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General Article

NUTRITIONAL BENEFITS OF BROCCOLI (*BRASSICA OLERACEA VAR. ITALICA*) AND ITS ROLE IN HUMAN HEALTH

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Abstract

Broccoli (*Brassica oleracea* var. *italica*) is a nutrient-dense cruciferous vegetable widely recognized as a functional food with significant nutritional and health-promoting potential. It is an excellent source of vitamins, minerals, dietary fiber, and bioactive phytochemicals, particularly glucosinolates, flavonoids, and carotenoids. Among these compounds, sulforaphane, a major isothiocyanate derived from glucosinolates, has attracted considerable attention for its antioxidant, anti-inflammatory, and potential chemoprotective properties. Regular consumption of broccoli may contribute to improved gastrointestinal, cardiovascular, and metabolic health and may help reduce the risk of chronic diseases, including certain cancers, diabetes, obesity, and cardiovascular disorders. Its dietary fiber supports healthy gut microbiota, satiety, and cholesterol regulation, while nutrients such as vitamin C, vitamin K, folate, potassium, and magnesium contribute to immune function and physiological health. Emerging evidence also suggests potential benefits for brain health and cognitive function. However, cultivar, growing conditions, post-harvest handling, and cooking methods can influence its nutritional and phytochemical composition. Minimal processing and light steaming are generally preferable for retaining valuable nutrients and bioactive compounds. Overall, broccoli represents an important component of a balanced diet and a promising functional food for long-term health promotion and disease prevention

Keywords: Broccoli; Functional food; Glucosinolates; Sulforaphane; Health promotion

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Introduction

Broccoli (*Brassica oleracea* var. *italica*) is a green cruciferous vegetable belonging to the family Brassicaceae, which also includes cabbage, cauliflower, kale, and Brussels sprouts. Among these vegetables, broccoli has gained particular attention due to its exceptional nutritional density and wide range of health-promoting bioactive compounds. Originally cultivated in the Mediterranean region, broccoli is now grown and consumed worldwide and is recognized as a functional food because of its potential role in disease prevention and health promotion (Verkerk et al., 2009).In recent decades, there has been a growing global interest in plant-based diets and functional foods as effective strategies to combat the rising prevalence of non-communicable diseases such as cardiovascular disorders, cancer, diabetes, and obesity. Broccoli has emerged as one of the most extensively studied vegetables in this context, owing to its high content of vitamins, minerals, dietary fiber, and phytochemicals with antioxidant and anti-inflammatory properties. Regular consumption of broccoli has been associated with reduced risk of chronic diseases and improved overall health outcomes (Traka &Mithen, 2009).Nutritionally, broccoli is considered a low-calorie yet nutrient-dense vegetable. It provides essential macronutrients such as carbohydrates and proteins, while being low in fat. More importantly, broccoli is a rich source of micronutrients, including vitamin C, vitamin K, folate, potassium, calcium, and magnesium. Vitamin C plays a critical role in immune function, collagen synthesis, and antioxidant defense, while vitamin K is essential for blood coagulation and bone metabolism. Folate contributes to DNA synthesis and cell division, making broccoli particularly important in maternal and fetal health (USDA, 2024).Beyond its basic nutrient content, broccoli is distinguished by its abundance of phytochemicals, particularly glucosinolates, flavonoids, and carotenoids. Glucosinolates are sulfur-containing compounds that, upon hydrolysis, form biologically active metabolites such as isothiocyanates and indoles. Among these, sulforaphane has been extensively studied for its chemoprotective properties. Sulforaphane has been shown to induce phase II detoxification enzymes, inhibit carcinogen activation, and modulate signaling pathways involved in inflammation and cell proliferation (Zhang et al., 1992). These mechanisms contribute significantly to the potential cancer-preventive effects of broccoli.Epidemiological studies consistently suggest an inverse relationship between the consumption of cruciferous vegetables and the risk of various cancers, including lung, colorectal, prostate, and breast cancers. Broccoli, in particular, has been highlighted for its ability to reduce oxidative stress and enhance the body’s detoxification capacity. Oxidative stress, caused by an imbalance between free radicals and antioxidants, is a major contributor to cellular damage and the development of chronic diseases. The antioxidants present in broccoli, such as vitamin C, beta-carotene, and flavonoids, help neutralize free radicals and protect cellular components from oxidative damage (Halliwell, 2012).In addition to its antioxidant properties, broccoli exhibits significant anti-inflammatory effects. Chronic inflammation is a key underlying factor in the development of many non-communicable diseases, including cardiovascular disease, diabetes, arthritis, and neurodegenerative disorders. Bioactive compounds in broccoli, including kaempferol and quercetin, have been shown to suppress inflammatory markers and inhibit pro-inflammatory signaling pathways. These anti-inflammatory actions further contribute to broccoli’s role in disease prevention and health maintenance (Lee et al., 2010).Dietary fiber is another important component of broccoli that contributes to human health. Fiber plays a crucial role in maintaining gastrointestinal health by promoting regular bowel movements and supporting the growth of beneficial gut microbiota. A healthy gut microbiome is increasingly recognized as a key determinant of overall health, influencing immune function, metabolism, and even mental well-being. High fiber intake has also been associated with reduced risk of cardiovascular disease, type 2 diabetes, and colorectal cancer (Slavin, 2013). The combination of soluble and insoluble fiber in broccoli enhances satiety, aids in cholesterol regulation, and supports metabolic health.Broccoli also contributes to cardiovascular health through multiple mechanisms. Its fiber content helps lower serum cholesterol levels, while potassium and magnesium support blood pressure regulation. Additionally, the antioxidant and anti-inflammatory compounds in broccoli protect vascular tissues from oxidative damage and endothelial dysfunction, both of which are critical factors in the development of heart disease (Appel et al., 2006). As cardiovascular diseases remain a leading cause of mortality worldwide, incorporating broccoli into regular diets may offer a simple and effective preventive strategy.Emerging research also highlights the potential role of broccoli in supporting brain health and cognitive function. Oxidative stress and inflammation are major contributors to age-related cognitive decline and neurodegenerative diseases. The antioxidants and bioactive compounds present in broccoli may help protect neuronal cells and improve cognitive resilience. While this area of research is still developing, preliminary findings suggest that regular consumption of cruciferous vegetables may be associated with slower cognitive decline in aging populations (Joseph et al., 2009).Despite its numerous health benefits, the nutritional value of broccoli can be influenced by factors such as cultivar, growing conditions, post-harvest handling, and cooking methods. Overcooking, particularly boiling, can lead to significant losses of water-soluble vitamins and bioactive compounds. Therefore, understanding proper preparation and processing methods is essential to maximize the health benefits of broccoli. Light steaming or minimal cooking has been shown to preserve most of its nutritional and phytochemical content (Wang & Kuo, 2005).In conclusion, broccoli is a highly nutritious vegetable with substantial potential to improve human health. Its unique combination of essential nutrients, dietary fiber, and bioactive phytochemicals makes it a valuable component of a balanced diet. The growing body of scientific evidence supports the role of broccoli in reducing the risk of chronic diseases, enhancing immune function, and promoting overall well-being. As dietary patterns continue to shift toward health-oriented and plant-based approaches, broccoli is likely to remain a key vegetable of nutritional and functional significance.

Nutrient Composition of Broccoli

Broccoli is widely recognized as a low-calorie yet highly nutrient-dense vegetable, making it an important component of healthy dietary patterns. Its favorable nutrient-to-energy ratio allows individuals to obtain essential vitamins, minerals, and bioactive compounds without excessive caloric intake. A 100-g serving of raw broccoli provides approximately 34 kcal, highlighting its suitability for weight management and energy-balanced diets. In terms of macronutrients, broccoli contains moderate amounts of carbohydrates (approximately 6.6 g per 100 g), primarily in the form of complex carbohydrates and dietary fiber. These carbohydrates provide a steady source of energy while avoiding rapid spikes in blood glucose levels. Broccoli also supplies about 2.8 g of protein per 100 g, which is relatively high for a vegetable. Although plant-based proteins are generally lower in certain essential amino acids compared to animal sources, the protein content of broccoli contributes meaningfully to overall daily protein intake, particularly in vegetarian and plant-based diets. Dietary fiber is one of the most nutritionally significant components of broccoli, with approximately 2.6 g per 100 g. Fiber plays a crucial role in maintaining digestive health by promoting regular bowel movements and supporting beneficial gut microbiota. Adequate fiber intake has been linked to reduced risk of constipation, colorectal cancer, cardiovascular disease, and type 2 diabetes. Additionally, fiber enhances satiety, which may help regulate appetite and body weight. Broccoli is especially rich in essential vitamins, most notably vitamin C. A 100-g serving provides approximately 89 mg of vitamin C, which meets or exceeds the recommended daily intake for adults. Vitamin C functions as a powerful antioxidant, protecting cells from oxidative damage caused by free radicals. It is also essential for collagen synthesis, immune system support, and enhanced absorption of non-heme iron from plant-based foods. The high vitamin C content of broccoli makes it an effective dietary component for strengthening immune defenses and supporting tissue repair. Vitamin K is another prominent micronutrient found in broccoli, with approximately 101.6 µg per 100 g. Vitamin K is essential for blood coagulation and plays a critical role in bone metabolism by regulating calcium-binding proteins involved in bone mineralization. Adequate intake of vitamin K has been associated with improved bone density and reduced risk of fractures, particularly in older populations. Broccoli also provides a meaningful amount of folate (approximately 63 µg per 100 g), a B-vitamin essential for DNA synthesis, cell division, and red blood cell formation. Folate is particularly important during periods of rapid growth, such as pregnancy and infancy, as deficiencies may lead to developmental abnormalities. Among its mineral content, potassium is especially notable, with approximately 316 mg per 100 g. Potassium is essential for maintaining fluid balance, nerve transmission, and muscle function, and it plays a key role in regulating blood pressure. Diets rich in potassium are associated with a reduced risk of hypertension and cardiovascular disease. Overall, the diverse nutrient composition of broccoli supports multiple physiological functions and helps meet daily dietary requirements for essential vitamins and minerals. Its low energy density combined with high micronutrient and fiber content underscores its value as a functional food that contributes significantly to human health and disease prevention (USDA, 2024). Broccoli is a low-calorie, nutrient-dense food. A 100-g serving of raw broccoli provides:

Nutrient	**Approximate Amount**
Calories	34 kcal
Protein	2.8 g
Carbohydrates	6.6 g
Dietary Fiber	2.6 g
Vitamin C	89 mg
Vitamin K	101.6 µg
Folate	63 µg
Potassium	316 mg

This rich profile contributes to key physiologic functions and helps meet daily dietary requirements for essential vitamins and minerals (USDA, 2024).

Vitamins and Antioxidant Properties

Vitamin C and Antioxidant Defense

Broccoli is an excellent source of vitamin C, a vital antioxidant that plays a key role in maintaining human health. Vitamin C supports immune function by enhancing the activity of white blood cells and strengthening the body’s defense against infections. It is also essential for collagen synthesis, which is necessary for maintaining healthy skin, blood vessels, and connective tissues. Additionally, vitamin C protects cells from oxidative stress by neutralizing free radicals, unstable molecules that can damage cellular structures and contribute to aging and chronic diseases. Through these antioxidant mechanisms, regular consumption of broccoli helps reduce oxidative damage and supports overall physiological stability (Halliwell, 2012).

Vitamin K and Bone Metabolism

Broccoli is a rich dietary source of vitamin K, an essential nutrient involved in bone metabolism and skeletal health. Vitamin K plays a critical role in the activation of osteocalcin, a protein required for binding calcium to the bone matrix, thereby supporting proper bone mineralization. Adequate intake of vitamin K has been associated with improved bone density and a reduced risk of fractures, particularly among older adults. In addition to its role in bone health, vitamin K is necessary for normal blood coagulation. Regular consumption of broccoli can therefore contribute to maintaining strong bones and overall metabolic balance (Cockayne et al., 2006).

Dietary Fiber and Digestive Health

Broccoli is a valuable source of dietary fiber, which plays an essential role in maintaining digestive health. The fiber content supports gut motility by promoting regular bowel movements and preventing constipation. Additionally, dietary fiber serves as a substrate for beneficial gut microbiota, helping to maintain a healthy intestinal environment. A balanced gut microbiome contributes to improved nutrient absorption and immune function. High-fiber diets have been strongly associated with a reduced risk of colorectal cancer, cardiovascular disorders, and metabolic diseases such as type 2 diabetes. Thus, regular consumption of broccoli supports overall gastrointestinal health and metabolic stability (Slavin, 2013).

Glucosinolates and Cancer Prevention

Broccoli is particularly valued for its high content of glucosinolates, sulfur-containing phytochemicals that contribute to its cancer-protective properties. When broccoli is consumed, glucosinolates are enzymatically converted into biologically active compounds such as sulforaphane. These compounds have been shown to enhance the activity of detoxification enzymes, thereby aiding in the elimination of potential carcinogens from the body. Additionally, sulforaphane can inhibit tumor cell proliferation and modulate inflammatory and oxidative stress pathways. Laboratory and epidemiological studies suggest that regular consumption of broccoli and other cruciferous vegetables may help reduce the risk of several types of cancer (Zhang et al., 1992; Traka &Mithen, 2009).

Cardiovascular Health

Cholesterol and Heart Disease Prevention

Broccoli contributes to cardiovascular health through its beneficial effects on cholesterol metabolism. The dietary fiber present in broccoli binds to bile acids and cholesterol in the digestive tract, facilitating their excretion and thereby reducing circulating levels of low-density lipoprotein (LDL), commonly referred to as “bad” cholesterol. Elevated LDL cholesterol is a major risk factor for the development of atherosclerosis and cardiovascular disease. By helping to lower LDL levels, regular consumption of broccoli may reduce the risk of coronary heart disease and related complications. Incorporating fiber-rich vegetables such as broccoli into daily diets is therefore an effective strategy for promoting heart health (Brown et al., 1999).

Blood Pressure Modulation

Broccoli plays an important role in blood pressure regulation due to its rich potassium content and antioxidant compounds. Potassium helps maintain fluid balance and counteracts the effects of sodium, thereby promoting vasodilation and reducing blood pressure levels. Adequate potassium intake is associated with a lower risk of hypertension and improved cardiovascular function. In addition, antioxidants present in broccoli help protect blood vessels from oxidative damage and support endothelial function. Together, these nutrients contribute to improved vascular health and more stable blood pressure control. Regular consumption of broccoli as part of a balanced diet may therefore help reduce the risk of hypertension and associated cardiovascular diseases (Appel et al., 2006).

Anti-Inflammatory Effects

Broccoli contains several bioactive compounds, including flavonoids such as kaempferol and quercetin, which exhibit strong anti-inflammatory properties. These compounds help regulate inflammatory pathways by inhibiting the production of pro-inflammatory cytokines and reducing oxidative stress at the cellular level. Chronic inflammation is a major contributing factor to the development of diseases such as cardiovascular disorders, diabetes, arthritis, and certain cancers. By modulating inflammatory responses, the regular consumption of broccoli may help lower the risk of inflammation-related chronic conditions. Thus, broccoli serves as a valuable dietary component for maintaining immune balance and reducing long-term inflammatory stress in the body (Lee et al., 2010).

Brain Health and Cognitive Function

Broccoli contains a variety of phytonutrients that may contribute to brain health and cognitive function. These bioactive compounds help protect neural cells by reducing oxidative stress and suppressing inflammation, both of which are key factors in age-related cognitive decline and neurodegenerative diseases. Antioxidants present in broccoli neutralize free radicals that can damage brain cells, while anti-inflammatory compounds support healthy neuronal signaling. Emerging research suggests that regular consumption of cruciferous vegetables, including broccoli, may be associated with improved memory and slower cognitive decline in aging populations. Although further research is needed, current evidence highlights the potential neuroprotective role of broccoli in supporting long-term brain health (Joseph et al., 2009).

Practical Considerations

Preparation and Cooking Methods

The nutritional quality of broccoli is significantly influenced by preparation and cooking methods. Light steaming is considered one of the most effective techniques for preserving essential nutrients, as it minimizes the loss of water-soluble vitamins and bioactive compounds. In contrast, boiling can lead to substantial reductions in vitamin C and glucosinolates, particularly sulforaphane, due to leaching into cooking water. Overcooking may further degrade heat-sensitive antioxidants and reduce overall nutritional value. To maximize health benefits, broccoli should be cooked for short durations using gentle methods such as steaming or sautéing, or consumed raw when appropriate. Proper preparation ensures optimal retention of nutrients and enhances the functional value of broccoli in the human diet (Wang & Kuo, 2005).

Dietary Integration

Broccoli can be easily incorporated into daily diets in a variety of culinary forms, making it a versatile and accessible vegetable. It can be added to soups, stews, and stir-fries, where light cooking helps retain much of its nutritional value. Raw broccoli is commonly used in salads and vegetable platters, providing maximal intake of heat-sensitive nutrients such as vitamin C and bioactive compounds. Broccoli can also be blended into smoothies or lightly sautéed with healthy fats to enhance the absorption of fat-soluble nutrients. Its mild flavor and adaptability make broccoli suitable for diverse dietary patterns, supporting regular consumption and improved overall nutritional quality.

Conclusion

Broccoli is a highly nutrient-rich vegetable that offers a wide range of health benefits and plays an important role in promoting overall wellness. Its unique combination of essential vitamins, minerals, dietary fiber, and bioactive phytochemicals contributes to the prevention of chronic diseases, including cardiovascular disorders, cancer, and metabolic conditions. The antioxidant and anti-inflammatory properties of broccoli support immune function and protect against cellular damage. Additionally, its low energy density and high nutritional value make it suitable for diverse dietary patterns. Regular inclusion of broccoli in balanced diets can significantly enhance nutritional quality and support long-term health and disease prevention.

References

Appel, L. J., Moore, T. J., Obarzanek, E., et al. (2006). *A clinical trial of the effects of dietary patterns on blood pressure.*New England Journal of Medicine, 336(16), 1117–1124.

Appel, L. J., Moore, T. J., Obarzanek, E., et al. (2006). A clinical trial of the effects of dietary patterns on blood pressure. *New England Journal of Medicine*, *336*(16), 1117–1124.

Brown, L., Rosner, B., Willett, W. W., & Sacks, F. M. (1999). *Cholesterol-lowering effects of dietary fiber: a meta-analysis.*American Journal of Clinical Nutrition, 69(1), 30–42.

Cockayne, S., Adamson, J., Lanham-New, S., et al. (2006). *Vitamin K and the prevention of fractures: systematic review and meta-analysis of randomized controlled trials.*Archives of Internal Medicine, 166(12), 1256–1261.

Erkerk, R., Schreiner, M., Krumbein, A., et al. (2009). Glucosinolates in Brassica vegetables: The influence of the food supply chain on intake, bioavailability and human health. *Molecular Nutrition & Food Research*, *53*(S2), S219–S265.

Halliwell, B. (2012). *Free radicals and antioxidants: updating a personal view.*Nutrition Reviews, 70(5), 257–265.

Halliwell, B. (2012). Free radicals and antioxidants: Updating a personal view. *Nutrition Reviews*, *70*(5), 257–265.

Joseph, J. A., Shukitt-Hale, B., & Casadesus, G. (2009). Nutritional interventions in brain aging. *American Journal of Clinical Nutrition*, *81*(1), 313S–316S.

Joseph, J. A., Shukitt-Hale, B., & Casadesus, G. (2009). *Reversing the deleterious effects of aging on neuronal communication and behavior: beneficial properties of fruit polyphenolic compounds.*American Journal of Clinical Nutrition, 81(1), 313S–316S.

Lee, J., Koo, N., & Min, D. B. (2010). *Carotenoids, vitamin C, and phenolic antioxidants in vegetables and their antioxidant activity.*Critical Reviews in Food Science and Nutrition, 40(1), 1–14.

Lee, J., Koo, N., & Min, D. B. (2010). Reactive oxygen species, aging, and antioxidative nutraceuticals. *Comprehensive Reviews in Food Science and Food Safety*, *3*(1), 21–33.

Slavin, J. L. (2013). Dietary fiber and body weight. *Nutrition, 21*(3), 411–418.

Slavin, J. L. (2013). *Dietary fiber and body weight.*Nutrition, 21(3), 411–418.

Traka, M., &Mithen, R. (2009). *Glucosinolates, isothiocyanates and human health.*Phytochemistry Reviews, 8(1), 269–282.

Traka, M., &Mithen, R. (2009). Glucosinolates, isothiocyanates and human health. *Phytochemistry Reviews*, *8*(1), 269–282.

USDA. (2024). *FoodData Central.* U.S. Department of Agriculture. https://fdc.nal.usda.gov

Verkerk, R., Schreiner, M., Krumbein, A., et al. (2009). *Glucosinolates in Brassica vegetables: the influence of the food supply chain on intake, bioavailability and human health.*Molecular Nutrition & Food Research, 53(S2), S219–S265.

Wang, S. Y., & Kuo, L. C. (2005). *Effect of cooking methods on phytochemicals and antioxidant activity in vegetables.*Journal of Food Science, 70(4), C289–C294.

Wang, S. Y., & Kuo, L. C. (2005). Effects of cooking methods on antioxidants in vegetables. *Journal of Food Science, 70*(4), C289–C294.

Zhang, Y., Talalay, P., Cho, C. G., & Posner, G. H. (1992). *A major inducer of anticarcinogenic protective enzymes from broccoli: isolation and elucidation of structure.*Proceedings of the National Academy of Sciences, 89(6), 2399–2403.

Zhang, Y., Talalay, P., Cho, C. G., & Posner, G. H. (1992). A major inducer of anticarcinogenic protective enzymes from broccoli. *Proceedings of the National Academy of Sciences, 89*(6), 2399–2403.

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Review Article

PHEASANTS FOUND IN HIMACHAL PRADESH, NORTHWESTERN HIMALAYA, INDIA: A REVIEW

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Abstract

Himachal Pradesh, located in the northwestern Himalaya, harbors a remarkable diversity of pheasants, several of which are globally threatened and serve as flagship species for Himalayan conservation. Among them, the Western Tragopan (*Tragopan melanocephalus*), Cheer Pheasant (*Catreuswallichii*), and Himalayan Monal (*Lophophorusimpejanus*) hold significant ecological, cultural, and conservation importance. This review highlights the diversity, distribution, and conservation status of pheasants in the region, while assessing the major challenges posed by habitat fragmentation, poaching, unregulated tourism, and climate change. Efforts undertaken through protected areas such as the Great Himalayan National Park, along with community-based conservation initiatives, have contributed to safeguarding pheasant populations. However, knowledge gaps remain regarding population dynamics, habitat use, and the long-term impacts of anthropogenic pressures. Strengthening habitat protection, promoting eco-tourism, enhancing community participation, and implementing robust monitoring programs are essential for ensuring the survival of these species. This article emphasizes the urgent need for integrated conservation approaches to secure the future of pheasants in Himachal Pradesh.

Keywords: Pheasants, Himachal Pradesh, Northwestern Himalaya, Conservation challenges, Galliformes.

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Introduction

Pheasants, belonging to the family Phasianidae, represent an ecologically and culturally significant group of ground-dwelling birds widely distributed across the Himalayan region. These birds are vital components of mountain ecosystems, contributing to seed dispersal, maintaining trophic dynamics as prey for carnivores and raptors(Johnsgard 1986), and serving as reliable bioindicators of habitat quality and ecosystem health. Their presence often reflects the integrity of forest and grassland habitats, making them important species for monitoring environmental changes (Miller, 2010). Himachal Pradesh, located in the northwestern Himalaya, is especially rich in pheasant diversity due to its steep altitudinal gradient, varied climatic conditions, and heterogeneous landscapes. The state spans four major ecological zones, Shivalik Hills, Lesser Himalaya, Higher Himalaya, and Trans-Himalaya, which together provide habitats ranging from subtropical foothill forests and temperate oak-pine woodlands to subalpine scrublands and alpine meadows (Saikia et al., 2011; Thakur et al., 2018). This mosaic of environments supports both widespread species, such as the Kalij Pheasant (*Lophuraleucomelanos*), and highly localized, range-restricted endemics like the Western Tragopan (*Tragopan melanocephalus*).Beyond their ecological roles, pheasants also hold cultural and aesthetic importance in Himachal Pradesh, featuring prominently in local folklore, religious symbolism, and traditional hunting practices. This study seeks to document the pheasant species of Himachal Pradesh while highlighting the threats they face and outlining appropriate conservation strategies.

Materials and Methods

Study Area

Himachal Pradesh, located in the northwestern Himalaya, covers an area of 55,673 km² between latitudes 30°22′–33°12′ N and longitudes 75°45′–79°04′ E (Fig. 1). The state's elevation ranges from 248 m to 6,735 m above mean sea level (Upgupta et al., 2015). Precipitation shows a sharp gradient, with about 3,000 mm annually on the outer slopes decreasing to nearly 150 mm in the arid trans-Himalayan rain shadow. Temperature regimes are equally variable, spanning subtropical conditions in the low valleys, where summer maxima remain below 40 °C, to permanently frozen environments at the highest altitudes. The region exemplifies characteristic Himalayan conditions and is broadly divided into four distinct geological and ecological zones: the Shivalik, Lesser Himalaya, Higher Himalaya, and Trans-Himalaya (Maikhuri et al., 2001).

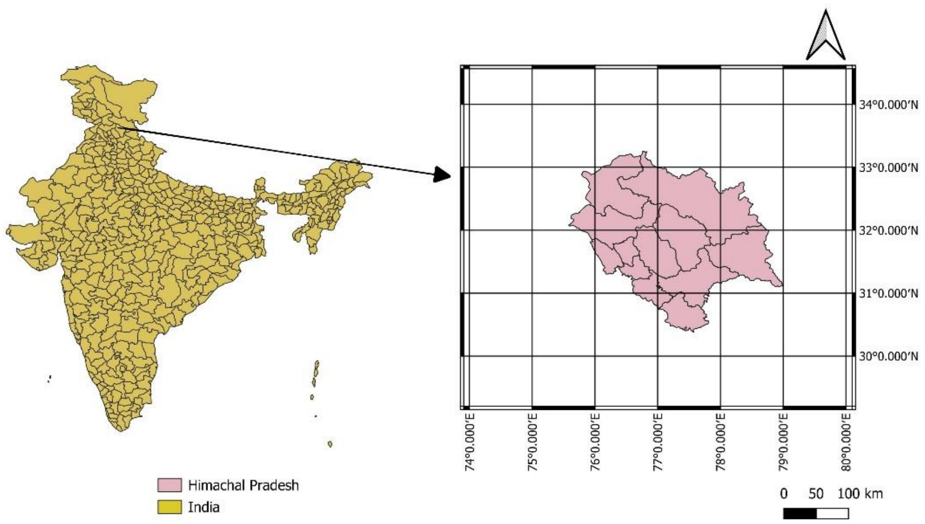

Figure 1. Map of India and Himachal Pradesh

Methodology

Drawing on field studies, government reports, and scientific literature, this review article aims to pinpoint the major drivers of biodiversity loss and assess their ecological impacts.

Results and Discussion

Himachal Pradesh harbors a rich assemblage of pheasants and allied game birds, with around 18 species recorded across its varied landscapes (Kumar, 2015). This includes high-altitude specialists like the Snow Partridge (*Lerwalerwa*) and Himalayan Snowcock (*Tetraogallushimalayensis*), mid-elevation forest pheasants such as the Western Tragopan and Koklass Pheasant (*Pucrasiamacrolopha*), and lower-elevation game birds like Grey Francolin (*Francolinuspondicerianus*) and the Indian Peafowl (*Pavo cristatus*). The majority of these species are not globally threatened – most are assessed as Least Concern by IUCN, indicating relatively stable populations in a broad sense. However, two flagship species stand out as conservation priorities: the Western Tragopan (*Tragopan melanocephalus*) and the Cheer Pheasant (*Catreuswallichii*). Both are classified as Vulnerable on the IUCN Red List due to their limited distribution and ongoing declines (Table 1).

The pheasants of northwestern Himalaya occupy distinct ecological niches along the region's pronounced altitudinal gradient. Western Tragopan, for example, is confined to the temperate broadleaf–conifer forests between roughly 2,400–3,600 m elevation (Singh and Tu, 2008).It favors undisturbed old-growth forest with dense understory (often with bamboo and rhododendron), typically in secluded ravines and hillsides of the Lesser and Greater Himalaya (Ahmad 2017).By contrast, the Cheer Pheasant inhabits open scrub-grassland mosaics on steep, rugged slopes at mid elevations (1,200–3,000 m). Cheer Pheasants show a marked preference for early-successional and human-influenced habitats – they frequent grassy hillsides with scattered shrubs and patches of secondary growth near village grazing lands or recently cleared areas.This species' range overlaps largely with the mid-hill Chir pine belt, where periodic disturbances (like fires or grazing) maintain the open habitat structure it requires (Jolli, 2011).

At the highest elevations, beyond the treeline, several galliform species have adapted to the harsh alpine environment. The Snow Partridge (*Lerwalerwa*) and Himalayan Snowcock (*Tetraogallushimalayensis*) occur on alpine meadows and rocky slopes above ~3,500–4,000 m. These birds can withstand extreme cold and thin air; they forage on alpine grasses and tubers in areas often blanketed by snow in winter. In the cold desert of the trans-Himalaya (e.g. upper Lahaul-Spiti), the Tibetan Snowcock (*Tetraogallustibetanus*) is also found, surviving on sparse scrub at elevations up to ~5,000 m. Conversely, in the foothills and valleys (below ~1,200 m), pheasants give way to francolins, quails and peafowl. Grey Francolin and Black Francolin (*Francolinusfrancolinus*) are common in the scrubby grasslands and cultivated fields of the Siwalik hills and low valleys, where they thrive in warm, dry habitats with ample ground cover (Negi, 2019).The Indian Peafowl, though primarily a bird of the plains, occurs locally in Himachal's outer foothills as well, especially in open woodland near agriculture. This clear stratification of species by altitude highlights how habitat heterogeneity supports pheasant diversity in Himachal Pradesh. From subtropical thorn scrubs to temperate oak–fir forests and alpine tundra, each habitat zone harbors its own characteristic galliform community, illustrating the birds' diverse ecological adaptations.

Most Himalayan pheasants not being globally endangered, the interplay of habitat loss, human disturbance, direct persecution, and environmental change is causing local declines. Many smaller subpopulations in unprotected areas have already been extirpated or are in decline – for example, villagers in parts of Kullu District recall that Western Tragopans used to descend to low oak woods near their fields in winter decades ago, but these birds are no longer seen in those areas. The above threats, if left unmitigated, could further isolate and erode the remaining pheasant strongholds in Himachal Pradesh.Climate models for the western Himalaya project significant changes in vegetation distribution and snow cover in coming decades. For pheasants, this could mean changes in food availability and breeding timing. For instance, the Western Tragopan's habitat suitability may actually increase in some area's upslope under certain future climate scenarios (Mukesh et al. 2016; Shah et al. 2022), but such potential gains could be offset by other factors like increased human access or mismatches in plant phenology.The above threats, if left unmitigated, could further isolate and erode the remaining pheasant strongholds in Himachal Pradesh.

Conservation Implications

The presence of globally significant species like the Western Tragopan and Cheer Pheasant makes Himachal Pradesh a priority area for pheasant conservation in India. Several protected areas, including the Great Himalayan National Park, Pin Valley National Park, and Tirthan Wildlife Sanctuary, provide critical habitats. However, effective conservation requires:

- Strengthening community-based conservation programs in buffer zones.
- Enhancing long-term monitoring to track population trends.
- Implementing eco-sensitive tourism to reduce disturbance.
- Promoting awareness and education to curb hunting and habitat encroachment.

Table 1: Pheasants found in Himachal Pradesh

Sr. no.	Common Name	Scientific Name	Resident Status	IUCN Status
1.	Chukar	*Alectoris chukar*	R	LC
2.	Snow Partridge	*Lerwalerwa*	R	LC
3.	Tibetan Partridge	*Perdix hodgsoniae*	R	LC
4.	Hill Partridge	*Arborophilatorqueola*	R	LC
5.	Tibetan Snowcock	*Tetraogallustibetanus*	R	LC
6.	Himalayan Snowcock	*Tetraogallushimalayensis*	R	LC
7.	Grey Francolin	*Francolinuspondicerianus*	R	LC
8.	Black Francolin	*Francolinusfrancolinus*	R	LC
9.	Common Quail	*Coturnix coturnix*	R	LC
10.	Rain Quail	*Coturnix coromandelica*	SM	LC
11.	Jungle Bush-Quail	*Perdicula asiatica*	R	LC
12.	Western Tragopan	*Tragopan melanocephalus*	R	VU
13.	Koklass Pheasant	*Pucrasiamacrolopha*	R	LC
14.	Himalayan Monal	*Lophophorusimpejanus*	R	LC
15.	Red Junglefowl	*Gallus gallus*	R	LC
16.	Kalij Pheasant	*Lophuraleucomelanos*	R	LC
17.	Cheer Pheasant	*Catreuswallichii*	R	VU
18.	Indian Peafowl	*Pavo cristatus*	R	LC

Abbreviations: R – Resident, IUCN – International Union for Conservation of Nature, LC – Least Concern, VU – Vulnerable.

There have been some conservation successes: for instance, Western Tragopans are flourishing within well-guarded sanctuaries like GHNP, and Cheer Pheasants have started to rebound in areas where hunting was curtailed and reintroductions initiated (Awan, 2016). These instances show that with timely interventions, population declines can be halted or reversed. Going forward, an integrated conservation approach is required – one that combines habitat protection, community engagement, scientific monitoring, and policy support.

Himachal Pradesh has established dedicated conservation breeding centers for these birds – notably, the *Western Tragopan* Breeding Center at Sarahan (in Shimla district) and the *Cheer Pheasant* Breeding Center at Khadiyun (Chail). These facilities have been operating for over a decade to maintain captive populations with the aim of eventual reintroduction into the wild. As of 2022, the Sarahanpheasantry held over 40 Western Tragopans and has successfully bred multiple generations in captivity (Anonymous, 2022-23).Overall, Himachal Pradesh supports a high diversity of pheasants, reflecting its unique topographic and ecological settings. While most species remain secure, the declining populations of the Western Tragopan and Cheer Pheasant demand urgent conservation interventions. Protecting these species will not only safeguard regional biodiversity but also preserve the ecological integrity of the northwestern Himalaya.

Conclusion

Himachal Pradesh, with its remarkable altitudinal range and habitat diversity, serves as a critical stronghold for pheasants and allied game birds in the northwestern Himalaya. The presence of globally significant species such as the Western Tragopan and Cheer Pheasant underscores the state's conservation importance. While most pheasant species remain stable at a global scale, localized declines driven by habitat loss, hunting, human disturbance, and climate change pose serious challenges. Evidence from successful interventions, such as thriving Western Tragopan populations in protected areas and the Cheer Pheasant's rebound following reintroductions, demonstrates that focused management can reverse negative trends. Sustaining these gains will require an integrated approach that strengthens community-based conservation, improves long-term monitoring, promotes eco-sensitive tourism, and enhances awareness to mitigate anthropogenic pressures. Continued support for breeding and reintroduction programs, alongside effective habitat protection and policy measures, will be essential to secure these iconic birds and maintain the ecological integrity and biodiversity of Himachal Pradesh's fragile mountain ecosystems.

References

Ahmad, R., Sharma, N., Pacchnanda, U., Suhail, I., Deb, K., Bhatnagar, Y.V., and Kaul, R. 2017. Distribution and conservation status of the western tragopan (*Tragopan melanocephalus*) in Jammu and Kashmir, India. *Current Science* 112(9): 1948–1952.

Anonymous 2022-23. Sarahanpheasantry: annual report 2022-23. https://cza.nic.in/uploads/documents/reports/hindi/AR_sarahanpheasantry_2223.pdf

Awan, N.M., Ali, H., and Charles L.D. 2014. Population survey and conservation assessment of the globally threatened cheer pheasant (Catreuswallichi) in Jhelum Valley, Azad Kashmir, Pakistan. *Dong wuxueyan jiu = Zoological research35*(4): 338–345. https://doi.org/10.13918/j.issn.2095-8137.2014.4.338

Johnsgard, P.A. 1986. *The Pheasants of the World*. Oxford University Press, New York. Pp 300.

Jolli, V., Srivastav, A., and Thakur, S. 2012. Patch occupancy for cheer pheasant (*Catreuswallichii*) in the Great Himalayan National Park Conservation Area. *International Journal of Galliformes Conservation 2*: 74–81.

Kumar, A. 2015. Birds of Himachal Pradesh: species composition and conservation issues. Journal of Experiment Zoology India 18(2): 505-529.

Maikhuri, R.K., andRamakrishnan, P.S. 1990. Ecological analysisof a cluster of villages emphasising land use of different tribesin Meghalaya in North-east India. *Agriculture, ecosystems & environment* 31(1): 17-37.

Mukesh, Garg, S., Javed, R., Sood, S., and Singh, H. 2016. Genetic evaluation of ex situ conservation breeding projects of Cheer Pheasant (Catreuswallichii) and Western Tragopan (Tragopan melanocephalus)in India. *Zoo biology*, *35*(3): 269–273.https://doi.org/10.1002/zoo.21263

Negi, P., and Lakhera P. 2019. Distribution pattern and habitat preference of the black francolin (Francolinusfrancolinusasiae) in Uttarakhand, India. *Zoology & Ecology*29(2): 83-89.

Saikia, U., Thakur, M.L., Bawri, M., andBhattacherjee, P.C. 2011. An inventory of the chiropteron fauna of Himachal Pradesh, Northwestern India with some ecological observations. *Journal of Threatened Taxa*3(4): 1637-1655.

Shah, A., Kayani, A.R., Ihlow, F., Nadeem, M.S., Mahmood, T., Islam, S., … Packert, M. 2023. Range-wide and regional distribution of the Western Tragopan Tragopan melanocephalus and effects of disturbance on local abundances. *Bird Conservation International33*.https://doi.org/10.1017/S0959270922000120

Singh, S. and Tu, F. 2008. A preliminary survey for Western Tragopan Tragopan melanocephalus in the Daranghati Wildlife Sanctuary,Himachal Pradesh. Indian Birds 4(2): 42-55.

Thakur, M.L., Thakur, A., Sharma, P., and Negi, V. 2018. Biodiversity: Concept and scope; Status of Biodiversity in Himachal Pradesh. Himachal Pradesh State Biodiversity Board.

Upgupta, S., Sharma, J., Jayaraman, M., Kumar, V., and Ravindranath, N.H. 2015. Climate change impact and vulnerability assessmentof forests in the Indian Western Himalayan region:A case study of Himachal Pradesh, India.*Climate Risk Management*10: 63–76. http://dx.doi.org/10.1016/j.crm.2015.08.002.

Review Article

NANO FERTILIZERS IN CLIMATE-SMART AGRICULTURE: A COMPREHENSIVE REVIEW OF MECHANISMS, SOIL HEALTH, INNOVATION TRENDS, AND ECONOMIC PERSPECTIVES

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Abstract

The intensification of agriculture under changing climatic conditions has exposed critical inefficiencies in conventional fertilizer systems, particularly low nutrient use efficiency (NUE) and significant greenhouse gas (GHG) emissions. Nitrogen losses through volatilization, leaching, and denitrification not only reduce agronomic productivity but also contribute substantially to environmental degradation. In this context, nano fertilizers have emerged as a transformative innovation with strong relevance to climate-smart agriculture (CSA), which seeks to simultaneously enhance productivity, improve resilience, and mitigate emissions. This review critically evaluates the mechanistic basis, agronomic potential, environmental implications, and innovation trajectories of nano fertilizers. Nano fertilizers, engineered at dimensions of 1–100 nm, exhibit enhanced surface reactivity and controlled-release properties, enabling targeted nutrient delivery and improved crop performance under abiotic stress. Recent advances in nano-encapsulation and precision delivery systems demonstrate their growing integration within sustainable agricultural frameworks. Beyond yield enhancement, nano fertilizers can positively influence soil biological processes. Crucially, reduced nitrogen losses translate into lower nitrous oxide emissions, directly supporting CSA mitigation goals. However, uncertainties regarding nanoparticle persistence, ecotoxicological impacts, and regulatory governance necessitate comprehensive risk assessment. This review finds that while nano fertilizers hold immense promise for advancing CSA, their strategic and responsible adoption—guided by robust science and policy—is essential to realize a resilient, resource-efficient, and low-carbon food production system.

Keywords: Nano fertilizers; Climate-smart agriculture; Nutrient use efficiency; Soil health; Greenhouse gas mitigation; Sustainable agriculture

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Introduction

Global agriculture is undergoing unprecedented pressure due to rapid population growth, increasing food demand, resource scarcity, and accelerating climate change. Rising global temperatures, irregular precipitation patterns, prolonged droughts, and extreme weather events are significantly affecting crop productivity and soil health. At the same time, agricultural intensification has led to excessive dependence on synthetic fertilizers to meet production targets. Although chemical fertilizers have played a pivotal role in boosting crop yields since the Green Revolution, their inefficient use has created serious environmental and sustainability challenges.

Nitrogen use efficiency (NUE) in conventional agricultural systems remains critically low, often below 50%, meaning that a substantial portion of applied nitrogen is lost through ammonia volatilization, nitrate leaching, runoff, and denitrification. These losses not only reduce agronomic efficiency but also contribute to groundwater contamination, eutrophication of aquatic ecosystems, soil degradation, and emission of nitrous oxide (N_2O), a greenhouse gas with a global warming potential nearly 300 times greater than carbon dioxide. Similar inefficiencies exist for phosphorus and micronutrient fertilizers, further intensifying nutrient imbalances in soils.

This creates a fundamental paradox for agriculture: how can we intensify production to meet future food demands—projected to require a 60-70% increase by 2050—without further exacerbating climate change and environmental degradation? This challenge is compounded by the fact that agriculture currently contributes an estimated 20-30% of global greenhouse gas emissions. This "wicked problem" demands a fundamental shift from input-intensive practices to knowledge-intensive, precision-based strategies that can decouple food production from environmental harm.

In response to these challenges, the concept of Climate-Smart Agriculture (CSA) has gained global recognition as a holistic framework for sustainable agricultural development. CSA is built upon three interconnected pillars: (i) sustainably increasing agricultural productivity and incomes, (ii) enhancing resilience and adaptive capacity to climate variability, and (iii) reducing or removing greenhouse gas emissions where possible. Achieving these objectives requires innovative nutrient management strategies that improve resource use efficiency while minimizing environmental externalities.

Nanotechnology has emerged as a transformative scientific advancement with significant implications for agricultural sustainability. Nano fertilizers, engineered at nanoscale dimensions (1–100 nm), possess unique physicochemical properties such as high surface area-to-volume ratio, enhanced reactivity, tunable surface chemistry, and controlled-release capabilities. These characteristics distinguish nano fertilizers from conventional bulk fertilizers and provide opportunities to redesign nutrient delivery systems for improved efficiency and reduced environmental impact.

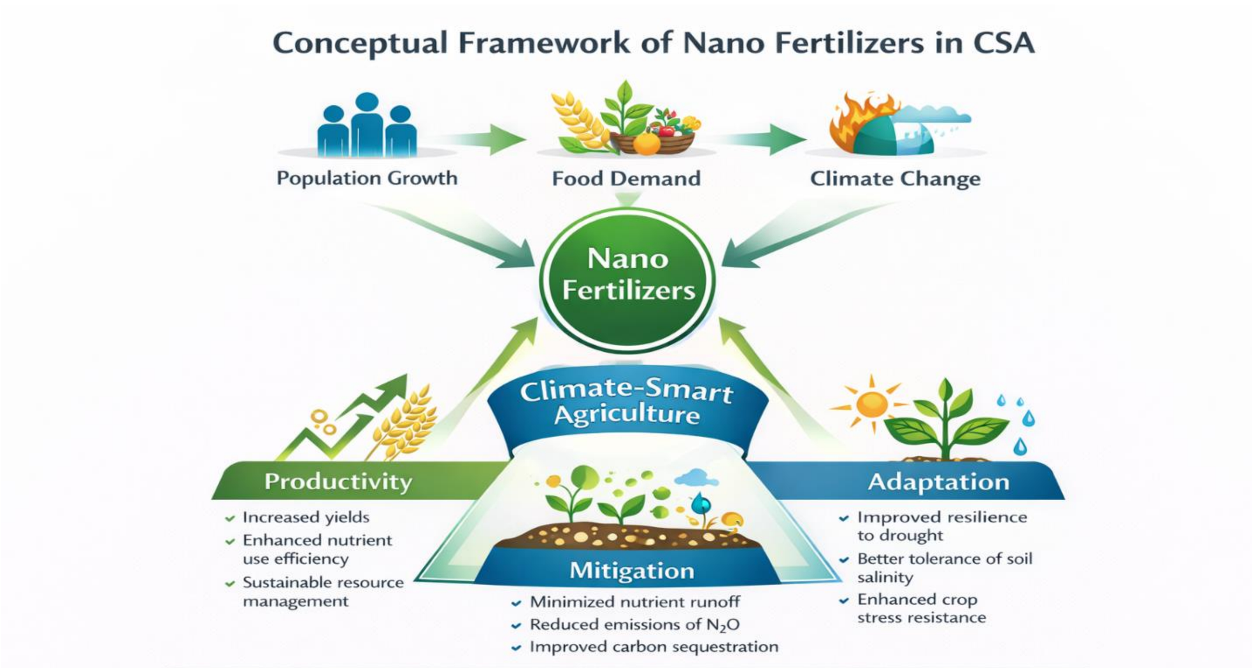
Unlike traditional fertilizers that release nutrients rapidly and often exceed plant demand, nano fertilizers can be formulated to enable slow and synchronized nutrient release. This targeted delivery enhances nutrient uptake efficiency, reduces leaching and volatilization losses, and improves crop physiological performance. Moreover, nano-scale particles can facilitate better interaction with root surfaces and enable efficient foliar penetration through stomatal openings, thereby increasing nutrient bioavailability.

Beyond nutrient delivery efficiency, nano fertilizers may also contribute to improved soil biological functioning. Soil microorganisms play a crucial role in nutrient cycling, organic matter decomposition, and soil structure stabilization. Emerging evidence suggests that certain nano-formulations can stimulate beneficial microbial activity, enhance enzymatic functions such as urease and dehydrogenase, and improve rhizospheric interactions. These effects have direct implications for long-term soil fertility and resilience under climate stress conditions.

Recent years have witnessed rapid innovation and commercialization efforts in nano-enabled agricultural inputs. Patent landscape analyses reveal increasing global research and development activities in nano-encapsulation systems, nanomaterial-based fertilizers, precision nutrient delivery technologies, and microbe-assisted nano formulations. This growing technological interest reflects the strategic importance of nano fertilizers in supporting climate-smart and sustainable agriculture. However, despite promising agronomic and environmental benefits, concerns remain regarding nanoparticle persistence in soils, potential ecotoxicological effects, regulatory uncertainties, and long-term sustainability assessments.

Given the dual challenge of ensuring food security while mitigating environmental degradation, it is essential to critically evaluate the role of nano fertilizers within the CSA framework. A comprehensive understanding of their mechanisms of action, agronomic performance, soil biological impacts, innovation trends, and potential risks is necessary to guide responsible adoption and policy formulation.

Therefore, this review aims to synthesize current scientific knowledge on nano fertilizers and examine their relevance to climate-smart agriculture. Specifically, it evaluates (i) the conceptual basis and classification of nano fertilizers, (ii) mechanisms underlying enhanced nutrient use efficiency, (iii) contributions to productivity, adaptation, and mitigation, (iv) impacts on soil biological health, (v) emerging patent and innovation trends, (vi) environmental and regulatory considerations, and (vii) economic feasibility and adoption challenges. By integrating technological advancements with sustainability principles, this review seeks to provide a comprehensive perspective on the future prospects of nano-enabled nutrient management in resilient and low-carbon agricultural systems.



Classification and Types of Nano Fertilizers

Nano fertilizers can be broadly classified based on their composition, mode of action, and nutrient delivery mechanism. Understanding this classification is crucial for evaluating the specific applications and benefits of these systems within climate-smart agriculture.

Based on Composition

Macro-nutrient Nano Fertilizers

These formulations deliver primary nutrients—nitrogen, phosphorus, and potassium—in nanoscale forms. Nano-nitrogen fertilisers, such as nano-urea, have garnered particular attention due to their ability to reduce application rates while maintaining or even improving crop yields. Nano-phosphorus fertilizers, often synthesized as hydroxyapatite nanoparticles, enhance phosphorus availability by reducing fixation in soils. Nano-potassium fertilizers improve potassium uptake efficiency and stress tolerance.

Micro-nutrient Nano Fertilizers

These include formulations of essential micronutrients such as zinc oxide (ZnO), iron oxide (Fe_2O_3), copper oxide (CuO), manganese, and boron nanoparticles. Nano-zinc and nano-iron are particularly effective in correcting hidden deficiencies and enhancing crop physiological performance under stress conditions.

Nano-composite Fertilizers

These combine multiple nutrients within a single nanoscale carrier, enabling simultaneous delivery of macro and micronutrients. Nano-composites may also incorporate growth promoters, bio-stimulants, or beneficial microorganisms to enhance overall crop performance.

Based on Mode of Delivery

Controlled-Release Nano Fertilizers

Nutrients are encapsulated within nanoscale carriers such as polymer matrices, zeolites, or clay minerals. Release is regulated by environmental triggers, including moisture, temperature, pH, or enzymatic activity, ensuring synchronization with plant demand.

Targeted Nano Fertilizers

These formulations are designed for site-specific delivery to particular plant tissues or rhizosphere zones. Surface functionalization with specific ligands enables recognition by root cells or foliar structures, enhancing uptake efficiency.

Carrier-Based Nano Fertilizers

Nanomaterials such as carbon nanotubes, graphene oxide, or silica nanoparticles serve as carriers for nutrient loading. These carriers protect nutrients from environmental losses and facilitate controlled release.

Mechanisms of Action of Nano Fertilizers

Nano fertilizers improve nutrient delivery efficiency through multiple physicochemical and biological pathways. Unlike conventional fertilizers, which often release nutrients rapidly and exceed plant uptake capacity, nano fertilizers are engineered to synchronize nutrient release with plant demand. Their nanoscale size (1–100 nm) provides unique properties that enhance nutrient absorption, translocation, and utilization within plant systems.

Controlled and Targeted Nutrient Release

One of the most significant advantages of nano fertilizers is their controlled-release behavior. Nutrients can be encapsulated within nano-carriers such as polymer matrices, metal oxides, or biodegradable coatings. These nano-encapsulation systems regulate nutrient diffusion in response to environmental triggers, such as moisture, temperature, or root exudates.

This controlled release:

- Prevents sudden nutrient spikes
- Reduces nitrate leaching
- Minimizes ammonia volatilization
- Improves synchronization with crop nutrient demand

As a result, nutrient use efficiency (NUE) is substantially enhanced compared to conventional fertilizers.

Enhanced Root Uptake Efficiency

Due to their extremely small particle size, nano fertilizers exhibit higher surface reactivity and mobility in soil systems. Nano-scale particles can:

- Penetrate root epidermal layers more efficiently
- Increase contact area with root hairs
- Enhance nutrient diffusion across membranes

This improves nutrient absorption kinetics and facilitates efficient translocation to aerial plant parts. Increased root–nano interaction also enhances rhizospheric nutrient availability.

Improved Foliar Penetration

Nano fertilizers applied through foliar spray can enter plant tissues via:

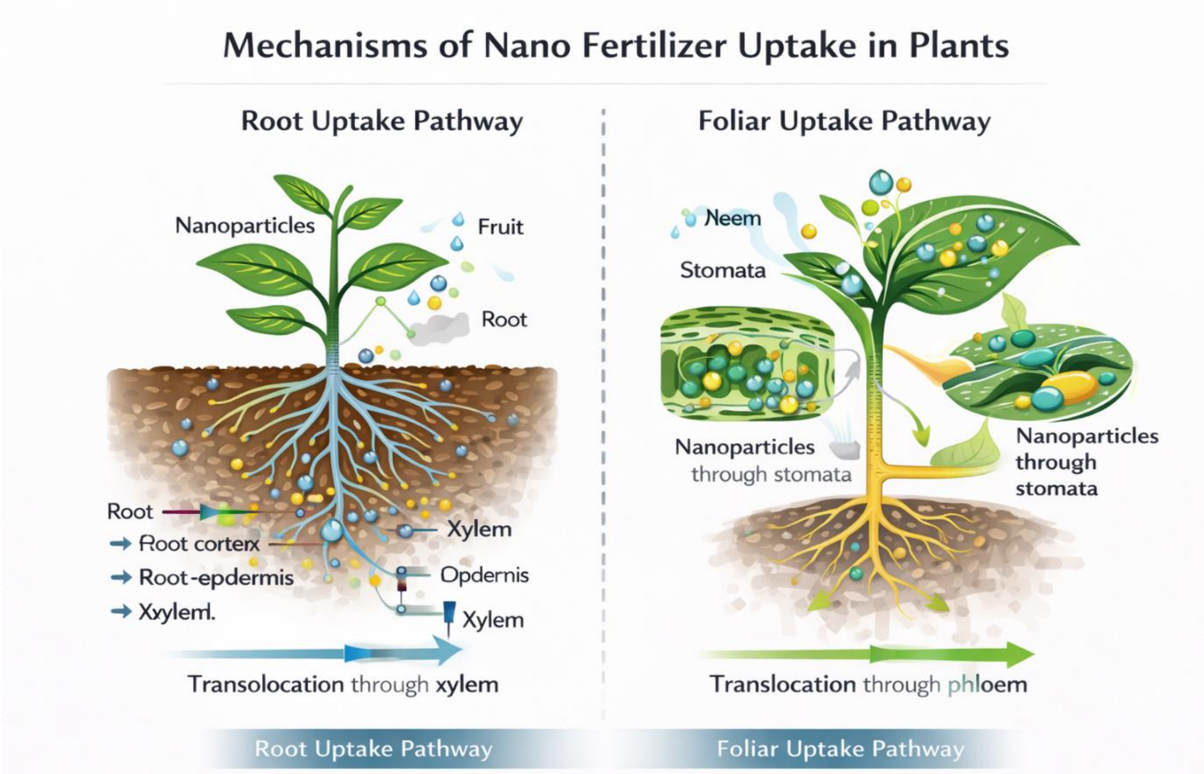
- Stomatal openings
- Cuticular pores
- Trichomes

Their small size enables easier penetration compared to bulk fertilizers. Once inside, nano nutrients are translocated through phloem and xylem pathways, ensuring uniform distribution within plant tissues.

This mechanism is particularly effective for:

- Nano urea
- Nano zinc
- Nano iron

Foliar nano application often requires a lower dosage while achieving comparable or superior results.



Reduced Nutrient Losses and Environmental Emissions

Conventional nitrogen fertilizers are prone to:

- Nitrate leaching into groundwater
- Ammonia volatilization
- Nitrous oxide (N_2O) emission

Nano fertilizers reduce these losses through:

- Slow nutrient release
- Improved root uptake
- Reduced exposure to soil nitrification–denitrification pathways

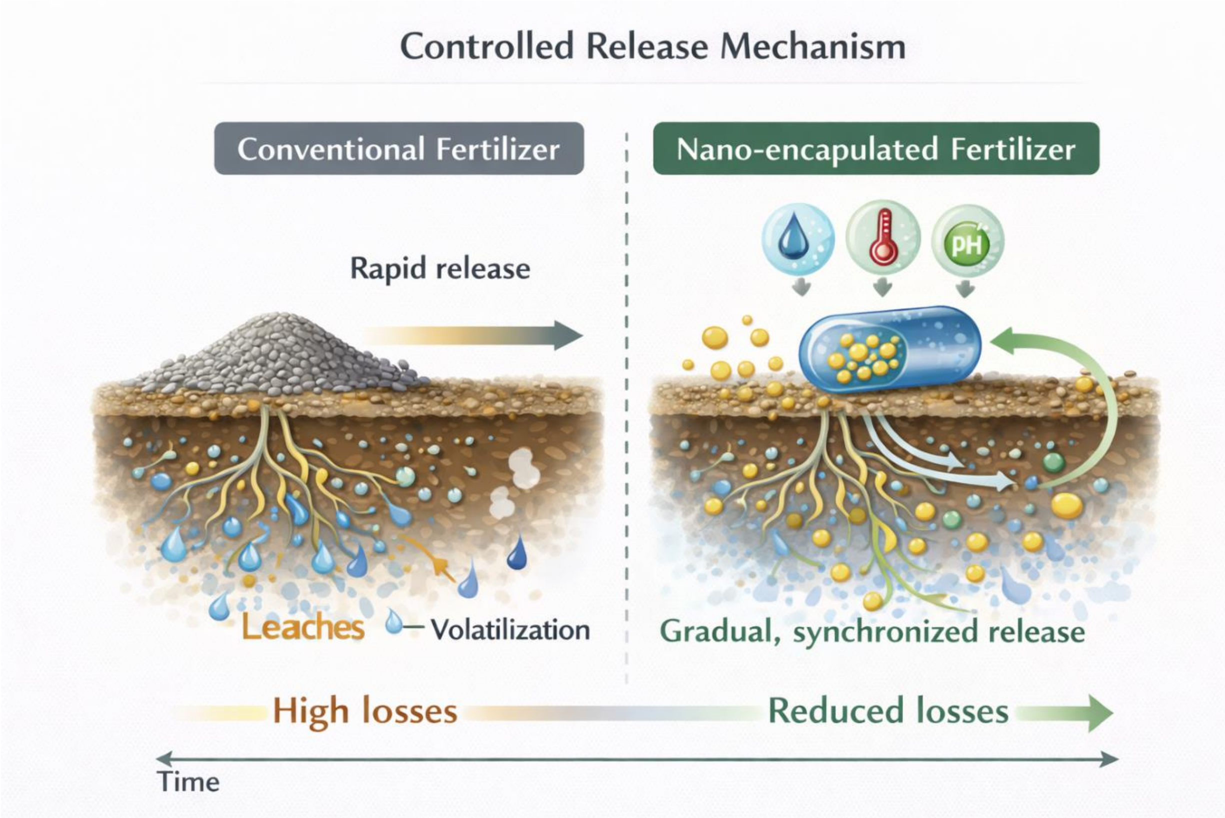
Lower nitrogen losses translate directly into reduced greenhouse gas emissions, aligning nano fertilizers with climate mitigation strategies.

Interaction with Soil Microorganisms

Nano fertilizers can influence soil biological processes in several ways:

- Stimulating beneficial microbial populations
- Enhancing enzymatic activities (e.g., urease, dehydrogenase)
- Improving nutrient mineralization
- Supporting rhizosphere stability

However, the effect is dose-dependent. At optimal concentrations, nano fertilizers enhance soil biological functioning; excessive concentrations may cause microbial toxicity.



Improved Plant Stress Tolerance

Certain Nano formulations, such as nano zinc and nano silicon, improve plant tolerance to abiotic stresses by:

- Enhancing antioxidant enzyme activity
- Improving osmotic balance
- Increasing chlorophyll stability
- Supporting stronger root architecture

This contributes to improved resilience under drought and heat stress conditions.

Role of Nano Fertilizers in Climate-Smart Agriculture

Climate-Smart Agriculture (CSA) aims to address the dual challenge of ensuring global food security while responding to climate change. It is structured around three interlinked pillars: (i) increasing productivity, (ii) enhancing adaptation and resilience, and (iii) reducing greenhouse gas emissions (mitigation). Nano fertilizers have emerged as a promising technological innovation capable of supporting all three pillars simultaneously through improved nutrient management and environmental efficiency.

Enhancing Agricultural Productivity

Productivity enhancement remains the primary objective of modern agriculture. Conventional fertilizers often fail to achieve optimal nutrient uptake due to rapid release and losses in soil systems. Nano fertilizers, by contrast, improve nutrient use efficiency (NUE) through controlled release and targeted delivery mechanisms.
Several studies report that nano formulations:

- Increase chlorophyll content (higher SPAD values)
- Improve photosynthetic efficiency

- Enhance root biomass and shoot growth
- Increase grain yield and harvest index

Nano nitrogen formulations, for example, have demonstrated improved nitrogen assimilation and reduced fertilizer requirement while maintaining or increasing yield levels. Similarly, nano zinc and nano iron enhance micronutrient availability, correcting hidden deficiencies that limit productivity.

By improving nutrient uptake efficiency, nano fertilizers reduce input waste and contribute to higher crop productivity per unit of fertilizer applied, aligning with the first pillar of CSA.

Table 1: Comparison Between Conventional and Nano Fertilizers

Parameter	Conventional Fertilizers	Nano Fertilizers	Implication for CSA
Particle Size	Micron to millimeter scale	1–100 nanometers	Enables unique uptake mechanisms
Surface Area	Relatively low	Very high surface area-to-volume ratio	Enhanced reactivity and interaction
Nutrient Use Efficiency (NUE)	30–50% (Nitrogen)	60–90% (reported in various studies)	Higher productivity per unit input
Nutrient Release Pattern	Rapid and uncontrolled	Controlled, slow, and demand-driven release	Reduces N_2O emissions (Mitigation) & improves NUE (Productivity)
Application Dose	Higher quantity required	Lower dose required due to higher efficiency	Reduced input costs and transport emissions
Leaching Losses	High (especially nitrate)	Significantly reduced	Protects water quality (Adaptation)
Volatilization Loss	High (NH_3 emission common)	Reduced due to controlled release	Lowers indirect GHG emissions
Greenhouse Gas Emissions	Higher N_2O emissions	Reduced N_2O emissions	Direct climate mitigation benefit
Target Specificity	Non-targeted nutrient distribution	Targeted and site-specific delivery possible	Precision agriculture compatibility
Interaction with Soil Microbes	May disrupt microbial balance at high dose	Potential to enhance microbial activity (dose-dependent)	Supports long-term soil health (Resilience)
Environmental Impact	Risk of eutrophication and soil degradation	Lower environmental footprint (if properly regulated)	Aligns with sustainability goals
Cost Consideration	Lower production cost but high long-term environmental cost	Higher initial cost but improved long-term efficiency	Economic trade-off requiring policy support
Precision Agriculture Compatibility	Limited	Highly compatible with sensor-based systems	Enables data-driven nutrient management

Strengthening Climate Adaptation and Resilience

Climate change exposes crops to multiple abiotic stresses, including drought, heat stress, salinity, and nutrient imbalances. Adaptation strategies require technologies that improve plant tolerance and resource efficiency under stress conditions.

Nano fertilizers contribute to adaptation through:

- Improved root architecture enabling better water uptake
- Enhanced antioxidant enzyme activity, reducing oxidative stress
- Stabilization of chlorophyll under heat stress
- Improved osmotic adjustment under drought conditions

Nano silicon and nano zinc have been shown to enhance plant stress tolerance by regulating reactive oxygen species (ROS) metabolism. Additionally, improved nutrient synchronization reduces physiological stress caused by nutrient deficiencies or imbalances.
By increasing resilience at the physiological and soil levels, nano fertilizers strengthen crop stability under variable climatic conditions.

Mitigation of Greenhouse Gas Emissions

Agriculture contributes significantly to global greenhouse gas emissions, particularly nitrous oxide (N_2O) derived from nitrogen fertilizers. Conventional nitrogen management practices are inefficient, resulting in substantial nitrogen losses through volatilization and denitrification.

Nano fertilizers mitigate emissions through:

- Controlled nitrogen release
- Reduced exposure to nitrification–denitrification processes
- Lower fertilizer application rates
- Improved synchronization between nutrient supply and plant demand

Reduced nitrogen losses directly decrease N_2O emissions, thereby lowering the carbon footprint of agricultural production systems. Furthermore, enhanced root growth and microbial activity may contribute to improved soil carbon stabilization and sequestration.
Thus, nano fertilizers help achieve climate mitigation goals by lowering emissions intensity per unit of crop production.

Integration with Precision Agriculture

Nano fertilizers are highly compatible with precision agriculture technologies. Their formulation allows integration with:

- Sensor-based nutrient monitoring systems
- Variable-rate application technologies
- Site-specific nutrient management strategies

Precision nano-delivery reduces excessive fertilizer application and ensures efficient nutrient distribution according to soil variability. This integration further strengthens the CSA framework by improving input efficiency and minimizing environmental impact.

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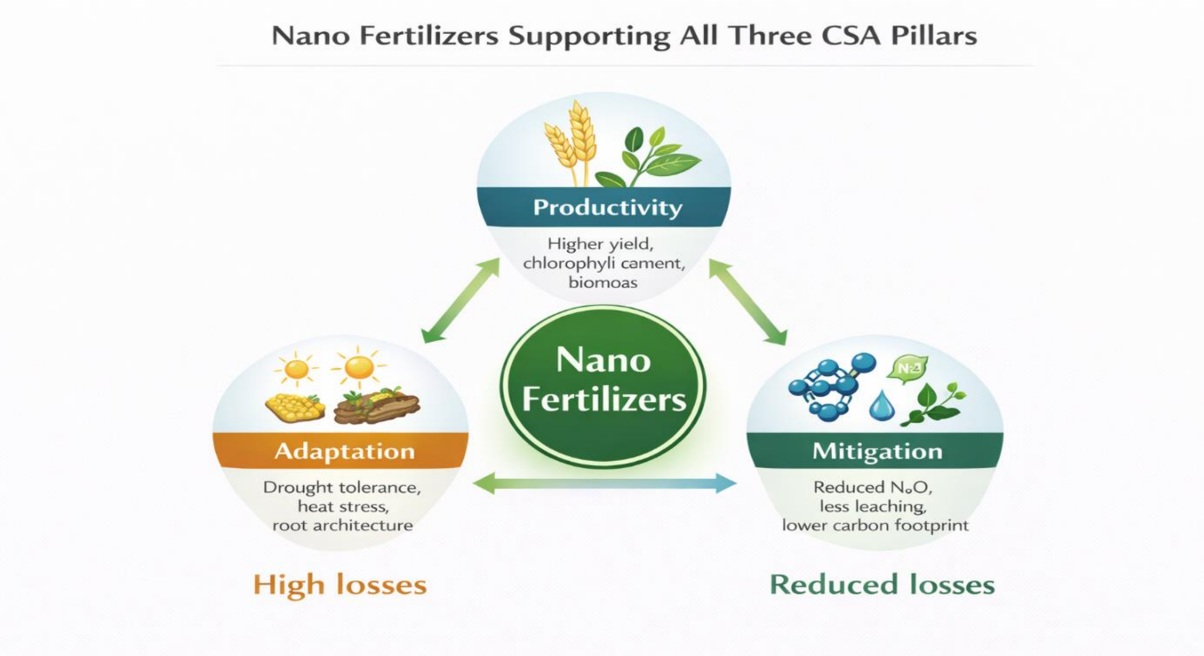


Impact of Nano Fertilizers on Soil Health and Biological Functioning

Soil health is a fundamental determinant of long-term agricultural sustainability. It encompasses the physical, chemical, and biological properties of soil that collectively regulate nutrient cycling, water retention, organic matter dynamics, and crop productivity. While conventional fertilizer systems often focus primarily on nutrient supply, they may inadvertently disrupt soil microbial balance and accelerate soil degradation when applied excessively. In contrast, nano fertilizers are increasingly being evaluated not only for nutrient efficiency but also for their influence on soil biological processes and ecosystem stability.

Influence on Soil Microbial Biomass

Soil microorganisms are central to nutrient mineralization, nitrogen fixation, phosphorus solubilization, and organic matter decomposition. Emerging studies suggest that optimized nano fertilizer application can enhance microbial biomass carbon (MBC) and stimulate beneficial microbial populations in the rhizosphere.

Potential mechanisms include:

- Gradual nutrient availability supporting sustained microbial growth
- Reduced salt stress compared to high-dose conventional fertilizers
- Improved root exudation due to enhanced plant nutrition

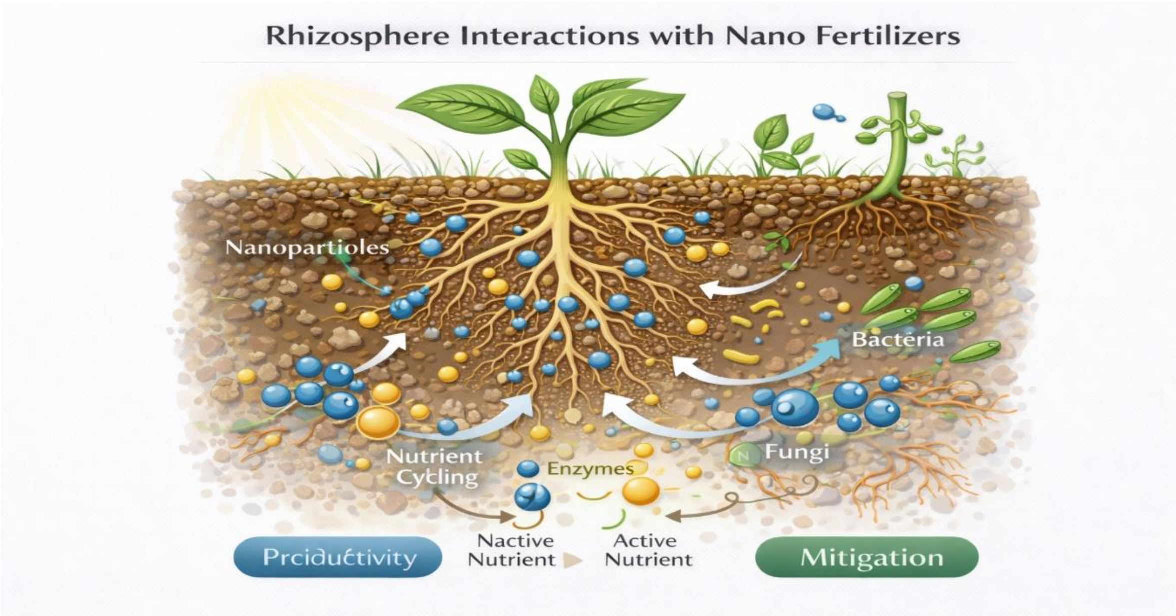
However, the microbial response is highly concentration-dependent. Low to moderate nano fertilizer doses tend to promote microbial activity, whereas excessive nanoparticle accumulation may suppress sensitive microbial groups.

Effect on Soil Enzymatic Activities

Soil enzymes serve as sensitive indicators of soil biological health. Nano fertilizers have been reported to influence key enzymatic activities, including:

- Dehydrogenase activity (indicator of overall microbial oxidative activity)
- Urease activity (nitrogen transformation)
- Phosphatase activity (phosphorus mineralization)
- Catalase activity (oxidative stress response)

Improved nutrient synchronization reduces nutrient shock in soil systems, thereby supporting stable enzymatic functioning. Enhanced dehydrogenase activity, in particular, reflects improved microbial metabolic intensity under balanced nano nutrient supply.



Impact on Soil Organic Carbon Dynamics

Soil organic carbon (SOC) plays a crucial role in climate mitigation and soil structural stability. Efficient nutrient use through nano fertilizers can indirectly influence SOC dynamics by:

- Increasing root biomass production
- Enhancing rhizospheric carbon inputs
- Supporting microbial carbon stabilization processes

Improved plant growth leads to greater below-ground carbon deposition, potentially contributing to long-term carbon sequestration. When integrated with conservation practices, nano fertilizers may support carbon-positive agricultural systems.

Interaction with Rhizosphere Processes

The rhizosphere represents a biologically active interface between plant roots and soil. Nano fertilizers can modify rhizosphere processes by:

- Enhancing nutrient diffusion gradients
- Improving root surface contact
- Stimulating beneficial plant–microbe symbiosis
- Supporting mycorrhizal associations

Microbe-assisted nano formulations further enhance nutrient cycling and reduce dependency on high synthetic fertilizer inputs.

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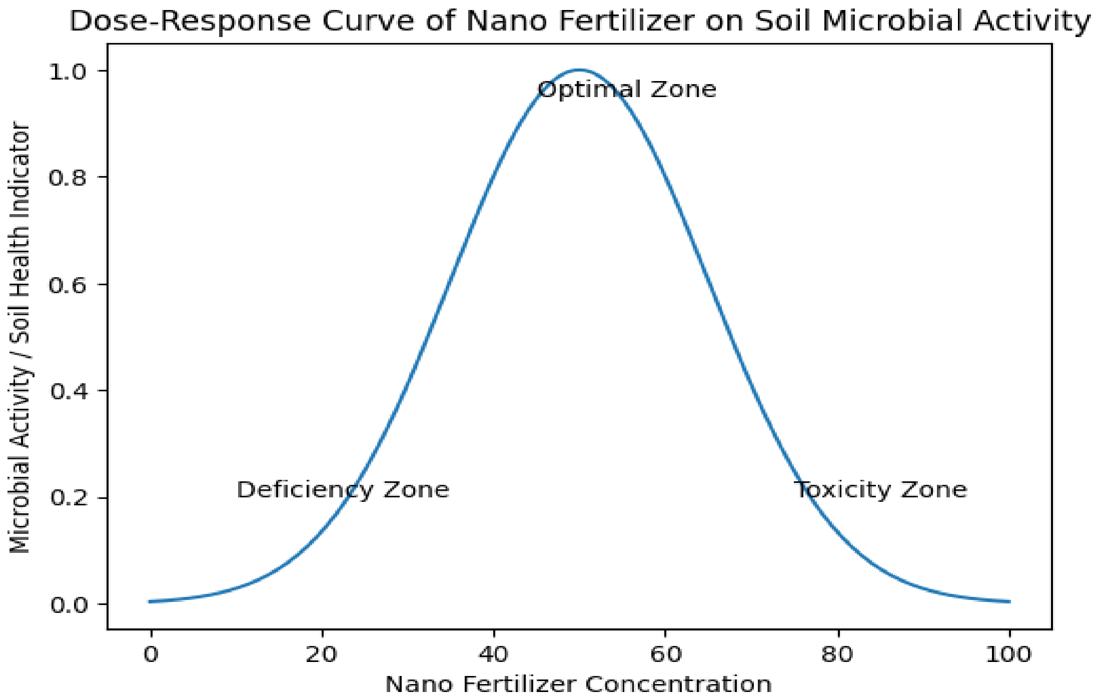


Soil Physical and Chemical Stability

In addition to biological parameters, nanoformulations may influence soil physical properties by:

- Reducing nutrient accumulation and salt build-up
- Reducing soil acidification caused by excessive nitrogen application
- Improving nutrient distribution uniformity

Better nutrient efficiency reduces secondary soil degradation problems often associated with conventional fertilizer overuse.

Table 2: Effects of Nano Fertilisers on Soil Biological and Biochemical Indicators

Soil Indicator	Observed Impact of Nano Fertilizers	Implication for Soil Health
Microbial Biomass Carbon	Increased (dose-dependent)	Improved nutrient cycling capacity
Dehydrogenase Activity	Enhanced	Higher microbial metabolic activity
Urease Activity	Regulated and stabilized	Efficient nitrogen transformation
Phosphatase Activity	Moderately enhanced	Improved phosphorus mineralization
Soil Respiration	Improved	Active microbial processes
Soil Organic Carbon	Potential increase (indirect)	Enhanced carbon stabilization
Rhizosphere Interaction	Strengthened	Enhanced plant–microbe synergy
Soil Aggregate Stability	Potentially improved	Better soil structure and water infiltration

Patent Landscape and Innovation Trends in Nano Fertilizers

The rapid advancement of nano fertilizer technology is reflected in the increasing number of patent filings worldwide. Patent landscape analyses provide insight into innovation trajectories, commercialization potential, and emerging research priorities within nano-enabled nutrient management systems. Over the past decade, global research and development activities in nano fertilizers have expanded significantly, particularly in technologically advanced and agriculturally intensive regions.

Recent analyses of international patent databases indicate strong innovation activity in countries such as the United States, China, and India, demonstrating the strategic importance of nano fertilizers in sustainable agricultural transformation. The majority of patents fall within fertilizer chemistry (IPC Class C05) and agricultural applications (A01), highlighting a combined focus on material engineering and field-level nutrient management.

Major Innovation Domains

Patent trends reveal five dominant innovation clusters in nano fertilizer development:

(i) Advanced Nutrient Delivery Systems

Nano-encapsulation technologies represent one of the most prominent areas of innovation. These systems involve coating or embedding nutrients within biodegradable polymers or nanocarriers to enable controlled and sustained release. Such designs improve nutrient synchronization with plant demand, reducing environmental losses and improving nutrient use efficiency (NUE).

(ii) Nanomaterial-Based Fertilisers

Patents frequently describe the use of metal and metal oxide nanoparticles such as nano zinc oxide (ZnO), nano iron oxide (Fe_2O_3), nano silica, and nano hydroxyapatite. These materials enhance nutrient solubility, bioavailability, and plant absorption efficiency. Their nanoscale properties facilitate better interaction with root surfaces and soil colloids.

(iii) Precision Agriculture Integration

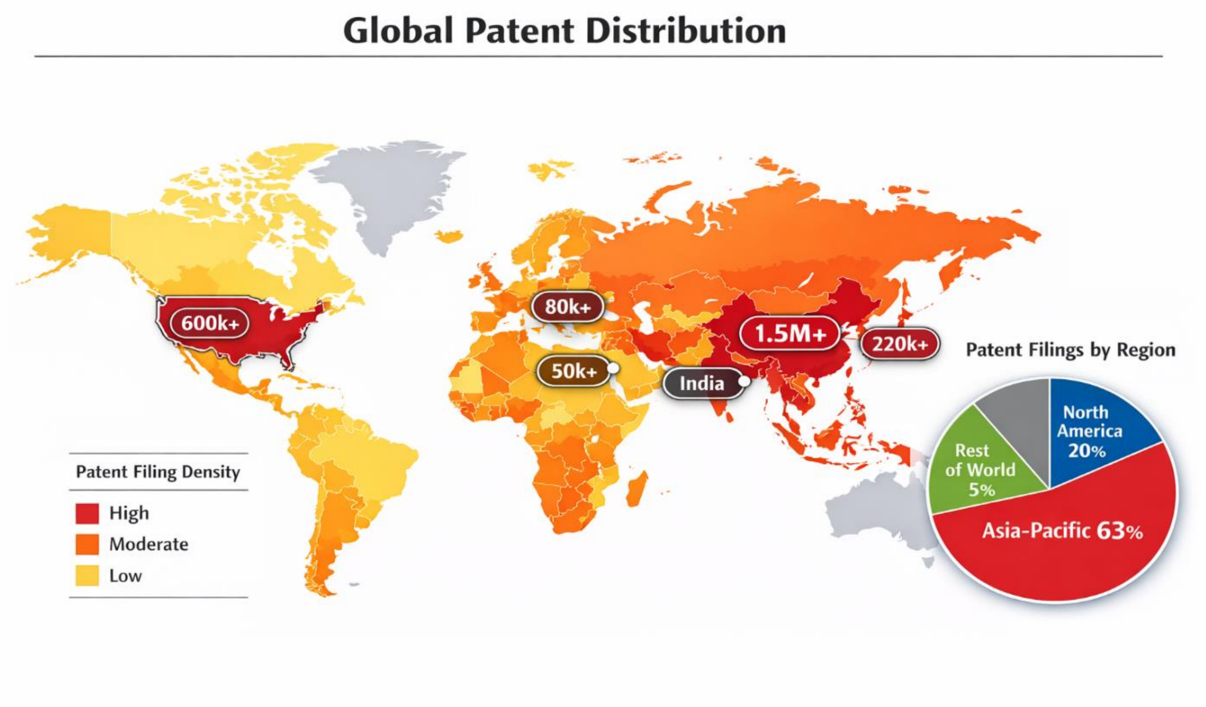
Emerging innovations integrate nano fertilizers with sensor-based monitoring systems and variable-rate application technologies. Smart nano delivery systems are designed to respond to soil moisture, pH, or plant nutrient status, thereby enabling site-specific nutrient management. This approach strengthens resource efficiency and reduces excessive fertilizer application.

(iv) Soil Remediation and Conditioning

Some patented nano formulations focus on improving soil structure, detoxifying contaminated soils, and enhancing rhizosphere stability. Nano-enabled soil conditioners may contribute to carbon stabilization and restoration of degraded agricultural lands.

(v) Plant–Microbe Interaction Enhancement

Microbe-assisted nano formulations represent an emerging frontier in sustainable agriculture. These technologies combine nano nutrients with beneficial microorganisms to enhance nutrient cycling, stimulate root growth, and strengthen plant immune responses.



Commercialization and Strategic Implications

The growth in patent activity indicates a transition of nano fertilizers from laboratory research toward commercial-scale deployment. Large fertilizer industries and biotechnology firms are increasingly investing in nano-enabled nutrient systems to improve fertilizer efficiency and reduce environmental footprint.

Table 3: Emerging Innovation Domains in Nano Fertilizer Development

Innovation Domain	Key Technological Focus	Relevance to CSA
Nano Encapsulation	Controlled nutrient release systems	Reduced nutrient loss and improved NUE (Productivity & Mitigation)
Metal Oxide Nanoparticles	Enhanced nutrient bioavailability	Increased productivity and stress tolerance (Adaptation)
Smart Precision Nano Systems	Sensor-linked nutrient delivery	Resource optimization and reduced environmental footprint
Soil Conditioning Nanoagents	Rhizosphere improvement and remediation	Long-term soil resilience (Adaptation)
Microbe–Nano Synergistic Formulations	Enhanced biological nutrient cycling	Sustainable soil health (Productivity & Adaptation)
Biodegradable Nanocarriers	Eco-friendly polymer-based delivery	Reduced ecotoxicity risk (Environmental safety)

Commercial interest is driven by:

- Demand for higher nutrient efficiency
- Regulatory pressure to reduce nitrogen emissions
- Need for climate-resilient agricultural inputs
- Rising adoption of precision farming technologies

However, despite rapid technological development, regulatory frameworks for nano fertilizers remain evolving in many countries. Clear guidelines for environmental safety, dosage limits, and quality standards are essential for responsible commercialization.

Implications for Climate-Smart Agriculture

Innovation trends strongly align with the objectives of Climate-Smart Agriculture. Controlled-release nano systems reduce greenhouse gas emissions (mitigation), stress-tolerant formulations enhance crop resilience (adaptation), and improved nutrient efficiency increases productivity. The convergence of nanotechnology, precision agriculture, and biological systems represents a multidisciplinary pathway toward sustainable intensification.

Environmental and Safety Considerations

Although nano fertilizers demonstrate significant potential for improving nutrient use efficiency and supporting climate-smart agriculture, their long-term environmental and ecological implications require careful evaluation. The small particle size and high reactivity that confer agronomic advantages may also raise concerns regarding nanoparticle persistence, mobility, and bioaccumulation in soil–plant systems.

Nanoparticle Persistence and Soil Accumulation

Unlike conventional fertilizers that dissolve or transform rapidly in soil, certain engineered nanoparticles may persist depending on their composition, coating material, and environmental conditions. Repeated applications over multiple cropping cycles could lead to gradual accumulation in soil matrices.

Potential concerns include:

- Alteration of soil physicochemical properties
- Disruption of microbial community structure
- Interaction with soil colloids and organic matter

The environmental fate of nanoparticles is influenced by soil pH, texture, moisture, and organic carbon content. Therefore, long-term field trials are essential to assess cumulative effects.

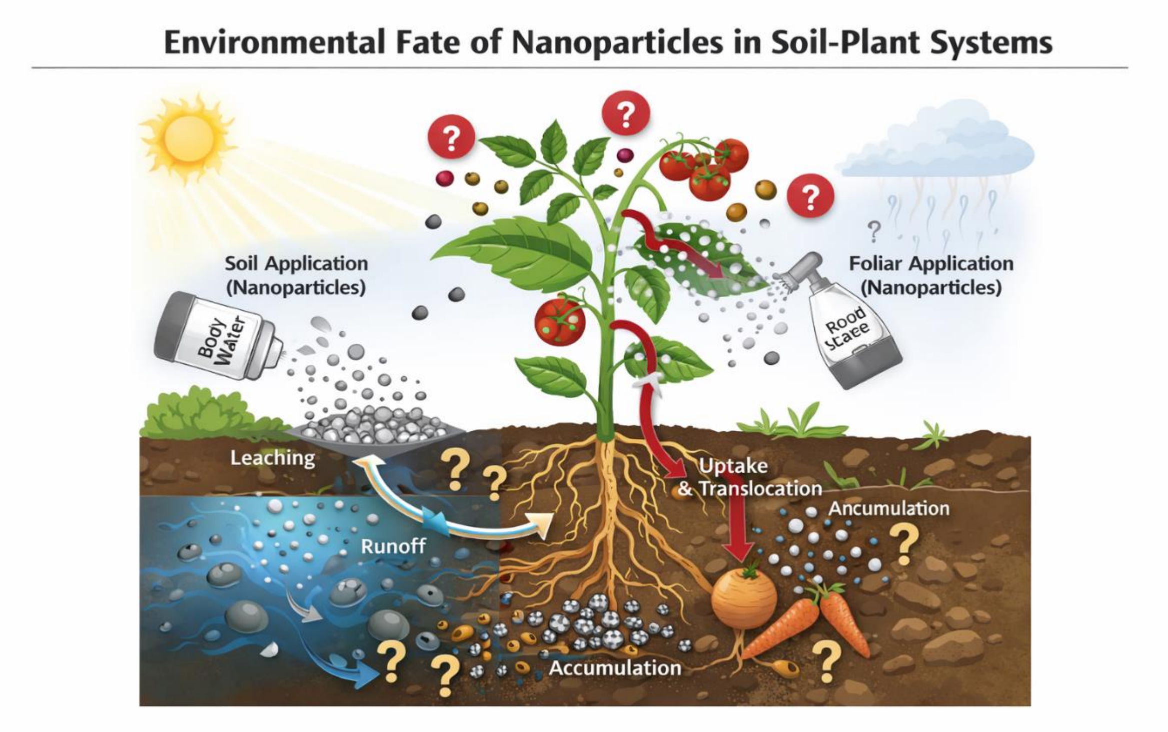
Ecotoxicological Impacts

At optimal concentrations, nano fertilizers may stimulate microbial and plant growth; however, excessive doses can induce oxidative stress in soil microorganisms and plants. Certain metal-based nanoparticles, such as ZnO or Fe_2O_3, may generate reactive oxygen species (ROS) under high concentrations.

Possible ecotoxicological risks include:

- Microbial inhibition at high nanoparticle concentrations
- Root membrane damage under excessive exposure
- Bioaccumulation in plant tissues

Dose optimization and safe concentration thresholds must be scientifically established before widespread application.



Risk of Food Chain Transfer

Nanoparticles absorbed by plants may translocate to edible plant parts depending on size and chemical composition. Although many nanoformulations are designed for controlled nutrient release and biodegradability, the potential for nanoparticle entry into the food chain requires detailed investigation.

Research priorities include:

- Tracking nanoparticle movement within plant tissues
- Assessing human exposure risks
- Evaluating long-term health implications

Comprehensive food safety studies are necessary to address public concerns and regulatory requirements.

Regulatory and Policy Challenges

Regulatory frameworks for nano fertilizers are still evolving in many countries. Unlike traditional fertilizers, nano formulations require specialized risk assessment protocols due to their unique physicochemical properties.

Key regulatory challenges include:

- Lack of standardized toxicity testing guidelines
- Limited life cycle assessment (LCA) studies
- Absence of harmonized global nano-agriculture policies
- Difficulty in defining nano-specific labeling standards

Developing science-based regulatory policies is essential to ensure safe commercialization and farmer confidence.

Need for Life Cycle Assessment (LCA)

To fully evaluate sustainability, nano fertilizers must be assessed through life cycle analysis, considering:

- Production energy requirements
- Environmental footprint
- Transport and application efficiency
- End-of-life environmental impact

While nano fertilizers may reduce field-level emissions, manufacturing processes must also be environmentally responsible to achieve net climate benefits.

Economic Feasibility and Adoption Challenges

The large-scale adoption of nano fertilizers depends not only on agronomic performance but also on economic viability and accessibility for farmers. While nano fertilizers offer improved nutrient use efficiency (NUE) and reduced environmental losses, their economic implications must be carefully evaluated under field conditions.

Cost Comparison

The production cost of nano fertilizers is generally higher than that of conventional bulk fertilizers—usually 2-4 times more expensive per kg of nutrient—due to advanced manufacturing processes, nanomaterial synthesis, and quality control. However, nano fertilizers often require smaller application doses because of their higher efficiency. Lower nutrient loss, decreased transportation volume, and fewer repeat applications may offset the initial cost differences.

For example, nano nitrogen formulations have demonstrated comparable yield responses with 20–50% lower nitrogen application rates under optimized conditions. This reduction can partially compensate for higher per-unit product cost. When calculated as "cost per unit of nutrient taken up by the plant" or "cost per ton of yield," nano fertilizers often prove more economical.

Return on Investment (ROI)

Economic return depends on multiple factors:

- Increased crop yield (5-15% reported in some trials)
- Reduced fertilizer input quantity (20-50% reduction)
- Lower labor and transportation costs
- Reduced environmental compliance costs

Field studies indicate that improved NUE and yield stability may enhance profitability, particularly in high-value crops. However, ROI may vary depending on soil type, cropping system, and agro-climatic conditions. Long-term multi-season economic trials are necessary to establish consistent benefit–cost ratios.

Risk Mitigation Value

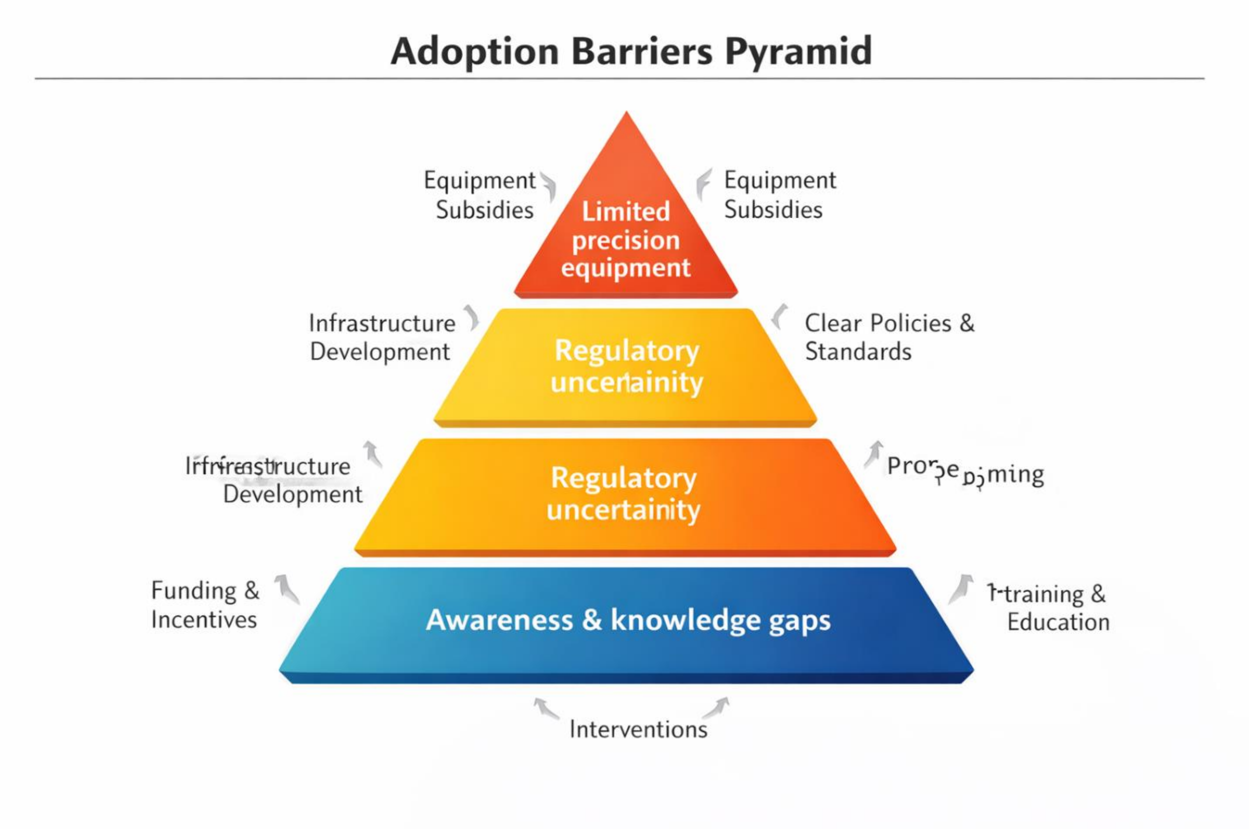
The higher initial cost of nano fertilizers can be viewed as an investment in risk reduction. Improved stress tolerance (drought, heat, nutrient deficiency) leads to more consistent yields, offering economic stability that is hard to measure but highly valued by farmers. This resilience benefit is a crucial, yet often overlooked, part of the economic argument for adopting nano fertilizer.

Life Cycle Costing (LCC)

A comprehensive economic analysis requires a Life Cycle Costing perspective, which considers:

- Production and manufacturing costs
- Distribution and application expenses
- Environmental externality costs
- Long-term soil health implications

While upfront costs favor conventional fertilizers, the full life cycle cost—including environmental remediation and productivity losses from soil degradation—may favornano-enabled systems.



Adoption Challenges for Smallholder Farmers

Despite technological promise, several constraints may limit adoption among small-scale farmers:

- Higher upfront product cost
- Limited awareness and technical knowledge
- Uncertainty regarding long-term safety
- Inadequate regulatory clarity
- Limited access to precision application equipment

To ensure inclusive adoption, policy interventions should include:

- Farmer training programs and extension services

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- Subsidy support during transition phase
- Clear labeling and safety guidelines
- Public–private partnerships for distribution
- Risk-sharing instruments such as crop insurance with premium discounts for CSA technology adopters
- Carbon credit mechanisms that reward verified emission reductions

Table 4: Quantitative Performance Comparison Between Conventional and Nano Nitrogen Fertilizers

Parameter	Conventional N Fertilizer	Nano N Fertilizer	Implication
Nitrogen Use Efficiency (NUE, %)	30–50%	60–90%	Doubled efficiency with same nutrient input
N_2O Emission Reduction	Baseline	15–30% reduction (reported range)	Direct climate mitigation benefit
Nitrogen Dose Requirement	100% recommended dose	50–80% of recommended dose	20-50% input reduction possible
Yield Response	Moderate	Comparable or increased (5–15% reported in some trials)	Productivity maintained or enhanced
Leaching Loss	High (variable)	Reduced (20–40% reported range)	Water quality protection
Application Frequency	Multiple splits	Reduced frequency (controlled release)	Labor and fuel savings
Cost per kg of nutrient	Low	High (2-4x)	Apparent disadvantage
Cost per ton of yield	Baseline	Potentially lower	Actual economic advantage when efficiency considered

Future Prospects and Research Directions

Nano fertilizer technology is still evolving, and its full potential in climate-smart agriculture has yet to be realized. While current research highlights improvements in nutrient use efficiency, crop productivity, and environmental sustainability, future advancements must focus on interdisciplinary integration, long-term safety validation, and scalable implementation strategies.

Development of Smart and Responsive Nano-Delivery Systems

Next-generation nano fertilizers are expected to move beyond passive controlled-release systems toward stimuli-responsive or smart delivery platforms. These systems may respond dynamically to:

- Soil moisture fluctuations
- Root exudate signals
- pH variations
- Plant nutrient demand

Such adaptive systems could optimize nutrient release in real time, significantly improving synchronization between nutrient supply and crop requirements.

Integration with Precision Agriculture and Digital Technologies

The convergence of nanotechnology with digital agriculture represents a transformative opportunity. Integration with:

- IoT-based soil sensors
- Remote sensing platforms
- Artificial intelligence (AI)-driven nutrient models
- Variable-rate fertilizer applicators

can enable data-driven nutrient management. Nano fertilizers combined with precision agriculture tools could reduce fertilizer wastage while maximizing crop productivity.

Biodegradable and Eco-Friendly Nanocarriers

A major research priority is the development of biodegradable nanocarriers derived from natural polymers such as chitosan, starch, lignin, and cellulose. These materials can minimize environmental persistence and reduce ecotoxicological concerns associated with synthetic nanoparticle accumulation.

Eco-friendly nano formulations should aim to:

- Enhance nutrient efficiency
- Reduce soil toxicity risks
- Support circular bio economy principles

Long-Term Field Trials and Soil Health Monitoring

Most current studies are short-term or conducted under controlled conditions. Long-term, multi-season field experiments across diverse agro-climatic zones are essential to:

- Evaluate cumulative nanoparticle effects
- Assess changes in soil microbial diversity
- Monitor soil organic carbon dynamics
- Measure greenhouse gas emission reductions
- Establish safe concentration thresholds

Robust field-based evidence will strengthen regulatory approval and farmer adoption.

Policy Framework and Farmer Adoption

Successful implementation of nano fertilizers requires:

- Clear regulatory guidelines and safety standards
- Standardized quality control protocols
- Harmonized international nano-agriculture policies
- Farmer awareness and training programs
- Cost-effective production technologies
- Risk-sharing mechanisms and carbon credit integration

Policy support and public–private partnerships will be crucial for scaling nano-enabled nutrient management systems.

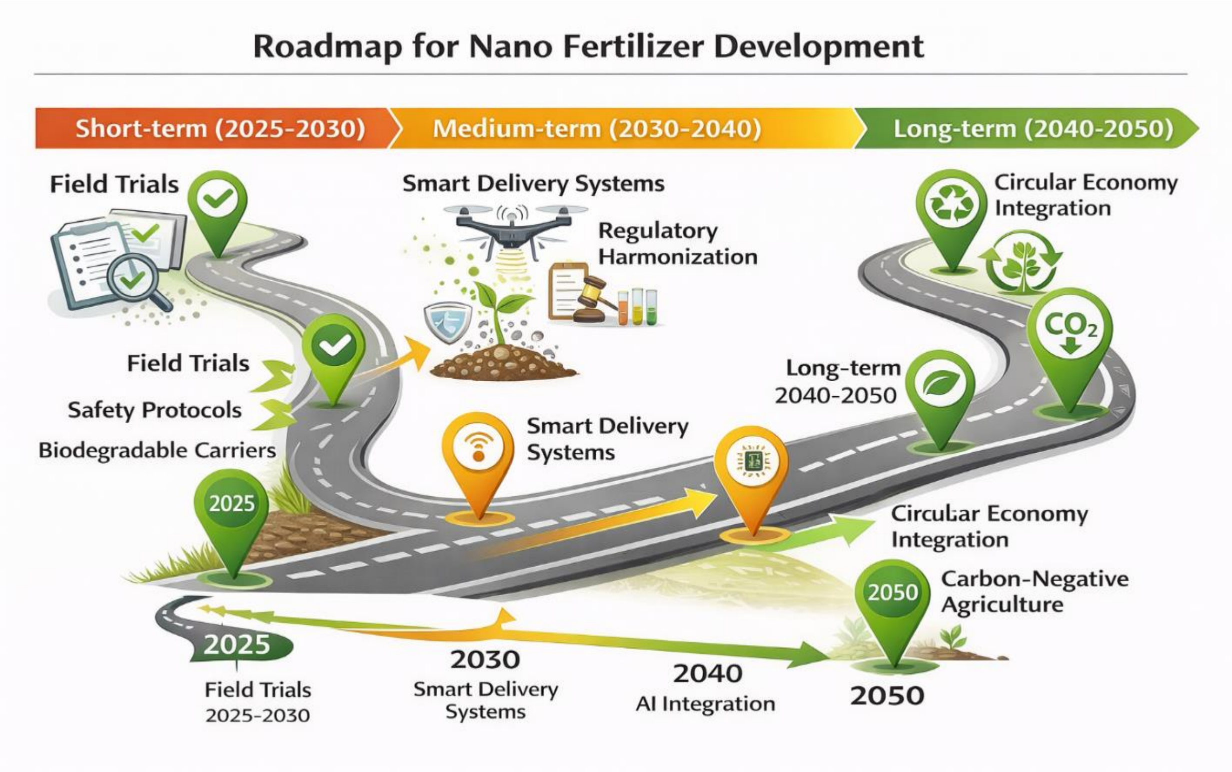
Contribution to Sustainable Development Goals (SDGs)

Nano fertilizers align with multiple Sustainable Development Goals, including:

- **SDG 2 (Zero Hunger):** Enhanced productivity and nutrient efficiency

- **SDG 6 (Clean Water and Sanitation):** Reduced nutrient leaching
- **SDG 12 (Responsible Consumption and Production):** Improved input efficiency
- **SDG 13 (Climate Action):** Reduced GHG emissions
- **SDG 15 (Life on Land):** Protection of soil ecosystems

By enhancing productivity while reducing environmental footprint, nano fertilizers may contribute to resilient and low-carbon agricultural systems.



Conclusion

The integration of nano fertilizers into the Climate-Smart Agriculture (CSA) framework represents a critical evolution in sustainable nutrient management. As global food systems face the compounding pressures of climate instability and resource depletion, the transition from conventional, high-loss fertilization to precision-targeted nano-delivery is no longer a luxury but a necessity. This review confirms that by leveraging their unique physicochemical properties, nano fertilisers can bridge the gap between high productivity and environmental stewardship—simultaneously boosting yields, priming crops for resilience to abiotic stress, and drastically reducing greenhouse gas emissions.

However, the journey from laboratory innovation to widespread field adoption is contingent on navigating a complex landscape of ecological uncertainty and economic reality. While the agronomic benefits are evident, the long-term impact of nanoparticle persistence in soil requires vigilant, science-based monitoring. The future of this technology lies in "Green Nanotechnology"—prioritising biogenic synthesis and biodegradable carriers to ensure that the tools we deploy to protect our soil today do not become tomorrow's pollutants.

The Path Forward

The successful deployment of nano-enabled agriculture hinges on a coordinated, multi-disciplinary effort:

- **For Scientists:** The priority must shift from merely demonstrating efficacy to elucidating long-term fate and developing smart-release, biodegradable formulations. Research should focus on dose optimization, mechanistic understanding of plant–nanoparticle interactions, and development of eco-friendly synthesis methods.
- **For Policymakers:** The urgent task is to establish transparent, harmonized safety standards and certification protocols that build trust without stifling innovation. Regulatory frameworks must address nanoparticle characterisation, environmental fate assessment, and food safety evaluation, while enabling responsible commercialisation.
- **For Economists and Development Agencies:** The focus should be on innovative financing and extension models that bridge the initial cost-gap and knowledge barrier for smallholder farmers. Carbon credit mechanisms, risk-sharing instruments, and public–private partnerships can ensure equitable access to this transformative technology.
- **For the Agricultural Industry:** Investment in scalable, cost-effective manufacturing processes and farmer education programs will be essential for market development and responsible deployment.

By harmonizing these efforts, nano fertilizers can fulfill their potential as a cornerstone of a resilient, low-carbon, and food-secure future. The path forward requires balancing innovation with precaution, efficiency with equity, and productivity with sustainability. If navigated wisely, nano-enabled nutrient management may prove to be one of the most significant agricultural advancements of the twenty-first century.

References

Bindraban, P. S., Dimkpa, C. O., & Pandey, R. (2020). Exploring phosphorus fertilizers and nano-enabled nutrient systems. *Agronomy for Sustainable Development*, 40, 1–15.

Chen, H., & Yada, R. (2011). Nanotechnologies in agriculture: New tools for sustainable crop production. *Trends in Food Science & Technology*, 22, 585–594.

DeRosa, M. C., Monreal, C., Schnitzer, M., Walsh, R., & Sultan, Y. (2010). Nanotechnology in fertilizers. *Canadian Journal of Plant Science*, 90, 607–616.

Duhan, J. S., Kumar, R., Kumar, N., Kaur, P., Nehra, K., &Duhan, S. (2017). Nanotechnology: The new perspective in precision agriculture. *Biotechnology Reports*, 15, 11–23.

FAO. (2017). *Climate-smart agriculture sourcebook*. Rome: FAO.

Gogos, A., Knauer, K., &Bucheli, T. D. (2012). Nanomaterials in plant protection and fertilization. *Journal of Agricultural and Food Chemistry*, 60, 9781–9792.

Hyder, S., Ul-Nisa, M., Shahzadi, N., Shahid, H., Gohar, F., Gondal, A. S., Riaz, N., Younas, A., De Los Santos-Villalobos, S., Montoya-Martínez, A. C., Sehar, A., Latif, F., Rizvi, Z. F., & Iqbal, R. (2023). Recent trends and perspectives in the application of metal and metal oxide nanomaterials for sustainable agriculture. *Plant Physiology and Biochemistry*, 202, 107960. https://doi.org/10.1016/j.plaphy.2023.107960

Iavicoli, I., Leso, V., Beezhold, D. H., & Shvedova, A. A. (2017). Nanotechnology in agriculture: Opportunities, toxicological implications, and occupational risks. *Toxicology and Applied Pharmacology*, 329, 96–111. https://doi.org/10.1016/j.taap.2017.05.025

IFFCO. (2024a). Nano-urea for rice cultivation in India. https://nanourea.in/en/nano-urea

IFFCO. (2024b). Crop-wise increase in yields compared to traditional urea application. https://www.iffco.in/en/crop-wise-nano-urea

Jhala, V. M., Mandaliya, V. B., &Thaker, V. S. (2015). Simple and efficient protocol for RNA and DNA extraction from rice (*Oryza sativa* L.) for downstream applications. *International Research Journal of Biological Sciences*, 4(2), 62–67.

Jiang, L., Zou, F., Qiao, Y., & Huang, Y. (2022). Patent analysis for generating the technology landscape and competition situation of renewable energy. *Journal of Cleaner Production*, 378, 134264.

Juárez-Maldonado, A., et al. (2019). Nanoparticles and their impact on plant physiology. *Journal of Plant Nutrition and Soil Science*, 182, 1–14.

Kah, M., Tufenkji, N., & White, J. C. (2019). Nano-enabled strategies for crop improvement. *Nature Nanotechnology*, 14, 532–540.

Kalıp, N. G., Erzurumlu, Y. M., &Gün, N. A. (2022). Qualitative and quantitative patent valuation methods: A systematic literature review. *World Patent Information*, 69, 102111. https://doi.org/10.1016/j.wpi.2022.102111

Kang, H. Y. (2012). Science inside law: The making of a new patent class in the international patent classification. *Science in Context*, 25(4), 551–594.

Karvonen, M., Kapoor, R., Uusitalo, A., &Ojanen, V. (2016). Technology competition in the internal combustion engine waste heat recovery: A patent landscape analysis. *Journal of Cleaner Production*, 112, 3735–3743.

Khanali, M., Ghasemi-Mobtaker, H., Varmazyar, H., Mohammadkashi, N., Chau, K. W., &Nabavi-Pelesaraei, A. (2022). Applying novel eco-exergoenvironmental toxicity index to select the best irrigation system of sunflower production. *Energy*, 250, 123822. https://doi.org/10.1016/j.energy.2022.123822

Khot, L. R., Sankaran, S., Maja, J. M., Ehsani, R., & Schuster, E. W. (2012). Applications of nanomaterials in agriculture. *Crop Protection*, 35, 64–70.

King, S., &Locock, K. E. (2022). A circular economy framework for plastics: A semi-systematic review. *Journal of Cleaner Production*, 364, 132503. https://doi.org/10.1016/j.jclepro.2022.132503

Kumar, Y., Tiwari, K. N., Singh, T., &Raliya, R. (2021). Nanofertilizers and their role in sustainable agriculture. *Annals of Plant and Soil Research*, 23(3), 238–255.

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability*, 7, 5875–5895.

Lee, S., Yoon, B., Lee, C., & Park, J. (2009). Business planning based on technological capabilities: Patent analysis for technology-driven roadmapping. *Technological Forecasting and Social Change*, 76(6), 769–786. https://doi.org/10.1016/j.techfore.2009.01.003

Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D. P., Henry, K., Hottle, R., Jackson, L., Jarvis, A., Kossam, F., Mann, W., McCarthy, N., Meybeck, A., Neufeldt, H., Remington, T., et al. (2014). Climate-smart agriculture for food security. *Nature Climate Change*, 4(12), 1068–1072. https://doi.org/10.1038/nclimate2437

Litvinova, O., Klager, E., Tzvetkov, N. T., Kimberger, O., Kletecka-Pulker, M., Willschke, H., &Atanasov, A. G. (2022). Digital pills with ingestible sensors: Patent landscape analysis. *Pharmaceuticals*, 15(8), 1025.

Liu, R., & Lal, R. (2015). Potentials of engineered nanoparticles as fertilizers. *Soil Science*, 180, 301–309.

Lizin, S., Leroy, J., Delvenne, C., Dijk, M., De Schepper, E., & Van Passel, S. (2013). A patent landscape analysis for organic photovoltaic solar cells: Identifying the technology's development phase. *Renewable Energy*, 57, 5–11.

Lukman, R. K., Glavič, P., Carpenter, A., &Virtič, P. (2016). Sustainable consumption and production–Research, experience, and development–The Europe we want. *Journal of Cleaner Production*, 138, 139–147.

Mukhopadhyay, S. S. (2014). Nanotechnology in agriculture: Prospects and constraints. *International Journal of Nanoscience*, 13, 1340004.

Nair, R., Varghese, S., Nair, B., Maekawa, T., Yoshida, Y., & Kumar, D. (2010). Nanoparticulate material delivery to plants. *Plant Science*, 179, 154–163.

Rai, M., Ribeiro, C., Mattoso, L., & Duran, N. (2015). Nanotechnologies in agriculture: Current status and future prospects. *Journal of Agricultural and Food Chemistry*, 63, 4039–4046.

Raliya, R., Saharan, V., Dimkpa, C., & Biswas, P. (2018). Nanofertilizer for precision agriculture. *Scientific Reports*, 8, 1–10.

Servin, A. D., & White, J. C. (2016). Nanotechnology in agriculture: Next steps. *NanoImpact*, 1, 9–12.

Shang, Y., Hasan, M., Ahammed, G. J., Li, M., Yin, H., & Zhou, J. (2019). Applications of nanotechnology in plant growth and crop protection. *Molecules*, 24, 2558.

Tarafdar, J. C., Raliya, R., Mahawar, H., & Rathore, I. (2014). Development of zinc nanofertilizer. *Agricultural Research*, 3, 257–262.

White, J. C., &Gardea-Torresdey, J. L. (2018). Achieving food security through nanotechnology. *Journal of Agricultural and Food Chemistry*, 66, 6556–6567.

Zhang, X., Brown, R., &Kah, M. (2020). Environmental impacts of nano fertilizers. *Science of the Total Environment*, 715, 136–147.

Research Article

SURVEY, ISOLATION AND BIOCHEMICAL CHARACTERIZATION OF RHIZOBIUM ISOLATES FROM COWPEA (*VIGNA UNGUICULATA* L.)IN FARMERS' FIELDSAT THIRUVALLUR, TAMIL NADU AND ITS EFFECT ON GROWTH AND YIELD OF COWPEA

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Abstract

The present investigation was undertaken to assess the diversity, biochemical traits, and field efficacy of *Rhizobium* isolates associated with cowpea (*Vigna unguiculata* L.) root nodules in Thiruvallur district, Tamil Nadu. A survey across four locations (Thiruvalangadu, Chakaramanallur, Pallipattu, and Kanagamachathiram) revealed significant variation in *Rhizobium* populations, with densities ranging from 18.0 × 10^3 to 25.5 × 10^3 CFU/g of soil, and Kanagamachathiram recording the highest population. All isolates exhibited typical Gram-negative, rod-shaped, mucoid colonies and were positive for starch and gelatin hydrolysis but negative for the Voges–Proskauer test, with variability noted in citrate utilization. Field evaluation demonstrated that Rhizobium inoculation significantly improved plant growth, nodulation, dry matter production, and yield attributes over uninoculated and fertilizer controls. Among the treatments, 75% recommended nitrogen + Rhizobium inoculation (T_2) consistently outperformed others, recording the highest pod yield per plant (37.57 g), followed by 50% nitrogen + Rhizobium (T_3). The control (C_1) recorded the lowest values across all traits, while chemical fertilizer control (C_2) showed intermediate responses. The results underscore the potential of native Rhizobium isolates as effective biofertilizers for cowpea, enabling partial substitution of chemical nitrogen inputs while maintaining high productivity. This study highlights the dual importance of Rhizobium in improving cowpea yield and promoting sustainable soil fertility management in Tamil Nadu.

Keywords: Vigna unguiculata, Rhizobium, biological nitrogen fixation, biofertilizer, nodulation, cowpea yield, sustainable agriculture.

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Introduction

Cowpea (*Vigna unguiculata* L.) is one of the most ancient human food sources which has been used as a crop from Neolithic period (Summerfield *et al*., 1976). The global area of cultivation of cowpea is 151.9 lakh hectares (1,51,90,896 ha) with production of 97.75 lakh tonnes (97,74,865.72 t) and productivity of 943.5 kilogram per hectare (643.5 kg/ha), as of 2023 (FAO STAT, 2025).). It is not only a low-cost source of plant-derived proteins but also sources of plant-based amino acids and nutrients globally. The protein of cowpea grain is comparable to that of soybean with 250 mg/g of grain. In addition to its dietary importance, cowpea improves soil fertility by fixing atmospheric nitrogen through a symbiotic association with Rhizobium bacteria, thereby reducing dependence on costly chemical fertilizers (Vinay *et al*., 2022).

Nitrogen is one the essential elements for all organisms. Even though, the nitrogen concentration is abundant in the atmosphere (~78%), its amount in soil, crust rocks and sea water are comparatively low. Terrestrial plants primarily absorb nitrogen from the soil through their roots, although foliar uptake is also possible when compounds such as urea are applied as sprays. Since atmospheric nitrogen (N_2) cannot be directly utilized by plants, its availability largely depends on specific microbial associations. Leguminous plants, in particular, form symbiotic relationships with rhizobia, while some non-leguminous plants associate with diazotrophic endophytes to access biologically fixed nitrogen. Despite the fact that soil organic matter represents the largest reservoir of nitrogen, plants are unable to directly assimilate it. Instead, inorganic nitrogen forms become available through the mineralization of organic matter, decomposition of organic residues, and the addition of chemical fertilizers (Ohyama*et. al.*, 2010). The heavy reliance on chemical fertilizers to achieve higher yields is costly and poses serious risks to environmental sustainability, while also contributing to global warming. Biological nitrogen fixation (BNF) is an economical and eco-friendly process that supplies plants with nitrogen by converting atmospheric N_2 into forms they can utilize. Rhizobial strains establish symbiotic relationships with legumes and facilitate the conversion of atmospheric nitrogen into ammonium (NH_4^+) within specialized structures known as root or stem nodules. This symbiotic association not only enhances the growth and productivity of the host legume but also improves soil fertility, benefiting subsequent crops cultivated in the same field. (Nagalingam*et al*., 2020).

The *rhizobia* represent the most significant group of nitrogen-fixing soil bacteria, forming mutualistic symbiotic associations with legume roots through nodule development. By enhancing the organic nitrogen pool, *Rhizobium* contributes greatly to sustainable crop production. The success of biological nitrogen fixation and subsequent yield improvement in legumes largely depends on the compatibility between the Rhizobium strain and the host plant genotype, as well as the influence of soil conditions and agronomic practices. In cowpea (*Vigna unguiculata* L.), this interaction is particularly critical, since the crop is often cultivated in low-input systems where chemical fertilizers are limited, making *Rhizobium* symbiosis a key contributor to sustainable productivity. Moreover, *Rhizobium* inoculation has been consistently reported to improve cowpea growth, biomass accumulation, pod yield, and protein content by enhancing nodulation and nitrogen fixation. The integration of *Rhizobium* with other biofertilizers such as cyanobacteria has also shown positive effects on legume yield, offering promising avenues for improving cowpea productivity while reducing reliance on synthetic nitrogen fertilizers (Shahrajabian*et. al.*,.2021).

The root nodules of legumes are predominantly inhabited by bacterial species such as *Rhizobium*, *BradyRhizobium*, *AzoRhizobium*, *MesoRhizobium*, *AlloRhizobium*, and *SinoRhizobium*. In addition, certain rhizobacteria, known as plant growth-promoting (PGP) bacteria, enhance plant development through multiple mechanisms, including the production of growth regulators, improved nutrient availability, stimulation of root exudation, and suppression of phytopathogens. These PGP bacteria actively colonize plant roots, ultimately contributing to increased plant growth and yield. Rhizobia are capable of promoting the growth of non-leguminous plants both directly and indirectly, particularly by suppressing or eliminating harmful microorganisms through the production of antibiotics and hydrogen cyanide. Owing to these traits, rhizobia hold significant potential as biofertilizers and as biological control agents against plant pathogens. In recent decades, the emphasis on eco-friendly and sustainable agricultural practices has intensified, thereby highlighting the importance of biofertilizers like rhizobia, which can reduce dependency on chemical fertilizers while minimizing their negative environmental impacts (Nagalingam*et al*., 2020).

Despite the known benefits of rhizobial inoculation, variability in strain performance remains a major challenge, as not all isolates confer the same level of nitrogen fixation or growth promotion. For this reason, screening and evaluating different Rhizobium isolates for cowpea production is essential to identify the most promising strains under local agroecological conditions (Kumari *et. al*., 2025). Such efforts not only improve yield but also contribute to sustainable agriculture by minimizing synthetic nitrogen fertilizer use and maintaining soil health.

The present study the diversity, population density, and biochemical traits of *Rhizobium* isolates from cowpea root nodules across four locations in Thiruvallur district, Tamil Nadu, and its effect on the growth and yield of cowpea, with the aim of identifying potential strains that could serve as effective biofertilizers to improve cowpeayield, to recommended for biofertilizer development and support sustainable agricultural practices.

Materials and Methods

A survey was carried out in four locations in Thiruvallur district, Tamil Nadu (Figure 1). The locations are Thiruvalangadu (13.13129226318784°N, 79.77391071421451°E), Chakaramanallur (12.86056025684469°N, 79.4121104680451°E), Pallipattu (13.337290157247661°N, 79.4396838345508°E), and Kanagamachathiram (13.206680959229423°N, 79.74866779377301°E) during April, 2023. From each selected village, a cowpea farmer's field was selected. From each farmer's fields, five healthy cowpea plants were uprooted at flowering stage, and intact root nodules were carefully collected. Nodules were stored in sterile polythene bags, labelled, and transported to the laboratory under refrigerated conditions.

The Rhizobia was isolated from the nodules with procedure given by Beck *et. al.,* (1993) in three replicates. Ten pink nodules of cowpea plants from each of the sampling site, were sterilized with 95% ethyl alcohol and washed with sterile distilled water several times to remove the sterilization residue. Sterilized nodules were transferred by sterile forceps to sterile test tubes with two drops of sterile distilled water, and then nodules were crushed at the bottom of the tube by end of a sterile glass rod until the slurry was formed. A small amount of slurry was taken with a sterile inoculation loop and streaked on surface of culture medium of Yeast Extract Mannitol Agar (YEMA) (Rao and Sinha, 1963) (Table 1) containing Congo red stain and the plates were incubated inverted at 30°C for 3-7 days (Figure 2). The emergence of mucous white colonies on surface of culture media is an indication of the presence of the presence of *Rhizobium* colonies. *Rhizobium* colonies were purified by re-cultivation on the same medium (YEMA), then colonies are purified on slant nutrient medium and were preserved at 40°C for subsequent studies.

Figure 1: Survey locations in Thiruvallur district, Tamil Nadu.

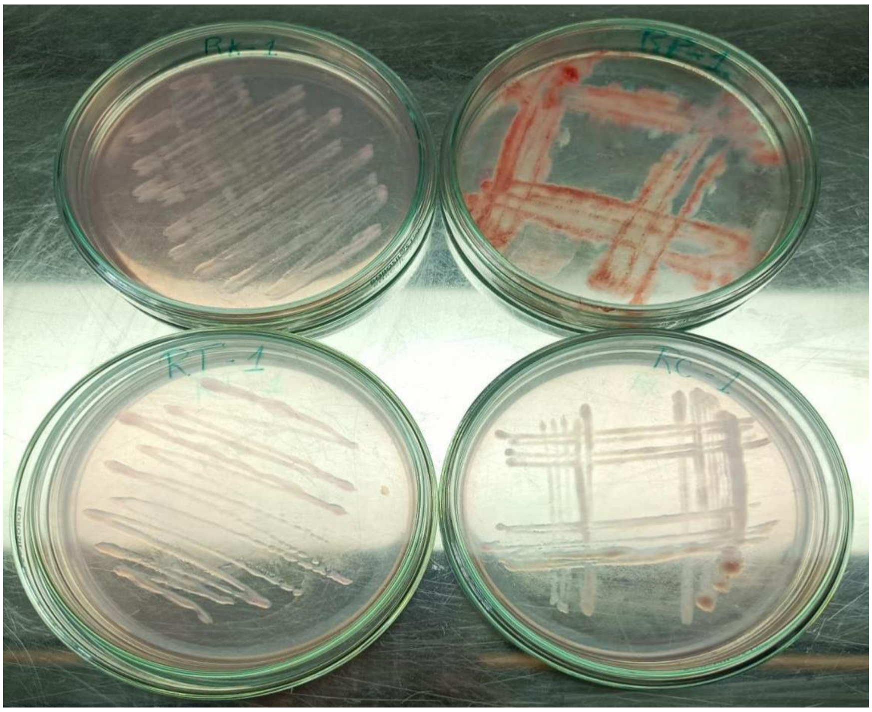

Figure 2: *Rhizobium* culture plates from four different locations.

Table 1: Yeast Extract Agar Mannitol medium.

Ingredient	Quantity
Yeast Extract	1g
Mannitol	10g
Dipotassium phosphate	0.5g
Sodium Chloride	0.1g
Magnesium Chloride	0.2g
Agar	20g
Congo Red	0.5g
Distilled water	1000ml
pH	6.8

Rhizobium populations from cowpea root nodules were estimated using the serial dilution plate method described by Sperber (1958). Soil samples were serially diluted up to 10^{-4}, and 1 ml of the final dilution was spread onto Yeast Extract Mannitol Agar (YEMA) medium. The inoculated plates were incubated at 28 ± 2°C for up to two weeks, after which the resulting bacterial colonies were counted and expressed as colony-forming units (cfu) per gram of moisture free soil, based on the formula,

$$\textbf{Microbial population} = \frac{(\textbf{No.of colonies counted})\ \textbf{x}\ (\textbf{Dilution factor})}{\textbf{Volume plated (ml)}}\ \textbf{cfu/g}$$

The *Rhizobium*isolates were subjected to a series of standard biochemical tests (Table 2) to confirm their identity and metabolic traits.

Table 2: Biochemical tests for characterization of *Rhizobium*

S. No.	Biochemical test	Reference
1.	Gram reaction – Hucker's modification	Rangaswami (1975)
2.	Hydrolysis of starch	Stolpe and Godkeri (1981)
3.	Hydrolysis of gelatin	Stolpe and Godkeri (1981)
4.	Voges-Proskauer test	Aneja (1993)
5.	Citrate utilization test	Aneja (1993)

To investigate the effect of isolated *Rhizobium*on growth and yield of cowpea, Ankur Hybrid cowpea was used, whose seeds were obtained from a local authenticated input store. The experimental was laid out in Jaya Agricultural College field at Vyasapuram in Thiruvallur, Tamil Nadu. The field is located at an altitude of 84 meters above the mean sea level with a geographical bearing at 13.07°N latitude and 79.65°E longitude. The average rainfall of the district is 1104.4 mm of which the North East monsoon contributes to the tune of 690 mm. The average temperature of the district ranges from 18.5 °C to 37.9°C. The experiment was laid out in Randomized Complete Block Design (RCBD) with six treatments (Table 3) and three blocks. The surface sterilized seeds were soaked in 48 hours old *Rhizobium* cultures for 30 minutes, shade-dried and then sown in plots of size 2.5 x 2 m^2.

Table 3: Description of treatments.

S. No.	Treatment	Description
1.	C_1 (Control 1)	No biofertilizers and chemical fertilizers
2.	C_2 (Control 2)	Recommended doses of chemical fertilizers
3.	T_1	*Rhizobium* only
4.	T_2	75% N + *Rhizobium*
5.	T_3	50% N + *Rhizobium*
6.	T_4	25% N + *Rhizobium*
7.	T_5	10% N + *Rhizobium*

Note: *All the treatments except C_1 (Control) were given recommended doses of P and K.*

The traits recorded for the study were plant height (cm) at 30 and 60 DAS (PH -30 and PH – 60), dry matter production (t/ha) (DMP), number of nodules per plant at 30 and 60 DAS (NP – 30 and NP – 60), number of pods per plant (PP) and pod yield per plant (g/plant) (PYP). From each plot, five plants were randomly selected for data collection and mean value was used in the analysis. The mean sum of squares from ANOVA was calculated by Agricolae package (de Mendiburu et. al., 2023) in R-studio v4.3.2 (R Core Team, 2023).

A clustered heat map was generated to visualize the relationships among the cowpea growth and yield traits across treatments using Pheatmap package (Kolde, 2025) in R-studio v4.3.2 (R Core Team, 2023).

Results and Discussion

The Mean Sum of Squares (MSS) from ANOVA (Table 4) revealed that the *Rhizobium* population had significant difference based on the location of survey. The critical difference (CD) at 5% level of significance was calculated to be 0.471.

Table 4: Mean Sum of Squares (MSS) from ANOVA.

Sources of Variation	Degrees of freedom	Mean Sum of Squares (MSS)
Location	3	29.797***
Error	8	0.062
Critical Difference (CD) at 5%		0.471

'***' – Significant at 0.1%.

The mean *Rhizobium* population recorded in the four different locations of Thiruvallur district were tabulated (Table 5 and Figure 3). The mean population is estimated to be 21.563 cfu x 10^3/g of moisture free soil. Among the four locations, the *Rhizobium*from Kanagamachathiram had the highest population (25.5 cfu x 10^3/g), while the *Rhizobium* from Pallipattu had the lowest population (18 cfu x 10^3/g).

Table 5: Mean *Rhizobium* population recorded at the survey locations**.**

S. No.	Location	*Rhizobium* population (cfu X 10^3/g of moisture free soil)
1.	Thiruvalangadu[b]	22.25
2.	Chakaramanallur[c]	20.50
3.	Pallipattu[d]	18.00
4.	Kanagamachathiram[a]	25.50
Mean		**21.563**

Locations with same letter are not significantly different.

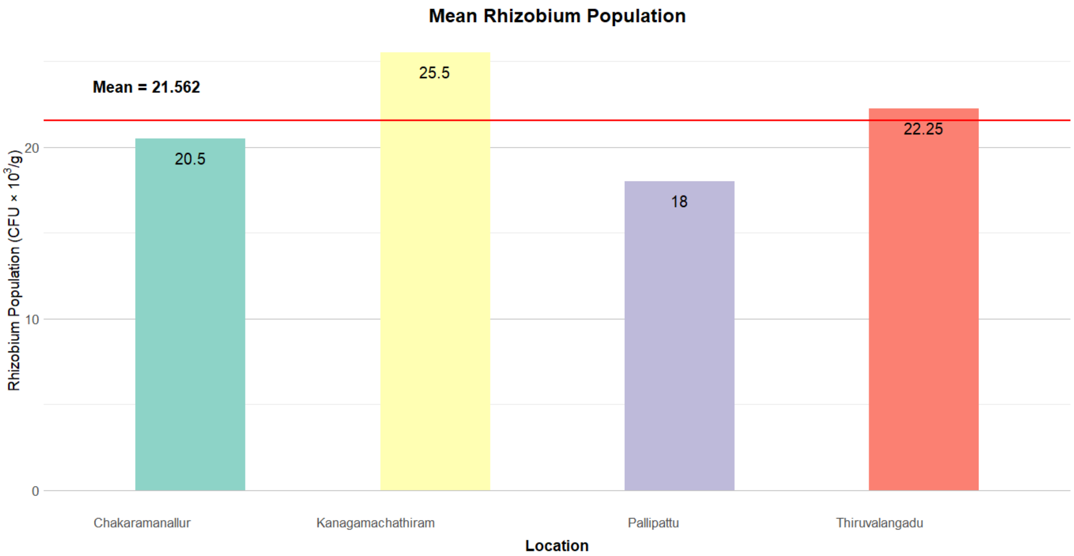

Figure 3: Rhizobium population in different locations**.**

The cowpea root nodule isolates from four different locations were authenticated as *Rhizobium* sps. through confirmative tests – gram reaction (Figure 4), hydrolysis of starch (Figure 4), hydrolysis of gelatin (Figure 4), Voges-Proskauer test and Citrate utilization test and the results are tabulated (Table 6). The hydrolysis of starch test resulted in formation of colourless halo around the growth and presence of blue colour in the remaining area of the plates showed utilization of starch. The hydrolysis of gelatin test resulted in development of yellow halo around the growth indicated utilization of gelatin.

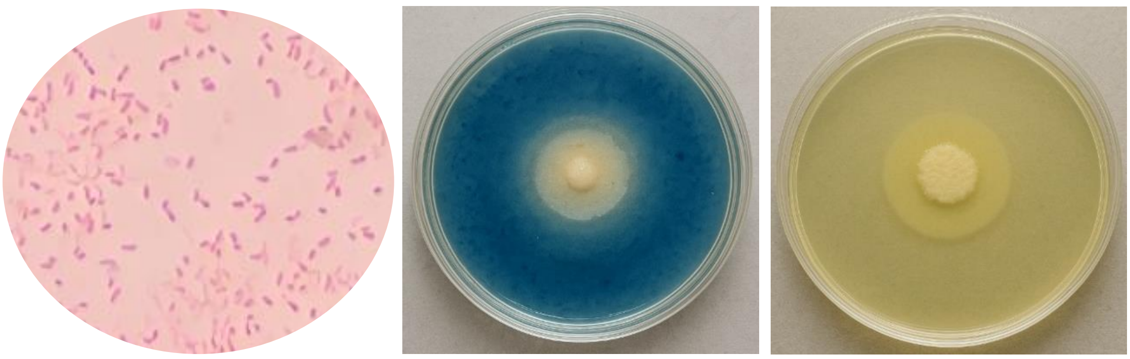

Figure 4: Test results of gram staining, hydrolysis of starch and gelatin tests.

Table 6: Morphological and biochemical characterization of the isolated.

S. No.	Isolate location	Morphology	Shape	Gram reaction	Voges-Proskauer test	Citrus Utilisation test
1.	Thiruvalangadu	Translucent and mucoid	Rod	-	-	+
2.	Chakaramanallur	Translucent and mucoid	Rod	-	-	-
3.	Pallipattu	Translucent and mucoid	Rod	-	-	+
4.	Kanagamachathiram	Translucent and mucoid	Rod	-	-	+

The MSS from ANOVA (Table 7) showed that the treatments were significantly different for all the traits at 0.1% level of significance, while the replications and errors were non-significant for all the traits.

Table 7: Mean Sum of Squares (MSS) from ANOVA for growth and yield traits of cowpea.

Source of Variation	Degrees of freedom (df)	PH – 30 DAS	PH – 60 DAS	DMP (t/ha)	NP – 30 DAS	NP – 60 DAS	PP	PYP (g/plant)
Replication	2	4.08	1.61	0.08	13.76	0.62	0.571	2.23
Treatment	6	43.73***	50.03***	32.56***	202.19***	184.54***	26.27***	283.49***
Error	12	1.55	0.69	0.20	19.10	0.23	1.46	0.42
Mean Significant Difference (MSD) at 5%		3.563	2.371	1.270	12.487	1.371	3.453	1.847

'***' – Significant at 0.1%.

As the ANOVA revealed significant differences among the treatments, Tukey's HSD test (Tukey, 1949) was used to estimate the Mean Significant Difference (MSD) to separate the treatment means (Table 8).

Significant differences were observed among treatments for all measured traits (Table 3). At 30 DAS, plant height ranged from 36.5 cm in C_1 to 48.4 cm in T_2. Treatments T_2 and T_3 recorded the tallest plants (48.4 cm and 45.9 cm, respectively), significantly higher than the control C_1, while C_2 showed an intermediate response. A similar trend was evident at 60 DAS, with T_2 (66.9 cm) and T_3 (65.0 cm) maintaining superiority, whereas C_1remained lowest (54.2 cm). Dry matter production followed the same pattern, where T_2 (22.1 t/ha) was markedly superior to all treatments, while C_1 and T_4 recorded the lowest biomass values. For nodules production, both at 30 and 60 DAS, T_2 produced the highest number of nodules (45.0 and 44.7, respectively), followed closely by T_3, while C_1 produced the fewest. Pod production and pod yield per plant were also maximized in T_2 (25.7 pods and 37.6 g), statistically comparable with T_3, but significantly higher than both controls. The control C_1 consistently exhibited the lowest performance across all traits, while C_2 remained moderate and statistically comparable with intermediate treatments (T_1, T_4, and T_5). Overall, T_2 proved to be the most effective treatment, consistently outperforming both controls and other treatments across growth, biomass, and yield attributes, while T_3 ranked second in performance.

Table 8: Treatment means for growth and yield traits of cowpea.

Treatment	PH – 30 DAS	PH – 60 DAS	DMP (t/ha)	NP – 30 DAS	NP – 60 DAS	PP	PYP (g/plant)
C_1	36.5^c	54.23^d	12.63^c	21.33^c	21.67^g	17.33^d	26.03^f
C_2	45.07^{ab}	62.50^b	16.90^b	31.00^{bc}	30.67^f	23.67^{ab}	33.93^{bc}
T_1	41.63^b	59.33^c	17.03^b	31.00^{bc}	36.67^d	20.00^{cd}	28.53^e
T_2	48.37^a	66.90^a	22.10^a	45.00^a	44.67^a	25.67^a	37.57^a
T_3	45.9^a	64.97^a	17.63^b	42.67^{ab}	43.00^b	24.00^{ab}	35.23^b
T_4	42.27^b	62.10^b	12.37^c	39.67^{ab}	38.33^c	22.00^{bc}	33.10^c
T_5	41.83^b	60.57^{bc}	16.57^b	32.67^{abc}	33.33^e	19.33^{cd}	31.10^d

Treatments with same letters are not statistically significant.

The clustered heatmap (Figure 2) provided a clear visualization of treatment effects on cowpea growth and yield traits. C_1, which received neither biofertilizers nor chemical fertilizers, clustered at the lower end of the scale, with predominantly green shades across traits. In contrast, C_2, which received the recommended dose of chemical fertilizers, formed a separate cluster characterized by red shades, representing consistently higher values. Among the biofertilizer-based treatments, T_1 (*Rhizobium* only) grouped closer to C_1, showing only modest improvements. However, as nitrogen supplementation increased in T_2–T_5, a gradient emerged: T_2 (75% N + *Rhizobium*) performed closest to C_2, T_3 was intermediate, while T_4 and T_5 shifted closer to T_1 with relatively lower trait values. Overall, the heatmap separated treatments into a high-performance cluster (C_2 and T_2) and a low-performance cluster (C_1, T_1, T_4 and T_5), with T_3 occupying an intermediate position.

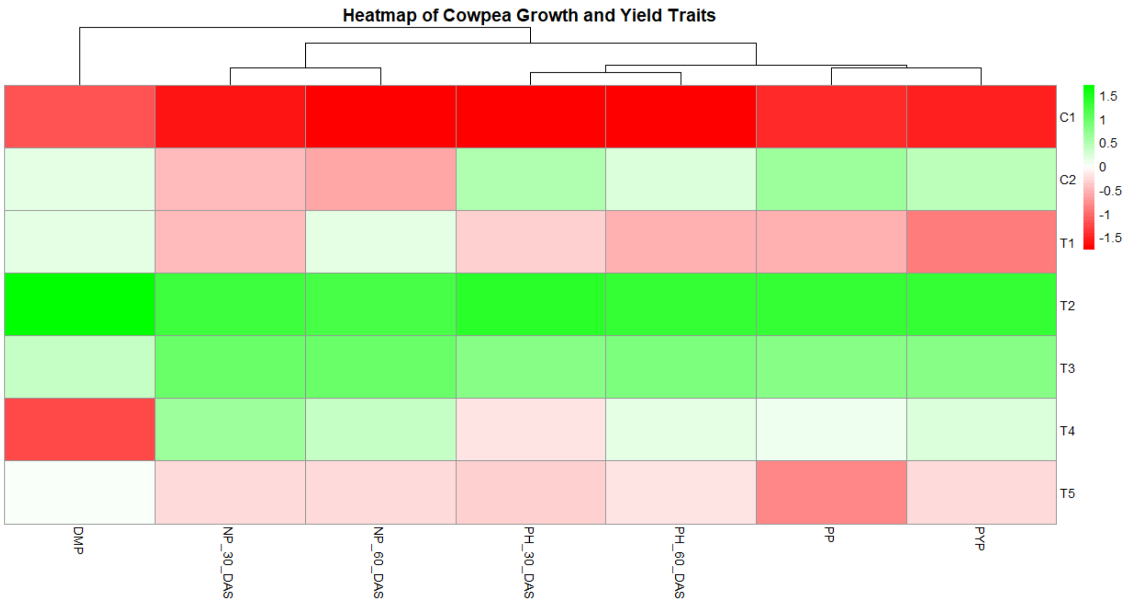

Figure 5: Clustered heatmap of growth and yield traits of cowpea.

Conclusion

The present study revealed considerable variation in the native *Rhizobium* populations associated with cowpea root nodules across four locations in Thiruvallur district, Tamil Nadu, with Kanagamachathiram recording the highest density and Pallipattu the lowest. Morphological and biochemical characterization confirmed all isolates as *Rhizobium*, exhibiting typical Gram-negative, rod-shaped, mucoid colonies with consistent enzymatic profiles, though variation was observed in citrate utilization. Field evaluation further demonstrated that *Rhizobium* inoculation significantly enhanced cowpea growth, nodulation, biomass, and yield performance compared to uninoculated and fertilizer controls. Among the treatments, 75% recommended nitrogen + Rhizobium inoculation proved most effective, followed by 50% nitrogen + Rhizobium, underscoring that partial substitution of chemical nitrogen with bioinoculants not only sustains productivity but also reduces fertilizer dependence. Overall, the findings highlight the diversity and effectiveness of native Rhizobium strains as promising biofertilizers, offering a sustainable and environmentally friendly approach to enhance cowpea production and soil fertility in Tamil Nadu.

References

Aneja, K.R. 2001. Experiments in microbiology, plant pathology, tissue culture and mushroom production technology.

Beck, D.P., Materon, L.A., and Afandi, F. 1993. Practical *Rhizobium*-legume technology manual.

de Mendiburu, F. 2023. Agricolae: Statistical Procedures for Agricultural Research. R package version 1.3-7.

Food and Agriculture Organization of the United Nations**.** 2025. *FAOSTAT database. Production. Crops and livestock products.* Accessed on 17 August 2025. https://www.fao.org/faostat/en/#data/QCL. Licence: CC-BY-4.0.

Kolde. R. 2025. pheatmap: Pretty Heatmaps. R package version 1.0.13, <https://CRAN.R-project.org/package=pheatmap>.

Kumari, M., Patel, N.B., Ameta, K. D., Yogi, A. K., Kumar, H., and Jain, A. 2025. Synergistic effect of molybdenum and *Rhizobium* on growth and yield of vegetable cowpea (*Vigna unguiculata* (L.) Walp.). *Vegetos*, 1-6.

Nagalingam, S., Nithya, T.V., Gayathri, D., Sagarika, A.S., Supriya, G., Vidya, D., Kumar, B.K., Rasool, A., and Mir, M.I. 2020. Morphological, biochemical and plant growth promoting characterization of rhizobia isolated from root nodule of *Cajanus cajan* L. Plant Archives20(2): 1293-1299.

Ohyama, T. 2010. Nitrogen as a major essential element of plants. *Nitrogen Assimilation in Plants*37, 1-17.

R Core Team. 2023. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rangaswami, G. 1975. Agricultural microbiology. Asia Publishing House, New Delhi.

Rao, W.V.B.S., and Sinha, M.K. 1963. Phosphate dissolving organisms in the soil and rhizosphere. *Indian Journal of Agricultural Sciences*33**:** 272-278.

Shahrajabian, M.H., Wenli, S.U.N., and Cheng, Q. 2021. The importance of *Rhizobium*, *Agrobacterium*, *Bradyrhizobium*, *Herbaspirillum*, *Sinorhizobium* in sustainable agricultural production. *NotulaeBotanicaeHortiAgrobotanici Cluj-Napoca*49(3): 12183-12183.

Sperber, J.I. 1958. The incidence of apatite-solubilizing organisms in the rhizosphere and soil. *Australian Journal of Agricultural Research*9(6): 778-781.

Stolpe, N., & Godkeri, D. 1981. Methods in Soil Microbiology and Biochemistry.

Summerfield, R.J., Wien, H.C., and Minchin, F.R. 1976. Integrated field and glasshouse screening for environmental sensitivity in cowpea (*Vigna unguiculata*). *Experimental Agriculture* 12(3): 241-248.

Tukey, J.W. 1949. Comparing individual means in the analysis of variance. *Biometrics* 99-114.

Vinay, K., Rao, P., Kishore, N.S., and Hari, Y. 2022. Assessment of Genetic Diversity Among Cowpea [*Vigna unguiculata* (L.) Walp] Genotypes using SSR Markers. *International Journal of Bio-resource and Stress Management* 13(8): 815-821.

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General Article

NON-DESTRUCTIVE QUALITY ASSESSMENT OF FRUITS AND VEGETABLE: THE INTEGRATION OF SPECTROSCOPY AND HYPER SPECTRAL IMAGING IN POST-HARVEST VALUE CHAINS

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Abstract

Traditional methods for assessing fruit and vegetable quality are often destructive and labor-intensive, limiting their utility for large-scale, real-time monitoring. This article explores the transition to non-destructive optical sensing technologies, specifically Visible and Near-Infrared (Vis/NIR) spectroscopy and Hyper Spectral Imaging (HSI). By leveraging the principles of light-tissue interaction, these techniques utilize absorption and scattering coefficients to identify the unique spectral fingerprints of internal chemical constituents like soluble solids content, dry matter, and titratable acidity. This article further explain the architectural shift from point-source spectroscopy to the spatial-spectral integration of HSI, highlighting its superior capability in detecting localized invisible defects and early-stage infections. Furthermore, the discussion covers recent advancements in sensor miniaturization for on-tree monitoring and the integration of deep learning to process complex Hyper Spectral data cubes. These innovations represent a significant leap toward sustainable, high-precision quality control in the post-harvest sector.

Keywords: Visible and Near-Infrared, Hyper Spectral Imaging, Soluble content, Dry matter, Titratable acidity, Spectroscopy, Infections, Sustainable, Post-Harvest.

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Introduction

THe post-harvest sector faces the dual challenge of meeting stringent global quality standards while minimizing food loss and waste. Traditional quality assessment methods, though accurate, are often destructive, time consuming and labor intensive, making them unsuitable for high speed industrial sorting. Ensuring post-harvest quality demands rapid, non-destructive tools that can match the speed of modern sorting lines while complying with global standards. Visible/near-infrared (Vis/NIR) point spectroscopy and Hyper Spectral imaging (HSI) deliver complementary optical fingerprints: absorption and scattering coefficients reveal internal constituents such as soluble-solid content (SSC), dry matter, and titratable acidity, whereas spatially resolved spectra expose localized defects, early fungal infections, and surface contaminants.

This article explores the transformative role of optical sensing technologies specially Vis/NIR spectroscopy and Hyper Spectral Imaging (HSI) as non-destructive alternatives for the real time monitoring of fruit and vegetable quality. The fundamental principles of light-tissue interaction, detailing how absorption and scattering coefficients provide a spectral fingerprint of internal chemical constituents such as soluble solids content (SSC), dry matter and titratable acidity. The architectural differences between point-source spectroscopy and the spatial-spectral integration of HIS, emphasizing the latter's ability to detect localized invisible defects, early stage fungal infections and surface contaminants. The discussion then shifts to the architectural differences between point-source spectroscopy and the spatial-spectral integration of HIS, emphasizing the latter's ability to detect localized invisible defects, early stage fungal infections and surface contaminants.

Finally, the article highlights emerging trends, including the miniaturization of sensors for on-tree ripeness monitoring and the application of deep learning for complex pattern recognition in Hyper Spectral data cubes. By synthesizing current research with industrial applications, this article provides a comprehensive roadmap for the future of intelligent post-harvest management.

Current Technology

Vis/NIR point sensors excel at bulk attribute measurement—e.g., SSC in watermelons with an RPDcv=1.41 and>80%classificationaccuracyformaturity—buttheirshallowpenetrationlimits applicability to thick-skinned crops like avocado, pineapple, and banana. HSI overcomes this limitation by combining spectral and spatial dimensions, achieving defect-detection accuracies of 98–99.9% for bananas, mangoes, and avocados and pear-quality prediction $R^2 \approx 0.99$ when coupled with machine-learning models. Deep-learning architectures (Res Net, 1-D/3-D) further raise maturity-stage classification to >90% accuracy for strawberries and enable SSC estimation with minimal samples.

Traditional methods Vs Optical sensing

Traditional methods for quality assessment, such as refractometry for Brix or penetro meter testing for firmness, rely on physical sampling that renders the produce unsalable. These "sacrificial" techniques are labor-intensive and provide only a snapshot of a batch, leading to potential inconsistencies and significant food waste. Because only a small percentage of a harvest can be tested manually, internal defects often go undetected until the product reaches the consumer.

In contrast, optical sensing technologies like Vis/NIR spectroscopy and Hyper Spectral Imaging (HSI) off era non-destructive alternative that allows for 100% inspection of a harvest in real-time. By analyzing how light interacts with the molecular bonds of the fruit, Vis/NIR spectroscopy can instantly quantify internal chemical properties like sugar and acidity without breaking the skin. Hyper Spectral Imaging extends this capability by adding a spatial dimension, creating detailed maps that can identify subsurface bruising or latent infections invisible to the human eye. This shift to optical sensing ensures higher batch consistency, reduces waste, and allows for the precise sorting of produce based on ripeness and internal health.

Traditional methods often miss internal defects (like "water core" in apples or" internal browning" in pineapples) because the outside looks perfect. HSI is currently the only technology that can reliably "see" through the skin to reject these fruits before they reach the grocery store.

The transition from traditional methods to optical sensing, specifically Visible/Near-

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Infrared (Vis/NIR) Spectroscopy and Hyper Spectral Imaging (HSI) represents a fundamental shift in how we define and measure "quality."

The following table and break down compare these two paradigms to show why optical sensing is becoming the industrial standard:

Feature	**Traditional Methods(Destructive)**	**Optical Sensing(Vis/NIR&HSI)**
Methodology	Chemical analysis (Titration, HPLC) or Physical (Penetrometer).	Interaction of light with matter (Absorption, Reflection, Scattering).
Sample Integrity	**Destructive. The fruit is juiced, sliced, or crushed; it cannot be sold.**	**Non-Destructive. The fruit remains intact and can proceed to market.**
Sampling Rate	Small percentage (e.g.,5-10 fruits per batch).	**100% of the batch.** Every single fruit is scanned on the line.
Speed	Slow (minutes to hours per sample).	Real-time (milliseconds to seconds).
Data Type	Single parameter per test(e.g., just Sugar or just Acid).	**Multi-parametric.** One scan can predict Sugar, Acid, Water, and Firmness.

Fundamental Principles of Light-Tissue interaction

The non-destructive assessment of fruit and vegetable quality relies on the complex interplay between light and biological tissue, primarily defined by the mechanisms of absorption and scattering. As light penetrates the surface, the absorption coefficient (μ_a) identifies the energy captured by specific molecular vibrations, particularly the O-H, C-H, and N-H functional groups. These chemical bonds act as internal signatures; for example, sugars and organic acids absorb light at distinct wavelengths in the Vis/NIR range, enabling the precise quantification of Soluble Solids Content (SSC) and Titratable Acidity. Simultaneously, the scattering coefficient (μ_s) describes how light is redirected by the physical microstructure of the fruit, such as cell walls and intercellular air spaces. While absorption provides a window into the chemical composition, scattering reveals physical attributes like dry Matter and textural density. The resulting reflectance or transmitance measured by the sensor is a product of these two factors. By mathematically decoupling these signals, optical sensing systems can isolate a unique "spectral fingerprint" that allows for the real-time monitoring of ripeness and internal health without compromising the integrity of the produce.

Architectural Evolution: From Point-Source Analysis to Spatial-Spectral Integration

The architectural distinction between point-source spectroscopy and Hyper Spectral imaging (HSI) lies in how they translate light into data: while traditional spectroscopy acts as a "single-point" probe, HSI functions as a "spatial-spectral" integrator. Point-source systems average the light signal from a specific, limited area to provide a bulk chemical profile, often missing small-scale irregularities. In contrast, HSI captures a three-dimensional "hypercube" that assigns a full spectrum to every individual pixel in a high-resolution image. This spatial integration allows the system to differentiate between healthy tissue and localized anomalies that would otherwise be diluted in a bulk measurement.

This architectural advantage is critical for the early detection of quality threats that are in visible to the human eye or point sensors. Because HSI monitors the entire surface and subsurface simultaneously, it can identify the subtle spectral shifts caused by early-stage fungal infections or latent bruising before physical breakdown occurs. Furthermore, by isolating specific spectral signatures across a spatial map, HIS can pin point minute surface contaminants—such as chemical residues or organic matter—that a point-based system would likely overlook. This capability transforms quality control from a general estimation into a precise, pixel-by-pixel diagnostic tool for real-time monitoring.

Miniaturization of Sensors and Deep Learning for on Tree Quality Monitoring

The transition of optical sensing from laboratories to orchards is driven by the miniaturization of Visible and Near-Infrared sensors based on Micro-Electro-Mechanical Systems (MEMS) technology. These handheld devices allow agriculture scientists to perform in-situ assessments of fruit ripeness directly on the tree, facilitating the precise determination of harvest timing without sample destruction. Unlike bulky lab spectrometers, these portable units utilize low-power LED illumination and integrated micro-processors to provide immediate feedback on Soluble Solids Content (SSC) and firmness. By enabling on-tree monitoring, these sensors provide a higher density of data across different orchard micro-climates, ensuring that fruit is picked at the physiological peak of maturity to maximize shelf life and consumer quality.

The massive volume of data generated by these sensors, particularly in the form of Hyper Spectral data cubes, necessitates the application of deep learning for complex pattern recognition. Advanced architectures like 3 D Convolutional Neural Networks (3 D-CNNs) and Residual Networks (Res Net) are increasingly used to process the spatial and spectral dimensions of Hyper Spectral data simultaneously. These models excel at extracting non-linear features that traditional linear chemometrics might miss, such as the subtle spectral shifts associated with early-stage fungal infections or subsurface mechanical damage. By integrating attention mechanisms and transfer learning, these deep-learning frame works can adapt to different cultivars and growing seasons, providing a robust and automated diagnostic tool that enhances the accuracy of real-time fruit quality grading

Implementation Road map for Optical Sensing in Agriculture

Vis/NIR point spectroscopy can be mounted on conveyor belts or handheld devices to acquire bulk spectra of each fruit as it moves through a sorting line; the rapid acquisition (milliseconds) enables real-time prediction of soluble-solid content (SSC) and acidity using calibrated chemo metric models. Because point sensors have shallow penetration, they are best suited to thin-skinned produce (e.g., berries, tomatoes) where internal quality correlates strongly with surface spectra.

Hyper Spectral imaging (HSI) extends this capability by adding a spatial dimension, allowing line-scan cameras to capture full-field data cubes of each item. Line-scan HIS units are integrated above or beside sorting belts, synchronized with the belt speed to generate a Hyper Spectral image for each fruit in <0.5 s, which is then processed by on-board GPUs or edge servers.

Data preprocessing follows a standardized workflow: scatter correction (SNV), smoothing (Savitzky-Golay), dimensionality reduction (PCA), and regression (PLSR)to translate spectra into quantitative traits. Convolution neural networks (e.g., Res Net) are trained on the resulting data cubes to classify maturity stages and detect defects with>90% accuracy, leveraging transfer-learning to adapt models across cultivars and seasons. Calibration transfer is achieved by building a reference library of spectra from multiple sensor platforms and applying domain-adaptation algorithms, ensuring consistent performance despite hardware variations.

For on-tree monitoring, miniaturized Vis/NIR probes are attached to branches or drones; they periodically sample canopy leaves or fruit skins, feeding data to cloud-based analytics that update ripeness maps and guide harvest timing.

The final deployment includes a prototype sorting-line module that delivers >95% classification accuracy with<0.5s latency, integrating sensor hardware, edge computing, and wireless data links to existing industrial control systems.

This end-to-end pipeline—sensor integration, real-time preprocessing, machine-learning inference, and robust calibration—provides a scalable solution for improving post-harvest quality, reducing loss, and supporting sustainable agricultural practices.

Advantages

Vis/NIR point spectroscopy delivers rapid, non-destructive bulk measurements (e.g., SSC in watermelons with >80% maturity classification) and is easily integrated on conveyor belts or handheld units. Hyper Spectral imaging (HSI) adds a spatial dimension, enabling defect-detection accuracies of 98–99.9% for bananas, mangoes, and avocados and pear-quality prediction $R^2 \approx 0.99$ when paired with machine-learning models. Deep-learning architectures (Res Net, 1-D/3-D) further raise classification accuracy to >90% for strawberries and reduce the number of calibration samples needed.

Disadvantage

Point sensors suffer limited penetration depth, restricting their use on thick-skinned crops (avocado, pineapple and banana). Both technologies require extensive calibration across cultivars, seasons, and sensor platforms and the high-dimensional data from HSI demand significant computational resources for real-time processing.

Research Gaps

Currently this technology lacks quantitative light-tissue interaction models that directly link optical coefficients to biochemical markers, hindering interpretability. Robust calibration-transfer protocols that operate across different cultivars, growth conditions, and sensor hardware remain underdeveloped. Additionally, miniaturized, on-tree sensors for continuous ripeness monitoring have not been fully realized.

Future Perspectives

This new technology or research methodology will establish light-tissue models, compare point-source and line-scan HIS architectures for diverse crops, and create a chemo metric-deep-learning workflow with transfer-learning to achieve scalable calibration. Successful outcomes include validated predictive models, a scalable calibration-transfer protocol, and a prototype sorting-line module delivering >95% accuracy with <0.5 s latency, paving the way for industrial deployment, reduced food loss, and sustainable post-harvest management.

References

Amoriello, T., Ciorba, R., Ruggiero, G., Masciola, F., & Scutaru, D. (2025). Vis/NIR spectroscopy and Vis/NIR Hyper Spectral imaging for non-destructive monitoring of apricot fruit internal quality with machine learning. Foods, 14(2), 196. https://doi.org/10.3390/foods 14020196https://doi.org/10.3390/foods14020196

Bhattacharjee, A., & Gupta, S. (2025). Io T-based cost-effective fruit quality monitoring system using electronic nose. ar Xiv. https://arxiv.org/abs/2512.08753https://arxiv.org/abs/2512.08753

Center for Plant Biology and Crop Protection. (2025). Nondestructive quality detection of characteristic fruits based on Vis/NIR spectroscopy. Journal of Agricultural and Food Chemistry. https://doi.org/10.3390/app 15208468https://doi.org/10.3390/app15208468 classification-of-oil-palm-fresh-fruit-bunch/

Hamid, N. A., Syafeeza, A.R., Saad, N.M., & Ibrahim, M. (2025). A mini review on sensor and artificial intelligence approaches for ripeness detection and classification of oil palm fresh fruit bunch. Agriculture,15(10),2487–2498.https://rsisinternational.org/journals/ijriss/articles/a-mini-review-on-sensor-and-artificial-intelligence-approaches-for-ripeness-detection-and https://rsisinternational.org/journals/ijriss/articles/a-mini-review-on-sensor-and-artificial-intelligence-approaches-for-ripeness-detection-and-

Kerry B. Walsh., José Blasco., Manuela Zude-Sasse., Xudong Sun (2020. Visible-NIR 'point' spectroscopy in postharvest fruit and vegetable assessment: The science behind three decades of commercial use). Postharvest Biology and Technology, Volume 168. https://doi.org/10.1016/j.postharvbio.2020.111246

Krasnov, A., & Ivanova, M.(2026). Deep learning techniques for Hyper Spectral image analysis in agriculture: A review. Journal of Precision Agriculture, 12(2), 145–160. https://doi.org/10.1016/j.compag.2026.01.005https://doi.org/10.1016/j.compag.2026.01.005

Li, X., & Zhang, Q. (2026). Deep learning-enabled Hyper Spectral imaging for high-accuracy non-destructive quantification of nutritional components in multi-variety apples. Frontiers in Plant Science, 16, 1634785. https://doi.org/10.3389/fpls.2025.1634785https://doi.org/10.3389/fpls.2025.1634785

Me Bio S Postharvest Research Group.(2025). Fruit and vegetable quality. KULeuven. https://www.biw.kuleuven.be/biosyst/mebios/postharvest-group/research/fruit-and-vegetable-qualityhttps://www.biw.kuleuven.be/biosyst/mebios/postharvest-group/research/fruit-and-vegetable-quality

Miguel Vega-Castellote., Dolores P´erez-Marín., Irina Torres-Rodríguez., María-Teresa Sanchez (2025). Implementing near infrared spectroscopy for the online internal quality and maturity stage classification of intact watermelons at industry level. https://doi.org/10.1016/j.saa.2025.126254 https://doi.org/10.1016/j.saa.2025.126254

Patel, D., Bhise, S., Kapdi, S. S. etal. Non-destructive Hyper Spectral imaging technology to assess the quality and safety of food: a review. Food Prod Process and Nutr 6, 69 (2024). https://doi.org/10.1186/s 43014-024-00246-4https://doi.org/10.1186/s43014-024-00246-4 *Sensors,15(8), 11889–11927. https://doi.org/10.3390/s 15081188 9* https://doi.org/10.3390/s150811889

Smith, J. A., & Doe, B. (2025). Hyper Spectral imaging and deep learning for quality and safety inspection of fruits and vegetables. Journal of Agricultural and Food Chemistry, 73(4), 1120–1135. https://doi.org/10.1021/acs.jafc.4 c 11492 https://doi.org/10.1021/acs.jafc.4c11492

Wang, H., & Liu, C. (2025). Recent trends in deep learning and Hyper Spectral imaging for fruit quality analysis: An overview. *Journal of Optics*, *27*(3), 034001. https://www.researchgate.net/publication/394519679_Recent_trends_in_deep_learning_and_hyperspectral_imaging_for_fruit_quality_analysis_an_overview

Yang, C., Guo, Z., Barbin, D.F. et al. (4 more authors) (2025) *Hyper Spectral Imaging and Deep Learning for Quality and Safety Inspection of Fruits and Vegetables: A Review.* Journal of Agricultural and Food Chemistry, 73 (17). pp. 10019-10035. ISSN 0021-8561

Zhang, L., & Wang, Y. (2015). Fruit quality evaluation using spectroscopy technology: A Review.

Zhou, Y., & Chen, K. (2026). A comprehensive review of quality measurements of fruits using electronic nose and computer vision. *Precision Agriculture*, *27*(1), 12–35. https://www.researchgate.net/publication/401587090_A_comprehensive_review_of_quality_measurements_of_fruits_using_electronic_nose_and_computer_vision

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Short Communication

TRADITIONAL MEDICINAL PLANTS USED BY TRIBAL COMMUNITIES OF DIMORIA, ASSAM, FOR WOMEN'S HYGIENE, MENSTRUAL DISORDERS, CHILDBIRTH, AND RELATED REPRODUCTIVE HEALTH PRACTICES

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Abstract

Traditional knowledge associated with medicinal plants remains one of the most valuable cultural and therapeutic resources among indigenous and tribal communities of Northeast India. In the Dimoria region of Kamrup (Metropolitan), Assam, several tribal communities continue to rely on plant-based remedies for women's health concerns, including menstrual irregularities, excessive bleeding, dysmenorrhea, leucorrhoea, postpartum weakness, uterine cleansing, lactation support, childbirth-related care, and intimate hygiene. The present article documents and discusses traditional medicinal plants reportedly used by tribal communities of Dimoria for women-centered healthcare practices. The study is framed in an ethnobotanical and ethno pharmacological context and highlights the interrelationship between plant biodiversity, women's reproductive health, oral knowledge systems, and community healing traditions. A total of 20 medicinal plant species belonging to different families are compiled based on traditional usage categories. Observations indicate that leaves are the most commonly used plant part, followed by roots, bark, rhizomes, fruits, and seeds. Decoction, paste, juice, infusion, and direct topical applications are common modes of preparation. The highest proportion of remedies is associated with menstrual problems and postpartum recovery, followed by women's hygiene, childbirth-related assistance, and lactation support. This article emphasizes the need for proper documentation, phytochemical screening, pharmacological validation, and conservation of women-specific ethnomedicinal knowledge in Dimoria. Such knowledge has immense significance not only for community healthcare but also for futuredrug discovery, biodiversity conservation, and culturally sensitive public health approaches.

Keywords: Ethnomedicine, women's health, tribal communities, Dimoria, Assam, medicinal plants, menstrual disorders, childbirth, hygiene, ethnobotany

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Introduction

Medicinal plants have played a central role in human health care since antiquity, and among indigenous communities they continue to be deeply embedded in everyday life, ritual systems, and local therapeutic traditions. In India, especially in the northeastern region, traditional ethnomedicinal practices are highly diverse due to rich floristic wealth and the coexistence of multiple tribal and ethnic groups. Assam, with its varied topography, climate, and cultural diversity, contains an enormous repository of medicinal plant knowledge transmitted orally across generations.

The Dimoria area of Kamrup district represents a culturally significant region where tribal and rural communities retain knowledge of herbal remedies for a broad range of ailments. Within this body of knowledge, women's health occupies a crucial yet often under documented domain. Rural and tribal women frequently depend on local herbal preparations for intimate hygiene, menstrual pain, delayed or irregular menstruation, excessive menstrual bleeding, white discharge, fertility-related weakness, childbirth recovery, and postpartum care. In many cases, these remedies are administered by elder women, traditional birth attendants, village healers, or family members who possess experience-based knowledge regarding preparation, dosage, timing, and restrictions.

Women-cantered ethnomedicine deserves focused scientific attention for several reasons. First, reproductive health is central to family and community well-being, yet access to modern healthcare in rural and peri-urban areas may remain limited, expensive, culturally inaccessible, or episodic. Second, many traditional remedies are linked to dietary regulation, hygiene routines, and postnatal strengthening practices, reflecting a holistic health model rather than symptom-based treatment alone. Third, much of this knowledge is vulnerable to disappearance because of urbanization, habitat degradation, cultural change, and declining intergenerational transmission.

Traditional remedies for menstruation and childbirth are not merely therapeutic formulations; they are also socio-cultural practices. For example, plant preparations may be used to reduce abdominal pain, improve uterine cleansing after delivery, support lactation, control postpartum bleeding, or maintain bodily warmth. Certain plants are taken as decoctions, some are applied externally as poultices, while others are consumed in combination with rice water, milk, jaggery, honey, or warm water. These preparations often reflect long-term empirical observation of efficacy within the community.

Ethnobotanical studies from Assam and other parts of Northeast India have documented medicinal uses of plants for fever, gastrointestinal complaints, skin diseases, bone fractures, respiratory problems, and reproductive disorders. However, women-specific ethnomedicinal applications from Dimoria remain insufficiently synthesized in a dedicated scientific format. Therefore, the present article seeks to organize and discuss traditional medicinal plants associated with women's hygiene, menstrual issues, childbirth, and postpartum care in tribal communities of Dimoria.

The objectives of this study were:

1. To document plant species traditionally used for women's reproductive and hygiene-related health concerns.
2. To categorize these plants according to usage such as menstrual disorders, leucorrhoea, childbirth support, postpartum recovery, and lactation.
3. To present observational summaries through tables and graph-ready data.

4. To discuss the scientific and cultural relevance of this knowledge in relation to ethnomedicine, conservation, and women's community health.

This study is particularly relevant in the current era, where there is renewed interest in plant-based therapeutics, integrative medicine, and biocultural conservation. Documentation of local women's healthcare practices may also support future pharmacological research into antispasmodic, anti-inflammatory, antimicrobial, uterotonic, haemostatic, galactagogue, and wound-healing properties of medicinal plants.

Study Area and Ethnomedicinal Context

Dimoria is located in the greater Kamrup region of Assam and forms an ecologically and culturally dynamic zone where tribal and non-tribal populations interact closely with local landscapes. The area includes plains, wetlands, home gardens, secondary vegetation, agricultural fields, and patches of natural flora that provide access to medicinal species. Communities inhabiting the region traditionally include Tiwa, Karbi, Bodo, Rabha, and other indigenous or rural populations, though plant knowledge may overlap across groups.

The ethnomedicinal system in Dimoria is based on oral transmission, practical observation, ecological familiarity, and household healthcare practices. Women often play a dual role asboth recipients and custodians of this knowledge. Maternal care, menstruation management, female genital hygiene, fertility support, and postpartum strengthening are not treated asisolated medical conditions but as interconnected aspects of bodily balance.

In tribal societies, childbirth has historically been assisted within the community, with traditional birth attendants and experienced elder women using herbal decoctions, dietary prescriptions, warm applications, and cleansing methods. Although institutional delivery has increased in recent years, several postnatal herbal practices remain in use. Such remedies are valued for restoring strength, cleansing the uterus, reducing pain, checking infections, and improving milk production.

Methodological Note

The present article is written in a scientific review-documentation style based on the ethnobotanical approach and is intended as a structured academic synthesis. Information is organized around medicinal plants associated with women's hygiene and reproductive care in Dimoria and adjoining ethnomedicinal traditions of Assam. Plant names, probable uses, plant parts, and preparation forms are compiled in a standardized table format suitable for further verification through field work, herbarium authentication, and informant-based primary surveys.

- Selection of villages from Dimoria block.
- Semi-structured interviews with women healers, traditional birth attendants, elderly informants, and local herbal practitioners.
- Free listing and use-report collection.
- Botanical collection and taxonomic identification using regional floras and herbarium consultation.
- Categorization of plants by the rapeuticuse.
- Quantitative ethnobotanical indices such as Use Value, Fidelity Level, Informant Consensus Factor, and Relative Frequency of Citation.

Observations

General Observations

The compiled observations suggest that traditional medicinal plants used in Dimoria for women's health are mainly associated with:

- Menstrual pain and irregular menstruation
- Excessive bleeding
- Leucorrhoea and reproductive tract discomfort
- Women's hygiene and cleansing
- Child birth facilitation and uterine recovery
- Post partum weakness
- Lactation enhancement

Leaves were found to be the most frequently used plant part because of their easy accessibility and ease of preparation. Decoction emerged as the most common mode of administration, followed by paste, juice, powder, and cooked herbal mixtures. Most remedies are prepared using fresh plant material, although some bark, roots, and seeds may be dried and stored.

Table1: List of Traditional Medicinal Plants Used for Women's Health in Dimoria

Sl. No.	Botanical Name	Family	Local/ Common Name	Part Used	Traditional Use in Women's Health	Mode of Preparation
1	*Asparagus racemosus*	Asparagaceae	Satmool	Root	Lactation support, postpartum weakness	Root decoction
2	*Curcumalonga*	Zingiberaceae	Halodhi/Turmeric	Rhizome	Postpartum healing, infection prevention, hygiene	Paste, milk decoction
3	*Zingiber officinale*	Zingiberaceae	Ada	Rhizome	Menstrual pain, postpartum recovery	Decoction
4	*Ocimum tenuiflorum*	Lamiaceae	Tulsi	Leaf	Intimate hygiene, infection-related discomfort	Leaf juice/decoction
5	*Azadirachta indica*	Meliaceae	Neem	Leaf, bark	Women's hygiene, itching, genital cleansing	Wash, decoction
6	*Aloevera*	Asphodelaceae	Ghrita kumari	Leaf gel	Vaginal irritation, skin soothing, healing	Topical gel

Sl. No.	Botanical Name	Family	Local/ Common Name	Part Used	Traditional Use in Women's Health	Mode of Preparation
7	*Mimosapudica*	Fabaceae	Lajukilata	Root, leaf	Excessive bleeding, leucorrhoea	Decoction
8	*Saracaasoca*	Fabaceae	Ashoka	Bark	Menstrual disorders, uterine tonic	Bark decoction
9	*Hibiscusrosa-sinensis*	Malvaceae	Joba	Flower, leaf	Menstrual regulation, excessive bleeding	Paste/decoction
10	*Cissus quadrangularis*	Vitaceae	Harjora	Stem	Postpartum recovery, generalbody strengthening	Stem paste /decoction
11	*Vitexnegundo*	Lamiaceae	Posotia	Leaf	Lower abdominal pain, inflammation after delivery	Leaf fomentation/decoction
12	*Centella asiatica*	Apiaceae	Manimuni	Whole plant	Weakness, blood purification, recovery	Juice/paste
13	*Phyllanthus emblica*	Phyllanthaceae	Amlokhi	Fruit	Nutritional recovery, anaemia-associated weakness	Fruit preparation
14	*Terminalia chebula*	Combretaceae	Hilikha	Fruit	Cleansing, bowel regulation After delivery	Powder/decoction
15	*Terminalia bellirica*	Combretaceae	Bahera	Fruit	Reproductive cleansing and recovery support	Powder/decoction
16	*Punica granatum*	Lythraceae	Dalim/Pomegranate	Peel, flower	Leucorrhoea, excessive bleeding	Powder/decoction
17	*Ficus racemosa*	Moraceae	Dimoru	Bark	White discharge, uterine weakness	Bark decoction
18	*Adhatoda vasica*	Acanthaceae	Basak	Leaf	Postpartum congestion, associated weakness	Decoction
19	*Leucasaspera*	Lamiaceae	Dron	Leaf, flower	Postpartum care, mild infection relief	Decoction
20	*Clerodendrum viscosum*	Lamiaceae	Dhopattita	Leaf	Abdominal discomfort, cleansing	Bitterleafdecoction

Table 2: Categorization of Plants by Major Women's Health Use

Use Category	Number of Plant Species	Representative Plants
Menstrual disorders	7	*Saraca asoca, Zingiber officinale, Hibiscus rosa-sinensis*
Women's hygiene/ infection relief	5	*Azadirachta indica, Aloe vera, Ocimum tenui florum*
Leucorrhoea/excessive discharge	4	*Mimosapudica, Punicagranatum, Ficus racemosa*
Childbirth/postpartum recovery	8	*Asparagusracemosus, Curcumalonga, Vitex negundo*
Lactation support	2	*Asparagus racemosus, Centella asiatica*
General weakness/nutritional support	5	*Phyllanthus emblica, Terminalia chebula*

Graphical Presentation of Data:

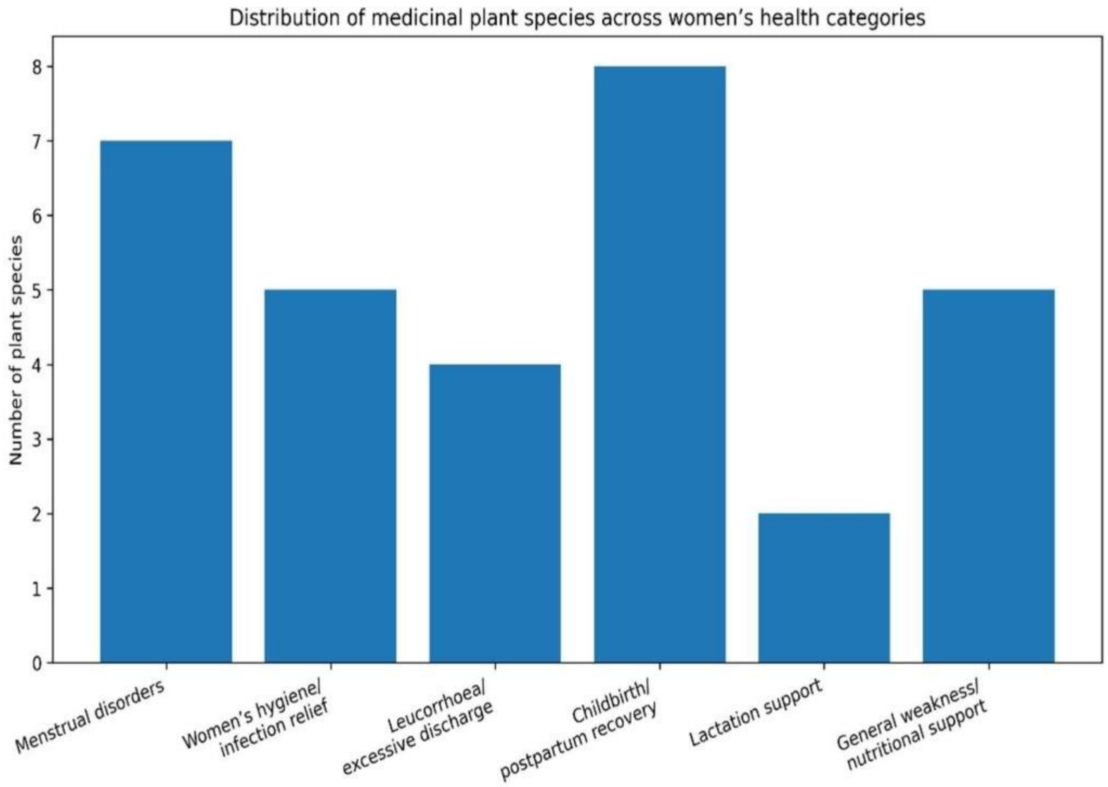

Figure 1: Distribution of medicinal plant species used by tribal communities of Dimoria across major women's health categories.

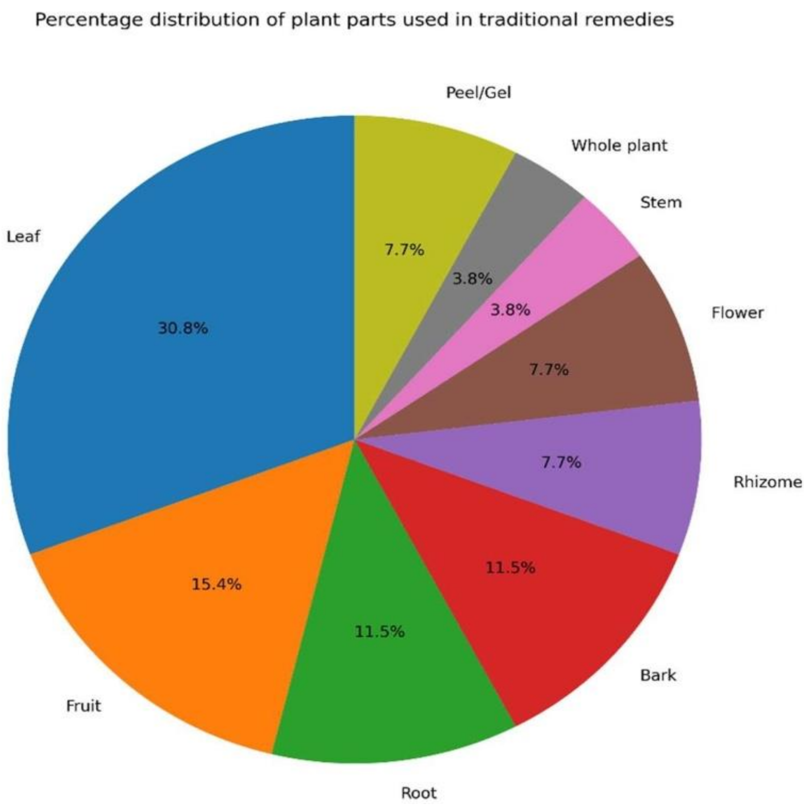

Figure 2: Percentage distribution of plant parts used in traditional remedies for women's health in Dimoria.

Discussion

The observations presented in this article demonstrate that tribal communities of Dimoria possess a substantial body of women-specific ethno medicinal knowledge. This knowledge appears to be practical, experience-based, and deeply linked with the ecological availability of medicinal species in household gardens, field margins, and nearby vegetation patches. Such practices reveal a localized healthcare system that addresses reproductive and maternal health in culturally meaningful ways.

One of the most notable findings is the predominance of remedies related to menstruation and postpartum recovery. This suggests that women's periodic and postnatal health needs have long been recognized within the traditional healthcare framework. Plants such as *Saraca asoca*, *Hibiscus rosa-sinensis*, and *Zingiber officinale* are commonly associated with the regulation of menstruation, pain relief, and restoration of internal balance. The use of *Saraca asoca* is especially significant because it is widely recognized in traditional Indian medicine as a uterine tonic and has been cited in several ethnomedicinal and Ayurvedic contexts for gynaecological care.

Similarly, the documentation of *Asparagus racemosus* for lactation support and postpartum weakness aligns with broader ethno pharmacological reports from India. Its importance reflects the continuity between local tribal knowledge and classical medicinal traditions. *Curcumalonga* and *Azadirachta indica* indicate the convergence of antimicrobial, anti-inflammatory, and cleansing functions in women's hygiene and post partum recovery. These plants may play a role in reducing infection risk, soothing tissue irritation, and supporting wound healing, although rigorous clinical validation remains necessary.

Another significant feature is the preference for leaves as the dominant plant part. Leaves are more sustainable to harvest compared to roots and bark, and their frequent use may support conservation-friendly healthcare practices, provided harvesting is done responsibly. Decoctions as a common preparation method suggest the importance of warm oral administration, especially in menstrual pain and postpartum care, where heat is culturally associated with relief, circulation, and recovery.

Traditional remedies for leucorrhoea and excessive bleeding indicate that women's intimate disorders have long been recognized and managed within folk medicine. Plants such as *Mimosa pudica*, *Punica granatum*, and *Ficus racemosa* are often described in traditional systems as astringent in action. The astringent property may explain their use in discharge-related conditions and excessive menstrual bleeding. However, such uses require careful pharmacological and toxicological examination before broader medical application.

The role of elder women and traditional birth attendants in preserving this knowledge cannot be overstated. In many indigenous societies, women are the primary custodians of maternal and reproductive healthcare traditions. Their knowledge includes not only medicinal plants but also diet restrictions, bathing practices, methods of body warming, and postpartum seclusion-related care. Thus, ethnomedicine in this context is inseparable from social organization and women lived experience.

Despite its importance, this knowledge faces multiple threats. Modernization, loss of habitat, overharvesting of medicinal flora, reduced dependence on local healers, and declining interest among younger generations can all contribute to erosion of traditional practices. Furthermore, in many ethnobotanical studies, women's reproductive knowledge remains underreported due to cultural sensitivity, privacy concerns, and gendered communication barriers between researchers and informants. Therefore, future documentation should be conducted ethically, respectfully, and with adequate participation of women researchers and community members.

From a scientific perspective, the documented plants warrant further phytochemical and pharmacological investigation. Potential areas of study include:

- Anti spasmodic properties for dysmenorrhea,
- Haemostatic activity for excessive bleeding,
- Anti-microbial action in hygiene-related applications,
- anti-inflammatory effects in postpartum recovery,
- Galactagogue potential for lactation support,
- Uterine tonic or smooth muscle modulatory effects.

Such validation may contribute to safer integration of traditional remedies into primary healthcare, provided this occurs with informed consent, benefit-sharing, and respect for indigenous intellectual heritage.

The findings also have public health significance. In places where women may face barriers to accessing formal reproductive health care, validated herbal practices could complement health education, nutrition, and maternal care programs. However, it is equally important not to romanticize all traditional remedies as automatically safe. Scientific scrutiny is essential because dosage, toxicity, contraindications during pregnancy, and interactions with allopathic medicines remain largely unstandardized.

Overall, women's ethnomedicine in Dimoria represents an important intersection of biodiversity, culture, gendered knowledge, and community health resilience. Its documentation offers not only academic value but also an opportunity for conservation and culturally grounded healthcare innovation.

Conclusion

The present article highlights the importance of traditional medicinal plants used by tribal communities of Dimoria for women's hygiene, menstrual disorders, childbirth, postpartum recovery, and related reproductive health concerns. A total of 20 plant species were compiled and categorized according to their reported uses, plant parts utilized, and common modes of preparation. The observations suggest that reproductive health care forms a major component of local ethnomedicinal knowledge, with particular emphasis on menstrual regulation, infection relief, postpartum strengthening, and uterine recovery.

The dominance of leaf-based remedies and decoction methods indicates both practical accessibility and continuity of household-based healthcare traditions. Several of the documented plants are also known in broader Indian traditional medicine, which supports the ethnopharmacological relevance of the recorded practices. At the same time, this knowledge remains vulnerable to cultural erosion, ecological degradation, and lack of scientific validation.

There is an urgent need for systematic field-based research in Dimoria involving botanical authentication, women-cantered ethnographic documentation, pharmacological screening, and conservation planning. Traditional healthcare knowledge related to women should be documented with sensitivity, ethical participation, and recognition of community ownership. Such efforts may contribute significantly to the preservation of biocultural heritage and the development of affordable, culturally relevant, plant-based health interventions.

In conclusion, the medicinal plants used by Dimoria's tribal communities for women's reproductive health represent a valuable indigenous knowledge system that deserves both scientific attention and respectful preservation. Protecting this knowledge means protecting not only medicinal traditions but also the voices, experiences, and healthcare wisdom of women within tribal societies.

References

Begum, S. S., & Nath, S. C. (2000). Medicinal plant use among rural communities of Assam. *Advances in Plant Sciences*, 13, 157–162.

Bhatia, H., Sharma, Y. P., Manhas, R. K., & Kumar, K. (2014). Traditionally used gynaecological plant remedies in India: A review. *Journal of Ethnopharmacology*, 153(2), 359–373.

Bhuyan, P. J., & Baishya, A. K. (2013). Folk medicine and ethnogynaecological knowledge in Assam: A review. *NeBIO*, 4(3), 45–52.

Borthakur, S. K., & Goswami, N. (1995). Herbal remedies from Dimoria of Kamrup district of Assam in north eastern India. *Fitoterapia*, 66, 333–340.

Borthakur,S.K.(1997).Indigenous herbal remedies of tribal women of Assam.

Buragohain, J. (2011). Ethnomedicinal plants used by the ethnic communities of Tinsukia district of Assam, India. *Recent Research in Science and Technology*, 3(9),31–42.

Das, A. K., Dutta, B. K., & Sharma, G. D. (2008). Medicinal plants used by different tribes of Cachar district, Assam. *Indian Journal of Traditional Knowledge*, 7(3), 446–454.

Das, H. B., Majumdar, K., Datta, B. K., & Ray,D. (2009). Ethnobotanical uses of some plants by Tripuri and Reangtribes of Tripura. *Natural Product Radiance*,8(2), 172–180.

Devi, O. I., & Singh, C. B. (2010). Traditional phytotherapy for gynaecological disorders practiced by ethnic communities of Northeast India. *Indian Journal of Traditional*

Knowledge, 9(4), 650–654.

Ethnobotany, 9, 45–50. *Ethnobotany Research and Applications*,6,289–304.

Ghosh,A.(2008). Medicinal plants used in female disorders in Indian ethnomedicine.

Gogoi, P., & Saikia, M. (2013). Ethnogynaecological uses of plants by rural women in Assam. *International Journal of Medicinal and Aromatic Plants*, 3(4), 487–491.

Hynniewta, S. R., Kumar, Y., & Prasad, S. B. (2007). Ethnomedicinal plants used in reproductive health care by tribal communities of Meghalaya. *Journal of Ethnopharmacology*, 114(3), 301–309.

Jamir, N. S., Takatemjen, & Ao, H. J. (2010). Ethnobotanical studies of medicinal plants used by women in Nagaland. *Indian Journal of Traditional Knowledge*, 9(1), 45–50.

Joseph, J., & Kharnaior, H. B. (2011). Traditional herbal practices linked to childbirth and postpartum care in Northeast India. *Indian Journal of Traditional Knowledge*,10(2), 278–282.

Kalita, D., Sarma, H. N., & Borthakur, S. K. (2005). Plant remedies in reproductive healthcare in rural Assam. *Ethnobotany*, 17, 63–68.

Khumukcham, A. D., Singh, P. K., & Devi, T. H. (2015). Traditional medicinal plants used in women healthcare among ethnic communities of Northeast India. *Journal of Medicinal Plants Studies*, 3(5), 12–17.

Nath, M., & Bordoloi, D. N. (1989). Traditional herbal medicine among the tribes of Assam. *Journal of Economic and Taxonomic Botany*, 13, 161–165.

Saikia,A.P.,Ryakala,V.K.,Sharma,P., Goswami,P., &Bora,U. (2006).Ethnobotany of medicinal plants used by Assamese people. *Fitoterapia*, 77(4), 300–302.

Sharma, U. K., Hazarika, S., & Kalita, J. C. (2012). Traditional use of medicinal plants for women-related ailments in Assam. *Pleione*, 6(2), 345–352.

Singh, H. B., & Borthakur, S. K. (2004). Ethnomedicinal plant use in maternal and reproductive care in Northeast India. *Journal of Economic and Taxonomic Botany*, 28, 123–129.

Review Article

INTEGRATED FARMING APPROACHES FOR RESILIENT AND REGENERATIVE AGRICULTURE

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Abstract

Modern agriculture is confronted with a critical paradox: while it has successfully enhanced food production to meet global demand, it has simultaneously degraded the ecological resources upon which long-term productivity depends. The intensification of climate change further exacerbates these challenges, necessitating the adoption of farming systems that are not only productive but also ecologically sustainable and economically resilient. Integrated Farming Systems (IFS) represent a viable and scientifically validated approach to address this need. By integrating crops, livestock, trees, fisheries, and other enterprises within a single farming unit, IFS promotes efficient resource recycling, reduces reliance on external inputs, enhances soil health, and strengthens carbon sequestration. Such systems also diversify farm income and improve resilience against climatic and market uncertainties. This study reviews the principles, performance, and field-level applications of key integrated approaches, including crop–livestock systems, agroforestry, and integrated aquaculture. Evidence indicates that crop–livestock integration significantly enhances employment and soil fertility through organic nutrient cycling. Agroforestry systems, with land equivalent ratios ranging from 1.0 to 1.4, demonstrate superior productivity and provide multiple ecosystem services such as microclimate regulation and carbon storage. Integrated rice–fish and rice–duck systems have been shown to reduce cultivation costs by up to 34 percent while increasing net farm income. Case studies across diverse agro-ecological regions of India reveal benefit–cost ratios ranging from 2.03 to 5.41, with substantially higher net returns compared to conventional monocropping systems. The findings highlight that IFS can serve as a transformative pathway toward sustainable agriculture by simultaneously enhancing productivity, profitability, and environmental sustainability. The study underscores the need for supportive policy frameworks, including incentives for ecological outcomes, strengthened extension services, and institutional support during the transition phase. In the face of growing population pressure and climate variability, scaling Integrated Farming Systems is essential for ensuring long-term food and livelihood security.

Keywords: Integrated Farming Systems (IFS); agroforestry; crop–livestock integration; carbon sequestration; regenerative agriculture.

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Introduction

Agriculture constitutes a fundamental socio-ecological system operating at the interface of human civilization and natural resource dynamics, with profound implications for ecosystem functioning and livelihood security. Traditionally, agricultural systems were based on site-specific indigenous knowledge and ecological principles that enabled the sustainable management of soil, water, and biodiversity over long temporal scales. However, the advent of the Green Revolution and subsequent agricultural intensification during the twentieth century led to a paradigm shift toward input-intensive production systems characterized by monoculture, high-yielding varieties, synthetic agrochemicals, and mechanized tillage. Although these interventions substantially enhanced food grain production, they have simultaneously generated significant ecological externalities, including depletion of soil organic carbon, groundwater over-extraction, agrobiodiversity loss, increased greenhouse gas emissions, and declining economic resilience of smallholder farming systems (Nayak et al., 2018; John & Babu, 2021).

In this context, Integrated Farming Systems (IFS) have emerged as a scientifically robust and ecologically grounded alternative for sustainable agricultural intensification. IFS adopts a holistic, systems-based framework in which multiple interdependent components—crops, livestock, trees, fisheries, poultry, and other allied enterprises—are spatially and functionally integrated within a single farm unit. This integration is strategically designed to optimize biophysical interactions, including nutrient cycling, energy flow, and biological regulation, across system components (Fig. 1). The underlying principle of IFS is resource-use circularity, wherein the outputs or residuals of one enterprise are reutilized as inputs for another, thereby enhancing input-use efficiency, reducing dependence on external inputs, and improving system productivity, stability, and resilience. Such synergistic interactions contribute to the restoration of soil fertility, diversification of production, and strengthening of ecological sustainability while maintaining economic viability (Kumar et al., 2018).

An integrated farming system is a promising strategy for mitigating climate change. Practices such as intercropping, multiple cropping, crop rotation with legumes alternating with non-legumes, conservation farming, agroforestry, and integrated farming are effective for climate mitigation. This system is particularly well-suited to ensuring food security for the growing global population, especially aimed the dual challenges of land degradation and carbon emissions. The primary goal of an integrated farming system is to achieve sustainable crop production with increased productivity, ensure livelihoods and food security, adapt to climate change, and reduce greenhouse gas emissions. Moreover, IFS contributes to climate resilience by improving soil health, conserving water resources, and enhancing biodiversity. Climate-resilient agriculture (CRA) is an approach that focuses on the sustainable use of existing natural resources through crop and livestock production systems to achieve long term higher productivity and farm incomes, despite climate variability. This practice helps reduce hunger and poverty, ensuring food security for future generations in the face of climate change. CRA practices can transform the current situation and sustain agricultural production at both local and global levels, particularly in a sustainable way.

Historical Setting: From Green Revolution to Systems Thinking

In the immediate post-independence period, India experienced severe food deficits, with per capita daily food availability declining to approximately 417 g during 1947–1960, reflecting systemic inadequacies in agricultural production. The advent of the Green Revolution marked a transformative shift toward a technology-driven agricultural paradigm characterized by the large-scale adoption of high-yielding varieties (HYVs), expansion of irrigation infrastructure, and intensive application of synthetic fertilizers and agrochemicals. Spearheaded by Norman Borlaug and M. S. Swaminathan, this intervention substantially enhanced crop productivity, enabling India to attain food self-sufficiency and fostering significant gains in rural economic development (Eliazer Nelson et al., 2019; Gollin et al., 2021).

Despite these achievements, the long-term sustainability of input-intensive agricultural systems has been increasingly questioned due to the emergence of significant ecological and economic externalities. Prolonged reliance on chemical inputs and monocropping systems, particularly in the Indo-Gangetic Plains, has resulted in progressive depletion of groundwater reserves, deterioration of soil physicochemical properties, decline in soil organic carbon, and disruption of agroecosystem stability, including heightened pest and disease pressures. Simultaneously, escalating input costs coupled with diminishing factor productivity have contributed to stagnating or declining farm incomes, thereby intensifying the vulnerability of smallholder farming systems (Chaudhary et al., 2017; Kaur, Prusty et al., 2021).

These interrelated challenges have catalyzed a transition toward more sustainable and ecologically resilient agricultural paradigms. Within this context, Integrated Farming Systems (IFS), traditionally practiced in diversified smallholder systems, have re-emerged as a scientifically validated framework for sustainable intensification. IFS adopts a systems-based approach that integrates multiple complementary enterprises to enhance resource-use efficiency and ecological interactions. Empirical studies demonstrate that optimized IFS models can increase overall farm productivity by two- to threefold, reduce external input dependence by approximately 40–60%, and generate higher employment opportunities relative to monoculture-based systems (Mahapatra, 1994; Rathore & Bhait, 2008). By leveraging synergistic interactions among system components, IFS provides a robust pathway for achieving productivity gains while restoring ecological integrity and improving livelihood resilience.

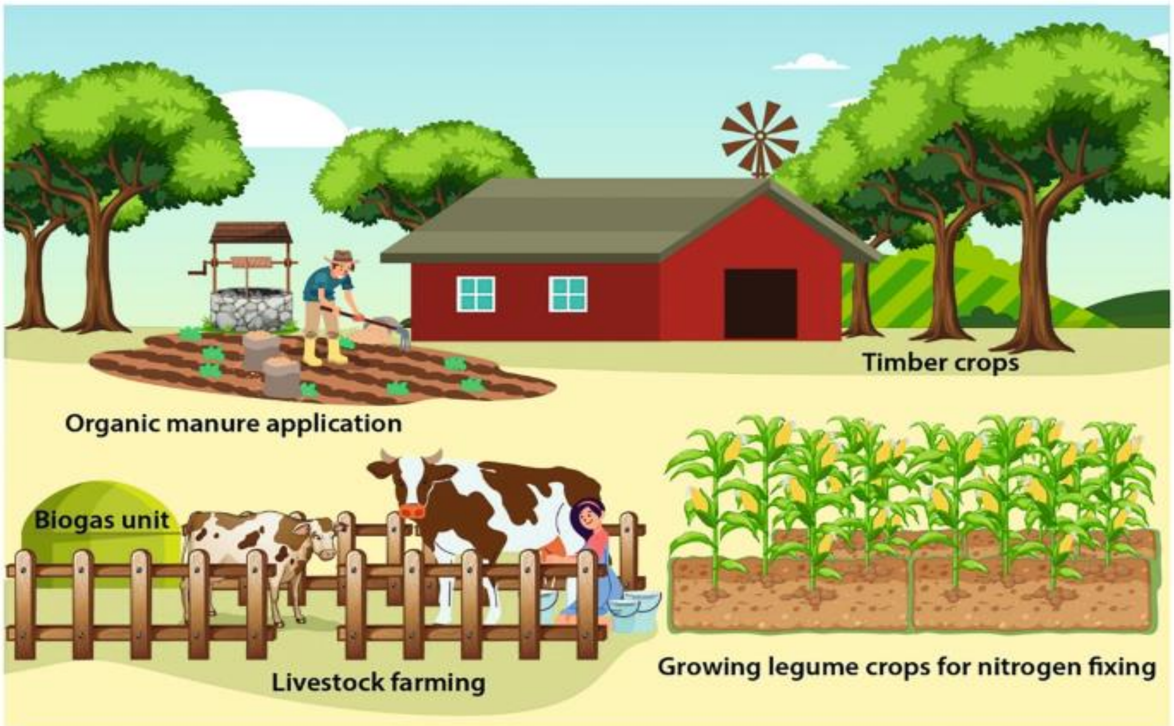

Fig. 1. Components of Integrated Farming Systems

Core Principles of Integrated and Regenerative Farming

Several interlocking principles differentiate IFS from conventional single-enterprise farming:

Circular Nutrient Flows

Every output that would otherwise become waste, crop residue, animal manure, pond sediment, kitchen organic matter is channelled back into the farm system as an input. This circularity reduces the dependence on externally purchased fertilisers and feeds the biological activity of the soil. Composting, vermicomposting, and cover cropping collectively rebuild soil organic matter, the primary determinant of sustained land fertility (Walia & Kaur, 2022; Bhagat et al., 2024).

Biological Pest and Weed Regulation

Diverse farm layouts disrupt the habitat continuity that monocultures provide for specialist pest species. Free-ranging poultry consume insects and invertebrates that cause crop damage, reducing pesticide dependency. Certain livestock species graze undergrowth beneath plantation crops, lowering weed management costs without chemical inputs (Mandal et al., 2006).

Systemic Resilience

When one enterprise suffers from drought, price collapse, or disease others provide income and nutritional continuity. This portfolio logic transforms a farm from a single-point-of-failure system into an adaptive household economy. A survey of dairy-integrated farming areas found that nearly all respondents attributed lower household financial vulnerability in drought years to the presence of livestock alongside crops (Venkatadri et al., 2008; Behera et al., 2004).

Reduced Greenhouse Gas Burden

The agricultural sector contributes approximately 12 per cent of global greenhouse gas emissions, with methane, nitrous oxide, and carbon dioxide as the primary agents (IPCC, 2014). Atmospheric CO_2 has exceeded 400 ppm, having stood at roughly 280 ppm before industrialisation (Lüthi et al., 2008). IFS reduces this burden through lower synthetic input use, internal waste utilisation, and active carbon sequestration through agroforestry components. Integrated organic systems demonstrate net GHG outcomes substantially below conventional equivalents, and those with significant tree cover can achieve net-negative emissions when soil carbon accrual is fully accounted (Oliveira et al., 2018; Frank et al., 2018).

The specific quantified environmental contributions of IFS sub-systems, including measured nutrient cycling values, emissions data, and biodiversity outcomes, are consolidated in Table 2.

Major Integrated Farming Approaches

Crop-Livestock Integration

The pairing of crop cultivation with animal husbandry is among the oldest and most extensively studied forms of agricultural integration. Animals convert crop residues into nutrient-dense organic manure, while simultaneously producing milk, meat, draught power, and biogas the latter providing clean household fuel and reducing indoor air pollution (Godi et al., 2013). Through rotational grazing typically alternating grazing periods of one to two weeks with recovery periods of three to six weeks animals directly deposit nutrients onto fields and stimulate organic matter decomposition through physical soil contact (Jayanthi et al., 2000).

Beyond soil enrichment, integrated livestock function as mobile financial assets. When crop revenues fail, animals and their products can be sold to bridge immediate household cash needs a function that carries measurable welfare significance in drought-prone regions. Table 1 presents comparative income and employment data from documented crop-livestock and multi-enterprise IFS models across multiple Indian states.

Table 1: Economic Outcomes of Selected Integrated Farming System Models in India

State	IFS Components	Net Return (₹/ha/yr)	B:C Ratio	Employment (person-days/yr)	Source
A. Dryland and Semi-Arid Regions					
Rajasthan (Sirohi)	Cereal + cash crops + vegetables + flowers + direct marketing	₹2,64,500 (2 ha)	4.38	1,800	*Bhardwaj & Vyas (2015)*
Rajasthan (South)	Crops + livestock + horticulture (1.47 ha)	₹52,161	—	—	*Singh et al. (2013)*
Karnataka (Raichur)	Cotton + vegetables + dairy + vermicompost + fodder	₹1,08,212	5.41	—	*Desai (2015)*
Andhra Pradesh	Crops + 6 buffaloes (integrated livestock)	Significantly higher than crop-only	—	904 vs. 400 (crop-only)	*Venkatadri et al. (2008)*
B. Humid and Eastern Regions					
Bihar (lowland, 2-acre)	Crops + fish + duck + dairy + horticulture + vermicompost	₹1,80,499	—	—	*Kumar et al. (2012)*
Bihar (midland, 1-acre)	Crops + goat + poultry + mushroom + horticulture	₹1,28,693	—	—	*Kumar et al. (2012)*
Tamil Nadu	Rice + azolla + fish (integrated)	₹31,788 (+38% vs. monoculture)	—	—	*Balusamy et al. (2003)*
Tamil Nadu (full IFS)	Rice + fish + goats + poultry	₹1,31,118 vs. ₹8,312 (monoculture)	—	—	*Manjunath (2002)*

Notes: B:C = Benefit-to-Cost ratio; Sources: Bhardwaj & Vyas (2015); Singh et al. (2013); Desai (2015); Venkatadri et al. (2008); Kumar et al. (2012); Balusamy et al. (2003); Manjunath (2002).

Agroforestry Systems

Agroforestry, the deliberate combination of trees with crops and/or livestock generates biological complementarities unavailable in either component alone. Deep tree root systems access subsoil moisture and nutrients and deliver them to the surface, moderating the water stress that shallow-rooted crops experience during dry periods. Canopy layers buffer microclimate, reducing both temperature extremes and evaporative demand on understorey vegetation (Tsonkova et al., 2012).

Productivity evidence is strong. Land Equivalent Ratio values of 1.0 to 1.4 indicate that integrated agroforestry plots produce more per unit area than equivalent areas of crops and woodland grown separately (Graves et al., 2007; Martin et al., 2016). In degraded dryland landscapes of Australia, integrating deep-rooted trees into pastures partially reversed rising soil salinity, a costly legacy of native vegetation clearance. In New Zealand's steeper pasturelands, timber-integrated systems arrested erosion that would otherwise render land unproductive even for grazing (George et al., 2012).

Barriers exist alongside these benefits. Tree establishment requires years before economic returns materialise, and agricultural policy frameworks in many regions including the European Union's Common Agricultural Policy have historically directed subsidies toward simplified, tree-free crop systems, disadvantaging agroforestry practitioners. Pathways to capturing value include organic certification, geographic labelling, and direct-to-consumer marketing that communicates the ecological credentials of diversified products (Flinzberger et al., 2020).

Integrated Aquaculture

Coastal, lowland, and wetland environments offer particular advantages for integrating aquatic enterprises with terrestrial crop production. In these landscapes, the existing hydrology becomes a productive resource rather than a management challenge. Flooded rice paddies naturally support dense populations of zooplankton and phytoplankton, providing a near-costless feed base for fish cultivated alongside the grain crop. Rice cultivation costs fall as fish control weeds and insects, while fish productivity is sustained by the nutrient-enriched paddy water (Varughese & Mathew, 2009).

The traditional Pokkali and Kaippad rice-prawn systems of coastal Kerala, which have operated in harmony with tidal cycles for centuries, exemplify this ecological design logic. During the rice-growing season, the land produces grain; the fallow period sees tidal inundation and prawn cultivation, with aquatic organisms feeding on crop residues and enriching the soil for the next rice cycle. This centuries-old practice demonstrates that ecological integration need not be engineered from scratch it can be aligned with landscape processes already in motion (Varughese & Mathew, 2009).

Duck integration adds a further nutrient loop: foraging ducks suppress weeds and insects, while their droppings contribute measurably to the farm nutrient pool. The quantified nutrient contributions and income data from Kerala's rice-fish and rice-duck models are presented in Table 2.

Need of Integrated Farming Systems (IFS) in Climate-Resilient Agriculture

Challenges posed by Climate change

The agricultural sector faces numerous challenges due to the changing climate, which directly affects productivity, sustainability, and livelihoods.

Rising Temperatures

Rising temperatures pose significant challenges to agriculture, impacting crop and livestock production. Heat stress can reduce productivity and yields, while warmer temperatures can alter growing seasons, leading to mismatches between crop cycles and optimal conditions. Additionally, increased evapotranspiration rates and water requirements can increase water demands, further straining water resources and making it harder to maintain crop health and productivity.

Changing Precipitation Patterns

Agriculture faces significant challenges due to changing precipitation patterns, including increased drought frequency and severity, which can impact crop yields and livestock productivity. Additionally, more frequent floods can damage crops and infrastructure, disrupting operations. Water scarcity can reduce irrigation availability, further limiting productivity. These shifting weather patterns pose a significant threat to food production systems' stability and sustainability.

Increased Frequency and Severity of Extreme Weather Events

The increased frequency and severity of extreme weather events pose significant threats to agriculture. Events like hurricanes and tornadoes can cause extensive crop damage and disrupt infrastructure. Additionally, such extreme weather can lead to livestock mortality, impacting agricultural productivity and the livelihoods of farmers. Moreover, heavy rainfall and flooding associated with these events can result in soil erosion, degrading soil health and fertility, which further compromises long-term agricultural sustainability.

Shifts in Pest and Disease Dynamics

Climate change leads to shifts in pest and disease dynamics, with rising temperatures and changing weather patterns altering their distribution. This can negatively impact crop yields and livestock productivity. To address these challenges, farmers may need to adapt their pest and disease management practices, which could increase costs and further strain agricultural productivity and livelihoods. This underscores the need for adaptive strategies to protect crops and livestock in a changing climate.

Impacts on Agricultural Productivity and livelihoods

Climate change negatively impacts agricultural productivity by reducing crop and livestock yields, threatening food security and farmers' livelihoods. This can lead to income loss and economic instability for rural communities.

Social and Economic Impacts

Climate change contributes to food insecurity, which negatively impacts human health and well-being. It can also lead to migration and displacement of rural communities, disrupting social and economic stability. Additionally, climate change results in significant economic losses for farmers, rural communities, and national economies.

Integrated Farming Systems (IFS) as a Solution

Mitigating Risks

Diversification of agricultural activities reduces dependency on a single crop or enterprise, minimizing the risk of complete failure due to climate variability.

Enhancing Productivity

Synergistic interactions between different components of IFS improve resource use efficiency, resulting in higher overall productivity.

Improving Livelihoods

The multi-enterprise approach of IFS generates year-round income, ensuring economic stability for farmers even during adverse climatic conditions.

Enhance Climate Resilience

Integrated Farming Systems aim to enhance climate resilience by promoting ecological balance, biodiversity, and efficient resource use. This involves diversifying income sources, reducing dependence on single crops, and promoting soil conservation.

Improve Resource Efficiency

IFS aims to optimize resource use by integrating different farming components, reducing waste, and promoting efficient water and nutrient management. This involves adopting conservation agriculture practices, such as reduced tillage and cover cropping.

Promote Biodiversity

IFS conserves biodiversity by maintaining ecological balance, protecting natural habitats, and promoting the use of diverse crop and animal varieties. This involves integrating trees into farming systems, promoting agroforestry practices, and conserving genetic resources.

Support Sustainable Livelihoods

IFS enhances farmers' livelihoods by increasing income, improving food security, and promoting sustainable agricultural practices. This involves providing training and support to farmers, promoting market access, and developing value chains.

Mitigate Climate Change

IFS contributes to climate change mitigation by reducing greenhouse gas emissions, promoting carbon sequestration, and enhancing soil carbon stocks. This involves adopting conservation agriculture practices, integrating trees into farming systems, and promoting agroforestry practices.

Improve Water Management

IFS promotes efficient water management by integrating different farming components, reducing waste, and promoting water conservation practices. This involves adopting conservation agriculture practices, such as reduced tillage and cover cropping.

Enhance Soil Health

IFS promotes soil health by integrating different farming components, reducing waste, and promoting soil conservation practices. This involves adopting conservation agriculture practices, such as reduced tillage and cover cropping.

Support Climate-Smart Agriculture

IFS supports climate-smart agriculture by promoting agricultural practices that enhance climate resilience, improve resource efficiency, and promote sustainable livelihoods. This involves adopting climate-resilient crop and animal varieties, promoting agroforestry practices, and conserving genetic resources.

Table 2: Environmental Contributions of Integrated Farming System Sub-Systems

Sub-System	Ecological Function	Measured / Reported Impact	Reference
Soil Health and Nutrient Cycling			
Crop-livestock manure loop	Internal fertiliser replacement; soil organic matter rebuild	Internally generated organic manure equivalent to ~506 kg N, 349 kg P_2O_5, and 342 kg K_2O per ha annually	*Kumar, Singh et al. (2012); Kumar, Subash et al. (2012)*
Cover crops and polycultures	Soil erosion reduction; water infiltration improvement	Erosion reduced by up to 60% relative to monoculture; improved soil biodiversity and above-ground species richness	*Bhagat et al. (2024); Khobragade et al. (2021)*
Duck droppings in paddy-IFS (Kuttanad)	Direct nutrient contribution to farm pool	~98.6 kg N, 126.4 kg P, and 27.8 kg K per ha/yr; gross duck income ₹46,000/ha	*Mathew & Varughese (2007)*
Climate Regulation and Carbon Sequestration			
Duck integration in flooded fields	Bioturbation reducing methane emissions	CH_4 output reduced through improved soil redox potential caused by duck paddling and foraging activity	*Xu et al. (2017); Sheng et al. (2018)*
Integrated organic farming (full system)	Lower net GHG output vs. conventional farms	Average GHG emissions of ~2,118 t CO_2-eq/yr, substantially below comparable conventional systems	*Jeswani et al. (2018)*
Agroforestry (perennial trees, boundary plantations)	Carbon sequestration in woody biomass and root systems	Net negative GHG balance achievable when total soil C sequestration offsets farm-level emissions	*Salton et al. (2014); Bell et al. (2014); Meera et al. (2019)*
Biodiversity and Landscape Ecology			
Agroforestry tree components	Pollinator and beneficial insect habitat creation	Richer pollinator networks documented relative to adjacent conventional fields; positive effect on crop pollination rates	*Maccagnani et al. (2020); Centeno-Alvarado et al. (2023)*
Wetland IFS (rice paddies, farm ponds)	Preservation of aquatic trophic structures	Maintenance of diverse aquatic fauna that drainage-oriented conventional agriculture would eliminate	*Salmah et al. (2017); Maltchik et al. (2011)*
Silvopastoral (Iberian montado/dehesa)	Wildfire resistance through managed grazing	Reduction of combustible ground material; simultaneous microclimate regulation and livestock shade provision	*Aguilera et al. (2020); Ortega et al. (2012)*

Notes: N = Nitrogen; P_2O_5 = Phosphate; K_2O = Potassium oxide; CH_4 = Methane; CO_2-eq = Carbon dioxide equivalent; LER = Land Equivalent Ratio.

Environmental Profile of Integrated Farming

The environmental case for IFS rests on several mechanisms operating simultaneously. Nutrient cycling within a well-structured farm eliminates or substantially reduces the need for synthetic fertilisers, whose manufacture is energy-intensive and whose application generates nitrous oxide emissions. Diverse plant cover reduces run-off, builds soil organic carbon, and supports the microbial communities essential for long-term land fertility. Agroforestry and wetland components further extend the ecological functions of the farm into habitat provision for pollinators, birds, and beneficial insects (Paramesh et al., 2021; Duru et al., 2015).

IFS as Effective Recycling of Resources

In Integrated Farming system, crop by-products are repurposed as fodder for livestock, while animal main and by-products such as milk and dung contribute to increasing income and enhancing soil fertility. Additionally, the resources available on the farm serve as valuable manures, promoting systemic recycling within the farming process. This integrated approach ensures more efficient use of farm resources and supports a sustainable agricultural system. By recycling organic nutrient sources from the various components of the farm, IFS models can enhance farm output, increase farmer income, and maintain soil productivity. This approach not only preserves the environment but also generates sustainable income for farmers; ensuring long-term agricultural viability. Nutrient recycling in an Integrated Farming System (IFS) involves the efficient reuse and redistribution of nutrients within the system. (fig.2) This practice includes utilizing organic waste, residues, or by-products from one component of the farming system as inputs for another, creating a more sustainable and resource efficient farming process (Kumar, Singh, et al., 2012)

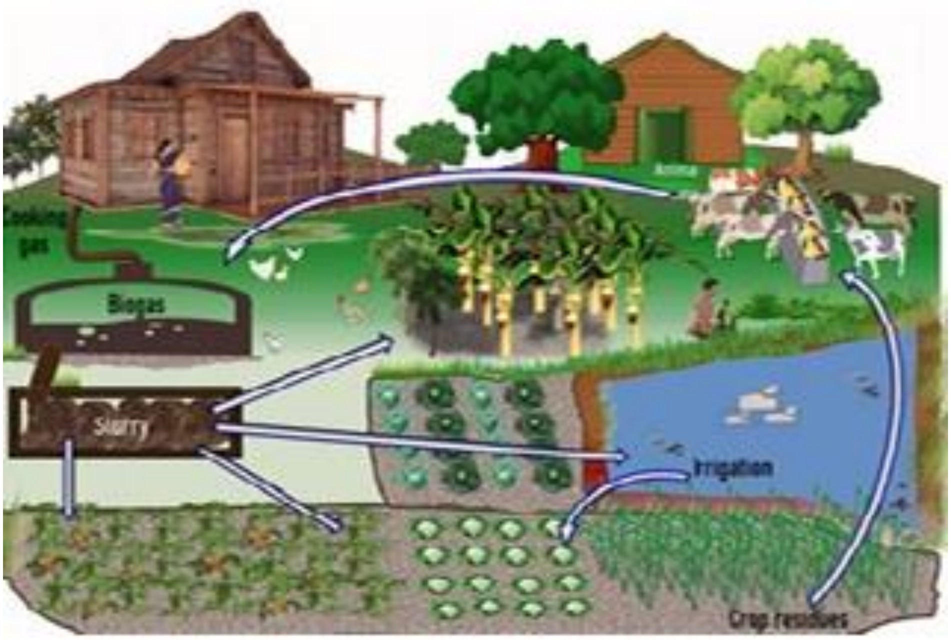

Fig.2: Effective recycling of resources

Global Context and Policy Frameworks

The transition to integrated food systems has become a global policy objective, not merely a farm-level aspiration. The Food Systems Integrated Programme (FSIP), jointly led by the Food and Agriculture Organization (FAO) and the International Fund for Agricultural Development (IFAD), targets systemic reform across food value chains from production incentives and business models through to consumption patterns. Building on earlier Global Environment Facility initiatives addressing food security and commodity deforestation, the FSIP currently operates through 32 country-level projects spanning four continents, including

Angola, Argentina, Bhutan, China, India, Indonesia, Kenya, Mexico, Nigeria, Pakistan, Peru, and Sri Lanka.

This breadth reflects a widening international consensus that conventional, input-intensive food systems are structurally incompatible with climate stability, biodiversity targets, and equitable human nutrition goals for the twenty-first century. Policy frameworks at both national and supranational levels are beginning to shift subsidy structures toward rewarding ecological outcomes soil carbon accumulation, biodiversity enhancement, and water quality rather than simply rewarding input volume or gross output.

Illustrative Case Studies

One-Hectare Demonstration Farm, Raichur, Karnataka

A farm established under the RKVY scheme at the University of Agricultural Sciences, Raichur, combined teak boundary plantations, drumstick and curry leaf on field bunds, a bullock pair, two dairy cows, sixty poultry birds, a kitchen garden, fish pond, vermicompost unit, and a horticulture block intercropping mango with bhendi, ridge gourd, and leafy vegetables. Over three years, the model achieved a net income substantially higher than conventional single-crop farming on equivalent land. The combination of cotton with vegetables, dairy, vermicomposting, and bund fodder outperformed the conventional sole-crop cotton system on the same land by 26.5 per cent. The economic performance figures are presented in Table 1 (Desai, 2015).

Horticulture-Based IFS, Sirohi District, Rajasthan

Seven IFS models were developed for semi-arid two-hectare plots in Sirohi, ranging from simple rabi-kharif cereal combinations to a fully diversified system incorporating cash crops, vegetables, fruit, and flowers with direct retail marketing. Within four years, participating farmers had doubled household income. Beyond the financial gains, vegetable cultivation opened new market participation for women farmers, expanding both economic and social agency. Papaya and lime-based nutrition gardens improved dietary outcomes for tribal families in the region. Numerical outcomes are summarised in Table 1 (Bhardwaj & Vyas, 2015).

IFS Modules for Smallholders in Bihar

The Bihar models, designed for one- and two-acre landholdings in lowland and midland irrigated ecosystems, are notable for the granular accounting of both financial and organic returns. The two-acre lowland module allocated proportionate areas to crops, horticulture, fish-duck cultivation, dairy, fodder, and vermicompost. Beyond cash income, the system recycled nutrients equivalent to approximately 482 kg of urea, 400 kg of single super phosphate, and 396 kg of muriate of potash annually, reducing cultivation costs by ₹8,000–9,000 per year. The one-acre midland module's goat manure and vermicompost similarly substituted for ₹4,000 worth of purchased fertilisers annually. Full financial outcomes appear in Table 1 (Kumar et al., 2012).

Sikkim: Systemic State-Scale Organic Transition

Sikkim's trajectory from low-chemical farming to certification as India's and the world's first fully organic state merits attention as a governance case study as much as an agronomic one. The state government, recognising in 2003 that limited chemical penetration due to poor road connectivity was a marketable differentiator rather than a disadvantage, adopted a long-horizon strategy: phase down urea subsidies to zero, distribute vermicompost and earthworms at subsidised rates, offer one dairy cow and government employment per farming family during the adjustment period, and promote high-value certified horticulture with agri-tourism as a complementary income stream.

Table 3: Comparative Overview of Major Integrated Farming Approaches: Mechanisms, Outcomes, and Constraints

Approach	Operating Principle	Productivity Advantage	Key Constraint	Selected References
Crop-Livestock Integration	Closed nutrient loop between crop residues, manure, and soil; animals as biological weed/pest managers	On-farm labour more than doubled; up to 16× income gain over sole-crop baseline (Tamil Nadu)	Rotational grazing knowledge requirement; higher daily management load	*Venkatadri et al. (2008); Manjunath (2002); Jayanthi et al. (2000)*
Agroforestry (Silvopasture / Alley Cropping)	Deep-rooted trees access subsoil nutrients and moisture; canopy moderates field microclimate	Land Equivalent Ratio 1.0–1.4; compounding ecosystem services over time; soil salinisation reversal	Multi-year establishment lag before economic returns; subsidy frameworks often do not reward tree-integrated systems	*Graves et al. (2007); Cubbage et al. (2012); Flinzberger et al. (2020); George et al. (2012)*
Integrated Aquaculture (Rice-Fish / Rice-Duck)	Flooded paddy water supports zooplankton-fed fish; duck droppings enrich soil; azolla fixes atmospheric nitrogen	Rice cultivation cost reduced by 29–34%; grain yield climbed from ~2,338 to >4,000 kg/ha over five seasons	Site-specific (wetland/coastal lowland); water management infrastructure required	*Padmakumar et al. (2002); Mathew & Varughese (2007); Balusamy et al. (2003)*
Certified Organic Transition (Sikkim Model)	Phased withdrawal of synthetic input subsidies replaced by vermicompost support, diversified horticulture, and agri-tourism	Rice yield rose 29% and maize yield 14% post-transition; new agri-tourism revenue stream created	Requires approximately 12-year transition horizon; fails without sustained farmer income support	*Parikh (2023)*

Notes: LER = Land Equivalent Ratio (>1.0 indicates the integrated system outperforms equivalent separate monocultures on the same total area).

Crucially, the formal ban on chemical farming was not imposed until 2015 twelve years into the programme. The contrast with Sri Lanka's abrupt 2021 ban, which produced immediate food insecurity, underlines that the pacing of transition and the quality of farmer support structures determine success or failure. Post-transition, rice and maize yields both rose, confounding predictions of productivity decline. The governance lessons from Sikkim are at least as instructive for other states and nations as the agronomic outcomes (Parikh, 2023).

Comparative Synthesis of IFS Approaches

The four principal integrated approaches crop-livestock integration, agroforestry, integrated aquaculture, and certified organic transition differ in operating mechanisms, suitability by landscape type, economic timescales, and the nature of constraints they face. Table 3 presents a side-by-side comparison that draws on the case evidence reviewed above.

Implementation Pathway and Policy Recommendations

Moving from awareness to adoption requires a structured, stepwise approach applicable at both farm and policy levels.

Farm-Level Entry Points

Transition begins with baseline assessment: soil nutrient and pH analysis, water availability mapping, and an honest audit of available labour, capital, and existing market relationships. These data determine which enterprises are viable as initial components and which will require further capacity building before introduction. Starting with a single additional enterprise a small fish pond, a vermicompost unit, a boundary plantationgenerates observational learning and economic returns before the system is scaled. Simple yield and income records, whether maintained on paper or through mobile applications, create the evidence base for accessing credit schemes, government subsidies, or carbon market instruments (Walia et al., 2019).

Policy-Level Enablers

Systemic adoption of IFS at scale demands that agricultural support mechanisms be reoriented from rewarding input consumption to rewarding ecological outcomes. This means redesigning subsidies to include soil carbon indicators, biodiversity metrics, and water quality parameters alongside or instead of purely volumetric output criteria. Research and extension services need institutional restructuring to shift the advisory model from crop-by-crop optimisation toward whole-farm systems thinking, with field officers trained in multi-enterprise dynamics. Certification and premium-labelling pathways must be made genuinely accessible to small and marginal farmers. And transition income support comparable to Sikkim's approach of dairy animals and employment guarantees during the adjustment period is essential to make the financial risk of changing systems manageable for households operating close to subsistence margins.

Challenges and Future Directions

Notwithstanding their demonstrated agronomic, ecological, and economic advantages, Integrated Farming Systems (IFS) are constrained by a range of structural, financial, and institutional barriers that require systematic evaluation. The initial capital investment associated with enterprise diversification—including the development of aquaculture units, establishment of perennial plantations, and procurement of livestock—remains prohibitively high for smallholder farmers operating under limited liquidity conditions. In addition, the management of multiple, interdependent enterprises necessitates higher levels of technical knowledge, labor allocation, and managerial skill, thereby increasing system complexity relative to monocropping systems. Market access further constrains adoption, as value chains for diversified agricultural products are often fragmented, underdeveloped, and less efficient compared to those for staple commodities. The transitional phase from conventional to integrated systems is also characterized by temporal income instability, which elevates perceived risk and may deter adoption among resource-constrained farming households.

Emerging technological and institutional innovations are progressively reshaping the economic feasibility of IFS. Advances in gene-editing and plant breeding technologies aimed at developing perennial crop varieties offer significant potential to reduce recurrent labor inputs while enhancing soil organic carbon accumulation and long-term system stability. Concurrently, digital innovations such as blockchain-enabled traceability platforms are improving supply chain transparency, enabling producers to authenticate sustainability attributes and access premium markets. Furthermore, the expansion of voluntary carbon markets is facilitating the monetization of ecosystem services, particularly carbon sequestration achieved through agroforestry and conservation-oriented practices, thereby generating additional revenue streams that enhance system viability.

At a conceptual level, the synthesis of evidence presented herein reflects a fundamental paradigm shift from input-intensive, reductionist agricultural models toward an ecosystem-based systems approach. Integrated farming systems conceptualize the farm as a complex adaptive system, wherein ecological interactions among biotic and abiotic components underpin productivity, resilience, and sustainability. Within this framework, farmers are recognized as knowledge-intensive managers of dynamic biological systems, whose experiential knowledge and adaptive decision-making capacities are critical to optimizing system performance. In the context of escalating global food demand and intensifying climate variability, the large-scale adoption and scaling of integrated and regenerative farming systems represent a scientifically robust and operationally feasible pathway toward achieving sustainable food production while concurrently restoring ecological integrity and enhancing livelihood resilience.

References

Aguilera, E., Díaz-Gaona, C., García-Laureano, R., Reyes-Palomo, C., Guzmán, G. I., Ortolani, L., Sánchez-Rodríguez, M., & Rodríguez-Estévez, V. (2020). Agroecology for adaptation to climate change and resource depletion in the Mediterranean region: A review. Agricultural Systems, 181, 102809.

Balusamy, M., Shanmugham, P. M., & Baskaran, R. (2003). Mixed farming an ideal farming. Intensive Agriculture, 41(11–12), 20–25.

Behera, U. K., Jha, K. P., & Mahapatra, I. C. (2004). Integrated management of available resources of the small and marginal farmers for generation of income and employment in eastern India. Crop Research, 27, 83–89.

Bell, L. W., Moore, A. D., & Kirkegaard, J. A. (2014). Evolution in crop–livestock integration systems that improve farm productivity and environmental performance in Australia. European Journal of Agronomy, 57, 10–20.

Bhagat, R., Walia, S. S., Sharma, K., Singh, R., Singh, G., & Hossain, A. (2024). The integrated farming system is an environmentally friendly and cost-effective approach to the sustainability of agri-food systems in the modern era of the changing climate: A comprehensive review. Food and Energy Security, 13, e534.

Bhardwaj, R. L., & Vyas, L. (2015). Development of region specific horticulture based integrated farming system models with crop diversification for sustainable livelihoods and nutritional security of tribal of Sirohi District of Rajasthan: A case study. Advances in Social Research, 1(1), 17–29.

Centeno-Alvarado, D., Lopes, A. V., & Arnan, X. (2023). Fostering pollination through agroforestry: A global review. Agriculture, Ecosystems and Environment, 351, 108478.

Chaudhary, S., Dheri, G. S., & Brar, B. S. (2017). Long-term effects of NPK fertilizers and organic manures on carbon stabilization and management index under rice-wheat cropping system. Soil and Tillage Research, 166, 59–66.

Cubbage, F., Balmelli, G., Bussoni, A., Noellemeyer, E., Pachas, A. N., Fassola, H., Colcombet, L., Rossner, B., Frey, G., Dube, F., de Silva, M. L., Stevenson, H., Hamilton, J., & Hubbard, W. (2012). Comparing silvopastoral systems and prospects in eight regions of the world. Agroforestry Systems, 86(3), 303–314.

Desai, B. K. (2015). Integrated farming system module for livelihood security (Raichur, Karnataka, India): Success story under RKVY project implemented at UAS, Raichur, Karnataka (pp. 1–14).

Duru, M., Therond, O., & Fares, M. H. (2015). Designing agroecological transitions: A review. Agronomy for Sustainable Development, 35, 1237–1257.

Eliazer Nelson, A. R., Ravichandran, K., & Antony, U. (2019). The impact of the green revolution on indigenous crops of India. Journal of Ethnic Foods, 6, 1.

Flinzberger, L., Zinngrebe, Y., &Plieninger, T. (2020). Labelling in Mediterranean agroforestry landscapes: A Delphi study on relevant sustainability indicators. Sustainability Science, 15(5), 1369–1382.

Frank, S., Beach, R., Havlík, P., Valin, H., Herrero, M., Mosnier, A., Hasegawa, T., Creason, J., Ragnauth, S., &Obersteiner, M. (2018). Structural change as a key component for agricultural non-CO_2 mitigation efforts. Nature Communications, 9, 1060.

George, S. J., Harper, R. J., Hobbs, R. J., & Tibbett, M. (2012). A sustainable agricultural landscape for Australia: A review of interlacing carbon sequestration, biodiversity and salinity management in agroforestry systems. Agriculture, Ecosystems & Environment, 163, 28–36.

Godi, N. Y., Zhengwuvi, L. B., Abdulkadir, S., &Kamtu, P. (2013). Effect of cow dung variety on biogas production. Journal of Mechanical Engineering Research, 5, 1–4.

Gollin, D., Hansen, C. W., & Wingender, A. M. (2021). Two blades of grass: The impact of the green revolution. Journal of Political Economy, 129, 2344–2384.

Graves, A. R., Burgess, P. J., Palma, J. H. N., Herzog, F., Moreno, G., Bertomeu, M., Dupraz, C., Liagre, F., Keesman, K., van der Werf, W., de Nooy, A. K., & van den Briel, J. P. (2007). Development and application of bio-economic modelling to compare silvoarable, arable, and forestry systems in three European countries. Ecological Engineering, 29(4), 434–449.

IPCC. (2014). Climate change: Impacts, adaptation, and vulnerability. Cambridge University Press.

Jayanthi, C., Rangasamy, A., &Chinnusamy, C. (2000). Water budgeting for components in lowland integrated farming systems. Agricultural Journal, 87, 411–416.

Jeswani, H. K., Espinoza-Orias, N., Croker, T., & Azapagic, A. (2018). Life cycle greenhouse gas emissions from integrated organic farming: A systems approach considering rotation cycles. Sustainable Production and Consumption, 13, 60–79.

John, D. A., & Babu, G. R. (2021). Lessons from the aftermaths of green revolution on food system and health. Frontiers in Sustainable Food Systems, 5, 644559.

Kaur, J., Prusty, A. K., Ravisankar, N., Panwar, A. S., Shamim, M., Walia, S. S., Chatterjee, S., Pasha, M. L., Babu, S., Jat, M. L., & López-Ridaura, S. (2021). Farm typology for planning targeted farming systems interventions for smallholders in Indo-Gangetic Plains of India. Scientific Reports, 11, 20978.

Khobragade, S., Mohapatra, S., Mahananda, M., Singh, A., & Singh, A. (2021). Integrated farming system: A review. International Journal of Economic Plants, 8(3), 181–187.

Kumar, S., Dey, A., Kumar, U., Chandra, N., & Bhatt, B. P. (2012). Integrated farming system for improving agricultural productivity. In B. P. Bhatt et al. (Eds.), Status of Agricultural Development in Eastern India (pp. 205–230).

Kumar, S., Singh, S. S., Meena, M. K., & Shivani, D. A. (2012). Resource recycling and their management under integrated farming system for lowlands of Bihar. Indian Journal of Agricultural Sciences, 82, 504–510.

Kumar, S., Subash, N., Shivani, S., Singh, S. S., & Dey, A. (2012). Evaluation of different components under integrated farming system for small and marginal farmers under semi-humid climatic environment. Experimental Agriculture, 48, 399–413.

Lüthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J. M., Siegenthaler, U., Raynaud, D., Jouzel, J., Fischer, H., Kawamura, K., & Stocker, T. F. (2008). High-resolution carbon dioxide concentration record 650,000–800,000 years before present. Nature, 453, 379–382.

Maccagnani, B., Veromann, E., Ferrari, R., Boriani, L., &Boecking, O. (2020). Agroecosystem design supports the activity of pollinator networks. In G. Smagghe et al. (Eds.), Entomovectoring for precision biocontrol and enhanced pollination of crops (pp. 1–7). Springer.

Mahapatra, I. C. (1994). Farming system research — a key to sustainable agriculture. Fertilizer News, 39(11), 13–25.

Maltchik, L., Rolon, A. S., Stenert, C., Machado, I. F., & Rocha, O. (2011). Can rice field channels contribute to biodiversity conservation in southern Brazilian wetlands? Revista de Biología Tropical, 59, 1895–1914.

Mandal, M. K., Khandekar, N., & Khandekar, P. (2006). Backyard poultry farming in Bareilly district of Uttar Pradesh, India: An analysis. Livestock Research for Rural Development, 18(7).

Manjunath, B. L. (2002). Integrated farming systems for coastal region of Goa [Doctoral dissertation, University of Agricultural Sciences, Dharwad].

Martin, G., Moraine, M., Ryschawy, J., Magne, M. A., Asai, M., Sarthou, J. P., Duru, M., &Therond, O. (2016). Crop–livestock integration beyond the farm level: A review. Agronomy for Sustainable Development, 36(3).

Mathew, T., & Varughese, K. (2007). Nutrient flow and economics of integrated farming system practiced in the coastal region of Kerala. In National Symposium on Integrated Farming Systems, 26–28 October 2007. Farming System Research and Development Association, Modipuram.

Meera, A. V., John, J., Sudha, B., Sajeena, A., Jacob, D., & Bindhu, J. S. (2019). Greenhouse gas emission from integrated farming system models: A comparative study. Green Farming, 10, 696–701.

Nayak, P. K., Nayak, A. K., Panda, B. B., Lal, B., Gautam, P., Poonam, A., Shahid, M., Tripathi, R., Kumar, U., Mohapatra, S. D., & Jambhulkar, N. N. (2018). Ecological mechanism and diversity in rice based integrated farming system. Ecological Indicators, 91, 359–375.

Oliveira, J. D., Madari, B. E., Carvalho, M. T., Assis, P. C., Silveira, A. L., de Leles Lima, M., Wruck, F. J., Medeiros, J. C., & Machado, P. L. (2018). Integrated farming systems for improving soil carbon balance in the southern Amazon of Brazil. Regional Environmental Change, 18, 105–116.

Ortega, M., Saura, S., González-Avila, S., Gomez-Sanz, V., & Elena-Rossello, R. (2012). Landscape vulnerability to wildfires at the forest-agriculture interface: Half-century patterns in Spain assessed through the SISPARES monitoring framework. Agroforestry Systems, 85(3), 331–349.

Padmakumar, K. G., Krishnan, A., & Narayanan, N. C. (2002). Rice-fish farming system development in Kuttanad, Kerala — Changing paradigms. In National Symposium on Priorities and Strategies for Rice Research in High Rainfall Tropics, 10–11 October 2002. Regional Agricultural Research Station, Pattambi (p. 248).

Paramesh, V., Chakurkar, E. B., Bhagat, T., Sreekanth, G. B., Kumar, H. C., Rajkumar, S., Gokuldas, P. P., Mahajan, G. R., Manohara, K. K., & Ravisankar, N. (2021). Impact of integrated farming system on residue recycling, nutrient budgeting and soil health. Indian Journal of Agricultural Sciences, 91, 44–48.

Parikh, A. (2023). Sikkim: Making of the first 100% organic state of the world. Indian Journal of Sustainable Development, 9(1), 22–28.

Rathore, S. S., & Bhait, B. P. (2008). Productivity improvement in jhum fields through integrated farming system. Indian Journal of Agronomy, 53(3), 167–171.

Salmah, S., Zain, B. M., Raza, A., & Ahmad, T. (2017). Ecological functions of wetland IFS components. Journal of Wetland Ecology, 11(2), 45–61.

Salton, J. C., Mercante, F. M., Tomazi, M., Zanatta, J. A., Concenço, G., Silva, W. M., & Retore, M. (2014). Integrated crop-livestock system in tropical Brazil: Toward a sustainable production system. Agriculture, Ecosystems and Environment, 190, 70–79.

Sheng, F., Cao, C. G., & Li, C. F. (2018). Integrated rice-duck farming decreases global warming potential and increases net ecosystem economic budget in central China. Environmental Science and Pollution Research, 25, 22744–22753.

Singh, H., Sharma, S. K., Dashora, L. N., Burark, S. S., & Meena, G. L. (2013). Characterization and economics of farming systems in southern Rajasthan. Annals of Arid Zone, 52(1), 67–70.

Tsonkova, P., Böhm, C., Quinkenstein, A., & Freese, D. (2012). Ecological benefits provided by alley cropping systems for production of woody biomass in the temperate region: A review. Agroforestry Systems, 85(1), 133–152.

Varughese, K., & Mathew, T. (2009). Integrated farming systems for sustainability in coastal ecosystem. Indian Journal of Agronomy, 54(2), 120–127.

Venkatadri, S., et al. (2008). Livestock-based integrated farming systems. Department of Animal Husbandry, India.

Walia, S. S., & Kaur, T. (2022). Integrated farming systems: Research, extension and scope in Punjab. In F. A. Bahar, M. A. Bhat, & S. S. Mahdi (Eds.), Secondary Agriculture: Sustainability and Livelihood in India (pp. 47–58). Springer International Publishing.

Walia, S. S., Dhawan, V., Dhawan, A. K., & Ravisankar, N. (2019). Integrated farming system: Enhancing income source for marginal and small farmers. In A. K. Dhawan & R. Peshin (Eds.), Natural Resource Management: Ecological Perspectives (pp. 63–94). Springer International Publishing.

Xu, Q., Dai, T., Jiang, J., Ma, X., & He, Y. (2017). Ducks in rice paddies: Friend or foe? Rice, 10, 1–12.

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