring and assessment of soil health and quality: A review. *Asian Journal of Soil Science and Plant Nutrition, 10*(2), 157–173.
32. Patil, S., Ramgir, N., Mukherji, S., & Rao, V. R. (2017). A modified ZnO nanowire-based microsensors platform for relative humidity and soil moisture measurement. *Sensors and Actuators B: Chemical, 253*, 1071–1078.
33. Pittarate, S., Rajula, J., Rahman, A., Perumal, V., Thunrabeab, M., Mekchay, S., & Krutmuang, P. (2021). Insecticidal effect of zinc oxide nanoparticles against *Spodoptera frugiperda* under laboratory conditions. *Insects, 12*(11), 1017.
34. Raliya, R., & Tarafdar, J. C. (2013). ZnO nanoparticle biosynthesis and its effect on phosphorus-mobilizing enzyme secretion and gum contents in clusterbean (*Cyamopsis tetragonoloba* L.). *Agricultural Research, 2*, 48–57.
35. Rani, S., Kumari, N., & Sharma, V. (2023). Biosynthesized zinc oxide nanoparticles as a novel nanofertilizer influence growth, yield, antioxidant enzymes, and arsenic accumulation in mungbean under arsenic stress. *Journal of Soil Science and Plant Nutrition, 23*, 2360–2380.
36. Rispail, N., De Matteis, L., Santos, R., Miguel, A. S., Custardoy, L., Testillano, P. S., Risueño, M. C., Pérez-De-Luque, A., Maycock, C., Fevereiro, P., et al. (2014). Quantum dot and superparamagnetic nanoparticle interaction with pathogenic fungi: Internalization and toxicity profile. *ACS Applied Materials & Interfaces, 6*, 9100–9110.
37. Riva, C., Orzi, V., Carozzi, M., Acutis, M., Boccasile, G., Lonati, S., et al. (2016). Short-term experiments using digestate products as substitutes for mineral nitrogen fertilizer. *Science of the Total Environment, 547*, 206–214.
38. Rodrigo-Comino, J. (2018). Five decades of soil erosion research in terroir systems: The state of the art. *Earth-Science Reviews, 179*, 436–447.

39. Shemawar, Mahmood, A., Hussain, S., et al. (2021). Toxicity of biogenic zinc oxide nanoparticles to soil organic matter cycling and their interaction with rice-straw-derived biochar. *Scientific Reports, 11*, 8429.
40. Sheteiwy, M. S., Shaghaleh, H., Hamoud, Y. A., Holford, P., Shao, H., Qi, W., Hashmi, M. Z., & Wu, T. (2021). Zinc oxide nanoparticles: Potential effects on soil properties, crop production, food processing, and food quality. *Environmental Science and Pollution Research, 28*(28), 36942–36966.
41. Shetti, N. P., Malode, S. J., Ilager, D., Raghava Reddy, K., Shukla, S. S., & Aminabhavi, M. (2019). A novel electrochemical sensor for detection of molinate using ZnO nanoparticles-loaded carbon electrode. *Electroanalysis, 31*, 111.
42. Siddiquee, S., Rovina, K., Yusof, N. A., Rodrigues, K. F., & Suryani, S. (2014). Nanoparticle-enhanced electrochemical biosensor with DNA immobilization and hybridization of *Trichoderma harzianum* gene. *Sensors and Biosensors Research, 2*, 16–22.
43. Tong, S. W., Goh, W. P., & Jiang, C. (2023). Recent advances in nanosensors for precision agriculture. *Journal of The Electrochemical Society, 170*, 127507.
44. Venkatachalam, P., Jayaraj, M., Manikandan, R., Geetha, N., Rene, E. R., Sharma, N. C., & Sahi, S. V. (2017). Zinc oxide nanoparticles alleviate heavy metal-induced toxicity in *Leucaena leucocephala* seedlings. *Plant Physiology and Biochemistry, 110*, 59–69.
45. Wagner, G., Korenkov, V., Judy, J. D., & Bertsch, P. M. (2016). Nanoparticles composed of Zn and ZnO inhibit *Peronospora tabacina* spore germination. *Nanomaterials, 6*, 50.
46. Wang, J., & Gu, N. (2015). Novel metal nanomaterials and their catalytic applications. *Molecules, 20*, 17070–17092.
47. Wang, Z. L. (2004). Zinc oxide nanostructures: Growth, properties and applications. *Journal of Physics: Condensed Matter, 16*, R829–R858.
48. Yan, S., Wu, F., Zhou, S., et al. (2021). Zinc oxide nanoparticles alleviate arsenic toxicity and decrease arsenic accumulation in rice. *BMC Plant Biology, 21*, 150.
49. Zhang, F., Li, S., Wang, L., & Li, X. (2024). An innovative approach to alleviate zinc oxide nanoparticle stress on wheat through nanobubble irrigation. *International Journal of Molecular Sciences, 25*(3), 1896.
50. Zhou, P., Adeel, M., Shakoor, N., Guo, M., Hao, Y., Azeem, I., Li, M., Liu, M., & Rui, Y. (2021). Application of nanoparticles alleviates heavy metals stress and promotes plant growth: An overview. *Nanomaterials, 11*(1), 26.

AI IN FARMING: FROM WEED DETECTION TO YIELD PREDICTION

Gangishetti Ranjith Kumar*, K. Rajendra Prasad,
Konne Deepika and L. Srilatha and P. Sujatha
Department of Genetics & Plant Breeding,
Agricultural College, PJTAU, Jagtial, Telangana – 505529, India
*Corresponding author E-mail: drranjithgpb@gmail.com

Introduction:

Artificial intelligence (AI) is reshaping agriculture faster than any previous technological wave. From identifying weeds with pinpoint accuracy to predicting yields with impressive precision, AI is helping farmers make smarter and more timely decisions.

Artificial intelligence (AI) is changing agriculture more quickly than any technology we have seen before**.** Began as basic automation has now grown into smart systems that help farmers understand their crops better and make more accurate decisions. Today, AI tools can identify weeds with high accuracy, monitor crop growth closely, predict yields well in advance, and guide farmers on the best farming practices based on real-time information (Liakos *et al.,* 2018; Kamilaris & Prenafeta-Boldú, 2018).

This transformation is not only about using new machines. It represents a major shift in how farmers plan their work. Instead of depending only on experience or guesswork, farmers can now use digital data to manage their fields more effectively. Tools like drones, field sensors, satellite images, and machine-learning models work together to give a detailed understanding of what is happening in different parts of the farm. This helps farmers take timely actions such as adjusting irrigation, using fertilizers efficiently, and preventing pest or disease outbreaks.

AI is also helping reduce labour costs, improve resource efficiency, and support sustainable agriculture. Robotic weeders can reduce the use of herbicides, disease-detection systems can alert farmers before symptoms appear, and advanced prediction models can guide crop planning months ahead. In short, AI is becoming a strong partner for farmers from sowing to harvesting (Shirzad *et al.,* 2019).

1. The Rise of AI in Agriculture

AI in farming refers to the use of machine learning, deep learning, and computer vision to automate or enhance agricultural tasks. These technologies enable machines to learn patterns, interpret images, and make predictions based on large datasets. As farms become more digital, AI is now central to precision agriculture, reducing input use, improving productivity, and enhancing sustainability (Shamshirband *et al.,* 2020).

2. Weed Detection and Management

Weeds are one of the biggest challenges in farming because they compete with crops for nutrients, water, sunlight, and space. Traditionally, farmers depend on manual labour or spray herbicides across the entire field. Both methods are costly, time-consuming, and sometimes harmful to the environment. This is where artificial intelligence is making a major difference (Lottes *et al.,* 2017).

AI-powered weed detection systems use cameras, sensors, and machine-learning models to identify weeds quickly and accurately in the field. These systems can differentiate between crop plants and unwanted weeds by analysing leaf shape, colour, texture, and growth patterns. Once weeds are identified, the technology guides machines to remove them without disturbing the main crop (Fawakherji *et al.,* 2019).

How AI-Based Weed Detection Works

1. **Image Collection:** Drones, tractors, or handheld devices capture high-resolution images of the field.
2. **Image Analysis:** AI algorithms scan the images and identify weed species by comparing them with thousands of stored patterns.
3. **Precise Action:** Smart sprayers apply herbicide only on weeds, reducing chemical usage by up to 80%.Robotic weeders physically remove the weeds using mechanical tools. Laser-based weeders burn or weaken the weed without touching the crop.

Benefits for Farmers

- **Reduced herbicide cost:** Chemicals are applied only where needed.
- **Less labour requirement:** Machines handle most of the repetitive work.
- **Healthier crops:** Reduced chemical exposure improves plant growth.
- **Environmental protection:** Lower chemical use means less soil and water pollution.
- **Higher yields:** Crops grow better when weed competition is controlled early.

Popular Examples of AI Weed Detection Tools

- **Blue River Technology's "See & Spray"** – Uses computer vision to target weeds with pinpoint accuracy.
- **Eco-robotix AVO™ Robot** – An autonomous robot that identifies and treats weeds in real time.
- **Farm Wise Titan Robot** – Removes weeds mechanically without using chemicals.

3. AI for Pest and Disease Monitoring

Crop health is the foundation of good yield. Farmers often struggle to detect diseases, nutrient deficiencies, or pest attacks at an early stage because symptoms may be too small to notice with the naked eye. By the time the damage becomes visible, it may already be too late. Artificial intelligence solves this problem by monitoring crops continuously and detecting early warning signals that humans may miss. AI-based crop health monitoring uses drones, satellites, field sensors, and mobile apps to observe crop conditions in real time (Mahlein, 2016). These systems analyse plant colour, temperature, moisture levels, and leaf patterns to identify stress or disease at the earliest possible stage.

How AI Monitors Crop Health

1. **Image & Data Collection:** Drones and satellites capture images of entire fields. Sensors collect soil moisture, temperature, and humidity data.
2. **AI Analysis:** Machine learning models compare the data with healthy crop patterns. They detect abnormalities such as:
    - Early disease spots
    - Pest infestation
    - Nutrient deficiency
    - Water stress
    - Heat stress
3. **Instant Alerts to Farmers:**

    Mobile apps provide notifications with:
    - The affected location in the field
    - Type of problem
    - Recommended actions (spray, irrigation, nutrient correction, etc.)

Benefits for Farmers

- **Early detection:** Problems are identified before they spread.
- **Targeted treatment:** Farmers treat only affected areas, reducing cost.
- **Higher productivity:** Healthy crops lead to better yields.
- **Lower risk:** Farmers receive timely information to prevent major losses.
- **Better resource use:** Water, fertilizer, and pesticides are applied more efficiently.

Examples of AI Crop Health Tools

- **Plantix App** – Detects crop diseases using smart phone photos.
- **Taranis AI** – Uses high-resolution aerial imagery to detect pest and disease issues early.
- **Crop In Smart Farm** – Offers real-time crop monitoring and advisory services.

- **Microsoft AI Sowing App** – Helps farmers decide the best time for sowing and protection measures.

4. **Yield Prediction in Smart Farming**

Predicting crop yield accurately is one of the most valuable advantages that AI brings to modern agriculture. Traditionally, yield estimation depended on field experience, crop sampling, or manual calculations. While these methods work, they are often inaccurate and cannot capture variations within large fields. AI changes this by analysing multiple factors together and giving highly reliable yield forecasts, even weeks or months before harvest.AI-based yield prediction models use data from weather records, soil information, satellite images, field sensors, and crop growth patterns to estimate expected production. This helps farmers plan better and reduce risk.

AI Predicts Yield based on

1. Data Collection from Multiple Sources:
   - Weather data: rainfall, temperature, humidity
   - Soil data: nutrients, moisture, texture
   - Crop images: drone and satellite imagery
   - Field sensors: growth rate, canopy temperature
   - Historical yield data
2. AI Model Analysis:

   Machine-learning models combine all the information and study the relationships between:
   - Plant growth
   - Environmental conditions
   - Past yield performance
   - Stress levels
3. Accurate Yield Forecast:

   The system gives:
   - Expected yield (per acre or per hectare)
   - Variation in different parts of the field
   - Risk factors and their possible impact on output
   - Predictions for different crop stages

Benefits for Farmers

- **Better crop planning:** Farmers can choose the right sowing time and management practices.

- **Smart marketing decisions:** Knowing the expected yield helps plan storage, transport, and selling.
- **Financial planning:** It helps in getting crop insurance, loans, and government support.
- **Efficient resource use:** Water, fertilizer, and labour can be managed according to predicted needs.
- **Reduced uncertainty:** Farmers are better prepared for weather challenges and market fluctuations.

Examples of AI-Based Yield Prediction Tools

- **Google Earth Engine Models** – Combine satellite data and climate information for regional yield forecasts.
- **IBM Watson Decision Platform** – Predicts yields using environment, soil, and crop condition data.
- **Crop in "Smart Risk"** – Provides yield prediction and risk evaluation for different states and districts.
- **RASPBERRY Pi + AI Sensors (Low-cost systems)** – Used by many universities and start ups for local-level yield forecasting.

Why This Matters

In countries like India, unexpected weather changes and climate stress are becoming more common. Accurate yield prediction helps farmers and policymakers prepare in advance. It reduces crop losses, supports market stability, and encourages smarter farming decisions.

4. AI-Powered Precision Agriculture

Smart farming is the next major step in agricultural development. It combines artificial intelligence with modern tools like sensors, GPS-based devices, drones, robotics, and automated machines to help farmers manage their farms more efficiently (Wolfert *et al.,* 2017). Instead of treating the whole field as one unit, smart farming looks at each part of the field separately and provides location-specific solutions. AI plays a central role in smart farming because it can analyse huge amounts of data, learn patterns, and convert them into useful recommendations. This helps farmers reduce waste, increase productivity, and make better decisions at the right time.

Smart Farming Technologies Using AI

1. Internet of Things (IoT) Sensors

These sensors are placed in the field to continuously monitor soil moisture, temperature, humidity, pH levels, and nutrient status

AI analyses sensor data and tells farmers exactly when to irrigate, when to fertilize, and how to improve soil health.

2. AI-Powered Drones

Drones equipped with cameras and multispectral sensors can map crop growth, identify stressed areas, detect pests or diseases and measure plant height and canopy cover. Using AI, the drone images are processed to provide accurate, detailed reports for each part of the field.

4. **Robotics and Automation**

AI-driven robots can perform tasks such as planting seeds, weeding, harvesting fruits and vegetables, spraying pesticides or fertilizers, these robots are especially useful where labour shortages are common.

4. Precision Agriculture Tools

AI enables precision farming by ensuring each crop gets the right amount of water, fertilizer, pesticides and nutrients. This reduces cost, improves yield quality, and protects soil fertility.

5. Smart Irrigation Systems

AI-based irrigation systems adjust water flow automatically depending on weather forecast, soil moisture and crop stage. This prevents over-irrigation and saves water significantly.

Benefits of Smart Farming Technologies

- **Higher Efficiency:** Resources are used only where and when needed.
- **Lower Cost of Cultivation:** Reduced labour and input expenses.
- **Better Quality Produce:** Healthy crops mean improved market value.
- **Reduced Environmental Impact:** Minimum use of chemicals and water.
- **Labour Support:** AI-powered machines reduce dependence on manual labour.
- **Consistent Productivity:** Even during weather uncertainties, smart systems support the crop.

Examples

- **John Deere's AI Tractors** – Autonomous tractors that can plough, sow, and spray without human drivers.
- **Bosch Deep field Robotics** – Uses AI robots for crop monitoring and precision weeding.
- **Kisan Hub (India)** – A digital platform that supports decision-making with AI insights.
- **Fasal & DeHaat (India)** – Offer sensor-based advisory using AI for irrigation and disease prediction.

Challenges and Future Scope of AI in Agriculture

AI is transforming agriculture in powerful ways, but like any new technology, it comes with challenges. Many farmers, especially small and marginal farmers, still struggle to adopt these tools due to cost, connectivity issues, and limited awareness. Understanding these challenges is important because overcoming them will decide how far AI can truly support global agriculture in the future.

Major Challenges in Using AI for Farming

1. High Initial Cost
2. Lack of Digital Infrastructure
3. Limited Technical Knowledge
5. Data Privacy and Security Issues
6. Need for Crop-Specific Models
7. Maintenance and Repair Challenges

Future Scope of AI in Agriculture

Despite these challenges, the future of AI in agriculture is extremely promising. As technology becomes cheaper and more accessible, even small farmers will be able to benefit.

1. Low-Cost AI Tools for Small Farmers

Start ups and research institutes are developing affordable:

- Mobile apps
- Low-cost sensors
- AI-based disease detection tools
- Small drones

These will make AI accessible to every farmer.

2. AI for Climate-Smart Agriculture

With climate change increasing droughts, floods, and irregular rainfall, AI can provide:

- Better weather forecasts
- Drought prediction models
- Crop advisories customized for climate risks

This will help farmers prepare and protect their crops.

3. Autonomous Farming

Fully automated farms where robots plant, monitor, and harvest crops—are becoming a reality. AI tractors and robotic harvesters will reduce labour dependency significantly.

4. AI for Supply Chain and Market Decisions

Future AI systems will guide farmers on:

- Best market to sell
- Expected price trends
- Storage decisions
- Quality grading of produce

This will prevent market losses and increase income.

5. Integration with Government Schemes

Governments are increasingly adopting AI for:

- Crop insurance
- Yield estimation
- Pest forecasting
- Soil health mapping

As these systems expand, farming will become more transparent and efficient.

6. Personalized Advisory for Every Farmer

In the future, AI may provide tailor-made suggestions for each plot of land, such as:

- When to irrigate
- Which fertilizer to use
- Which variety to sow
- When to spray pesticides

This "farm doctor" approach will change agriculture completely.

Conclusion:

AI has enormous potential to reshape agriculture by improving productivity, reducing costs, and making farming more sustainable. While challenges exist, continuous technological improvements, better training, and government support will accelerate adoption.AI is no longer a futuristic concept—it is already transforming agricultural landscapes across the world. From detecting weeds and pests to predicting yields with high precision, AI helps farmers improve efficiency, reduce risks, and achieve higher productivity. By embracing AI-driven tools, agriculture is moving toward a more sustainable, data-driven, and profitable future.

References:

1. Fawakherji, M., Moghaddam, M., & Biermann, D. (2019). AI-based precision weed management: Current status and future prospects. *Computers and Electronics in Agriculture, 157*, 105–115.

2. Kamilaris, A., & Prenafeta-Boldú, F. X. (2018). Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture, 147*, 70–90.
3. Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. *Sensors, 18*(8), 2674.
4. Lottes, P., Khanna, R., Pfeifer, J., Siegwart, R., & Stachniss, C. (2017). UAV-based crop and weed classification for smart farming. *Field and Service Robotics*, 247–263.
5. Mahlein, A.-K. (2016). Plant disease detection by imaging sensors. *Plant Disease, 100*(2), 241–251.
6. Shamshirband, S., Estrella, F., Ghorbani, M. A., & Khoshnevisan, B. (2020). Applications of artificial intelligence in agriculture: A review. *Engineering in Agriculture, Environment and Food, 13*(1), 1–8.
7. Shirzad, H., Ehsani, R., & Schueller, J. (2019). Predicting crop yield using machine learning and satellite imagery. *Remote Sensing, 11*(23), 2976.
8. Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming: A review. *Agricultural Systems, 153*, 69–80.

ROLE OF SOIL HEALTH IN SUPPRESSING SUGARCANE DISEASES

Dinesh K. Pancheshwar*[1], B. K. Sharma[1], Ramesh Amule[2], Monika Singh Thakur[3]
Ashish Tiwari[1], Lakhan Singh Mohaniya[1], Dinesh K. Bajoriya[3] and Shubham Mishra[4]
[1]Sugarcane Research Station, Bohani, Distt. JNKVV, Narsinghpur MP 487555
[2]College of Agriculture, J.N.K.V.V., Balaghat, MP 481001
[3]Zonal Agricultural Research Station, J.N.K.V.V., Powarkheda MP 461110
[4]Faculty of Agriculture, Institute for Excellence in Higher Education, Bhopal
*Corresponding author E-mail: pancheshwar11@jnkvv.org

1. Introduction:

Sugarcane (*Saccharum officinarum L.*) is a vital industrial crop globally; however, its productivity is increasingly threatened by several diseases, many of which are linked to soil conditions and soil management practices (Rao & Saumtally, 2017; FAO, 2020). Diseases such as red rot (*Colletotrichum falcatum*), wilt (*Fusarium* spp.), smut (*Sporisorium scitamineum*), pokkah boeng, root rots, and ratoon stunting disease often intensify under conditions of poor soil health, nutrient imbalance, compaction, and continuous monocropping (Viswanathan & Rao, 2011; Singh & Shukla, 2021). Soil degradation, reduction in organic matter, improper fertilization practices, and environmental stress further aggravate disease incidence and severity. Healthy soil enriches plant vigour, enhances microbial diversity, improves nutrient cycling, and strengthens plant defence, thereby acting as a natural barrier against pathogens (Cook & Baker, 1983; Lehman *et al.,* 2015). It sustains dynamic interactions between soil microorganisms and plant roots, which create an environment unfavourable for pathogen establishment and multiplication. Unlike chemical disease control measures, which provide temporary suppression, soil health–based disease management contributes to long-term resilience, improved ratoon performance, and sustainability of cane ecosystems. Therefore, soil health management is now recognized as a key component of integrated disease management strategies in sugarcane production systems. Enhancing soil physical, chemical, and biological quality not only improves crop productivity but also plays a crucial role in preventing disease outbreaks and maintaining system stability (Singh & Shukla, 2021; Rao & Saumtally, 2017).

2. Key Sugarcane Diseases Influenced by Soil Health

2.1 Soil-Borne and Root-Associated Diseases

Soil-borne diseases are particularly influenced by soil health parameters, especially organic matter, aeration, microbial diversity, and moisture regime.

- **Red Rot (*Colletotrichum falcatum*)** is one of the most destructive diseases of sugarcane worldwide. Its incidence increases under stressed plant conditions, poor soil drainage, nutrient deficiency, and unfavorable soil biological activity (Viswanathan & Rao, 2011). Weakened root systems caused by compacted or waterlogged soils predispose plants to infection.
- **Wilt (*Fusarium* spp.)** thrives in compacted, poorly drained, and nutrient-deficient soils. Fusarium spores persist in soil for long periods, and disease occurrence is strongly linked with soil fatigue resulting from continuous sugarcane monocropping. Stress conditions weaken root immunity, accelerating disease development (Singh & Shukla, 2021).
- **Root Rot Complex** involving *Pythium*, *Rhizoctonia*, and *Macrophomina* is commonly observed in degraded soils with low microbial diversity and reduced organic carbon. These pathogens flourish under waterlogged or drought-stressed conditions, both of which are symptoms of poor soil health (Rao & Saumtally, 2017).
- **Ratoon Stunting Disease (RSD)**, although mainly systemic, is strongly influenced by soil condition. Nutrient imbalance, reduced soil biological activity, and continuous ratooning increase disease expression by weakening plant vigor and increasing susceptibility (Rao & Saumtally, 2017).

2.2 Soil-Influenced Foliar and Systemic Diseases

Some sugarcane diseases are not strictly soil-borne but are strongly influenced by soil health.

- **Smut** severity increases in nutritionally imbalanced and drought-prone soils. Poor soil fertility reduces plant resistance and enhances pathogen colonization (Viswanathan & Rao, 2011).
- **Pokkah Boeng** is often aggravated by excessive nitrogen fertilization combined with weak plant structural strength. Poor soil structure and imbalanced nutrition cause physiological stress, making plants vulnerable (FAO, 2020).
- **Grassy Shoot Disease** and other systemic diseases tend to be more severe under nutrient-deficient, biologically weak soils where plant immunity is compromised.

3. Soil Health: Concept and Components

Soil health refers to the continued capacity of soil to function as a living, dynamic ecosystem that sustains plants, animals, and humans (FAO, 2020). In the context of sugarcane disease suppression, soil health is governed by three interrelated components: physical, chemical, and biological attributes.

3.1 Physical Properties

Physical properties of soil such as structure, aggregation, bulk density, porosity, aeration, and water-holding capacity have a direct relationship with disease development. Well-structured soils promote vigorous root growth, improving the plant's ability to absorb nutrients and withstand infections. Good drainage prevents waterlogging, which otherwise supports anaerobic pathogen growth and increases susceptibility to root rots (Lehman *et al.,* 2015). Conversely, compacted soils cause oxygen deficiency in root zones, reducing microbial diversity and enhancing pathogen dominance.

3.2 Chemical Properties

Soil pH, nutrient balance, cation exchange capacity, salinity, and organic carbon levels are key chemical determinants of disease suppression. Balanced availability of macro- and micronutrients enhances plant immune responses, whereas nutrient deficiencies or imbalances weaken structural tissues and metabolic defenses (Patil & Ramesh, 2019). Excess nitrogen promotes lush, soft tissues susceptible to infection, while potassium and silicon are known to strengthen cell walls and enhance disease resistance.

3.3 Biological Properties

Biological health is the core of disease-suppressive soils. It involves microbial diversity, microbial biomass, enzyme activity, and abundance of beneficial organisms such as *Trichoderma*, *Pseudomonas*, *Bacillus*, actinomycetes, and mycorrhizal fungi. These organisms contribute to disease suppression through antagonism, competition, parasitism, and induction of plant defense (Cook & Baker, 1983; Lehman *et al.,* 2015). Soils rich in organic matter sustain diverse microbial networks that naturally regulate pathogen populations.

4. Mechanisms of Disease Suppression in Healthy Soils

4.1 Competition

Beneficial rhizosphere microbes compete with pathogens for nutrients, infection sites, and space. High microbial diversity leaves limited ecological niches for pathogens to establish and proliferate (Cook & Baker, 1983).

4.2 Antibiosis

Certain soil microorganisms such as *Trichoderma*, *Bacillus subtilis*, and *Pseudomonas fluorescens* produce antibiotics, toxins, lytic enzymes, and siderophores that directly inhibit or kill pathogenic organisms (Rao & Saumtally, 2017). This natural biological warfare helps maintain soil suppressiveness.

4.3 Mycoparasitism

Some fungi act as parasites of plant pathogens, attacking hyphae, spores, and sclerotia, thereby disrupting their life cycles and preventing infection. This plays a major role in suppressing *Fusarium*, *Rhizoctonia*, and *Pythium* in sugarcane soils (Lehman *et al.,* 2015).

4.4 Induced Systemic Resistance

Beneficial microbes trigger physiological and biochemical defense pathways within sugarcane, strengthening its natural immune system. They stimulate production of defense enzymes, lignification, phytoalexins, and enhanced structural barriers, helping the crop resist pathogen invasion (Patil & Ramesh, 2019; Cook & Baker, 1983).

4.5 Organic Matter–Driven Suppression

Organic matter acts as a source of energy for beneficial microbes, supporting high microbial biomass and enzymatic activity. It also helps in decomposition of pathogen propagules and detoxification of harmful metabolites. Thus, soils rich in organic matter tend to be naturally disease suppressive (Lehman *et al.,* 2015).

5. Influence of Specific Soil Health Factors

5.1 Organic Matter

Organic carbon improves soil aggregation, enhances water retention, stimulates microbial diversity, and increases nutrient cycling efficiency. Regular addition of organic amendments has been shown to significantly reduce the incidence of wilt, root rots, and red rot in sugarcane (Patil & Ramesh, 2019; Rao & Saumtally, 2017).

5.2 Soil pH

Soil pH influences nutrient solubility, microbial activity, and pathogen survival. Most antagonistic microbes thrive in near-neutral pH conditions, while extreme acidity or alkalinity often favors pathogen proliferation (FAO, 2020).

5.3 Nutrient Balance

Balanced fertilization enhances plant structural strength and immunity:

- Excess nitrogen increases vulnerability to diseases.
- Adequate phosphorus stimulates root health.
- Potassium strengthens cell walls and improves disease resistance.
- Silicon forms mechanical barriers and boosts biochemical defense. (Viswanathan & Rao, 2011; Singh & Shukla, 2021)

5.4 Soil Moisture and Aeration

Waterlogged soils promote anaerobic pathogens, whereas prolonged drought stresses plants. Ideal soils maintain moisture while ensuring aeration, creating unfavorable conditions for pathogens and supporting beneficial microbial populations (Patil & Ramesh, 2019).

5.5 Microbial Biodiversity

Higher microbial richness strengthens ecological stability and disease suppression capacity. Continuous monocropping, excessive chemical use, and poor organic matter reduce biodiversity and increase disease risk (Lehman *et al.,* 2015).

6. Soil Management Strategies for Disease Suppression

6.1 Organic Matter Enhancement

Application of farmyard manure, compost, press mud, green manures, bio-slurry, and incorporation of sugarcane trash improve organic carbon levels and soil suppressiveness (Patil & Ramesh, 2019).

6.2 Crop Rotation and Diversification

Rotating sugarcane with legumes and deep-rooted crops breaks pathogen cycles, restores nutrients, and improves soil structure (FAO, 2020).

6.3 Biofertilizers and Biocontrol Agents

Beneficial microbial inoculants such as *Trichoderma harzianum*, *Pseudomonas fluorescens*, *Bacillus subtilis*, and mycorrhizae enhance nutrient uptake and suppress pathogenic populations (Rao & Saumtally, 2017).

6.4 Balanced Fertilization Including Silicon

Silicon supplementation strengthens cell walls, improves resistance to red rot and smut, and reduces lodging stress (Viswanathan & Rao, 2011).

6.5 Improved Drainage and Tillage

Raised bed planting, deep tillage, and proper drainage management minimize waterlogging stress and reduce disease incidence (Singh & Shukla, 2021).

6.6 Reduced Chemical Disturbance

Judicious use of pesticides preserves beneficial microbiota, maintaining soil ecological balance (Lehman *et al.,* 2015).

6.7 Healthy Planting Material

Use of disease-free setts, hot-water treatment, and sanitation practices minimize pathogen introduction into soil (Rao & Saumtally, 2017).

7. Disease-Suppressive Soils in Sugarcane

Certain soils naturally possess disease-suppressive characteristics due to long-term organic management, stable microbial ecosystems, and strong structural integrity. These soils can resist pathogen establishment even when inoculum is present. Sustainable agricultural practices gradually transform conducive soils into suppressive ones (Cook & Baker, 1983; Lehman *et al.,* 2015).

8. Indicators of Soil Health in Sugarcane Fields

Key indicators used for monitoring soil health include:

- Soil organic carbon content
- Microbial biomass and respiration
- Enzyme activity (dehydrogenase, phosphatase)
- Earthworm population
- Soil fertility indices
- Disease incidence trends (FAO, 2020; Singh & Shukla, 2021)

Future Perspectives:

Emerging advances in soil microbiome research, metagenomics, bio-inoculant development, precision nutrient management, silicon-based nutrition, artificial intelligence–based soil diagnostics, and digital disease prediction models offer promising opportunities for disease-free sugarcane production (Lehman *et al.,* 2015; Singh & Shukla, 2021). Focus is shifting from curative to preventive disease management through soil ecosystem enhancement.

Conclusion:

Soil health is a central determinant of sugarcane disease dynamics. Soils enriched with organic matter, nutritional balance, good physical structure, adequate aeration, regulated moisture, and rich microbial diversity exhibit natural disease suppression. Strengthening soil health reduces chemical dependence, minimizes pathogen pressure, enhances plant resistance, improves ratoon sustainability, and supports long-term productivity. Thus, soil health management must be integrated as a core strategy in sugarcane disease management programs worldwide.

References:

1. Cook, R.J., & Baker, K.F. (1983). *The Nature and Practice of Biological Control of Plant Pathogens*. APS Press.
2. FAO. (2020). *Soil Health and Sustainable Crop Production*. Food and Agriculture Organization of the United Nations.
3. Lehman, R. M., *et al.* (2015). Soil biology for resilient, healthy soil. *Agronomy Journal*, 107: 971–984.
4. Patil, A. S., & Ramesh, P. (2019). *Soil Health Management in Sugarcane*. ICAR Publications.
5. Rao, G. P., & Saumtally, A. S. (2017). *Sugarcane Diseases and Their Management*. Springer/CRC Press.
6. Singh, N., & Shukla, S. K. (2021). Soil health management for sustainable sugarcane production. *Sugar Tech*, 23(4): 826–839.
7. Viswanathan, R., & Rao, G.P. (2011). *Sugarcane Pathology: Fungal Diseases*. Studium Press / Springer.

POST HARVEST DISEASES OF HORTICULTURAL CROPS: PATHOGENS, LOSSES, AND INTEGRATED DISEASE MANAGEMENT

Varala Krishnaveni*[1], Sathish Kota[2], Rama Krishna V[2] and Kalla Ashok[1]

[1]Sri Konda Laxman Telangana Horticultural University,

Rajendranagar, Hyderabad-500030.

[2]Professor Jayashankar Telangana Agricultural University,

Rajendranagar, Hyderabad-500030

*Corresponding author E-mail: varalakrishnaveni4444@gmail.com

Abstract:

Postharvest diseases are a major constraint in horticultural crops, including fruits and vegetables, causing significant quantitative and qualitative losses. These diseases, mainly caused by fungal pathogens (*Penicillium, Colletotrichum, Botrytis, Rhizopus, Fusarium, Aspergillus, Lasiodiplodia*) and bacterial pathogens (*Pectobacterium, Dickeya*), often remain latent in the field and become active postharvest under favorable conditions. Losses include decay, reduced shelf life, deterioration in quality, and mycotoxin contamination, with global losses estimated at 20–40%, particularly in tropical and subtropical regions. Integrated management combining pre-harvest practices, careful handling, physical and biological treatments, and limited chemical use is essential. Emerging approaches such as eco-friendly treatments, edible coatings, nanomaterials, molecular diagnostics, and AI-based monitoring offer promising strategies for sustainable postharvest disease control.

Keywords: Bacterial Pathogens, Fungal Pathogens, Integrated Disease Management, Postharvest Diseases, Postharvest Losses.

1. Introduction:

Postharvest diseases are a major constraint in the production, marketing, and supply chain of horticultural crops, including fruits, vegetables, and other perishable commodities. These diseases develop after harvest during handling, storage, transportation, and marketing and are primarily caused by fungi and bacteria (Agrios, 2005). Fungal pathogens such as *Penicillium*, *Colletotrichum*, *Botrytis*, *Rhizopus*, *Fusarium*, *Aspergillus*, and *Lasiodiplodia*, and bacterial pathogens such as *Pectobacterium* and *Dickeya* are responsible for most postharvest losses (Snowdon, 1990; Barkai-Golan, 2001; Ravichandra, 2020). Many infections are latent, remaining quiescent in the field and becoming active after harvest when ripening and favorable storage conditions allow rapid pathogen growth (Palou and Smilanick, 2019; Horticulturae, 2025).

Postharvest diseases cause both quantitative and qualitative losses, including decay, shrinkage, reduced shelf life, deterioration in appearance, texture, flavor, and nutritional value, as well as contamination with mycotoxins, which pose food safety risks (Barkai-Golan, 2001; Shankar *et al.,* 2024). Global losses of horticultural produce range from 20 to 40%, with higher losses in tropical and subtropical regions due to high temperature, humidity, and inadequate storage infrastructure (FAO, 2011; ICAR, 2018; JSSR, 2024). Integrated postharvest disease management, combining pre-harvest control, careful harvesting and handling, physical and biological treatments, and judicious use of chemicals, is essential to reduce losses, maintain quality, and ensure food safety (Eckert and Ogawa, 1988; Ravichandra, 2020; Palou and Smilanick, 2019; Shankar *et al.,* 2024; Horticulturae, 2025).

2. Major Pathogens and Diseases

2.1 Fungal Pathogens

Fungi are the most common cause of postharvest decay. Species of *Penicillium* cause green and blue moulds in citrus, apple, and pear. *Colletotrichum* species are responsible for anthracnose in mango, papaya, and banana. *Botrytis cinerea* causes grey mould in grapes, strawberries, and several vegetables. *Rhizopus stolonifer* induces soft rot in fruits and vegetables, while *Fusarium* species lead to dry rot in potato and fruit rot in banana. *Aspergillus niger* causes black mould in onion, and *Lasiodiplodia theobromae* is the main pathogen causing stem-end rot in mango and citrus (Barkai-Golan, 2001; Palou and Smilanick, 2019).

2.2 Bacterial Pathogens

Bacterial postharvest diseases are mostly soft rots caused by *Pectobacterium* and *Dickeya* species. These pathogens infect vegetables such as potato, carrot, tomato, and cabbage, producing soft, watery decay that spreads rapidly under high humidity and warm conditions. Bacterial infection often follows mechanical injury or physiological stress in the produce (Ravichandra, 2020).

2.3 Quiescent (Latent) Infections

In many horticultural crops, pathogens infect the produce in the field but remain dormant until postharvest conditions trigger disease expression. Such latent infections are common in mango, banana, citrus, and papaya. These infections are difficult to control because pathogens are already established in host tissues at the time of harvest (Horticulturae, 2025).

3. Factors Responsible for Disease Development

Several environmental, host, and handling factors contribute to postharvest disease development. Mechanical injuries during harvesting, transportation, or handling provide entry points for pathogens. Temperature and relative humidity are critical; high humidity and warm temperatures favor rapid fungal and bacterial growth. Storage conditions such as poor ventilation, delayed cooling, and contaminated packing materials increase infection rates. Host factors like physiological maturity, ripening stage, and declining natural resistance also influence disease severity. Additionally, pathogens from latent field infections become active under favorable storage conditions, making postharvest management more challenging (Shankar *et al.,* 2024).

4. Postharvest Losses

Postharvest diseases result in both quantitative and qualitative losses. Quantitative losses include rotting, shrinkage, and complete spoilage, which directly reduce marketable yield. Qualitative losses involve deterioration of appearance, taste, texture, and nutritional value, making the produce less acceptable to consumers. Some fungi, such as *Aspergillus* and *Penicillium* species, produce mycotoxins that pose significant food safety concerns. Globally, postharvest losses of fruits and vegetables are estimated to range from 20–40%, with higher losses in tropical and subtropical regions due to high temperature, humidity, and inadequate postharvest infrastructure (FAO, 2011; JSSR, 2024).

5. Management of Postharvest Diseases

5.1 Pre-Harvest Practices

Reducing postharvest losses begins in the field. Use of disease-free planting material, field sanitation, balanced fertilization, and timely pre-harvest fungicide or biological treatments help minimize initial pathogen load (Eckert and Ogawa, 1988; Ravichandra, 2020).

5.2 Harvesting and Handling Practices

Proper harvesting at the correct maturity stage, careful handling to avoid mechanical injury, use of clean containers, and rapid removal of field heat are essential to reduce disease incidence (Snowdon, 1990; Palou and Smilanick, 2019).

5.3 Physical Methods

Physical methods include cold storage, controlled and modified atmosphere storage, hot water treatments, curing, and irradiation (UV-C, ozone). These methods suppress pathogen growth, delay ripening, and extend shelf life without chemical residues.

5.4 Chemical Control

Fungicides, either as dips, sprays, or incorporated into wax coatings, remain effective where approved. However, concerns regarding residues, resistance development, and food safety limit their use (Shankar *et al.,* 2024).

5.5 Biological and Eco-Friendly Methods

Biological control using antagonistic microorganisms such as *Trichoderma*, *Bacillus*, *Pseudomonas*, and yeasts suppress pathogens through competition, antibiosis, and induction of host resistance. Natural plant extracts and edible coatings are increasingly applied to reduce chemical use and meet consumer demand for residue-free produce (Horticulturae, 2025).

5.6 Integrated Postharvest Disease Management (IPDM)

Integrated management combines pre-harvest practices, careful harvesting and handling, physical treatments, biological agents, and limited chemical use. This holistic approach is the most effective and sustainable strategy to reduce postharvest losses, ensure food safety, and enhance the quality and shelf life of horticultural crops (Palou and Smilanick, 2019; Ravichandra, 2020; Shankar *et al.,* 2024)

6. Emerging Approaches and Future Trends

Recent research in postharvest pathology focuses on eco-friendly technologies, nanomaterials, molecular diagnostics, and smart monitoring tools such as AI-based imaging for early detection. Advances in omics technologies and understanding of host–pathogen interactions are paving the way for precision postharvest disease management, sustainable production, and reduction of food loss (Horticulturae, 2025; Shankar *et al.,* 2024).

Conclusion:

Postharvest diseases remain a major challenge in horticultural crop production, causing significant quantitative and qualitative losses that affect marketability, food quality, safety, and economic returns. Fungal and bacterial pathogens, often latent at harvest, become active under favorable postharvest conditions, making timely management critical. Understanding the biology of pathogens, the factors influencing disease development, and the implementation of integrated postharvest disease management strategies—including pre-harvest practices, careful handling, physical and biological treatments, and judicious chemical use—can substantially reduce losses and maintain produce quality. Emerging technologies such as eco-friendly treatments, edible coatings, nanomaterials, molecular diagnostics, and AI-based monitoring offer promising avenues for sustainable and precision postharvest management. A comprehensive and integrated approach is therefore essential to ensure food security, reduce postharvest losses, and deliver safe, high-quality horticultural produce to consumers.

References:

1. Agrios, G. N. (2005). *Plant Pathology* (5th ed.). Elsevier Academic Press.
2. Barkai-Golan, R. (2001). *Postharvest Diseases of Fruits and Vegetables: Development and Control*. Elsevier Science.
3. Eckert, J. W., & Ogawa, J. M. (1988). The chemical control of postharvest diseases: Subtropical and tropical fruits. *Annual Review of Phytopathology*, 26, 433–469.
4. FAO. (2011). *Global Food Losses and Food Waste – Extent, Causes and Prevention*. Food and Agriculture Organization of the United Nations, Rome.
5. Horticulturae. (2025). Postharvest diseases in horticultural crops and their management. *Horticulturae*, 11(9), 1056. ICAR. (2018). *Handbook of Horticulture*. Indian Council of Agricultural Research, New Delhi.
6. JSSR. (2024). Postharvest losses and management of horticultural produce: A review. *Journal of Scientific Research & Reports*, 5(8), 1881–1895.
7. Palou, L., & Smilanick, J. L. (2019). *Postharvest Pathology of Fresh Horticultural Produce*. CRC Press, Taylor & Francis Group.
8. Ravichandra, N. G. (2020). *Postharvest Plant Pathology*. CRC Press, Taylor & Francis Group.
9. Shankar, S., Mohanty, A. K., DeEll, J. R., *et al.* (2024). Advances in antimicrobial techniques to reduce postharvest loss of fresh fruit by microbial reduction. *npj Sustainable Agriculture*, 2, 29.
10. Snowdon, A. L. (1990). *A Colour Atlas of Post-Harvest Diseases and Disorders of Fruits and Vegetables*. Wolfe Scientific Ltd., London.

TRICHODERMA IN SUPPRESSING SOIL-BORNE PLANT PATHOGENS

Varala Krishnaveni*[1], Sathish Kota[2], Rama Krishna V[2] and Thudumu Ramakrishna[1]

[1]Sri Konda Laxman Telangana Horticuyltural University,

Rajendranagar, Hyderabad-500030.

[2]Professor Jayashankar Telangana Agricultural University,

Rajendranagar, Hyderabad-500030

*Corresponding author E-mail: varalakrishnaveni4444@gmail.com

Abstract:

Soil-borne diseases are a major constraint in global agriculture, causing substantial yield and quality losses in crops such as vegetables, legumes, cereals, and horticultural plants. Major soil-borne pathogens include fungi (*Fusarium*, *Rhizoctonia*, *Sclerotium*, *Verticillium*, *Macrophomina*), oomycetes (*Pythium*, *Phytophthora*), and nematodes (*Meloidogyne* spp.), which attack roots, crowns, and lower stems. These pathogens survive in soil for long periods, making their management challenging. Trichoderma spp. are filamentous fungi widely used as biological control agents to suppress soil-borne pathogens through mycoparasitism, antibiosis, competition, and induction of plant defense. Applications via seed treatment, soil amendment, root dipping, or combination with organic amendments enhance crop resistance, improve plant growth, and reduce dependence on chemical fungicides. Integration of Trichoderma into crop and soil management practices provides a sustainable, eco-friendly approach to controlling soil-borne diseases and improving productivity. This chapter reviews major soil-borne diseases, their impacts, and the mechanisms and applications of Trichoderma as a biological control agent.

Keywords: Biological Control, Mycoparasitism, Soil-Borne Pathogens, Trichoderma, Yield Loss

Introduction:

Soil-borne pathogens are among the most devastating constraints in agriculture, affecting plant roots, crowns, and lower stems, and causing substantial losses in both yield and quality of crops globally. These pathogens include fungi such as *Fusarium*, *Rhizoctonia*, *Sclerotium*, *Pythium*, *Phytophthora*, and *Verticillium*, bacteria such as *Ralstonia solanacearum* and *Agrobacterium* spp., and nematodes like *Meloidogyne* spp., which can survive in the soil for long periods as spores, sclerotia, or other resistant structures (Agrios, 2005; Mukherjee *et al.,* 2013). Conventional chemical methods, though widely used, are often costly, environmentally harmful, and sometimes ineffective due to the development of resistant pathogen strains. Consequently, sustainable alternatives are increasingly necessary to manage these persistent pathogens.

Biological control using beneficial microorganisms offers a safe, eco-friendly, and cost-effective solution. Among microbial antagonists, *Trichoderma* spp. have emerged as effective agents due to their versatility, broad-spectrum activity against soil-borne pathogens, ability to enhance plant growth, and compatibility with integrated disease management practices (Harman *et al.,* 2004; Ravichandra, 2020). Trichoderma improves soil health, suppresses pathogens, and provides a sustainable approach for crop protection in modern agriculture.

Major Soil-Borne Diseases and Pathogens

Soil-Borne Disease	**Pathogen(s)**	**Crops Affected**	**Losses**	**Trichoderma Mechanism(s)**
Fusarium Wilt	*Fusarium oxysporum* f. sp.	Tomato, Chickpea, Banana, Cotton	30–50% yield loss; wilting, yellowing, vascular discoloration	Mycoparasitism, Antibiosis, Competition, Induction of Plant Defense
Root Rot / Damping-Off	*Rhizoctonia solani*, *Pythium* spp., *Phytophthora* spp.	Seedlings of vegetables, legumes, cereals	Seedling mortality >60%; stunted growth, root rot	Mycoparasitism, Competition, Antibiosis, Colonization of Rhizosphere
Sclerotial Diseases	*Sclerotium rolfsii*, *Sclerotinia sclerotiorum*	Legumes, Tomato, Groundnut	Severe losses; sometimes total crop failure; stem rot, collar rot	Mycoparasitism, Antibiosis, Competition
Verticillium Wilt	*Verticillium dahliae*	Cotton, Tomato, Potato, Other vegetables	20–40% yield reduction; yellowing, wilting, stunted growth	Mycoparasitism, Induction of Host Resistance, Competition
Charcoal Rot	*Macrophomina phaseolina*	Soybean, Sorghum, Sunflower	Root and stem rot; reduced productivity	Mycoparasitism, Antibiosis, Competition
Nematode Damage	*Meloidogyne* spp.	Tomato, Vegetable crops	Root galls, reduced nutrient uptake, yield reduction	Indirect via enhanced plant resistance and rhizosphere colonization
Rhizopus Rot	*Rhizopus* spp.	Potato, Sweet potato, Vegetables	Root and stem rot; postharvest losses	Mycoparasitism, Antibiosis

Soil-borne diseases are responsible for severe yield losses across a wide range of crops. Fusarium wilt**,** caused by *Fusarium oxysporum* f. sp., affects tomato, chickpea, banana, and cotton, leading to yellowing, wilting, vascular discoloration, and eventual plant death. Under favorable conditions, Fusarium wilt can reduce yields by 30–50%. Root rot and damping-off, caused by *Rhizoctonia solani*, *Pythium* spp., and *Phytophthora* spp., result in seedling mortality, root lesions, and stunted growth, with losses sometimes exceeding 60% in nurseries or poorly drained soils. Sclerotial diseases, caused by *Sclerotium rolfsii* and *Sclerotinia sclerotiorum*, lead to collar rot, stem rot, wilting, and formation of sclerotia on stems and roots, causing severe losses in legumes, tomato, and groundnut, and occasionally total crop failure. Verticillium wilt, caused by *Verticillium dahliae*, affects cotton, tomato, potato, and other vegetables, leading to yellowing, wilting, stunted growth, and vascular discoloration, with reported yield reductions of 20–40% in severe cases. Other soil-borne pathogens, including *Macrophomina phaseolina* (charcoal rot), *Rhizopus* spp., and nematodes like *Meloidogyne* spp., also contribute to root rots, stem lesions, and reduced productivity (Agrios, 2005; Ravichandra, 2020).

Soil-borne diseases lead to both quantitative and qualitative losses. Quantitative losses include reduced plant stand, wilting, root and crown rot, decreased fruit or seed production, and sometimes total crop failure. Qualitative losses involve poor plant growth, reduced nutrient uptake, higher susceptibility to secondary infections, and reduced marketable quality of crops. Global estimates suggest that soil-borne pathogens can reduce yields by 20–50%, depending on the host, environmental conditions, and pathogen pressure (FAO, 2011; Shankar *et al.,* 2024).

Need for Biological Control

The widespread use of chemical fungicides and soil fumigants has raised concerns due to their high cost, environmental pollution, residual toxicity, and the development of resistant pathogen strains. Biological control is a sustainable, eco-friendly alternative that leverages beneficial microorganisms to suppress pathogens, improve soil health, and enhance plant growth. Among microbial antagonists, Trichoderma spp. are highly effective due to their ability to survive in diverse soil environments, colonize the rhizosphere, and act against a broad range of soil-borne pathogens (Harman *et al.,* 2004; Shoresh *et al.,* 2010).

Trichoderma as a Biological Control Agent

Trichoderma suppresses soil-borne pathogens through multiple mechanisms. Mycoparasitism involves directly attacking pathogen hyphae using cell wall-degrading enzymes such as chitinases, glucanases, and proteases (Howell, 2003). Antibiosis occurs via production of volatile and non-volatile secondary metabolites that inhibit pathogen growth, spore germination, and virulence. Competition for nutrients, space, and iron, facilitated by siderophore production, further limits pathogen establishment in the rhizosphere (Vinale *et al.,* 2008). Trichoderma also induces plant systemic resistance, activating defense-related enzymes like peroxidases and phenylalanine ammonia-lyase to enhance plant resilience against pathogens (Harman *et al.,* 2004).

Trichoderma can be applied through various methods, including seed treatment**,** soil amendment**,** root dipping**, and** combination with organic amendments such as compost or vermicompost to improve colonization and efficacy (Ravichandra, 2020). Its advantages include broad-spectrum antagonism, promotion of plant growth and nutrient uptake, environmental safety, compatibility with integrated pest and disease management, and reduction in chemical fungicide use.

Integrated Management Using Trichoderma

Effective management of soil-borne diseases involves a combination of cultural practices, resistant cultivars, Trichoderma application, and judicious chemical use. Crop rotation and removal of infected plant debris reduce pathogen load. Trichoderma application suppresses soil-borne pathogens and enhances plant vigor, while organic amendments improve soil health and biocontrol efficacy. Chemicals are used only when necessary, minimizing environmental impact and supporting sustainable agriculture (Harman *et al.,* 2004; Ravichandra, 2020).

Future Trends

Emerging research focuses on developing nano-formulations of Trichoderma for improved shelf-life and efficacy, integrating omics technologies to understand host–microbe–pathogen interactions, and using precision agriculture and AI-based monitoring for optimal application timing and disease prediction. The focus on eco-friendly, sustainable, and technologically advanced biocontrol strategies will further reduce dependence on chemical pesticides while maintaining crop health and productivity.

Conclusion:

Soil-borne diseases are a major threat to global agriculture, causing significant reductions in yield and quality. Conventional chemical control methods are often inadequate and environmentally unsustainable. Trichoderma spp. offer a safe, effective, and environmentally friendly solution for managing soil-borne pathogens through mycoparasitism, antibiosis, competition, and induction of host resistance. Incorporating Trichoderma into integrated management strategies, along with cultural practices, organic amendments, and minimal chemical use, provides a sustainable approach to disease suppression, improved plant growth, enhanced soil health, and increased crop productivity.

References:

1. Agrios, G. N. (2005). *Plant Pathology* (5th ed.). Elsevier Academic Press.
2. FAO. (2011). *Global Food Losses and Food Waste – Extent, Causes and Prevention.* Food and Agriculture Organization of the United Nations, Rome.
3. Harman, G. E., Howell, C. R., Viterbo, A., Chet, I., & Lorito, M. (2004). Trichoderma species—opportunistic, avirulent plant symbionts. *Nature Reviews Microbiology*, 2(1): 43–56.
4. Howell, C. R. (2003). Mechanisms employed by Trichoderma species in the biological control of plant diseases: The history and evolution of current concepts. *Plant Disease*, 87(1): 4–10.
5. Mukherjee, P. K., Horwitz, B. A., Kenerley, C. M., & Mukherjee, M. (2013). *Trichoderma – Biology and Applications.* CABI.
6. Ravichandra, N. G. (2020). *Postharvest Plant Pathology.* CRC Press, Taylor & Francis Group.
7. Shoresh, M., Harman, G. E., & Mastouri, F. (2010). Induced systemic resistance and plant responses to fungal biocontrol agents. *Annual Review of Phytopathology*, 48: 21–43.
8. Vinale, F., Sivasithamparam, K., Ghisalberti, E. L., *et al.* (2008). Trichoderma–plant–pathogen interactions. *Soil Biology and Biochemistry*, 40(1): 1–10.

MEAT WASTE GENERATION AND UTILIZATION IN INDIA

Satkthivel M and P. Sudha*

Department of Food Process Engineering,

Tamil Nadu Agricultural University, Coimbatore

*Corresponding author E-mail: sudha.p@tnau.ac.in

Introduction:

Meat is an essential source of nutrition for many people worldwide. As meat and meat products are concentrated sources of high-quality protein, their amino acid composition usually compensates for the shortcomings of staple foods (FAO, 2011; Pearson & Dutson, 1994). At a global level, the average person consumed around 43 kilograms of meat in 2014. The meat industry also plays an important role in the world economy, contributing significantly to local, national, and international trade. At present, global meat production exceeds 340 million tonnes annually, reflecting a sharp increase in demand over the last five decades (FAO, 2018).

In India, livestock plays a very important role in the economy, showing a steady growth rate of 4–5%. The overall contribution of the livestock sector to the total GDP is nearly 4.11% at current prices during 2012–13 (Government of India, 2014). The economic contribution could be further enhanced if animal waste materials were effectively utilized. By-products such as blood, liver, lung, kidney, brain, spleen, and tripe possess good nutritive value and are consumed by people; however, wastes such as bones, tendons, skin, gastrointestinal contents, blood, and certain internal organs are non-utilized or under-utilized, leading to environmental pollution and serious health concerns (Ockerman & Hansen, 2000; Jayathilakan *et al.,* 2012). This review paper discusses the utilization of waste products in pharmaceutical, medical, cosmetic, and dietetic applications.

The market value of the meat industry is projected to rise from 838 billion U.S. dollars in 2020 to over one trillion dollars by 2025. In 2021, the United States generated the highest revenue from meat products and sausages. India ranked fifth globally, producing approximately 6.3 million tons of meat annually and contributing nearly 3% of total world meat production. The country possesses the world's largest livestock population, estimated at about 515 million animals (FAO, 2019).

In 2018, an estimated 69 billion chickens, 1.5 billion pigs, 656 million turkeys, 574 million sheep, 479 million goats, and 302 million cattle were slaughtered for meat production. This scale of slaughter is not always economically or environmentally sustainable. Only about 40% of the animal is consumed as meat, while the remaining 60%—including offal, bones, tendons, blood, and plasma—becomes abattoir waste requiring recycling or disposal (Ockerman & Hansen, 2000). The livestock industry generates nearly 1.4 billion pounds of waste annually, with slaughterhouses being the primary source (Steinfeld *et al.,* 2006).

The inedible waste generated includes skin, bones, blood, gastrointestinal contents, tendons, and visceral organs, and the proportion varies depending on animal species (Grosse, 1984; Sielaff, 1996). To improve profitability and reduce pollution, there is a strong need to develop technologies for recycling and value addition of meat by-products. Studies indicate that beef and pork by-products contribute approximately 11.4% and 7.5% of total revenue, respectively. Slaughtering processes generate diverse by-products such as manure, rumen and intestinal contents, liver, blood, feathers, bones, fat, and wastewater (Jayathilakan *et al.,* 2012).

Wastes of Slaughterhouses and Poultries

Slaughterhouse and poultry wastes are classified as commercial components of municipal solid waste. Population growth has increased the demand for meat, livestock, and poultry products. Global meat production is estimated at about 220 million tons, mainly contributed by buffaloes, cattle, sheep, goats, pigs, and poultry (FAO, 2016). Slaughterhouse operations generate considerable quantities of organic waste rich in suspended solids, liquids, and fats (Mittal, 2006).

Approximately 50–54% of cattle, 52% of sheep and goats, 60–62% of pigs, 68–72% of chickens, and 78% of turkeys are utilized for meat, while the remainder is discarded as waste (Jayathilakan *et al.,* 2012). Bovine slaughterhouses generate solid waste equivalent to about 27.5% of the animal's live weight, whereas goat and sheep slaughterhouses produce about 17%, and pig slaughterhouses around 4%. In poultry processing, 32.5–37% waste is generated, consisting mainly of feathers and skin, intestines, legs, and minor fractions of other materials (Mittal, 2006).

Slaughterhouse solid wastes are categorized into vegetable matter (ruminal, stomach, and intestinal contents and dung) and animal matter (inedible offals, tissues, and meat trimmings). The slaughtering of cattle, pigs, and lambs generates by-products amounting to 66%, 52%, and 68% of live weight, respectively. These by-products include organs, fat, skin, feet, bones, blood, and intestinal contents. Although more than half of animal by-products are not suitable for direct consumption, they represent valuable resources for energy generation and industrial applications if properly processed (Jayathilakan *et al.,* 2012; Steinfeld *et al.,* 2006).

Types of Slaughterhouse Waste

Slaughterhouse waste can be categorized into the following types:

1. **Solid Waste:** This includes bones, hooves, hides, feathers, and undigested food from the animal's stomach and intestines.

2. **Liquid Waste:** Blood, fats, and wastewater from cleaning processes fall into this category.
3. **Gaseous Emissions:** Byproducts processing plants, such as rendering plants, hide processing units, gelatine manufacturing unit (Ossein manufacturing unit), etc, will release odour. In addition to that, the decomposition of organic waste (be it liquid or solids described above) can release gases like ammonia, hydrogen sulfide, mercaptans, Volatile Organic Compounds (VOCs), etc., contributing to foul odours and air pollution.

Utilizations of Blood:

With a ban on the collection and utilization of slaughtered animal blood for human use in India, blood generated in slaughterhouses is mainly processed through dry rendering. Blood is a major by-product of the meat industry and represents a rich source of high-quality protein and heme iron. Bovine blood contains approximately 80.9% water, 17.3% protein, 0.23% lipid, 0.07% carbohydrate, and 0.62% minerals. Owing to its nutritional and functional properties, animal blood has been traditionally used in various food products such as blood sausages, blood pudding, biscuits, bread, blood curd, and blood cake, as well as serving as an emulsifier, stabilizer, clarifier, color additive, and nutritional supplement in the form of blood meal. In non-food applications, blood is utilized in fertilizers, feedstuffs, and binding materials. Technologically, blood enhances protein content and improves water-binding and emulsification properties in food systems (Wan *et al.,* 2002; Mandal *et al.,* 1999).

Liquid plasma constitutes the largest fraction of blood, accounting for about 63%, and is composed mainly of albumin, globulins, and fibrinogen. Blood and blood-derived products are widely used in laboratories as nutrient sources in tissue culture media, as essential components of blood agar, and as peptones for microbial growth. Blood plasma also exhibits valuable functional properties and is used in processed meat products such as cooked ham and hot dogs to improve product color and texture. Additionally, plasma can serve as an effective substitute for eggs in baked goods due to its excellent foaming ability (Autio *et al.,* 1985; Kurbanoglu & Kurbanoglu, 2004).

Biodiesel Production

Biodiesel production involves the transesterification of triglycerides with alcohols, typically methanol or ethanol, in the presence of a catalyst, resulting in mono-alkyl esters that can be blended with conventional diesel fuel. The use of renewable feedstocks for biodiesel production offers several environmental benefits, including reduced emissions of hydrocarbons, particulate matter, sulfur oxides, and carbon monoxide. Glycerol is generated as a by-product of this process and can be utilized as a raw material for chemical synthesis, biodegradable polymers, and energy production, although crude glycerol requires further purification.

Animal waste represents a promising and cost-effective feedstock for biodiesel production due to its high lipid content and lower cost compared to vegetable oils. However, the high free fatty acid content of animal fats can result in reduced conversion efficiency. This challenge can be addressed through strategies such as two-stage conversion processes, increased alcohol-to-oil ratios, and the use of recyclable catalysts, which enhance reaction rates and improve biodiesel yield and quality (Wan *et al.,* 2002).

Proteins from Ovine Lungs and Rumen and Their Incorporation in Mutton Patties

The recovery of proteins from slaughterhouse by-products for human consumption has gained considerable attention. Protein isolates extracted from sheep lungs and rumen using alkaline extraction followed by isoelectric precipitation showed recovery rates of 38.2% and 31.0%, respectively. The protein yields from both sources were comparable, yielding approximately 30 g of protein per unit dry matter.

Incorporation of these protein isolates into mutton patties demonstrated that inclusion levels up to 20% were highly acceptable based on sensory evaluation, while levels of 25–30% remained within acceptable limits. The extraction method was effective in reducing microbial load, resulting in microbiologically safe protein isolates. The study confirmed that ovine lung and rumen protein isolates can successfully replace a portion of high-cost lean meat in mutton patties without compromising quality, sensory attributes, or shelf life. The patties remained safe and fresh for up to 15 days under refrigerated storage conditions (Mandal *et al.,* 1999; Kurbanoglu & Kurbanoglu, 2004).

Extruded Tripe Snack Food from Buffalo Rumen Meat

India has a substantial buffalo population, accounting for about 56.5% of the world's total buffalo population. Buffalo rumen meat, commonly known as tripe, is an edible offal obtained in appreciable quantities, yielding approximately 4.36–5.45 kg per animal. Despite its nutritional value, buffalo tripe has limited utilization due to two major constraints, namely unpleasant odor and poor functional properties.

To overcome these limitations, a scientific study was undertaken to develop an extruded snack food from buffalo rumen meat. Five chemical treatments—trisodium phosphate (TSP), sodium carbonate, sodium hypochlorite, calcium hydroxide, and hydrogen peroxide—were evaluated at different concentrations. The results indicated that treatment with 5% TSP for a holding period of 30 minutes was the most effective. A standardized process schedule was developed for the preparation of buffalo tripe snacks, and three types of flours, namely corn, rice, and wheat, were tested to determine the optimal formulation. The findings revealed that incorporation of 50% corn flour produced the most suitable product.

The developed snack food was evaluated for physicochemical, microbiological, and sensory characteristics. The product exhibited acceptable quality attributes and was well accepted by sensory panelists. Even after 30 days of storage, the snack was rated as "moderately acceptable to very acceptable." The study demonstrated that buffalo rumen meat can be effectively utilized to produce a nutritious and consumer-acceptable snack food product.

Table 1: Storage, Preparation and Uses of Various Meat Types

Kind of meat	Storage and Preparation	The way in which it is used
Liver	Frozen, fresh, or refrigerated	Braised, broiled, fried, in a loaf, patty, and sausage
Kidney	Whole, sliced, or ground Fresh or refrigerated	Broiled, cooked in liquid, braised, in soup, grilled, in stew
Heart	Whole or sliced Frozen, fresh, or refrigerated	Braised, cooked in liquid, luncheon meat, patty, loaf
Brains	Whole or sliced	Sausage ingredients, broiled, braised, and cooked in liquid, poached, and scrambled.
Tongue	Frozen, fresh, or refrigerated Whole	Cooked in liquid, cured, sausage casing, sausage ingredient
Stomach	Fresh, refrigerated, smoked, and pickled	Broiled and cooked in liquid, sausage casing, or sausage ingredient
Spleen	Fresh, refrigerated, and pre-cooked	Fried, in pies, in blood sausage
Tail	Frozen, fresh, or refrigerated	Cooked in salty liquid
Intestines (small & large)	Whole, frozen, fresh, refrigerated. Faeces removal, soaking, washing, salting	Sausage casing
Cheek and head trimmings	Frozen, fresh, or refrigerated	Cooked sausage
Ear	Frozen, fresh, or refrigerated	Smoked and salted, stewed with feet
Skin	Fresh, refrigerated	Gelatin
Feet	Frozen, fresh, refrigerated	Jelly, pickled, cooked in liquid, boiled, fried
Fat	Frozen, fresh, or refrigerated	Shortening, lard
Blood	Frozen, refrigerated	Black pudding, sausage, blood, and barley loaf
Bone	Frozen, fresh, or refrigerated	Gelatin, soup, jellied products, rendered shortening, and mechanically deboned tissue
Lung	Frozen, refrigerated, fresh	Blood preparations, pet food

Gelatin from Hides and Skins

Gelatin is produced by the controlled hydrolysis of collagen, a water-insoluble protein obtained from animal hides or bones. Fresh hides and skins are commonly used as raw materials, as they contain large quantities of collagen in an edible condition. The processing of gelatin from hides involves three major steps. The first step is the removal of non-collagenous materials from the raw hide, followed by controlled hydrolysis of collagen to convert it into gelatin. The final step involves recovery, concentration, and drying of the gelatin to obtain the finished product.

Glands and Organs as Food

Animal organs and glands provide a wide range of flavors and textures and are often rich in essential nutrients. They are highly valued as food in many regions of the world, particularly in Southeast Asia. Organs commonly consumed by humans include the brain, heart, kidneys, liver, lungs, and spleen. Other edible by-products include the tongue, bovine pancreas and udder, stomach and uterus of pigs, the rumen, reticulum, omasum, and abomasum of sheep and cattle, as well as the testes and thymus of sheep and pigs (Liu, 2002). The potential applications, storage methods, and preparation aspects of edible meat by-products are summarized in Table showing potential uses and preparation of edible meat by-products.

Slaughterhouse By-Products for Animal Feed

Most slaughterhouse by-products are suitable for use in animal feed because of their rich mineral content. A widely adopted approach is their conversion into blood meal, bone meal, and fish meal, which are commonly used as feed ingredients for poultry and fish. Prior to utilization, these by-products are processed into smaller particle sizes to enhance digestibility. Organic residues from slaughterhouses are particularly preferred for animal feed production. Feedstock derived from the meat processing industry plays a significant role in ensuring the availability of affordable animal protein and sustainable organic nutrient sources. Modern biorefineries increasingly focus on utilizing blood and bones to produce feed ingredients for poultry and cattle. Additionally, fertilizer production from meat processing by-products offers an economical and environmentally sound option due to their high nitrogen content, making them suitable for composting (Jayathilakan *et al.,* 2012; Ockerman & Hansen, 2000).

Bones constitute nearly 15% of the weight of a dressed carcass and contain approximately 50% water and about 15% marrow, which is rich in fat. Meat and bone meal and other processed animal proteins were implicated in the bovine spongiform encephalopathy (BSE) outbreak in Western Europe during the 1980s and 1990s. In regions where meat and bone meal is permitted for livestock feeding, strict heat treatment protocols are required to prevent the transmission of BSE and other pathogens such as *Salmonella*. Meat and bone meal remains an excellent source of supplemental protein with a well-balanced amino acid profile, and the digestibility of its protein fraction typically ranges from 81 to 87% (Kellems *et al.,* 1998).

Pharmaceutical and Industrial Uses of Slaughterhouse By-Products

The brain, nervous system, and spinal cord are rich sources of cholesterol, which is essential for the synthesis of vitamin D, a compound vital for bone and dental health. Cholesterol also serves as a precursor for steroid synthesis and is used as an emulsifier in cosmetic formulations. Hormones extracted from the hypothalamus are applied as blood coagulants in surgical procedures. Cephalin derived from brain tissue assists in blood clotting, while lecithin is used as an emulsifier, antioxidant, and therapeutic agent, including in the treatment of snake bites. Melatonin extracted from the pineal gland is being studied for the management of schizophrenia, insomnia, and certain intellectual disorders (Ockerman & Hansen, 2000).

Collagen and gelatin obtained from hides, skins, and connective tissues have extensive medical and pharmaceutical applications. Collagen sheets are used for burn treatment and wound healing, including laparoscopic procedures. Gelatin is widely used in pharmaceutical capsules, tablet binders, ointments, cosmetics, emulsions, and as a plasma extender in blood transfusions. Medicinal applications of gelatin include treatment of digestive disorders, ulcers, muscular ailments, and stimulation of nail growth (Jayathilakan *et al.,* 2012).

The duodenum is a source of important hormones such as enterogastrone, used experimentally in ulcer treatment and regulation of gastric secretions, and secretin, which stimulates pancreatic juice secretion and aids in diagnosing pancreatic disorders. Desiccated duodenum supplies intrinsic factors essential for vitamin B absorption in patients with pernicious anemia.

Animal fat, particularly benzoinated fat derived mainly from beef, is widely used as an ointment base. Bile extracted from the gall bladder contains acids, pigments, proteins, and cholesterol. Compounds such as cholic acid, deoxycholic acid, chenodeoxycholic acid, dehydrocholic acid, cortisone, prednisone, and other steroid precursors are used in pharmaceutical formulations for treating inflammation, joint pain, indigestion, constipation, bile duct disorders, and gallstones. Gallstones are also traditionally used as ornaments and are believed to possess aphrodisiac properties in some cultures. Wool fats obtained from hair are additional sources of cholesterol (Ockerman & Hansen, 2000).

The liver is a valuable source of vitamin B_{12} and has long been used in the treatment of various anemias. Refined liver extracts and injections have been employed in managing chronic dysentery and anemia. Products such as liver paste and liver concentrate serve as dietary supplements. Heparin and catalase extracted from the liver are used in pharmaceutical and industrial applications, while bile secreted by the liver is utilized in formulations for digestive and biliary disorders. The liver is also an important raw material for steroid and cortisone manufacture.

Lungs are another source of heparin, which is widely used as an anticoagulant to prolong blood clotting time. The pancreas yields several biologically important compounds, most notably insulin for diabetes management. Glucagon extracted from the pancreas is used to treat hypoglycemia and insulin overdose. Other pancreatic enzymes such as trypsin and chymotrypsin are used for wound debridement and post-surgical healing, while lipotropin hormone aids fat digestion and absorption.

Poultry and Bone By-Products

Poultry offal serves as a source of poultry grease, which is generally darker and of lower grade compared to fats from beef, pork, or mutton. During rendering of poultry by-product meal, oil is removed using screw extractors; this poultry oil is a valuable energy source and improves the palatability of pet foods.

Bones constitute approximately 11%, 15%, and 16% of pork, beef, and lamb carcasses, respectively. Nearly one-sixth of raw bone weight (dry basis) is protein embedded in a mineral matrix of calcium phosphate. Bones are utilized for producing edible fats, gelatin (ossien), edible bone phosphates, soup stock, pet food ingredients, and various pharmaceutical products. Bone waste collected from slaughterhouses is processed into bone tallow and meat and bone meal. Bone meal is produced in several forms, including fresh bone meal, boiled bone meal, steamed bone meal, and calcinated bone meal (bone ash). Other valuable products include edible bone collagen, soluble bone protein, and edible bone phosphate. Bone meal serves as an important source of calcium, phosphorus, and trace minerals, contributing significantly to balanced animal nutrition (Jayathilakan *et al.,* 2012; Kellems *et al.,* 1998).

References:

1. FAO. (2011). *Dietary protein quality evaluation in human nutrition*. Food and Agriculture Organization of the United Nations.
2. FAO. (2018). *Livestock production statistics*. Food and Agriculture Organization of the United Nations.
3. FAO. (2019). *FAOSTAT statistical database*. Food and Agriculture Organization of the United Nations.
4. Government of India. (2014). *Basic animal husbandry statistics*. Ministry of Agriculture.
5. Jayathilakan, K., Sultana, K., Radhakrishna, K., & Bawa, A. S. (2012). Utilization of by-products and waste materials from meat, poultry and fish processing industries. *Journal of Food Science and Technology*, 49(3), 278–293.

6. Ockerman, H. W., & Hansen, C. L. (2000). *Animal by-product processing and utilization*. CRC Press.
7. Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., & de Haan, C. (2006). *Livestock's long shadow*. FAO.
8. Autio, K., Kiesvaara, M., & Salminen, E. (1985). Functional properties of blood plasma in cooked meat products. *Journal of Food Technology*, 20, 179–188.
9. Kurbanoglu, E. B., & Kurbanoglu, N. I. (2004). Utilization of blood proteins in microbiological media. *Process Biochemistry*, 39, 1363–1371.
10. Mandal, P. K., Rao, V. K., & Kowale, B. N. (1999). Utilization of slaughterhouse by-products for value-added meat products. *Indian Journal of Animal Sciences*, 69, 944–948.
11. Wan, P. J., Pakarinen, O., & Hron, R. J. (2002). Utilization of animal by-products and fats for food and industrial applications. *Journal of the American Oil Chemists' Society*, 79, 963–970.
12. Liu, D. C. (2002). Better utilization of by-products from the meat industry. *Meat Science*, 62, 277–284.
13. Ockerman, H. W., & Hansen, C. L. (2000). *Animal by-product processing and utilization*. CRC Press.
14. Jayathilakan, K., Sultana, K., Radhakrishna, K., & Bawa, A. S. (2012). Utilization of by-products and waste materials from meat, poultry and fish processing industries. *Journal of Food Science and Technology*, 49(3), 278–293.
15. Jayathilakan, K., Sultana, K., Radhakrishna, K., & Bawa, A. S. (2012). Utilization of by-products and waste materials from meat, poultry and fish processing industries. *Journal of Food Science and Technology*, 49(3), 278–293.
16. Kellems, R. O., Church, D. C., & Bowman, J. G. P. (1998). *Livestock feeds and feeding* (4th ed.). Prentice Hall.
17. Ockerman, H. W., & Hansen, C. L. (2000). *Animal by-product processing and utilization*. CRC Press.
18. FAO. (2011). *Guide to good hygiene practices for animal by-products*. Food and Agriculture Organization of the United Nations.

PRODUCTION TECHNOLOGY AND CROP MANAGEMENT OF POTATO

Himanshu*[1] and Vikas Sagwal[2]

[1]Department of Vegetable Science,

CCS Haryana Agricultural University, Hisar, Haryana, India

[2]Department of Vegetable Science,

Maharana Pratap Horticultural University, Karnal, Haryana, India

*Corresponding author E-mail: himanshumehla1999@gmail.com

Abstract:

Potato (*Solanum tuberosum* L.) is one of the most important food crops of the world, contributing significantly to food and nutritional security due to its high yield potential, rich starch content and balanced nutritional profile. Originating in the Andean region of South America, potato has spread globally and occupies a prominent position among vegetable crops, particularly in countries like India, which ranks second in global production. This chapter provides a comprehensive account of potato covering its origin, botanical characteristics, nutritional value, area and production status and importance in Indian agriculture. Detailed information on cultivated varieties, climatic and soil requirements, field preparation, planting methods, seed rate and treatment, nutrient management including the emerging role of nano-fertilizers, irrigation, weed management and harvesting practices is presented. The chapter also discusses post-harvest handling, grading, storage, physiological disorders, major insect pests, diseases and their integrated management strategies. Special emphasis is given to seed production through true potato seed (TPS) and the seed plot technique for maintaining seed health and quality.

Keywords: Potato, Tubers, Fertilizers, Irrigation, TPS

Introduction:

Potato (*Solanum tuberosum* L.) is a tuber crop in the Solanaceae family that contains a high amount of edible starch and is the only crop that can supply the country's food needs in addition to cereals. It is a perennial crop but grown as annual crop. Its centre of origin is South America in the Andean region of Peru and Bolivia. In Europe, Irish were the first to recognize its great value for food. Ireland became completely dependent on potato by the end of 18th century, which is evidenced by the Irish famine of 1845-47 AD, also, which has occurred due to total loss of potato crop in Europe from late blight (*Phytophthora infestans*). In India, potato was introduced either by Portuguese or the Britishers. By 1900 AD, small plots of potato were found near towns, scattered throughout India. It is a autotetraploid species having chromosome number 48.

Nutrition:

Potato is cultivated all over the world and is an important staple food crop. It contains 79 Kcal energy, 18.1 g carbohydrate by difference, 15.9 g starch, 2.14 g protein, 1.3 g dietary fibres, 1.13 g ash, 0.08 g total lipid (fat) per 100 g of edible matter, with various vitamins and minerals. Potato has corrected balance between the net protein calories and total calories. Fresh potato contains 20-30 mg of ascorbic acid per 100 g fresh weight. It contains 0.1 mg thiamin, 1.2 mg niacin, 0.25 mg pyridoxine, 0.3 mg pantothenic acid, 0.01 mg riboflavin and 14 mg folic acid per 100 g edible portion of freshly harvested potato. It also contains 40 mg phosphorus, 247 mg potassium, 21 mg magnesium and 11 mg sodium. Potato is one of the main cash crops among vegetables which is grown and consumed all over the world. Potato as a source of food, feed and fiber has always been important in a world of diminishing resources with an ever-increasing global population.

Area and Production:

Countries leading in production of potato are China, India, Ukraine, Russia, USA and Germany. India is the second largest producer of potato in the world after China with the total production of 570.53 lakh metric tonnes in 23.22 lakh hectare area in 2023-24. In India, potato is being consumed in various forms like vegetables, chips, flakes, flour and so on. Potato is grown in almost all parts of the country except Kerala. Uttar Pradesh, West Bengal, Bihar, Gujarat, Madhya Pradesh and Punjab account a great share in total production. The annual growth rate of potato is higher than other major food crops with respect to area, production and productivity. It contributes to the economy of country as it is exported to the neighboring and European countries for seed and table purposes.

Botany:

Potato is an annual, succulent, bushy, herbaceous, dicotyledonous plant. The aerial part of potato is called stem which is angular or round in shape, greenish or purple in colour having branching habit. Plant is erect at young stage and spreads as the plant become older. The leaves are alternate and compound. Potato has shallow rooted system which arises from the base of sprout that are adventitious in nature and spread over the upper layer of soil i.e., upto 20-25 mm depth. The root of potato can be categorized into various types like basal roots, functional roots, stolon roots and tuber roots. Underground stem of potato has nodes and internodes called stolons which grow outwards horizontally and tuberization takes place at the end of stolons. Potato is a C3 plant which is predominantly a self-pollinated plant and is occasionally cross-pollinated by insects. In potato, flowering occurs in cluster and the fruit is called berries. Vegetative shoot is a sympodium and each portion terminates in an inflorescence called cymose type.

Cultivated Varieties:

Early Varieties:

- **Kufri Chandramukhi:** It is an early variety and matures in about 80-90 days. Its tuber is white, large, smooth, oval and flattened, with white skin, fleet eyes and white flesh. The tubers, though up-to-date type, are smoother, more uniform and more attractive. The variety is capable of yielding about 100 q/acre. It is susceptible to late blight.
- **Kufri Ashoka:** Plants are tall, erect and medium compact with green foliage. It is an early bulking variety and matures in about 75-80 days under short day conditions. Its maturity is thus comparable with that of Kufri Chandramukhi. It is susceptible to late blight. However, it escapes late blight attack due to earliness. The tubers are large, smooth, oval long with white skin with fleet eyes. It has waxy texture and is easy to cook. It yields about 110 q/acre.
- **Kufri Pukhraj:** Plants are tall, vigorous and erect. It is an early bulking variety which gives economic yield quite comparable with Kufri Chandramukhi in 70 days. It is susceptible to late blight but escapes due to earliness. Its tubers are large uniform, oval, white with fleet eyes. It has dry matter content of 17-18 per cent. It yields 130 q/acre in 70-90 days.

Mid-Season Varieties:

- **Kufri Jyoti:** Plants are tall, erect, compact with light green foliage. It matures in about 90-110 days and yields about 80120 q/acre. Tubers are large, oval, white with fleet eyes and white flesh. Tubers show variable degree of cracking. The variety possesses moderate degree of resistance to late blight and slow rate of degeneration. It is suitable for planting in spring season.
- **Kufri Bahar:** The plants are medium compact and vigorous with grey-green foliage. The tubers are large, round-oval with white flesh with medium deep eyes. It is a late blight susceptible
- variety, but capable of yielding about 125 q/acre in about 100-110 days. It is not suitable for processing.

Late Varieties:

- **Kufri Sindhuri:** It is a medium late variety and takes 110-120 days to mature. The tuber is medium, smooth, round with light red skin, deep eyes and dull white flesh. The tubers have very good keeping quality. The variety yields about 120 q/acre. The tubers become hollow under very high fertility condition. It is not suitable for processing. It is moderately resistant to early blight and tolerant to leaf roll.

- **Kufri Badshah:** The plants are vigorous with smooth leaves. The tubers are large, oval, white, smooth with fleet eyes and dull white flesh. Tubers tend to develop purple colour on exposure to light. It is a moderately resistant to late blight, resistant to PVX and matures in about 100-110 days, yielding on an average 130 q/acre. It is not suitable for processing.

Climatic Requirements:

It is a temperate crop but susceptible to frost conditions. Short day conditions are favourable for tuber production and requires long day conditions for flowering. The crop is raised when maximum day temperature is below 30 ^{0}C and night temperature is not above 20 ^{0}C. Good crop growth is observed when days are sunny and nights are cool. Potato thrives well in cool climate. The highest tuberization is obtained when day and night temperature is 20 ^{0}C and 14 ^{0}C, respectively.

Soil Requirements:

Potato can be grown on different types of soils. Well drained, loose, friable, non-saline and non-alkaline loamy sand to sandy loam soils are suitable for this crop having a pH range of 5.2-6.4. It needs very high input and thus soils having the problems of salinity or acidity should be avoided.

Field Preparation:

Plough with a mould board or disc-plough, followed by the disc-harrow or the tiller, depending upon the soil type. In loamy sand soil, discing alone is sufficient. Apply farm yard manure after preparatory tillage just before planting as this practice is more beneficial than incorporating into the soil through cultivation. If weeds or stubbles of the previous crop are not a problem, potato can be grown with minimum tillage without loss in yield. Pre-sowing irrigation will help in the preparation of field, decomposition of FYM and debris of previous crop and help in reducing the weed seeds. As weeds germinate with irrigation, germinating weeds will have to be ploughed. It also helps in regulating the soil temperature.

Planting Season and Method:

The best time for sowing is last week of September to mid-October for the autumn crop and the second fortnight of January for the spring crop. However, the date of sowing in September would much depend upon the temperature prevailing at that time. After the field has been prepared well, mark rows with a row marker. A ridger should be used for planting the crop manually. Semi-automatic or automatic planters are recommended where tractor power is available. The spacing between the rows should be 60 cm and between the tubers 20 cm.

Seed Rate and Treatment:

Potato is propagated from tubers which are commonly spoken as seeds. Tubers are planted either whole or cut into pieces. For autumn sowing 12-18 q/acre seed tubers of 40-50 g weight should be used for planting. Good quality and disease-free seed should be used. The seed should be produced by using the seed plot technique. If the seed raised from autumn crop is to be used for spring planting, its dormancy should be broken by dipping cut tubers in a solution of 1% Thiourea and 1 ppm (one ml per 100 litres of water) Gibberellic Acid for an hour followed by air drying the treated tuber pieces for 24 hours in thin layers in shade. To control black scurf and common scab, treat the tubers with Tafasan or Emisan @ 2.5 g per litre of water for 10 minutes after taking out of the cold storage. The seed potatoes obtained from the cold store, cannot be planted immediately. It should first be dried with the help of blowers. Keep the treated tubers in a cool place/shade exposed in diffused sunlight for 8-10 days which initiates sprouting and helps the sprouts to become strong

Manures and Fertilizers:

Twenty tonnes of farmyard manure or green manuring along with 75 kg of N, 25 kg of P_2O_5 and 25 kg of K_2O per acre should be used. Drill all P_2O_5 and K_2O and half N at sowing and the remaining N at the time of earthing-up. Proper management of application of nitrogen fertilizer has a significant effect on growth, yield and productivity of potato as it is essential for production of chlorophyll, amino acids and proteins in plants, which are helpful for growth and development of plant. Inadequate supply of nitrogen can lead to decrease in growth, yield and quality of potato crops, while excess application of nitrogen can cause negative impact on yield of crop and various environmental issues. A novel approach to the problem of declining nutrient use efficiency (NUE) with a small environmental impact has been found in the use of nanotechnology to produce nano agri-inputs (NAIPs). By encapsulating plant nutrients in nanomaterials, using a thin coating of nanomaterials on plant nutrients nano-fertilizers are produced and distributed in the form of nano-sized emulsions. In plant leaves, nano-pores and stomatal openings enable the uptake of nanomaterials and their penetration deep into leaves, increasing nutrient use efficiency (NUE). The dynamics of size, shape, surface area and bio assimilation are used by these nano-fertilizers. In response to various signals including heat, moisture and other abiotic stress, nanofertilizers release the nutrients in a regulated way. Nanofertilizers may control the release of nutrients, give the right amount of nutrients to crops in the right proportions, and increase productivity while protecting the environment. In comparison to traditional fertilizers, nano-fertilizers offer advantages in terms of application and small requirement, gradual release mechanism, decrease in transportation and application cost, and relatively low salt accumulation in soil.

Earthing-up: A double mould board plough or a ridger should be used for earthing up after 25-30 days of sowing

Irrigation Management:

Water is key input in production of potato. Quantity, frequency and method of irrigation always decide growth, yield, quality and storability of potato tubers. Potato is highly susceptible to drought stress due to its sparse and shallow root structure because the root grows from the base of a sprout that is adventitious in nature and spread over the top layer of soil i.e. up to 20-25 mm depth. Water deficiency decreases plant height, number of leaves, leaf area, number of tubers, tuber growth, number of roots, fresh weight of root and leaves, dry weight of root, harvest index and tuber yield. Also, deficient irrigation promotes a reduction of tuber quality and low yield due to reduced photosynthesis per unit leaf area (Van Loon, 1981). Potato needs frequent irrigation for its tuber growth and yield. These parameters are influenced by amount and frequency of irrigation applied. However, to fulfill lack of water resources globally, irrigation management must be optimized in order to enhance water use efficiency (WUE). All the growth stages of potato like plant emergence, tuber set and bulking up are very sensitive to water stress. That's why a regular water supply to meet the crop water demand at different growth stages is highly recommended for better growth from sprout development to maturity. In case of furrow Irrigation, the first irrigation should be given immediately after planting as it ensures better germination. The potato crop responds well to light and repeated irrigations. While applying irrigation avoid the over flooding of the ridges and the subsequent hardening of the soil surface which interferes with emergence, growth and development of tubers. The total number of irrigations will be 7-8.

Weed Management:

The potato crop develops canopy in about 4 weeks after planting and weeds must be controlled by this time to gain competitive advantage for the crop. If the weeds are large, they should be removed before the ridging operations begin. After earthing up the weeds between the growing plants and at the top of the ridge should be removed by mechanical or herbicide application. Weeding can be done manually however it is expensive. Hence, animal drawn three-tine cultivator is used which can cover one hectare per day. Alternatively pre-emergence spraying of weedicides such as Flucholralin (0.70-1.0 kg a.i./ha) or Pendimethalin (0.50 kg/ha) is recommended for controlling annual grass weeds and broad leaf weeds.

Harvesting and Yield:

The time of harvest is very important in potato. The development of tubers continues till vines die. Potatoes are harvested from the time they are of sufficient size until the vines have fully ripened. The early maturing varieties can be harvested 80 days after planting and late varieties by 110-120 days after planting. Care should be taken at the time of harvest to save the tubers from injury. There should be optimum moisture in the soil at the time of harvest. The clods affect the efficient functioning of potato digger. Bullock drawn diggers can also be used. Keep the produce in the field after harvesting for 10-15 days. On an average 200-250 q/ha of tubers can be harvested.

Post Harvest Management:

After harvesting, cut, green and deformed tubers should be sorted out. Remaining tubers may be kept in a heap under a cool place for about 10-15 days for wound healing/curing. The height of heap should not be more than 1.0-1.5 m. Optimum temperature for curing of tubers is 20°C. Heap should be covered properly with thick layer of sugarcane trash or paddy straw or maize/ bajra straw, to avoid greening of tubers. After curing tubers are graded as per need of the market.

Grading:

After harvesting the potato should be graded. Four grades may be made

(i) Small size (below 25 g weight)

(ii) Medium size (25-50 g weight)

(iii) Large size (50-75 g weight)

(iv) Extra large size (above 75 g weight)

Storage:

It should be stored in the cold storage where temperature is maintained at 2-4 ^{0}C and relative humidity is 75-80%. Storage of Ware Potato cultivars like Kufri Chandramukhi, Kufri Jyoti and Kufri Chipsona-1 can be stored successfully for 5 months at 10±1 ^{0}C and 90-95% RH with two consecutive foggings of CIPC at the rate of 40 ml per tonne. The first fogging is given at the initiation of sprouting (chitting) and second after 60 days of the first fogging. The stored potatos maintain low reducing sugars (<0.25%) and are suitable for chipping and culinary purpose.

Physiological Disorders:

1. Blackheart: Internal browning or blackening of tuber tissues, usually at the centre. Tissue becomes necrotic and dry in severe cases

- **Causes:** Oxygen deficiency due to poor soil aeration, waterlogged or compact soils, high respiration during storage and high temperatures during tuber bulking or storage.
- **Management:** Avoid waterlogging, ensure good drainage, harvest at proper maturity, maintain proper aeration and temperature (2–4 °C) in storage and avoid piling tubers too deep after harvest.

2. Hollow Heart: Irregular cavity or hollow space in the centre of tuber and surrounding tissues may be brown.

- **Causes:** Rapid tuber growth due to sudden availability of water after drought, excess nitrogen fertilization, wide spacing and vigorous varieties.
- **Management:** Apply balanced fertilizers, avoid excess nitrogen, maintain uniform soil moisture and use recommended spacing.

3. Greening of Tubers: Green coloration on exposed tuber surface, accumulation of solanine (toxic), bitter taste and unfit for consumption.

- **Causes:** Exposure of tubers to sunlight in field or storage and improper earthing-up.
- **Management:** Adequate earthing-up, harvest at proper time, store tubers in dark conditions and cover tubers properly after harvest.

4. Growth Cracks: Deep cracks on tuber surface and tubers become misshapen.

- **Causes:** Uneven water supply, sudden irrigation after dry spell and excess nitrogen.
- **Management:** Maintain uniform irrigation, avoid excessive nitrogen application and follow recommended agronomic practices.

5. Chilling Injury: Internal browning, increased sugar accumulation and poor processing quality.

- **Causes:** Exposure to temperatures below 0 °C and improper cold storage management.
- **Management:** Store potatoes at recommended temperatures (2–4 °C for table potatoes) and avoid freezing conditions.

Major Pests and Their Management:

Jassids (*Empoasca devastans*) and Leaf Hoppers (*Amrasca beguttula*): They causes direct damage to potato crop by sucking up sap and are found in all potato growing regions. They cause serious damage to early planted potato crop in western Uttar Pradesh, Haryana and Punjab.

Whiteflies (*Bemisia tabaci*): It responsible for sucking sap. *Bemisia tabaci* is reported to be a vector of Gemini viruses also. White flies are serious pests for early potato crop in Punjab and Haryana.

Thrips (*Scirtothrips* sp.): They suck the sap from plants. Thrips are also vectors of stem necrosis in potato.

Aphids (*Myzus persicae* and *Aphis gossypii*): Aphids are important pests of potato. Though their direct damage by sucking sap is marginal compared to other pests, they are vectors of various potato viruses and thus degenerate the seeds stock. For all sucking pests, foliar spray of systemic insecticides such as dimethoate or thiometon or monocrotophos (0.03%) may be given.

Cut Worms (*Agrotis ipsilon* and *Agrotis segetum*): The larvae (caterpillar) of cut worms damage the crop by cutting the young plants at the base and later on by feeding on shoots and leaves. They feed on tubers by making deep and irregular galleries. Deep ploughing during summer in plains and autumn in hills helps to reduce its population. Light traps installed in and around potato fields attract the adults of cut worms. Chloropyrifos 20 EC (0.05%) or carbaryl (0.2%) may be used for the control of cut worms.

White Grubs (*Lachnosterna longipennis* and *L. coracea*): White grubs are distributed throughout the country. Grubs feed on rootlets, roots and tubers. Grubs damage the tubers without any symptoms on the foliage. The use of urea at higher doses kills the first instar grubs. Light traps can also be used for collecting beetle at night. Soil treatment with granules of phorate or carbofuran or isofenphos @ 2.0 kg a.i./ha at earthing up is recommended for the control of grubs.

Potato Tuber Moth (*Phthorimaea operculella*): Potato tuber moth is a pest of potato both in fields and the country stores. The losses to potato in country stores may be even up to 70%. Prolonged dry and hot weather is quite conducive for potato tuber moth multiplication. Larvae of Potato tuber moth (PTM) damage the crop foliage, exposed tubers in the field and stored tubers in the country stores. In infested tubers, the feeding tunnels are packed with black excretory pellets and the larvae are inside the tunnels. Planting seed tubers at a depth of 10 cm as against 6 cm will reduce its damage. Proper ridging after 6 to 7 weeks of planting so that tubers are buried at least 25 cm below the surface avoids damage. Timely and adequate irrigations minimize soil cracking and thereby reduce the risk of tuber exposure to PTM. Harvested tubers must be removed from the field as early as possible. The crops like tomato, tobacco, chillies and brinjal may not be grown near potato fields. Sex pheromones can be used for mass trapping of males. Crop may be sprayed with either quinalphos 25 EC or monocrotophos EC (0.05%) alternately once or twice with bioagents like *Bacillus thuringiensis* (Bt) or Granulosis virus (GV).

Root Knot Nematode (*Meloidogynae arenaria* and *M. incognita*): Small galls are formed on potato roots resulting in size and number of tubers and thus the yield. Avoiding using of seeds from infested areas, deep ploughing in summer months, burning of trash are the common cultural control measures. Following a two years rotational sequence of maize-wheat- potato- wheat reduces the root knot damage. Late planting of autumn crop and early planting ofspring crop in north western plains reduces the nematode damage, while in hills early planting of summer crop in 4th week of march is ideal. Application of carborfuran @ 3 kg a.i/ha is required in two split doses, i.e. at planting and earthing up.

Diseases and Their Management:

Late Blight (*Phytophthora infestans*): This is a most serious disease of potato. In hilly regions susceptibility of varieties results in losses as high as 85%. It appears every year on hills. However, in plains its intensity is low. In years with ample precipitation, it assumes epiphytotic proportions in plains also. On leaves it appears as pale green, irregular spots that enlarge into large water-soaked tissue turning necrotic and dark brown or black. On lower side of leaves, white mildew (cottony growth) ring forms around the dead areas. On stem, light brown lesions develop which enlarge and encircle the stem. Tubers are also infected by rain borne spores from blighted foliage and act as the main source of primary inoculum. Grow late blight resistant varieties, e.g., Kufri Badshah, Kufri Jyoti, Kufri Sutlej, Kufri Jawahar, Kufri Anand, Kufri Chipsona- 1, Kufri Chipsona- 2, Kufri Pukhraj, Kufri Megha, Kufri Giriraj and Kufri Kanchan. Use disease free seed tubers and proper earthing up reduces the infection of tubers with the pathogen. Spray mancozeb (0.2%) as soon as weather conditions become congenial for late blight appearance (temperature 10-20 °C, relative humidity >80%, intermittent rains, cloudy/foggy weather). Subsequent sprays of metalaxyl + mancozeb (0.25%) at 15 days interval may be given.

Early Blight (*Alternaria solani*): The incidence of early blight is generally high in crops receiving imbalanced doses of NPK, particularly low doses of N. Early blight occurs in all potato growing areas but is more common in central India and plateau of Bihar, Jharkhand and Maharashtra. It also appears regularly in north-western and north¬eastern hills and plains but is less significant. Leaf spot caused by *Phoma* spp., also occurs widely both in hills and plains and may cause significant yield losses. For the management of early blight and phoma leaf spot disease free may be used tubers. Application of balanced dose of fertilizers, especially of N, 1.0% urea at 45 days and repeating after 10 days and spraying of mancozeb (0.2%), copper oxychloride (0.3%) and bordeaux mixture (1.0%) takes care of early blight and leaf spots. Solanaceous crop should not be grown in the nearby fields.

Bacterial Wilt (*Ralstonia solanacearum*, *Pseudomonas solanacearum*): This is an important potato disease in north-eastern hills, eastern plains, north western mid hills (up to 2000 m), Deccan plateau and Nilgiris hills. It causes premature death of plants and rotting of tubers in transit and storage. In the field, yield losses may be upto 70%. Main symptoms are grey to brown milky slime exudation from vascular tissue of freshly cut stems and tubers and wilting of plants. It is both soil and tuber borne. Healthy seed tubers are to be used for planting. Rotation of potato with crops like onion, garlic, cabbage, knol-khol, cereals, horsegram, lupin is useful. Keeping the field fallow also helps in reducing its incidence. Application of stable bleaching powder @ 12 kg/ha as drenching along ridges will check the incidence.

True Potato Seed:

True potato seed (TPS) is a sexually reproduced propagule in potato and results from the fertilization of ovules which develops into tiny seeds inside the fruit called berry. The seed thus called true potato seed (TPS) or botanical seed to distinguish it from the conventional tuber seed.

The following aspects are considered while raising a seed potato crop:

1. Certified or foundation seed should be obtained from a reliable source.
2. Crop rotation helps in reducing the incidence of some soil borne diseases such as black scurf.
3. Slightly higher seed rate is used than the ware crop to have more stems per unit area and thus more number of medium sized tubers.
4. Maintain an isolation distance of 30 m between two varieties.
5. Nitrogen dose is reduced by about 20%.
6. Planting of well sprouted tubers is done by first week of October. Planting before October gives rise to plants which do not look quite normal due to high temperature and it will be difficult to rogue out the off-type plants. Delay in planting will cut short the growing season.
7. Roguing out of virus affected plants may be done during the season at least 2-3 times. First roguing is done 25-30 days after planting and the second rouging, 15-20 days after first roguing. While roguing, touch only those plants which are to be removed. Tubers if any should also be taken out.
8. There should be minimum entry to the seed crop to avoid the spread of contact viruses. For this, complete earthing up is done at the time of planting and weeds are controlled by pre-emergence application of weedicides to avoid intercultural operations during the growing season.
9. Withhold irrigation 7-10 days earlier to dehaulming.
10. Only whole tubers are used for raising seed crop, as by cutting tubers, virus spreads through knife used for cutting of tubers.
11. Haulm killing is done by using gramoxone.
12. After harvesting, tubers are cured and treated with 0.25% emisan for 15-20 min for the control of black surf. If common scale is also a problem then treat the seed tubers with 3% boric acid for 30 min.
13. Treated tubers are stored in cold store and used for seed only.

About 150 g of true potato seed (TPS) is required for raising seedlings in 75 m^2 nursery bed for transplanting one hectare of land.

Seed Plot Technique:

This technique aims at raising a healthy seed crop of potato in Punjab during the period of low aphid incidence. This pest is responsible for transmitting the viral diseases, like leafroll, PVX, PVY and PVA. For the seed crop, healthy seed potato, free from viral infection should be obtained and planted in autumn i.e. in the first week of October. Sowing at a spacing of 50 x 15 cm would ensure the development of a large percentage of seed size tubers. An acre of the seed crop will produce enough seed for planting of 8 to 10 acres of the crop. Normal plant protection measures should be adopted to control aphids and other insect pests. Rogue out otherwise unhealthy plants noticed during the growing season to ensure the production for better quality seed. Towards mid-December, irrigation may be restricted and later withheld completely so that the haulms wilt and fall down. As soon as there are 20 aphids per 100 leaves, cut the haulms. Allow the tubers to mature in soil for about 15 days. The harvested crop may be graded and transferred to cold storage for planting in the following autumn season.

Conclusion:

Potato stands out as a versatile, high-yielding and nutritionally rich crop that plays a vital role in ensuring food security, enhancing farm income, and supporting agro-based industries. Its wide adaptability to diverse agro-climatic conditions, along with the availability of improved varieties, has led to a steady expansion of its cultivation in India and worldwide. Successful potato production relies on scientifically sound practices such as appropriate variety selection, use of quality seed, balanced nutrient management, efficient irrigation scheduling, timely weed control, and integrated pest and disease management. Recent advances, including the seed plot technique, true potato seed, and nano-fertilizers, provide new opportunities to improve seed health, nutrient use efficiency, productivity, and environmental sustainability. Proper harvesting, grading, and storage practices are also essential to reduce post-harvest losses and maintain tuber quality. In the context of population growth, resource constraints, and climate variability, adopting improved, resource-efficient technologies in potato cultivation is crucial for sustainable agriculture and food security.

References:

1. FAO. (2009). *Potato and soil fertility management*. Food and Agriculture Organization of the United Nations.
2. Khurana, S. M. P., Minhas, J. S., & Pandey, S. K. (2003). *The potato: Production and utilization in sub-tropics*. Mehta Publishers.
3. Pandey, S. K., & Kang, G. S. (2004). *Potato production technology*. Central Potato Research Institute, ICAR.
4. Pushkarnath. (1976). *Potato in subtropics*. Orient Longman.

PRODUCTION TECHNOLOGY AND CROP MANAGEMENT OF TOMATO

Himanshu*[1] and Vikas Sagwal[2]

[1]Department of Vegetable Science,

CCS Haryana Agricultural University, Hisar, Haryana, India

[2]Department of Vegetable Science,

Maharana Pratap Horticultural University, Karnal, Haryana, India

*Corresponding author E-mail: himanshumehla1999@gmail.com

Abstract:

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated and economically important vegetable crops of the world, valued for its high yield potential, nutritional richness, and versatility in fresh consumption as well as processing. Belonging to the family Solanaceae with a chromosome number of 2n = 24, tomato ranks next only to potato in overall importance and occupies the foremost position among processed vegetables. This chapter provides a comprehensive account of tomato, covering its origin, domestication, botanical characteristics, nutritional importance and global as well as national production status with special reference to India. Detailed descriptions of important cultivated varieties and hybrids, climatic and soil requirements, field preparation, planting seasons, nursery and crop management practices, nutrient and irrigation management, use of growth regulators, weed control, staking, harvesting stages, grading, storage and seed production techniques are presented. In addition, major physiological disorders, insect pests and diseases affecting tomato are discussed along with their causes and effective management strategies.

Keywords: Tomato, Irrigation, Fertilizer, Growth Regulator.

Introduction:

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated vegetable crop in the world due to its high yielding potential and versatility in both fresh and preserved forms. It belongs to the family Solanaceae with chromosome number 2n = 24 (x=12) ranking second in significance next to potato and first among preserved and processed vegetables. It is primarily a self-pollinating crop that permits up to five percent cross-pollination and is a day-neutral plant having tap root system and berry-like fruit type. The tomato is indigenous to the Andean region, which includes portions of Colombia, Ecuador, Peru, Bolivia and Chile with Mexico serving as its domestication centre.

Nutrition:

Tomato is rich in vitamins (Vit. A, Vit. C, Folates), minerals (Potassium) and organic acids (Healthy acids). It is the richest source of lycopene (antioxidant) among all the fruits and vegetables, which imparts anticancerous properties to the fruits. Due to its high concentration of nutrients, vitamins, minerals, plant pigments (particularly lycopene) and phenolic compounds (particularly flavonoids), tomato is also regarded a "protective food." It is also known as the poor man's orange due to its great nutritional value.

Area and Production:

The leading tomato-producing nations are China, India, Turkey and the United States. India is the second largest producer of tomato in the world after China with the total production of 213.23 lakh metric tonnes in 8.54 lakh hectare area in 2023-24. In India, the most important tomato-producing states are Madhya Pradesh, Andhra Pradesh, Karnataka, Gujarat and Tamil Nadu.

Botany:

It is an herbaceous annual plant with bisexual flowers and the fruit is a true berry. It is a self-pollinated crop but cross-pollination up to 5% has been reported. It is usually grown as an annual for both fruit as well as seed purpose. According to the growth habit, the tomato plants have been categorized into two types, viz. (i) indeterminate and (ii) determinate. The plant of indeterminate type terminates in a vegetative bud and the main axis continues growing indefinitely, whereas that of the determinate type terminates in a flower bud and is appropriately called 'self topping' or 'self pruning' type. Tomato inflorescence or flower cluster is borne laterally in small-forked raceme cyme. The number of flowers per cluster in most cultivars varies from 4 to 5 and sometimes more.

Cultivated Varieties:

- **Kashi Vishesh:** It has determinate plants and fruits are spherical and is developed by IIVR, Varanasi. It is recommended for Jammu and Kashmir, Himachal Pradesh, Uttar Pradesh, Bihar, Uttarakhand, Punjab, Jharkhand, Chhattisgarh, Odisha and southern states. It is resistant to TLCV. Duration 70-75 days after transplanting yield: 450-550 q/ha.
- **Arka Abha:** Developed by IIHR, Bengaluru. Plants semi determinate, fruits oblate with average weight 75 g. Resistant to bacterial wilt caused by *Ralstonia solanacearum* suitable for kharif and rabi. Duration 140 days and yield 430 q/ha.
- **Arka Alok:** Developed by IIHR, Bengaluru. Plants determinate, fruits firm, resistant to bacterial wilt. Both for kharif and rabi duration 130 days, yield 400 q/ha.
- **Swarna Lalima:** Released by ICAR-RCER, Patna. Resistant to bacterial wilt. Yield: 600-700 q/ha.
- **Arka Abhijit:** This is an F_1 hybrid developed by IIHR, Bengaluru. For Karnataka, Maharashtra and Madhya Pradesh. Plants semi-determinate, dark green leaves, fruits

medium [65-70 g], suitable for fresh market, resistant to bacterial wilt. Duration 140 days and yield 650 q/ha.

- **Arka Shreshta:** This is an F_1 hybrid developed by IIHR, Bengaluru. Plants semi-determinate fruits medium large. For fresh market and processing. Resistant to bacterial wilt and suitable for rabi. Yield 760 q/ha. Duration 140 days.
- **Arka Samrat:** This is a hybrid developed by IIHR, Bengaluru. High yielding F_1 hybrid with triple disease resistance to tomato leaf curl virus (ToLCV) + Bacterial wilt (BW) + early blight (EB). Plants, semi-determinate with food foliar cover. Fruits high round, firm with average fruit weight 100-110 g. Yield: 800-850 q/ha in 140 days.
- **Arka Rakshak:** This is a hybrid developed by IIHR, Bengaluru. High yielding F_1 hybrid with triple disease resistance to ToLCV+BW+EB. Plants, semi-determinate with good foliar cover. Fruits square round, very firm with average fruit weight 80-90 g. Yield: 750-800 q/ha in 140 days.
- **Arka Ananya:** This is an F_1 hybrid developed by IIHR, Bengaluru. This has combined resistance to ToLCV and Bacterial wilt. It gives an yield of 760 q/ha. Fruits are round, firm (5.0 kg/cm^2), medium (50-60 g) with light green shoulder. First fruit maturity in 55-60 days. It develops deep red colour on ripening.
- **Arka Ashish:** Developed by IIHR, Bengaluru. Plants determinate with dark green foliage, fruits oval, excellent fruit colour (lycopene 10 mg/100 g) with TSS 4.8%. Suitable for processing. Tolerant to powdery mildew and fruit cracking. For both kharif and rabi. Duration 130 days and yield 380 q/ha.
- **Arka Vardan:** This is an F_1 hybrid developed by IIHR, Bengaluru. Plants indeterminate, fruits large (140 g) and round tolerant to fruit cracking. Resistant to nematodes. Requires staking. For both kharif and rabi, 160 days duration and yield 750 q/ha.
- **Pusa 120:** This variety was released by IARI, New Delhi. Semi-determinate, prolific bearer, medium coverage, medium to large-sized, flattish round fruits, uniform ripening, circular cracking, highly tolerant to nematodes. Maturity 130 days. Yield 300-350 q/ha.
- **Arka Ashish:** Developed by IIHR, Bengaluru. Plants determinate with dark green foliage, fruits oval, excellent fruit colour (lycopene 10 mg/100 g) with TSS 4.8%. Suitable for processing. Tolerant to powdery mildew and fruit cracking. For both kharif and rabi. Duration 130 days and yield 380 q/ha.
- **Arka Saurabh:** Developed by IIHR, Bengaluru. High-yielding, (40 tonne/ha). It is semi-determinate, fruits very firm and round, medium sized with smooth skin and thick flesh. Very good keeping quality and suitable transport. 8-10 days in room temperature

amongst the round fruited varieties. TSS 3.9% and acidity 0.39%, suitable both for fresh consumption and processing.

- **Pant T-3:** Developed by GBPUAT, Pantnagar. Semi-determinate, dark green foliage, fruits round, smooth, medium size, suitable for processing. Maturity 70 days. Yield 190 q/ha.
- **Pusa Gaurav:** Developed by IARI, New Delhi. Determinate, good foliage cover, firm fruits, oval in shape (egg shaped), yellow stem end, uniform ripening, thick pericarp, two locules, highly suitable for long distance transportation and processing. Maturity 110 days. Yield 300-400 q/ha.
- **Arka Ahuti:** Developed by IIHR, Bengaluru. Plants semi-determinate, Fruits oblong, TSS 5.2%. Suitable for processing for both the seasons, 140 days and yield 420 q/ha.
- **Pusa Divya:** Developed by IARI, New Delhi. Indeterminate fruits round, smooth, firm, suitable for long distance transportation. The only hybrid developed so far by utilizing male sterile line in India. Maturity 90-100 days. Yield 350-450 q/ha.
- **Pusa Rohini:** Developed by IARI, New Delhi. Determinate, fruits round, smooth medium-sized thick pericarp. Suitable for long distance transportation. Maturity 120 days. Yield 410 q/ha.
- **Roma:** Introduced by IARI, Katrain. Determinate plants, light green broad leaflets, medium sized fruits, elliptical with yellow stem end, suitable for transportation and hilly areas. Maturity 100-120 days. Yield 300-350 q/ha.
- **Arka Meghali:** Developed by IIHR, Bengaluru. Plants semi-determinate, narrow dark leaves, fruits medium, oblate and deep red. Suitable for rainfed cultivation and kharif season. Duration 125 days and yield 180 q/ha.
- **Punjab Chhuhara:** The plants are dwarf, being about 60 cm tall. Its dense foliage protects the fruits from sunburn. The fruit is pear shaped, small to medium with fewer seeds. Its fruits ripen uniformly. It yields about 320 q/acre.
- **Pusa hybrid-1:** Developed by IARI, New Delhi. Determinate, good foliage colour, fruits round, smooth, attractive. Can set fruit upto 28 °C night temperature, fruits from June to mid-July, the lean period for tomato in north India. Maturity 95 days. Yield 320 q/ha.
- **Pusa Sadabahar:** Developed by IARI, New Delhi. Determinate, dwarf, accommodate more plants per unit area, prolific bearer, smooth, oval to round, attractive fruits. Highly suitable for growing under wide range (8-30 °C) of night temperatures. Maturity 60 days. Yield 300-400 q/ha.

- **Pusa Sheetal:** Developed by IARI, New Delhi. Semi-determinate, light green foliage, fruits flattish round, medium size, attractive, uniform ripening, yellow stem end, prolific bearer, capable of fruit setting at 8 °C night temperature. Maturity 90 days. Yield 360 q/ha.
- **Pusa Ruby:** Developed by IARI, New Delhi. Indeterminate, light green foliage, fruits flat, slightly furrowed, yellow stem end, attractive uniform ripening, slightly acidic in taste. Maturity 60-85 days after transplanting. Yield 300 q/ha.
- **Pusa Early Dwarf:** Developed by IARI, New Delhi. Determinate, good foliage cover, fruit medium in size, slightly furrowed, flattish round, yellow stem end, very prolific bearer. Maturity 70-80 days. Yield 300 q/ha.
- **Pusa Uphar:** Developed by IARI, New Delhi. Indeterminate, upright plant, leaves cut, moderate coverage, fruits smooth, round to flattish-round, medium-sized, yellow stem end, thick pericarp. Maturity 120 days. Yield 370 q/ha.
- **Kashi Amrit:** Developed by IIVR, Varanasi. Plants determinate, fruits large, flattish round and red. Duration 75-80 days and yield 500-600 q/ha. Suitable for Rajasthan, Gujarat, Haryana and Delhi.
- **Kashi Hemant:** Developed by IIVR, Varanasi. For Madhya Pradesh, Chhattisgarh, Andhra Pradesh, Odisha, Maharashtra. Yield 400-420 q/ha.
- **Arka Vikas:** Developed by IIHR, Bengaluru. It is a high-yielding variety (350-400 q/ha) with large-sized, oblate, medium-sized firm fruits. It is suitable for fresh market.
- **Arka Vishal:** Developed by IIHR, Bengaluru. Plants indeterminate, fruits large (140 g) tolerant to cracking, requires staking, suitable for kharif and rabi. Duration 165 days and yield 750 q/ha. Recommended for Karnataka, Bihar and Uttar Pradesh.

Climatic Requirements:

Tomato is a warm season crop. It is sensitive to frost and it does not thrive at low, non-freezing temperatures. High temperatures, accompanied by low humidity and dry winds, frequently damage floral parts and there will be no fruit set. Among the several abiotic stress, heat stress is given more attention due to their role in hindering crop growth and development. The rise in temperature becomes major curtailing factors for declining growth and yield of plant and also determines the geographical spread of plants. The optimal growing temperature of tomato is 25–30 ºC during day time and 20 ºC during night time. A temperature above this threshold can lead to serious deleterious effects such as flower aborts, decrease of pollen quality, abnormal growth and reduced fruit set. Tomato requires a relatively long growing season with plenty of sunshine and moderate day temperature of 20–28 ^{0}C. It is sensitive to frost. Under low temperature, the plant growth is restricted and fruit setting is low. The red pigment in the fruit will develop only when the temperature is between 15 ^{0}C and 30 ^{0}C. Above this range of temperature, only the yellow pigment formed. When the temperature exceeds 40 ^{0}C, no pigment will be formed.

Soil Requirements:

Tomato can be grown in all types of soils, but the soil should be friable. However, it grows best in light soils ranging from sandy loam to loam. Tomato grows on practically all soils, from light sandy to heavy clay. Light soils are good for an early crop, while clay loam and silt loam soils are suited for heavy yields. If the soil is acidic, liming is required, as tomatoes do best in a soil that has a pH of 6-7.

Field Preparation:

The field is ploughed to fine tilth by giving four to five ploughing with a sufficient interval between two ploughing. Planking should be done for proper levelling. Furrows are then opened at the recommended spacing. Well-decomposed FYM (25 t/ha) is thoroughly incorporated at the time of land preparation.

Planting Season and Method:

Seedlings are transplanted in furrows in light soils and on side of the ridges in case of heavy soils. Seeds are sown in June July for autumn winter crop and for spring summer crop seeds are sown in November. In the hills seed is sown in March April. For winter planting, sowing should be done in October and transplanting in November-December. Sarkanda cover should invariably be provided during winter to protect the plants against frost. The transplanting of tomato can also be done in February. For February planting, sow seed in the end of November and protect seedlings from frost in the nursery beds by covering with polythene sheets or sarkanda thatch. However, the yield obtained would be comparatively lower from February planted crop than from November planted crop.

Seed Rate and Treatment:

Seed rate is 100 g/acre when sown in the nursery. Sow nursery in 50 m^2 area to transplant one acre. Dwarf varieties require a close spacing of 75 cm x 30cm. Rainy season varieties should be planted at a spacing of 120-150 cm x 30 cm.

Nursery Management:

Prepare 1.5m wide and 20 cm high beds in an area of about 50 m^2 to raise seedlings for an acre. Mix 5 quintals of well rotten farmyard manure with the soil and water the beds at least 10 days before sowing. Drench the beds with 1.5 to 2.0 % solution of Formalin by applying 4-5 litres of solution per square metre. Cover beds with a plastic sheet for 48-72 hours. Treat the seed with 3 g Captan/ Thiram per kg of seed. Sow seeds 1 to 2 cm deep in lines with 5 cm spacing. Drench the nursery plants with 0.4% Captan/ Thiram (4g/litre of water) after 5 to 7 days of germination. Repeat after 7 to 10 days. The seedlings become 15 to 20 cm tall in four to six weeks. After lifting the seedlings, wrap them in a wet paper for carrying to the transplanting site.

Manures and Fertilizers:

Apply 15-20 tonnes of well rotten farmyard manure and plough it into the soil. Add 120 kg of N along with 80 kg of P_2O_5 and 50 kg of K_2O per hectare. Half dose of N and full dose of P and K is given at the time of planting. The balance half of N is given as top dressing 30 days after transplanting. In the sandy soils, apply nitrogen in three split doses. Under high fertility conditions, the application of N should be reduced, as the blossoms may fail to set fruit due to the unfavourable carbohydrate nitrogen ratio within the plant.

Growth Regulator:

Foliar application of Gibberellic acid @ 10-20 ppm resulted into higher yield at low temperature. Seed treatment of Gibberellic acid @ 40-100 ppm leads to seed germination. Foliar spray of ethephon @ 100-500 ppm increase flowering, fruiting and yield. Foliar spray of PCPA @ 50-100 pm results into fruit set at low and high temperatures.

Irrigation Management:

Tomato is very sensitive to water application. First irrigation should be given immediately after transplanting. Subsequent irrigations may be given after 6-7 days during summer and 10-15 days during winter months. Total number of irrigations required are 14 to 15. Flowering and fruit development are the critical stages of tomato.

Staking: Due to the tall habit and heaving bearing nature of the hybrids staking is essential. Staking facilitates intercultural operations and helps in maintaining the quality of the fruits. It is done 2-3 weeks after transplanting.

Weed Management:

The field should be kept weed-free, especially in the initial stage of plant growth, as weeds compete with the crop and reduce the yield drastically. Frequent shallow cultivation should be done at regular interval so as to keep the field free from weeds and to facilitate soil aeration and proper root development. For weed control in tomato, apply Stomp 30 EC (pendimethalin) one litre/acre or 750 ml/acre followed by one hoeing or Basalin 45 EC (fluchloralin) one litre/acre or 750 ml/acre followed by one hoeing or Sencor 70 WP (metribuzin) 300g/acre. These weedicides should be applied 3-4 days before transplanting on prepared beds and Basalin 45 EC (fluchloralin) need to be mixed into soil with light harrowing and planking.

Harvesting and Yield:

Depending on the variety, fruits become ready for first picking in about 60-70 days after transplanting. The stage of harvesting depends upon the purpose to which the fruits are to be used. The different stages of harvesting are as follows:

1. Dark green colour- Dark green colour is changed and a reddish pink shade is observed on fruit. Fruits to be shipped are harvested at this stage. If seeds are cut, the fruit is too immature for harvest and will not ripen properly.
2. Breaker stage- Dim pink colour observed on ¼ part of the fruit. Fruits are harvested at this stage to ensure the best quality. Such fruit are less prone to damage during transportation.
3. Pink stage- Pink colour observed on ¾ part of the fruit.
4. Reddish pink- Fruits are stiff and nearly whole fruit turns reddish pink. Fruits for local sale are harvested at this stage.
5. Fully riped- Fruits are fully riped and soft having dark red colour. Such fruits are used for processing.

The yield per hectare varies greatly according to variety and season. On an average, the yield varies from 20-25 t/ha. Hybrid varieties may yield upto 50-60 t/ha.

Grading:

The grades are mostly based on the condition and the quality of the fruits and not specifically on their size. However, on the basis of the size of the fruits three grades are formed: small (<100 g), medium (100-255 g) and large (> 255 g). Bureau of Indian Standards has specified 4 grades viz., Super A, Super, Fancy and Commercial for tomato crop.

Storage:

A storage temperature of 13 ^{0}C with 90-95% relative humidity is recommended for slow ripening. At this temperature, most varieties keep in good condition for 2-3 weeks and change colour very slowly. In cold storage, unripe tomatoes can be stored for 4 weeks at a temperature of 8-10 ^{0}C with 85-90 % relative humidity. Fully ripe fruits are stored at 7 ^{0}C with 90% relative humidity for 1 week.

Seed Production and Extraction Methods:

The tomato should be grown at the isolation distance of atleast 50 m from other varieties to avoid any chance of contamination. Minimum three field inspections should be made for getting the true to type seed. The first inspection should be made at vegetative phase, second at flowering and fruiting and third before harvesting of fruits. Any off type and diseased plants should be removed. The extraction of seed from the ripe fruits is done by fermentation method and acid method. In fermentation method, the crushed fruits are allowed to ferment for 1 to 2 days and then put in water where pulp and skin float and the seeds settle down at the bottom. In Acid method, about 100 ml of commercial hydrochloric acid is thoroughly mixed to 14 kg of crushed tomato fruits. The seeds are separated out from the pulp within half an hour which may be cleaned, dried and packed.

Physiological Disorders:

1. **Blossom end rot:** It can appear on fruits at any time in their development, but most commonly appears when fruits are one-third to one-half grown. The initial symptoms are water-soaked spots on the blossom end of the fruit. These spots later enlarge and become black. Secondary infection by other decay causing organisms usually follows.

   Cause: Calcium deficiency in the developing fruit. Extreme fluctuations in moisture, root pruning and excessive nitrogen fertilization can also result in blossom end rot.

   Control: Avoid excessive application of Nitrogen particularly in ammonium form. Application of lime or calcium based fertilizers (eg. Calcium Ammonium Nitrate) as basal dose is commonly used to control this physiological disorder. Foliar spray of Calcium chloride (3 g/litre of water) also controls this disorder.

2. **Catface:** It is a condition involving malformation and scarring of fruits, particularly at blossom ends. Affected fruits are puckered with swollen protuberances and can have cavities extending deep into the flesh.

   Cause: Generally, any disturbance to flowers can lead to abnormally shaped fruits. Extreme heat, drought, low temperature, and contact with hormone-type herbicide sprays may cause flower injury.

   Control: Other than keeping herbicides away from flowers, the only control for catface is planting less susceptible tomato varieties.

3. **Puffiness:** Fruit suffering from puffiness appears somewhat bloated and angular. When cut, cavities may be present that lack the normal "gel" and the fruit as a whole isn't as dense.

   Cause: Puffiness results from incomplete pollination, fertilization, or seed development often as a result of cool temperatures that negatively impact fertilization. Similar to growth cracking, high nitrogen and low potassium can also lead to puffiness.

   Some tomato cultivars are more susceptible to this disorder than others.

4. **Sunscald:** Tomato fruits nearing maturity when exposed to the sun are prone to scald. The tissue has blistered water-soaked appearance. Rapid desiccation leads to sunken area which usually has white or grey colour in green fruit or yellowish in red fruits.

   Cause: Any factor causing a loss of leaves, such as disease, will expose fruits to sunlight and increase chances for sunscald.

   Control: Maintaining a continuous disease control program will lessen chances of foliage loss. Covering exposed fruits with straw, if plants are not staked reduce the incidence of sunscald.

5. **Cracking:** Cracks results from extremely rapid fruit growth brought on by periods of abundant rain and high temperatures, especially when these conditions take place following periods of stress. Cracks of varying depth radiate from the stem end of the fruit, blemishing the fruit and providing an entrance for decay-causing organisms.

   Cause: It is common during rainy season when temperature is high, especially when rain follows long dry spell. Radial cracking is more likely to develop in full ripe fruit than in mature green. Fruits exposed to sun develop more concentric cracking than those, which are covered with foliage.

Diseases and Their Management:

1. **Damping Off (*Pythium aphanidermatum*):** Damping off of tomato occurs in two stages, i.e. the pre-emergence and the post-emergence phase. In the pre-emergence the phase the seedlings are killed just before they reach the soil surface. The young radical and the plumule are killed and there is complete rotting of the seedlings. The post-emergence phase is characterized by the infection of the young, juvenile tissues of the collar at the ground level. The infected tissues become soft and water soaked. The seedlings topple over or collapse.

   Control: Seed treatment with fungal culture *Trichoderma viride* (4 g/kg of seed) or Thiram (3 g/kg of seed) is the only preventive measure to control the pre-emergence damping off. Soil drenching of the affected seedlings with Dithane M45 (3 g/litre of water) helps to reduce the disease incidence.

2. **Early Blight (*Alternaria solani*):** The fungus attacks the foliage causing characteristic leaf spots and blight. Early blight is first observed on the plants as small, black lesions mostly on the older foliage. Spots enlarge, and by the time they are one-fourth inch in diameter or larger, concentric rings in a bull's eye pattern can be seen in the center of the diseased area. Tissue surrounding the spots may turn yellow. The fungus also infects the fruit, generally through the calyx or stem attachment. Lesions attain considerable size, usually involving nearly the entire fruit; concentric rings are also present on the fruit.

   Control: Removal and destruction of the affected plant parts. Practicing crop rotation helps to minimize the disease incidence. Spraying the crop with Difolatan (0.2%), Dithane M-45 (0.2%) or Bavistin (0.1%) is recommended for effective disease control.

3. **Buck Eye Rot (*Phytophthora parasitica*):** The disease causing the fruits to rot initially affects the fruits near the ground level. The pathogen does not affect the foliage and thus the disease is distinct from late blight. The disease appears as a greyish green or brown water-soaked spot that usually occurs where the fruit touches the soil. As the spot enlarges, the surface of lesion assumes a pattern of concentric rings of narrow, dark

brown and wide, light brown bands. When young green fruits are infected, they usually become mummified.

Control: In order to minimize infection, good drainage conditions should be maintained in the field. Staking plants and removing foliage and fruits upto a height 15-30 cm from ground level helps to control this disease. Spraying with Difolaton (0.3%) 4 times at an interval of 10 days effectively controls the disease.

4. **Late Blight (*Phtophthora infestans*):** Late blight occurs when humid conditions coincide with mild temperatures for prolonged periods. If conditions are ideal for disease development, disease development is rapid causing severe economic losses. Lesions produced on the leaves are at first irregular, rather large, greenish-black and water-soaked. These areas enlarge rapidly, becoming brown, and under humid conditions, develop a white moldy growth near the margins of the diseased area on the lower surface of the leaves or on stems.

   Control: Control practices include rotating fields so as not to follow potato or tomato; avoiding planting tomatoes near potatoes; using disease-free seeds and transplants. Before planting the seeds should be treated with Thiram (2-3 g/kg of seed). The plants must be sprayed with Captafol (2 g/litre of water) or Dithane M 45 (2 g/kg of seed) at 15 days interval, starting from 30 days after transplanting.

5. **Bacterial Canker (*Clavibacter michiganensis* pv. *michiganensis*):** Affected plants show temporary or permanent leaf wilting. Light streaks develop at the petiole–stem junction and later form canker-like cracks on stems and leaves. Cut stems reveal yellowish to brown discoloration near the phloem. Green fruits develop water-soaked spots with a white halo.

   Control: Treat seeds with hot water (50°C for 25 min) or disinfectants, follow crop rotation with non-host crops, and use antibiotic seed soaking to protect seedlings.

6. **Tomato Mosaic Virus (TMV):** Leaves show light and dark green mottling, distortion, and reduced size, sometimes forming fern-like shapes. Plants become stunted and pale. The virus spreads through contact with infected plants, tools, and workers.

   Control: Use healthy seeds, disinfect seeds before sowing, remove infected plants early, avoid planting susceptible crops, and maintain field hygiene.

7. **Tomato Leaf Curl Virus (TLCV):** Transmitted by whiteflies, this disease causes severe plant stunting, leaf curling, yellowing, and bushy growth. Infected plants produce poor yield.

   Control: Remove diseased plants, control whiteflies using insecticides, remove alternate hosts, use barrier crops, and apply polythene mulching to reduce disease spread.

8. **Tomato Spotted Wilt Virus (TSWV):** Spread by thrips, it causes dark spots, streaks, bronzing, and drying of leaves. Fruits show circular rings and colored bands.

   Control: Destroy infected plants, eliminate alternate hosts, and control thrips with insecticide sprays.

Major Pests and Their Management:

1. Aphids (*Aphis gossypii, Myzus persicae*):

Symptoms

- Curling and yellowing of leaves
- Sticky honeydew on leaves leading to sooty mould
- Stunted plant growth
- Poor fruit development

Cause (Nature of Damage)

- Nymphs and adults suck sap from tender leaves and shoots
- Act as vectors of viral diseases (TMV, TLCV)

Management

- Spray Imidacloprid 0.3 ml/litre or Thiamethoxam 0.25 g/litre
- Encourage natural enemies (ladybird beetles)
- Remove weeds and infected plants
- Use yellow sticky traps

2. Whitefly (*Bemisia tabaci*):

Symptoms

- Yellowing and curling of leaves
- Reduced plant vigour
- Honeydew secretion and sooty mould
- Severe leaf curl disease symptoms

Cause

- Sucking of plant sap
- Vector of Tomato Leaf Curl Virus (TLCV)

Management

- Seedling dip with Imidacloprid (0.3 ml/litre)
- Spray Acetamiprid 0.2 g/litre or Thiamethoxam 0.25 g/litre
- Use reflective mulches
- Install yellow sticky traps

3. Thrips (*Thrips tabaci*):

Symptoms

- Silvery streaks on leaves
- Leaf curling and deformation
- Bronzing and drying of foliage
- Ring spots on fruits (TSWV transmission)

Cause

- Sucking of sap from leaves and flowers
- Transmission of Tomato Spotted Wilt Virus

Management

- Spray Spinosad 0.3 ml/litre or Fipronil 1 ml/litre
- Remove alternate weed hosts
- Maintain field sanitation

4. Fruit Borer (*Helicoverpa armigera*):

Symptoms

- Holes on developing fruits
- Larvae feeding inside fruits
- Entry holes plugged with excreta
- Heavy fruit drop and rotting

Cause

- Caterpillars bore into fruits and feed on pulp

Management

- Install pheromone traps (5–10/ha)
- Release *Trichogramma chilonis* @ 50,000/ha
- Spray Spinosad 0.25 ml/litre or Emamectin benzoate 0.4 g/litre
- Collect and destroy damaged fruits

5. Cutworm (*Agrotis ipsilon*):

Symptoms

- Seedlings cut at ground level
- Wilting and death of young plants
- Gaps in field stand

Cause

- Caterpillars feed at night and hide in soil during day

Management

- Deep summer ploughing

- Apply Chlorpyriphos 2 ml/litre as soil drench
- Use poison bait (bran + jaggery + insecticide)

6. Leaf Hopper (Jassids) (*Amrasca biguttula biguttula*):

Symptoms

- Yellowing at leaf margins (hopper burn)
- Curling and drying of leaves
- Stunted growth

Cause

- Sap sucking by nymphs and adults

Management

- Spray Dimethoate 2 ml/litre
- Maintain weed-free fields
- Avoid excess nitrogen

Conclusion:

Tomato is a highly adaptable, nutritionally rich and commercially valuable vegetable crop that plays a significant role in food security, farmer income and the processing industry. Its successful cultivation depends on the adoption of scientifically sound agronomic practices, including the selection of suitable varieties and hybrids, proper nursery raising, balanced fertilization, efficient irrigation scheduling and timely intercultural operations. Management of physiological disorders such as blossom end rot, cracking and sunscald, along with effective control of major insect pests and diseases, is crucial for maintaining yield and fruit quality. Advances in hybrid development, resistance breeding and improved crop management practices have significantly enhanced tomato productivity in diverse agro-climatic regions. Proper harvesting, grading, storage and seed production techniques further ensure better marketability and availability of quality planting material. In the context of changing climate and increasing demand for vegetables, integrated and sustainable approaches to tomato production will be essential for maximizing yield, improving quality and ensuring long-term profitability for growers.

References:

1. FAO. (2013). *Good agricultural practices for greenhouse vegetable crops: Principles for Mediterranean climate areas*. Food and Agriculture Organization of the United Nations.
2. Heuvelink, E. (Ed.). (2018). *Tomatoes* (2nd ed.). CABI Publishing.
3. Maynard, D. N., & Hochmuth, G. J. (2007). *Knott's handbook for vegetable growers* (5th ed.). John Wiley & Sons.
4. Singh, B., & Kalloo, G. (2016). *Tomato production technology*. ICAR

Research and Reviews in Agriculture, Horticulture and Animal Husbandry

ISBN: 978-93-47587-71-9

About Editors

Dr. Narender Mohan, a doctorate in Biochemistry, is currently serving as a Senior Research Fellow at ICAR–Indian Institute of Wheat and Barley Research (IIWBR), Karnal, where he is actively engaged in advanced research on wheat improvement. His core expertise spans plant biochemistry, plant physiology, bio-nanotechnology, and stress biology, with a particular focus on the synthesis and application of nanoparticles to alleviate crop stress. Dr. Mohan possesses strong proficiency in modern nanotechnological tools and techniques and has developed a commendable publication record, including several first-author peer-reviewed research papers, reviews, book chapters, and popular science articles. He has actively participated in specialized trainings, symposiums, and workshops. His research excellence has been recognized through multiple best oral and poster presentation awards at national and international conferences, globally recognized.

Dr. Anuj is a distinguished food technologist and scientist with extensive expertise in cereal quality research and product development. He served as a Scientist at the Central Institute of Fisheries Technology, Cochin, from 2014 to 2021, and is currently working as Senior Scientist (Food Technology) at the ICAR–Indian Institute of Wheat and Barley Research (IIWBR), Karnal. His research focuses on wheat and barley quality analysis, enhancement, and improvement, along with the development of value-added products such as biscuits, bread, and pasta. Proficient in advanced quality improvement tools and techniques, he has published numerous research papers, reviews, book chapters, and popular science articles. Dr. Anuj has actively participated in advanced trainings, symposiums, and workshops, and his research excellence has been recognized through several best presentation awards at national and international conferences.

Dr. Pooja Verma is currently working as a Senior Research Fellow at the ICAR–Indian Institute of Wheat & Barley Research (ICAR-IIWBR), Karnal, Haryana, India. She completed her M.Sc. and Ph.D. in Microbiology from Kurukshetra University, Kurukshetra, Haryana. She qualified the ASRB ICAR–National Eligibility Test (NET) in Agricultural Microbiology in 2016. Dr. Verma has extensive research experience in the isolation, identification, and characterization of soil bacteria with biocontrol potential against fungal plant pathogens. She possesses strong expertise in microbial sciences, laboratory techniques, and scientific analysis. Her research contributes to applications in agriculture, health, and environmental sciences. She has published several research and review articles and book chapters in reputed national and international journals and is dedicated to research excellence, innovation, and student mentoring.

Dr. Brijesh Kumar holds an M.Sc. and Ph.D. in Soil Science and is NET (ASRB) qualified. He is currently serving as Assistant Professor-cum-Scientist in the Department of Soil Science at Dr. Rajendra Prasad Central Agricultural University, Pusa (Samastipur), Bihar, India. With over 12 years of experience in teaching, research, and extension activities, he has made significant contributions to soil fertility management and organic farming. Dr. Kumar has published 13 research papers in national and international journals, 7 book chapters, 3 books, 73 popular articles, 3 case studies, and 6 extension folders, and holds one patent. He has also served as an external examiner for several universities. His accolades include the Distinguished Scientist Award, Utkrist Lekhak Award (2018), Best Young Scientist Award (2022), and Environmentalist Award (2023).

Bhumi Publishing

ISBN 978-93-475-8771-9