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Integrated weed and biofertilizer management strategies for sustainable barley production

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Abstract

Barley is one of the most important cereals grown globally for food, feed, and industrial uses. Weed control and overuse of chemical fertilizers, however, have limited its productivity, impacting soil health, environmental quality, and the sustainability of the agricultural system. The practice of Integrated Weed and Biofertilizer Management has become a green and sustainable solution to boost the productivity of barley while reducing environmental hazards. This review emphasises the importance of implementing integrated weed management strategies, such as cultural, mechanical, biological, and chemical control, in controlling weeds during key growth phases of barley. At the same time, the use of biofertilizers like nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, potassium-mobilizing bacteria, and arbuscular mycorrhizal fungi increases the availability of nutrients, root development, soil microbial activity, and plant resistance to biotic and abiotic stresses. The synergistic effect of weed management and biofertilizer application leads to better NUE, better growth of crops, better yield, and better soil fertility. Moreover, integrated strategies help minimize dependence on synthetic agrochemicals, decrease production expenses, and promote agricultural systems that are eco-friendly. Recent developments in the use of microbial inoculants, precision weed management, and integrated nutrient management practices are also discussed, giving prospects for sustainable cultivation of barley. Overall, the integration of weed management strategies and biofertilizers presents a viable route to sustainable barley production, promoting productivity, profitability, and ecological balance amidst evolving climatic conditions.

Keywords: Barley, biofertilizers, integrated weed management, sustainable agriculture, soil health

1. Introduction

In global cereal cultivation, barley is one of the most important crops for food, feed, and brewing purposes, and in India, it plays a crucial role, especially for the smallholders and for input-efficient cultivation on the marginal lands. The production of barley is essential for food security and the income of farmers in rural areas, but is increasingly threatened by poor soil quality, climate risks, and high input costs. Traditional use of synthetic fertilizers and herbicides has led to higher yields but with drawbacks of soil health deterioration, herbicide resistance, environmental pollution, and high production costs, which pose a risk of long-term sustainability (Hasan *et al.*, 2021; Al-Shammmary *et al.*, 2024) ^[21, 3]. Among biotic constraints, weeds are the most serious factors that compete with the crop for water, nutrients, light, and space and cause significant losses in yields if they are not properly managed (Hasan *et al.*, 2021; Gao & Su, 2024) ^[21, 19]. Inappropriate weed control, poor or only chemical control, can alter weed flora, induce weed biotype selection, and impact the beneficial flora, and fertility amendments can inadvertently favour weed control if not properly integrated with integrated weed management (IWM) (Little *et al.*, 2021) ^[28]. Weeds also have a significant impact on the nutrient uptake, thereby affecting nutrient dynamics of the crop-soil system, which decreases the efficiency of nitrogen fertilizer use and offsets the advantage of nutrient inputs (Little *et al.*, 2021; Gao & Su, 2024) ^[28, 19]. Biofertilizers and associated biostimulants can provide a complementary solution for nutrient management in a sustainable way. Different organic inputs, such as plant growth-promoting microbes, vermicompost, and other microbial inputs, can help increase nutrient availability, enhance soil structure and microbial diversity, improve nutrient use efficiency, and

strengthen stress and pest tolerance, which will support more sustainable crop production systems (Sande *et al.*, 2024; Shahwar *et al.*, 2023) ^[38, 41]. Organic and biological resources used in combination with lower mineral fertilizations can result in better yield, soil health, and environmental outcomes than mineral sources alone (Sande *et al.*, 2024; Al-Shammary *et al.*, 2024) ^[3, 38]. Integrated weed management and nutrient management (biofertilizer) approaches are required to combine optimal chemical fertilizer and herbicide use with weed management in order to address the dual problems of weed pressure and minimize reliance on chemical fertilizers and herbicides. These can help barley to outcompete weeds, increase nutrient cycling, and produce yield without compromising the long-term soil and environmental quality (Hasan *et al.*, 2021; Shahwar *et al.*, 2023) ^[21, 41]. Labor costs have also been increasing, and the availability of other agricultural inputs is limited, forcing farmers to increasingly rely on herbicides to control weeds. However, indiscriminate and unwarranted overuse of herbicides has resulted in changes in weed flora and the development of herbicide-resistant weed species. Thus, the development and deployment of new herbicide mixtures that have different modes of action are required for effective and sustainable weed control (Das *et al.*, 2026) ^[12].

2. Barley Production and Sustainability Challenges

Barley is an important cereal crop globally, and is essential for animal feed and malting, as well as in some areas, for food. Climate change, land degradation, and the use of agrochemicals pose threats to its sustainability as they are putting pressure on stable yields and long-term soil health (Capasso *et al.*, 2021; Karunarathne *et al.*, 2023) ^[9, 24]. Intensification and breeding have led to improved yields of barley, particularly in mechanised systems, but also led to loss of genetic diversity, which has made it less resilient to harsh and variable environmental conditions (Capasso *et al.*, 2021; Visioni *et al.*, 2023) ^[9, 50]. Traditional landraces and wild relatives tend to have higher performance under stress conditions compared to modern cultivars with high-yielding potential, with landraces reported to produce up to 20% more than improved cultivars under stressful conditions (Capasso *et al.*, 2021) ^[9]. In places where water and other inputs are insufficient, barley is still a significant crop, with some areas using it as their sole cereal (Visioni *et al.*, 2023; Karunarathne *et al.*, 2023) ^[50, 24]. Abiotic stresses like salinity, cold, waterlogging, drought, and heat are already limiting production of barley in major producing regions and are increasingly affecting the crop's production (Capasso *et al.*, 2021; Karunarathne *et al.*, 2023) ^[9, 24]. These stresses are likely to increase with climate change, impacting barley supplies and applications, including malting, but with a focus on basic feed and food applications (Capasso *et al.*, 2021; Karunarathne *et al.*, 2023) ^[9, 24]. Meanwhile, biotic interactions, such as with mycorrhizal fungi, can also increase the availability of nutrients and resistance to stress, and wild relatives and landraces can be a source of alleles to increase resilience to these stresses (Capasso *et al.*, 2021) ^[9]. Soils are also eroded and are being over-fertilised with large amounts of agrochemicals, which compromises sustainability. Pesticide usage reviews reveal that

soils are a significant store of pesticide residues, can remain in the environment for years, are re-emitted to air and water, and can negatively affect soil quality, biodiversity, and sustainability (Tudi *et al.*, 2021) ^[49]. Degradation products can impact microbial community, decomposition of organic matter, and nutrient availability, which may affect long-term productivity and environmental and human health risks (Tudi *et al.*, 2021) ^[49]. This equilibrium between yield advancement and a diminished reliance on agrochemicals while simultaneously preserving barley's genetic diversity is, thus, very crucial to sustainable barley production (Capasso *et al.*, 2021; Visioni *et al.*, 2023) ^[9, 50].

3. Weed Flora and Weed Dynamics in Barley Fields

Barley crop-weed principles are generally observed in the weed flora and dynamics of barley fields. Weeds impact yield and grain quality primarily by competing for light, water, and nutrients, and the extent of damage is highly dependent on the time when weeds emerge and the type of weed (grass vs broadleaf) and management strategy (intensive vs light) (Gao & Su, 2024; Little *et al.*, 2021) ^[19, 28]. Barnyardgrass (*Echinochloa crus-galli*), crabgrasses (*Digitaria* spp., *Eleusine indica*), and other grasses with similar growth form, height, and N-use to the crop pose an important challenge as a major grassy weed in barley and other cereals, particularly in dense stands and under high N (Little *et al.*, 2021; Singh *et al.*, 2022) ^[28, 44]. Broadleaf weeds often found in cereal and legume cropping systems, like *Amaranthus retroflexus*, *Chenopodium album*, *Portulaca oleracea*, *Convolvulus arvensis*, and *Cyperus* sedges, are at risk of becoming problem weeds when broadleaf control is insufficient and may also harbor pests and diseases (Singh *et al.*, 2022; Negewo *et al.*, 2023) ^[44, 35]. This flora is likely to change further under climate change, in favour of species that are highly plastic and grow quickly (Malhi *et al.*, 2021; Kumar *et al.*, 2023) ^[26, 32].

Many of the problem species have a peak emergence early in the season (barnyardgrass, lambsquarters, ragweed) or emergence that lasts long during the season (redroot pigweed, chickweed), and others have a midseason (*C. rosea*) or late season emergence (*C. arvense*) (Brown *et al.*, 2022) ^[7]. Weed communities can also emerge in fields following a predictable pattern, based on the crop rotation history, leading to emergence times becoming somewhat predictable (Brown *et al.*, 2022; Scavo & Mauromicale, 2021; Blank *et al.*, 2023) ^[6, 7, 40]. In cereals, the most severe competition is likely to occur when the weeds grow in synchrony with or shortly after the crop, and the critical period of weed control is a few weeks after sowing of the crop, beyond which weed control is likely to result in large loss of yields, often double digits (Gao & Su, 2024; Sharma & Rayamajhi, 2022; Singh *et al.*, 2022) ^[19, 43, 44]. In field crop crops uncontrolled weeds cause yield losses of around 30-40%, and up to 80% in case of severe infestation and result in penalties in grain quality due to reduced kernel size, weed seeds in grain, moisture and nutrient depletion (Gao & Su, 2024; Singh *et al.*, 2022; Sharma & Rayamajhi, 2022; Karavidas *et al.*, 2022) ^[19, 23, 43, 44] (Table 1).

Table 1: Weed types, emergence, competition, and losses in barley-like cereal systems

Aspect	Key points for barley-type cereals	Citations
Major grassy weeds	Barnyardgrass, crabgrasses, other Poaceae sharing height, fast growth, high N-responsiveness with cereals; very competitive under fertilization	(Little <i>et al.</i> , 2021; Singh <i>et al.</i> , 2022) ^[28, 44]
Major broadleaf/sedge weeds	<i>Amaranthus</i> spp., <i>Chenopodium album</i> , <i>Portulaca oleracea</i> , <i>Convolvulus arvensis</i> , <i>Cyperus</i> spp. widely reported in field crops and legumes; often dominant without targeted control	(Negewo <i>et al.</i> , 2023; Singh <i>et al.</i> , 2022) ^[35, 44]
Seasonal emergence patterns	Many key species peak early; some mid/late or with extended emergence, shaping the timing of control and rotation planning	(Brown <i>et al.</i> , 2022; Blank <i>et al.</i> , 2023) ^[6, 7]
Critical competition period	Early growth stages (first weeks after sowing) are most sensitive; weeds emerging then cause the largest yield and quality loss	(Gao & Su, 2024; Sharma & Rayamajhi, 2022) ^[19, 43]
Typical yield/quality losses	Commonly ~30-40% yield loss without control; up to 80% under heavy pressure, with poorer grain size and contamination	(Gao & Su, 2024; Singh <i>et al.</i> , 2022) ^[19, 44]

4. Effect of Weeds on Growth and Yield of Barley

In barley, the growth and yield are strongly influenced by the occurrence of weeds, which compete with the crop for water, nutrients, and other resources, and change the crop's environment seasonally. They affect not only tillering and biomass production, but also grain yield, harvest index, and the profitability of the farm. Competition for nutrients and moisture is an inherent component of weed growth, and often the demand for nutrients and the root system is greater than that of barley, which may limit the amount of nutrients and soil water available for barley uptake (Little *et al.*, 2021; Malhi *et al.*, 2021) ^[28, 32].

Nitrogen, phosphorus, or potassium can stimulate weed growth and height under fertilization, to the extent or more than the crop, which can reduce the effectiveness of fertilization and may even result in yield loss due to increased weed competition (Little *et al.*, 2021) ^[28]. Weeds are also a competitor for light and space; taller or faster-growing species will shade barley, reducing its amount of photosynthesis and dry matter accumulation. Weeds that emerge before or are taller than the crop are particularly good at intercepting light and taking over canopy space (Little *et al.*, 2021) ^[28] (Figure 1).

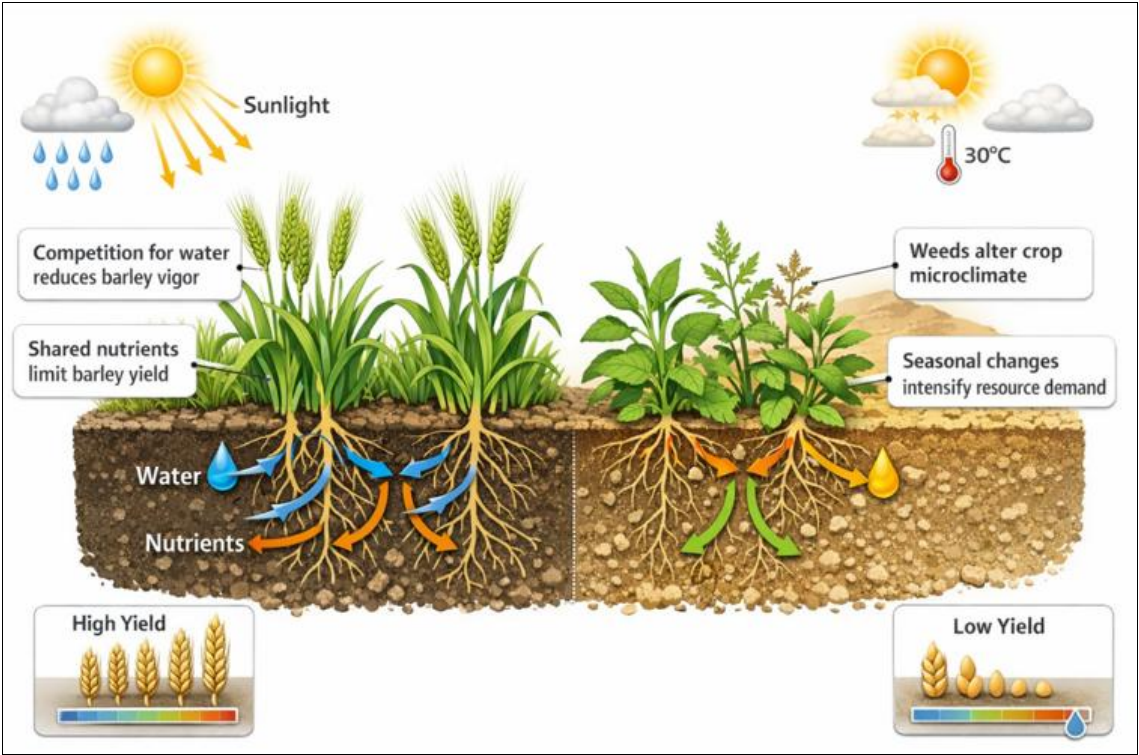


Fig 1: This shows how the growth and productivity of barley are affected by weed competition as influenced by environmental conditions. Weeds also compete for water, nutrients, sun, and soil resources with barley, affecting the crop microclimate and increasing stress conditions, decreasing crop vigour and yield compared to the vigour and yield of well-managed barley fields where the growth of weeds is minimal.

In early growth, this competition has a negative effect on tillering and biomass production due to resource competition, which limits the number of productive tillers and the shoot weight produced. In weed-crop studies, weed biomass is often negatively correlated with crop yield and is used as a proxy for weed competition (Little *et al.*, 2021; Malhi *et al.*, 2021) ^[28, 32]. Additionally, climate change (e.g., increased CO₂, temperature changes) may exacerbate the crop-weed competition in cereal crops and negatively impact crop growth (Tudi *et al.*, 2021; Malhi *et al.*, 2021) ^[32, 49]. There is a reduction in tiller number,

plant height, and biomass, which results in lower grain yield and harvest index, as fewer spikes are formed and more assimilates are used for competitive survival than for grain filling (Little *et al.*, 2021; Malhi *et al.*, 2021) ^[28, 32]. Uncontrolled weeds can result in yield losses of approximately 33% for most major field crops, and losses from weed infestations are estimated to exceed tens of billions of dollars globally every year, both due to yield loss and high weed-control costs (Gao & Su, 2024; Eschen *et al.*, 2021) ^[16, 19].

5. Conventional Weed Management Practices in Barley

Traditional management in barley and other herbaceous field crops involves both manual/mechanical and cultural and chemical methods, but there is increasing awareness of over-dependence on herbicides, the evolution of herbicide resistance, and environmental risks (Gao & Su, 2024; Ghatrehsamani *et al.*, 2023) [19, 20]. Recent strategies increasingly focus on the combination of these tactics instead of relying on any one tactic (Gao & Su, 2024; Ghatrehsamani *et al.*, 2023) [19, 20]. The control of weeds has to be done within the initial 30 to 40 days of sowing, as the weeds pose the greatest threat to production in the early stages of crop growth, as they compete the most in the initial stages. The management of weeds in rice may take three methods: chemical, mechanical, and cultural (Das and Sarkar, 2026) [13].

Manual and mechanical weed control involves hand weeding, hoeing, inter-row cultivation, and various mechanical implements. The methods include tillage, cutting, and burrowing to achieve a high removal rate of weeds and do not leave any chemical residues on crops (Gao & Su, 2024) [19]. They are, however, labour-intensive, can damage crops, and intensive tillage can lead to soil compaction and affect the structure and development of roots (Gao & Su, 2024) [19].

Cultural practices are considered “indirect” weed control and play an important role in IWM. These involve crop rotation, planting competitive cultivars, increasing planting density, cover crops and mulches, planting dates, row spacing, and strategic placement of fertilizer to favour the crop as opposed to weeds (Ghatrehsamani *et al.*, 2023) [20]. These methods can also help to manage weed emergence, lower weed seedbank inputs, and potentially decrease the requirement for herbicide applications when properly designed and executed (Gao & Su, 2024;

Ghatrehsamani *et al.*, 2023) [19, 20].

Herbicide use is still the most common chemical control approach in herbaceous crops. Many herbicides that have different modes of action have been developed since the introduction of 2,4-D, which has significantly reduced the need for manual weeding (Gao & Su, 2024) [19]. Although herbicides are highly effective and convenient to use, high amounts and continuous use have resulted in the emergence of herbicide-resistant weeds and significant environmental pollution, such as soil and water pollution and human and animal health hazards (Ghatrehsamani *et al.*, 2023; Gao & Su, 2024) [19, 20].

Given that resistance can develop rapidly with the use of sole herbicide-based management, and that such control can also have ecological impacts, the reviews strongly support diverse and integrated management strategies that combine mechanical, cultural, biological, and carefully managed chemical practices to maintain an effective and sustainable weed control system in barley systems and beyond (Gao & Su, 2024; Ghatrehsamani *et al.*, 2023) [19, 20].

6. Biofertilizers and Their Role in Barley Production

Biofertilizers are microbial inoculants added to the plant, soil, or seed to increase nutrient supply or availability in the plant rhizosphere or interior, thereby enhancing plant growth. They are highlighted as low-cost, eco-friendly tools that aid in the reduction of reliance on synthetic NPK fertilizers, increase soil fertility, and sustain high yields under stress conditions (Zuluaga *et al.*, 2024; Mahmud *et al.*, 2021) [31, 54]. Their role in barley production is related to improving N use efficiency, root establishment, stress tolerance, and sustainable low-input systems (Figure 2).

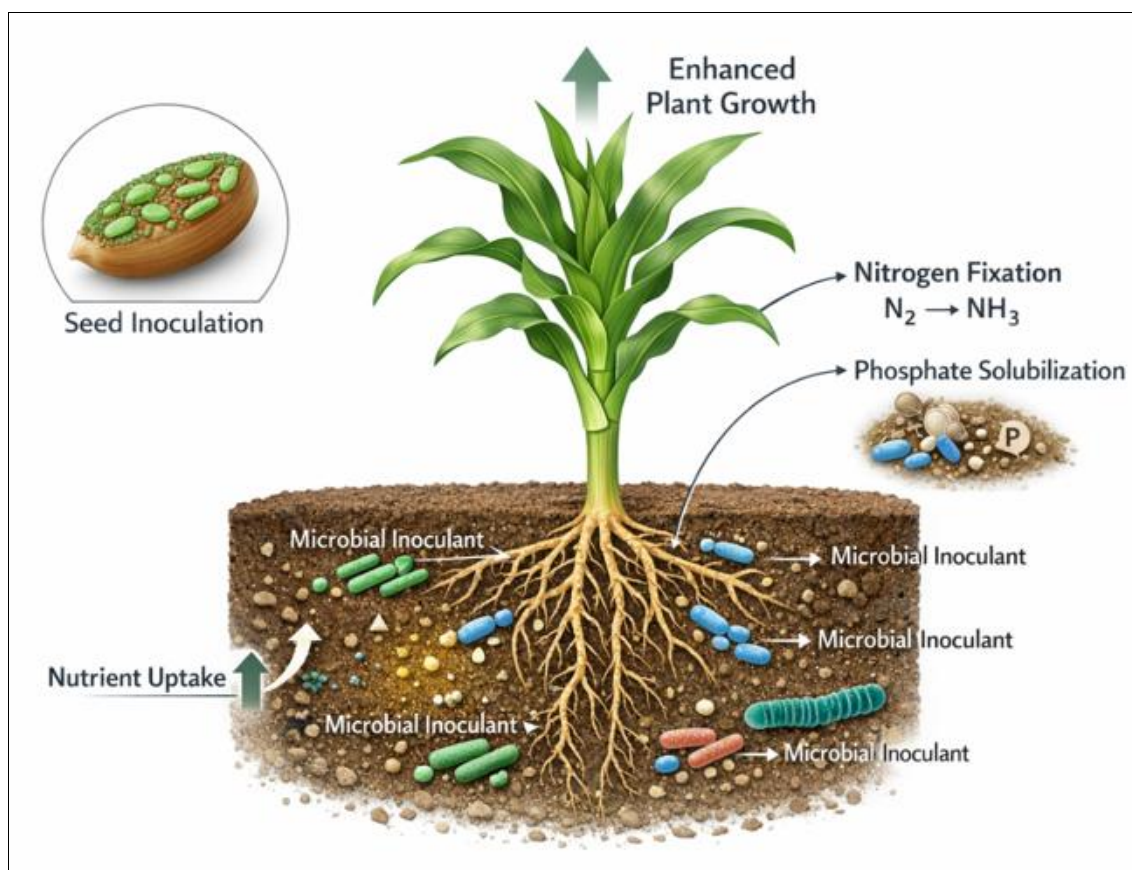


Fig 2: The diagram illustrates how biofertilizers and microbial inoculants (s) can improve plant growth and uptake via seed inoculation and root colonization. The beneficial microorganisms enhance rhizosphere properties such as nitrogen fixation, phosphate solubilization, and nutrient availability, resulting in better root growth and crop productivity.

The major groups of biofertilizers include (in barley and other cereals) nitrogen-fixing microorganisms, phosphate-solubilizing bacteria (PSB) and fungi, potassium-solubilizing and mobilizing microbes, arbuscular mycorrhizal fungi (AMF), and various plant growth-promoting rhizobacteria (PGPR). N-fixing bacteria (e.g., *Azotobacter*, *Azospirillum*, *Rhizobium* [like PGPR], etc.) convert atmospheric N₂ into plant-usable NH₄⁺, which provides direct N nutrition to the plant and decreases the N requirement of chemical sources (Shahwar *et al.*, 2023; Samantaray *et al.*, 2024) [37, 41]. PSB and phosphate-solubilizing fungi promote the release of organic acids and phosphatases, which break down insoluble mineral and organic P into orthophosphate, which is available for uptake by plants and thus compensates for the low availability of P commonly found in soils, limiting crop production (Timofeeva *et al.*, 2022; Fu *et al.*, 2024) [46, 18]. Potassium-solubilizing bacteria (KSB) mobilize K minerals and make them soluble, leading to an increase in K supply and consequently enhancing the water relations and stress tolerance of plants (Zuluaga *et al.*, 2024; Mahmud *et al.*, 2021) [31, 54]. AMF can significantly increase P absorption in P-deficient soils when combined with PSB and silicon (Etesami *et al.*, 2021) [17], as they form symbiotic associations with roots, which increase

the absorbing surface through the development of hyphae and will improve the uptake of P and micronutrients. Broad PGPR groups (*Bacillus*, *Pseudomonas*, *Enterobacter*, *Herbaspirillum*) can be used as multifunctional biofertilizers, with many strains having the ability to fix N, to mobilize P and K, to chelate Fe with siderophores, and to produce phytohormones, which all contribute to nutrient uptake, root architecture, and resistance to abiotic stresses (Timofeeva *et al.*, 2023; Zuluaga *et al.*, 2024) [47, 54]. Biological nitrogen fixation, solubilization/mineralization of P and K through organic acids and enzymes, siderophore-mediated iron chelation, better micronutrient uptake, and indirect effects like better soil structure, microbial diversity, and induced resistance all contribute to the nutrient mobilization and growth promotion effects in the crop (Timofeeva *et al.*, 2023; Mahmud *et al.*, 2021; Shahwar *et al.*, 2023; Liu *et al.*, 2024; Zuluaga *et al.*, 2024) [47, 31, 41, 54]. The use of compatible biofertilizers along with reduced mineral fertilization is emphasized as a key strategy for maintaining or boosting crop production (including cereals) while reducing input costs and environmental impacts (Table 2) (Timofeeva *et al.*, 2023; Zuluaga *et al.*, 2024; Samantaray *et al.*, 2024) [47, 54, 37].

Table 2: Major Biofertilizer Functional Groups and Key Roles

Biofertilizer group/trait	Main nutrient(s) affected & key mechanisms	Typical microbial examples	Citations
Nitrogen-fixing microbes	Convert atmospheric N ₂ to NH ₃ /NH ₄ ⁺ ; increase plant-available N, reduce synthetic N need.	<i>Azotobacter</i> , <i>Azospirillum</i> , <i>Rhizobium</i> -like PGPR	(Shahwar <i>et al.</i> , 2023; Samantaray <i>et al.</i> , 2024) [41, 37]
Phosphate-solubilizing microbes (PSB/PSF)	Solubilize inorganic P via organic acids; mineralize organic P via phosphatases, phytases.	Bacteria (e.g., <i>Bacillus</i> , <i>Pseudomonas</i>); fungi (<i>Penicillium</i> , <i>Aspergillus</i> , etc.)	(Timofeeva <i>et al.</i> , 2022; Fu <i>et al.</i> , 2024) [46, 18]
Potassium-solubilizing microbes	Release K ⁺ from insoluble K minerals, enhancing K nutrition and stress tolerance.	Various PGPR (e.g., <i>Pseudomonas</i> , <i>Bacillus</i>)	(Zuluaga <i>et al.</i> , 2024; Mahmud <i>et al.</i> , 2021) [31, 54]
Arbuscular mycorrhizal fungi	Extend root absorptive area; enhance P and micronutrient uptake, especially in low-P soils.	AMF genera form root symbioses	(Etesami <i>et al.</i> , 2021) [17]
PGPR consortia (multi-trait)	Combine N fixation, P/K solubilization, siderophores, and phytohormones to promote growth and stress tolerance.	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Enterobacter</i> , <i>Herbaspirillum</i> , etc.	(Timofeeva <i>et al.</i> , 2023; Zuluaga <i>et al.</i> , 2024) [47, 54]

7. Influence of Biofertilizers on Soil Health

In general, microbial inoculants and bio-organic fertilizers, which are categorized as biofertilizers, have a positive effect on soil health by modifying microbial community, nutrient dynamics, and soil organic matter, contributing to more sustainable management than chemical fertilizers alone. This works primarily by increasing the activity of the soil organisms, improving nutrient cycling, and a gradual improvement of the physical soil properties. Use of biofertilizers or organic-microbial inputs enhances the microbial activity and diversity of soils due to their ability to provide carbon substrates and beneficial microbes, thereby improving vital ecosystem services like decomposition of soil biomass, transformation of soil nutrients, reduction of pathogen populations, and mitigation of greenhouse gas emissions (Xing *et al.*, 2025; Samantaray *et al.*, 2024) [37, 52]. The use of bio-organic fertilizers with plant growth-promoting microbes and their interaction with the native soil microbiota enhances soil enzymatic activity, nutrient cycling, and rhizosphere health, thereby minimizing reliance on synthetic inputs and fostering long-term soil biological function (Samantaray *et al.*, 2024) [37]. The use of microbial inoculants can improve soil fertility and nutrient cycling by promoting various microbial processes such as nitrogen fixation, phosphorus solubilization, and potassium mobilization, while their combined application with mineral fertilizers can stabilize microbial communities, boost enzyme activities (e.g., β glucosidase, urease), and accelerate organic matter

decomposition and nutrient turnover (Samantaray *et al.*, 2024; Xing *et al.*, 2025) [37, 52]. This balanced fertilization increases the availability and retention of nutrients for plants, enabling them to more effectively absorb the nutrients and reducing losses through leaching and gaseous emissions (Xing *et al.*, 2025) [52]. Soil organic matter builds up with repeated organic-microbial inputs, leading to better aggregation, porosity, and water-holding capacity. Microorganisms promote the formation of aggregates by breaking down the residues and exuding binding substances to produce a stronger, looser, and well-aerated structure, which is beneficial to root growth and the rehabilitation of degraded soils (Xing *et al.*, 2025) [52]. Biofertilizers and bio-organic amendments are integrated into soil health and management strategies, aiming to boost microbial processes, fertility, organic matter, and soil structure, and minimize the use of synthetic fertilizers and pollution (Samantaray *et al.*, 2024; Xing *et al.*, 2025) [37, 52].

8. Interaction Between Weed Management and Biofertilizers

Weed management and biofertilizer interactions focus on the impact of weed management on soil microbial communities and the impact of soil microbial communities on weed management, weed competitiveness, and the effectiveness of integrated management. Conventional weed control using herbicides has been shown to have a negative effect on non-target soil microorganisms and biodiversity, leading to interest in approaches that allow for maintenance or enhancement of

beneficial microbiomes and control weeds (Little *et al.*, 2021) [28]. Using biofertilizers, such as PGPR, mycorrhizae, and microbial composts, is promoted as a way to improve soil health, nutrient cycling, and plant resilience, which indirectly influences weed-crop interactions (Dzvene & Chiduza, 2024; Gao & Su, 2024) [14, 19].

Integrated weed management systems, which involve a combination of organic amendments, reduced chemical usage, and diverse plantings, can lead to more complex microbial communities and more stable plant-soil dynamics, while weed management systems that rely on fewer plants and/or fewer nutrients discommode plant-soil interactions and simplify microbial communities (Wang *et al.*, 2024; Al-Shammery *et al.*, 2024) [3, 51]. Microbial inoculants have been reviewed, and it has been observed that they improve plant growth by means of N fixation, P and K solubilization, production of siderophores and

phytohormones, and induced resistance, which can boost plant competitiveness against weeds without being used as a herbicide (Samantaray *et al.*, 2024; Gao & Su, 2024) [19, 37].

Biofertilizers also promote beneficial microbes that play a role in suppressing diseases and pests, often in a push-pull or other agroecological approach, and can fit into integrated pest/weed management plans, including non-chemical weed management (Dzvene & Chiduza, 2024; Alkharabsheh *et al.*, 2021) [1, 14]. When combined with other practices like organic matter additions, mulches, and diversified rotations, there is a synergistic effect where soil structure, microbial activity, and competitiveness of crops are improved, synthetic fertilizers and pesticides can be reduced, and productivity and ecosystem services are maintained (Dzvene & Chiduza, 2024; Al-Shammery *et al.*, 2024; Chen *et al.*, 2024) [14, 3, 11] (Figure 3).

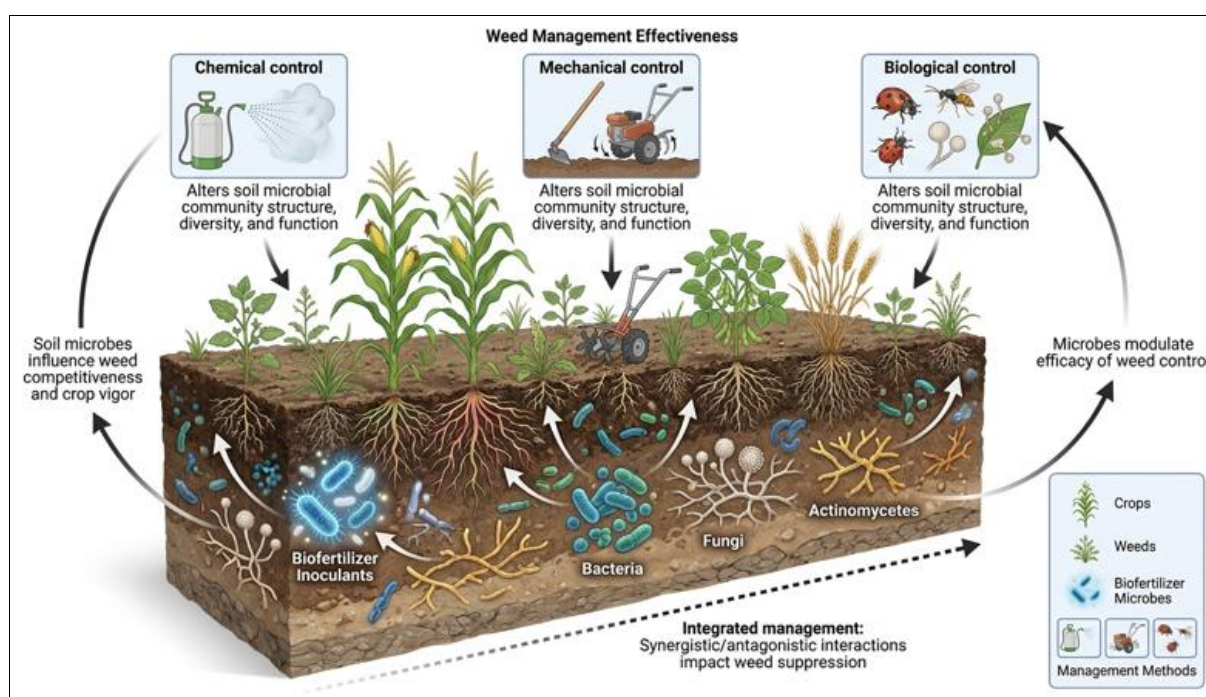


Fig 3: The diagram depicts the relationship between weed management practices and soil microbial communities in agriculture. Chemical, mechanical, and biological weed control techniques have the potential to impact the diversity and role of beneficial microbes, including bacteria, fungi, and actinomycetes, and biofertilizer inoculants can increase crop vigour and help in integrated weed control to facilitate sustainable crop production.

9. Integrated Weed and Biofertilizer Management Strategies

Integrated weed and biofertilizer management is a strategy to achieve high yield without relying on herbicides and synthetic fertilizers. Recent reviews highlight the need to integrate cultural practices, microbial inoculants, and precision tools into a system, as opposed to looking at fertility and weed control in isolation (Sande *et al.*, 2024; Gao & Su, 2024) [19, 38]. Weed suppression, condition soil for better health, and promote beneficial microbes through cultural practices including optimized tillage, crop rotation, mulching, and living or dead cover crops. Mulches and leaf residues decrease weed emergence, erosion, and nutrient loss and improve soil organic matter and microbial activity (Sande *et al.*, 2024; Gao & Su, 2024) [19, 38]. Integrated management of living mulches demonstrated that management of the mulch vigor (either mechanically or chemically) results in the suppression of weeds, enhancement of resource-use efficiency, and desirable survival of cash crops (Bhaskar *et al.*, 2021) [5]. Crop rotation and intercropping can also help to reduce the weed pressure and

improve nutrient recycling and soil fertility, particularly when legumes or other biologically active crops are involved (Sande *et al.*, 2024; Scavo & Mauromicale, 2021; Khamare *et al.*, 2022) [25, 38, 40].

Plant growth-promoting rhizobacteria (PGPR) and other microbes boost uptake of nutrients (N, P, K, and micronutrients), root growth, and stress tolerance and enable the reduction in the application of mineral fertilizers without compromising yield (Shahwar *et al.*, 2023; Zuluaga *et al.*, 2024) [41, 54]. The use of integrated nutrient management systems (INM) (i.e., mineral fertilizers, organic amendments, and biofertilizers) generally increases soil biological activity and crop performance in comparison with using mineral fertilizers alone (sole synthetic fertilizers - SSF) (Sande *et al.*, 2024) [38]. In microbial weed management, microbial products that also serve as biocontrol agents or bioherbicides, such as allelopathic or pathogen-based products, can be used, which can decrease the use of synthetic herbicides and increase the range of weed control options (Shahwar *et al.*, 2023; Hernández-Fernández *et al.*, 2021;

Elnahal *et al.*, 2022; Scavo & Mauromicale, 2021) ^[41, 15, 22, 40]. This integration is further optimized with site-specific and precision techniques such as variable-rate fertilizer placement

and site-specific weed management using sensors and machine vision, promoting efficient and environmentally responsible systems (Gao & Su, 2024) ^[19] (Table 3).

Table 3: Integrated Cultural-Biofertilizer-Weed Management Options

Component/practice set	Main functions in an integrated strategy	Citations
Cultural practices (rotation, intercropping, mulching, residues) + biofertilizers	Suppress weeds, enhance soil fertility, support beneficial microbiomes, reduce synthetic inputs.	(Sande <i>et al.</i> , 2024; Scavo & Mauromicale, 2021; Bhaskar <i>et al.</i> , 2021; Khamare <i>et al.</i> , 2022) ^[38, 40, 5, 25]
Herbicides + bioherbicides / microbial agents	Lower herbicide dose, diversify weed control modes of action, support sustainability	(Hernández-Fernández <i>et al.</i> , 2021; Scavo & Mauromicale, 2021) ^[22, 40]
Integrated nutrient management + microbial inoculants	Improve nutrient cycling, plant nutrition, and soil biology while limiting fertilizer overuse.	(Shahwar <i>et al.</i> , 2023; Sande <i>et al.</i> , 2024; Zuluaga <i>et al.</i> , 2024) ^[41, 54, 38]
Living mulches + precision management	Long-term weed suppression, improved soil health, managed crop-mulch competition	(Sande <i>et al.</i> , 2024; Bhaskar <i>et al.</i> , 2021) ^[38, 5]

10. Effect on Growth, Yield, and Nutrient Uptake of Barley

Biofertilizers affect the growth and yield of barley primarily through the ability to release growth-promoting substances, enhance nutrient availability (N, P, K, and micronutrients), and increase the stress tolerance of the plants. While most of the information provided is from cereals in general (maize, wheat, rice, barley groups), the mechanisms and responses outlined are of direct relevance to the barley crop as a nutrient-demanding grain crop (Shahwar *et al.*, 2023; Allouzi *et al.*, 2022) ^[41, 2]. Microbial inoculants like plant growth-promoting rhizobacteria (PGPR) can improve early root growth, nutrient uptake, and the balance of hormones, resulting in quicker emergence, stronger seedlings, and improved stand establishment during germination and crop establishment. Nitrogen-fixing, phosphorus-solubilising, and production of phytohormones such as auxins and gibberellins are consistently reported to improve early growth, thus resulting in increased crop productivity during later stages of growth (Shahwar *et al.*, 2023) ^[41]. During the crop development, biofertilizers are believed to provide the plants with better water and soil condition, increase plant height, plant tiller number and plant biomass through various direct and indirect mechanisms: biological nitrogen fixation, solubilization of P and K, stimulation of the acquisition of micronutrients by siderophores and expansion of root system and photosynthesis (Allouzi *et al.*, 2022; Shahwar *et al.*, 2023) ^[41, 2]. Microbial and organic amendments proved to be able to improve vegetative growth and total dry matter in production as the total mineral fertilizer was reduced when using them compared to the unfertilized and only mineral fertilizer control plants, according to reviews (Allouzi *et al.*, 2022) ^[2]. These enhancements result in better grain and straw production in cereals, with many studies showing that biofertilizer or vermicompost-biofertilizer-mineral fertilizer combinations led to significant increases in grain yield, kernel weight, and grain nutrient content (Shahwar *et al.*, 2023; Allouzi *et al.*, 2022) ^[41, 2]. The use of integrated nutrient management with the addition of microbial inoculants can increase nutrient uptake and nutrient use efficiency due to the beneficial effects of microbial inoculants in the soil, which boost its biological activity, decrease losses, or synchronize nutrient delivery according to the crop needs (Allouzi *et al.*, 2022) ^[2]. Increased availability of N and P uptake and micronutrients from biofertilizers also increases the quality of grain, such as protein and mineral contents, thus resulting in healthier and more nutritious cereal grains and reduced use of synthetic fertilizers (Shahwar *et al.*, 2023; Allouzi *et al.*, 2022) ^[41, 2].

11. Economic and Environmental Benefits: The use of

integrated approaches in agriculture, including integrated farming systems (IFS), has gained popularity for its economic and environmental advantages. These systems bring together agriculture, livestock, horticulture, and other elements within the same farm to generate positive interactions that increase the productivity, profitability, and sustainability of the farm. IFS models have been proven to improve the productivity and profitability of smallholder and marginal farmers by making the best use of resources and recycling farm waste on the farm. It not only increases income and employment but also ensures nutritional security by diversifying the outputs such as cereals, vegetables, milk, and meat, which provide an additional nutritional benefit (Bhagat *et al.*, 2024) ^[4].

Integrated approaches have a number of key economic benefits, including cost-effectiveness. IFS helps to minimize the use of external inputs like chemical fertilizers and herbicides by eliminating the need to buy them by reusing farm waste, for instance, the use of crop residues for animal feed, or of manure as fertilizer. That results in reduced input expenses for farmers while at the same time, farmers do not lose their yields or have them regress. Diversification inherent in IFS also helps them to limit the effect of crop failures caused by pests, diseases, or climate extremes on income and helps to buffer against fluctuations in the market. IFS also provides diversity, which is important because it limits the impact of crop failure due to pests, diseases, or extreme weather on income and helps buffer against market fluctuations (Bhagat *et al.*, 2024) ^[4]. Furthermore, by combining various management strategies like crop rotation, conservation tillage, applying organic amendments, and adjusting the soil microbiome under certain conditions, the productivity of integrated management can boost yields by 15-30% relative to conventional monocultures, and the costs of production will eventually decline (Liang *et al.*, 2025) ^[27].

In an environmental context, integrated systems help to greatly minimize the need for chemical fertilizers and herbicides. Nutrient runoff and contamination of the environment are reduced by the use of organic manures, composts, cover crops, and biological pest control. Conservation tillage and residue retention have positive effects on soil structure, soil fertility, and erosion. Overall, these practices help improve soil health by boosting soil organic matter and fostering soil microbial diversity (Liang *et al.*, 2025) ^[27]. Some other biodiversity benefits of integrated systems include the provision of habitat for beneficial organisms.

Integrated approaches play a crucial role in carbon sequestration and climate resilience, one of the most significant ecological advantages. Agroforestry (planting of trees with crops),

integration of perennial forage, mulching, and reduced tillage are options for biomass and soil carbon sequestration. Net carbon sequestration (or negative greenhouse gas emissions) has been reported in well-designed IFS models as a result of carbon sequestration from higher biomass production and improved soil carbon storage (Bhagat *et al.*, 2024) ^[4]. On a global level, combining several sustainable practices can sequester billions of tons of CO₂ per year and decrease soil erosion by billions of tons per year (Liang *et al.*, 2025) ^[27]. Such climate mitigation benefits are important to achieve the international sustainability targets.

Synthetic agrochemicals create fewer pollution hazards, which further improves environmental safety. Integrated systems help to foster ecosystem services like natural enemy control for pest management, nutrient cycling, water holding, and better farm microclimate. These strategies mimic natural processes in varied ecosystems and help establish resilience to climate variability and extreme events. To conclude, integrated agriculture practice is an all-inclusive solution that will not only help farmers make a profit but also help them manage their initiatives for long-term ecological benefits. These minimize the use of chemical inputs while minimizing reliance on monocrop production methods, diversifying the resource base, and enhancing yields, profitability, soil health, biodiversity conservation, carbon sequestration, and climate resistance (Bhagat *et al.*, 2024; Liang *et al.*, 2025) ^[4, 27].

12. Recent Advances and Emerging Technologies

The use of nanotechnology, biological inputs, and digital tools is now becoming more common in barley production due to recent developments. The idea of nano-biofertilizers is to increase nutrient-use efficiency and stress tolerance, whereas the use of artificial intelligence for sensing and precision machinery is aimed at targeting weeds more selectively, thereby providing support to climate-smart, resource-efficient systems (Sharma *et*

al., 2022; Miller *et al.*, 2025) ^[42, 34]. Nano biofertilizers integrate biofertilizers with nanoparticles (metal/organic) to formulate smart fertilizers that boost nutrient availability, plant development, and stress tolerance to biotic and abiotic stresses (Sharma *et al.*, 2022) ^[42]. They can be formulated to slowly or slowly and steadily release nutrients and can decrease the environmental impacts of traditional fertilizers by increasing fertilizer use efficiency and decreasing the amount of fertilizer needed (Sharma *et al.*, 2022) ^[42]. They are recommended as a key element of smart farming but have been scarcely tested on farms and in the environment (Sharma *et al.*, 2022; Miller *et al.*, 2025) ^[42, 34]. Precision weed management has gained in importance, and digital solutions like machine vision, robotics, and smart sprayers, which allow the identification of plants and weeds and target herbicide or mechanical control for weed management only, are being more widely used. Optical and hyperspectral data are used in AI-driven systems with deep learning, support vector machines, and other models to identify weeds and direct specific interventions to manage them, reducing chemical usage and enhancing sustainability (Miller *et al.*, 2025) ^[34]. Weed detection and precision management in general are key elements, where drones and other remotely sensed platforms, especially with the addition of artificial intelligence, play a central role. Combined with a high spatial resolution, a UAV with an RGB, multispectral, or hyperspectral sensor in the payload can create maps of weed patches to allow for site-specific control and for the application of autonomous or robotic systems for intelligent mechanical weed control and spot spraying (Miller *et al.*, 2025) ^[34]. Finally, across these innovations, a climate-smart integrated approach is observed where the three technologies - nanobiofertilizers, precision water-nutrient management, and AI-guided weed control - are combined to boost yield per unit input, decrease pollution, and create climate-smart resilience to stress caused by climate change (Sharma *et al.*, 2022; Miller *et al.*, 2025) ^[42, 34] (Table 3).

Table 4: Emerging Tools for Smart Nutrients and Weeds

Innovation type	Main functions and promises	Citations
Nano-biofertilizers	Smart nutrient delivery, stress tolerance, reduced fertilizer load	(Sharma <i>et al.</i> , 2022) ^[42]
AI + drones / remote sensing	High-resolution weed mapping, targeted interventions, and lower herbicide use	(Miller <i>et al.</i> , 2025) ^[34]

13. Challenges and Constraints

A challenge in integrated weed and biofertilizer management is due to biological complexity as well as socio-technical barriers. Despite the ability of microbial inoculants to improve nutrient use efficiency and reduce reliance on agrochemicals, their performance is inconsistent, they have short shelf lives, and adoption is low, which limits their impact on a large scale. These are particular concerns if biofertilizers are to be incorporated into integrated management systems. One of the major challenges is high variability in field performance. Biofertilizer products such as PGPR are effective in pots or greenhouses, but their effectiveness varies between farmers' fields due to several reasons: the relationship between them and their environment is complex and may vary among regions and countries; they interact with native microbiota and crop genotype, which can differ significantly; dose and application method can also differ, and efficacy can change depending on the climatic conditions (Zuluaga *et al.*, 2024; Shahwar *et al.*, 2023) ^[54, 41]. Meta-analyses and reviews have found wide variations in yield responses (Zuluaga *et al.*, 2024) ^[54] and also warned that there is a lack of standardized protocols for selection, formulation, and agronomic testing that makes results difficult to repeat and/or gives farmers less confidence in the results. This variation also

makes weed and pest management more difficult to integrate, as there is a need for a consistent response to varying fertilizer and herbicide rates.

Misconceptions about microbes as disease agents, lack of clarity regarding the economic evidence, poor communication between farmers, industry, researchers, and government, and a lack of clarity in the product markets are all hindering farmer awareness and adoption (Allouzi *et al.*, 2022; Shahwar *et al.*, 2023) ^[2, 41]. Reviews indicate farmer education, participatory field trials, and improved extension should be used to develop farmer-specific inoculant strategies (Allouzi *et al.*, 2022) ^[2]. Technical constraints: Technical constraints involve the poor quality of the product over time, temperature, and contamination, financial risks, and limited shelf life and storage sensitivity of live inoculants, which necessitate cold chains and suitable carriers and careful handling of the product (Shahwar *et al.*, 2023; Sarker *et al.*, 2021) ^[41, 39]. Not only fertilizers but also pesticides and even herbicides may cause a problem because, with the change in soil pH, moisture, and chemical input, the survival or activity of inoculated microbes may be reduced (Shahwar *et al.*, 2023) ^[41]. There are several significant research gaps, such as the need for long-term field trials across environments, for efficacy protocols to be standardized, to better understand plant-

soil-microbe interactions in complex systems, or to establish regulatory and labeling procedures for microbial products (Zuluaga *et al.*, 2024; Canfora *et al.*, 2021) ^[8, 54]. For integrated and reliable weed-biofertilizer management, these will be essential.

14. Future Research Directions

Research into integrated biofertilizer and weed/nutrient management should shift from mono-function single-strain biofertilizers toward multifunctional, system specific, biofertilizers systems that are reliable and perform under field conditions over the long-term while preserving soil health and productivity. The development of microbial associations with multiple functions is a key concern. Reviews on the synthetic and natural consortia highlight that compatible microbial consortia can provide more comprehensive and durable benefits compared to individual strains, such as the synergistic production of phytohormones, stress tolerance, biocontrol, P solubilization, and N fixation, and the design of microbial consortia is complex, while the risk of failure is high when antagonistic microbes are mixed (Timofeeva *et al.*, 2023; Chaudhary *et al.*, 2023) ^[47, 10]. The bottom-up strategy to screen and co-cultivate candidate plant growth-promoting microorganisms (PGPMs) within a synthetic consortium, sometimes combined with non-microbial biostimulants, is suggested as a promising approach to obtain robust products based on biostimulants (Tabacchioni *et al.*, 2021; Chaudhary *et al.*, 2023) ^[10, 45]. A second emphasis is on the development of consortia and strains that are compatible with other inputs and practices. Microbial consortia are regarded as important components of integrated nutrient management approaches, which incorporate organic matter amendment, biofertilization, and mineral fertilizers for resilient yields and less reliance on chemical inputs (Sande *et al.*, 2024; Marzouk *et al.*, 2024) ^[38, 33]. Future research is encouraged to come up with formulations that are compatible with common farming practices, including types of herbicides and pesticides, and to test the formulations in various soils, climates, and crops to provide region-specific integrated management modules with established field performance (Timofeeva *et al.*, 2023; Chaudhary *et al.*, 2023) ^[47, 10]. Long-term and systems-level studies are consistently identified as missing. The importance of having no decadal data on the impacts of integrated fertilization and microbial inputs on microbial networks, soil health, and yield stability is emphasized, as is the need for multi-year, multi-site trials comparing conventional, organic, conservation agriculture, and biofertilizer-based systems (Xing *et al.*, 2025; Sabir *et al.*, 2021) ^[52, 36]. These trials should specifically test the potential of conservation tillage, diversified rotations, and residue management, and test the use of biofertilizers, to examine integrated packages in terms of their long-term effects on soil biodiversity, carbon sequestration, and climate resilience (Liu *et al.*, 2025; Xing *et al.*, 2025) ^[29, 52]. Lastly, the research agendas highlight the need for the integration of advanced tools (omics, metagenomics, modelling) into participatory, region-adapted system design so that microbial consortia and integrated modules are agronomically and economically viable to the farmer and adaptable to conservation agriculture and organic farming (Marzouk *et al.*, 2024; Xing *et al.*, 2025) ^[33, 52].

15. Conclusion

The use of integrated weed and biofertilizer management is a sustainable and eco-friendly management system that will be a means to increase the productivity of barley with low reliance on

chemical inputs. When used together, effective weed control and beneficial microbial inoculants will enhance crop development, nutrient uptake, soil capacity, and resource-use efficiency. In barley, the use of an integrated approach is likely to reduce weed competition throughout the critical growth stages and enhance tillering, biomass, yield, and grain quality. At the same time, the use of biofertilizers like nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, and plant growth-promoting rhizobacteria improves the uptake of nutrients, increases root growth, and maintains soil microbial balance. These practices also help to minimize the amount of herbicide and fertilizer used, production costs, and environmental pollution. With shifting climatic conditions, soil health issues, and growing concerns about sustainable agriculture, the production of barley is becoming more critical. Integrated management strategies derive long-term benefits for soil productivity, conservation of biodiversity, climate resilience, and economic profit for farmers. Furthermore, the use of combined weed and biofertiliser management has the potential to be a key component of environmentally responsible and resource-efficient barley production systems. Sustainable barley production and global food security can be further consolidated in upcoming research by location-specific technologies, multi-functional microbial consortia, and precision-based integrated management practices.

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