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INTEGRATED NUTRIENT MANAGEMENT IN CEREAL CROPS FOR FOOD AND FODDER: A REVIEW

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ABSTRACT
The Poaceae family of cereal crops is essential to both livestock feed systems and global food security, yet widespread soil nutrient depletion and an excessive dependence on inorganic fertilizers continue to limit their output. With special attention to wheat, rice, maize, pearl millet, sorghum, and fodder oats, this review focuses on recent research on Integrated Nutrient Management (INM), the combined, careful application of inorganic fertilizers, organic amendments, and bio fertilizers across important food and fodder cereals. A narrative and comparative analysis of peer reviewed field and pot culture studies from indexed worldwide and regional agricultural journals, primarily published between 2020 and 2026. The literature on the combined effects of inorganic fertilizers, organic manures, and microbial bio fertilizers (phosphate solubilizing bacteria, Azospirillum, and Azotobacter) on yield, nutrient use efficiency, soil health, and produce quality was gathered and synthesized across Poaceae cereal and forage grass species. In terms of crop production, nutrient uptake, and soil biological indicators, the combined application of 50 to 75% of the prescribed inorganic dose with organic sources (farmyard manure, vermicompost, compost, or biochar) and microbial inoculants consistently outperformed single inorganic or sole organic treatments across crops. In fodder oats specifically, partial substitution of inorganic fertilizer with farmyard manure, vermicompost, and plant growth promoting microbes improved both green fodder yield and crude protein content while reducing the recommended fertilizer dose by up to 25%. Integrated Nutrient Management offers a scientifically sound and economically viable strategy for sustaining the productivity of Poaceae food and fodder crops while safeguarding long term soil fertility. Fodder oats remain comparatively underrepresented in the INM literature relative to wheat, rice, maize and pearl millet, indicating a clear research gap that future crop specific, phosphorus focused studies should address.

KEYWORDS: *Integrated Nutrient Management, Poaceae, Cereal Crops, Fodder Oats, Phosphorus, Bio Fertilizers, Soil Health, And Nutrient Use Efficiency*

1. INTRODUCTION

The Poaceae (Gramineae) family of cereal crops plays a critical dual function in world agriculture, serving as both the main source of calories for human populations and the foundation of animal feeding systems in the majority of tropical and subtropical countries. While species like pearl millet, sorghum, and oats are commonly planted as dual purpose crops, providing both grain and green or dry fodder to maintain dairy and draught animals, wheat, rice, and maize alone account for the majority of the world's directly eaten calories (Kour, 2023; Majeed et al., 2025). This dual food and feed identity places an unusually heavy growth nutrient demand on cereal-cropped soils, since both grain filling and vegetative biomass accumulation must be supported within a single growing season. In the past, this need has been satisfied by heavily utilizing inorganic fertilizers, especially phosphate and nitrogen. Decades of unbalanced inorganic fertilization have been linked to declining soil organic carbon, deteriorating soil physical and biological properties, and diminishing marginal returns to fertilizer application, despite the fact that this strategy supported the yield gains of the Green Revolution (Paramesh et al., 2023; Urmi et al., 2022). In particular, phosphorus presents a special management challenge because, depending on the pH of the soil, a large amount of applied phosphate is rapidly fixed into calcium, iron, or aluminum complexes, rendering it unavailable to the growing crop even in situations where total soil phosphorus reserves are substantial.(Majeed et al., 2025; Sun et al., 2026.)

The most popular conceptual answer to these limitations is Integrated Nutrient Management (INM). While INM does not completely oppose the use of inorganic fertilizers, it does advocate for the careful blending of mineral fertilizers with biological inputs (such as phosphate-solubilizing bacteria, Azospirillum, Azotobacter, and arbuscular mycorrhizal fungi) and organic sources (such as farmyard manure, compost, vermicompost, crop residues, green manure) (Kour, 2023; Torres-Cuesta et al., 2023). While bio fertilizers increase the biological availability of otherwise fixed nutrients and inorganic fertilizers provide an instantaneous nutrient pool to meet peak crop need, organic sources release nutrients gradually, boost soil structure, and promote microbial biomass (Imran, 2024)

With a focus on phosphorus management, this review summarizes recent research (mostly from 2020 to 2026) on INM methods across important Poaceae food and fodder crops. Before concentrating on fodder oats (*Avena sativa*.) as a crop directly relevant to winter forage systems in the Indian subcontinent and similar temperate–subtropical transition zones, it draws comparative evidence from wheat, rice, maize, pearl millet, sorghum, and perennial forage grasses. The review's objectives are to: (i) summarize the physiological and edaphic justification for INM in grass family crops; (ii) synthesize crop specific evidence of INM effects on yield, nutrient use efficiency, and quality; and (iii) identify research gaps that warrant additional crop specific investigation, especially in phosphorus enriched amendments for fodder oats.

2. SCOPE AND OBJECTIVES

This review is purposefully limited to nutrient management practices in cereal and fodder crops in the Poaceae (Gramineae) family, which includes dual purpose or fodder oriented species (pearl millet, sorghum, oats) as well as grain oriented cereals of significant food security importance (wheat, rice, and maize). Unless they directly relate to an INM strategy under discussion, species outside of this family and nutrient management techniques unrelated to integrated nutrient management (like foliar micronutrient spraying in isolation or precision fertigation technology) are outside the purview of this synthesis.

Within this scope, the review addresses four key objectives. First establishing the physiological and soil based rationale for grouping Poaceae food and fodder crops under a unified nutrient management framework. Secondly synthesizing recent, field validated findings on integrated nutrient management (INM) components i.e. inorganic fertilizers, organic amendments, and microbial bio fertilizers and their interactions. Thirdly comparing crop specific INM responses among wheat, rice, maize, pearl millet, sorghum, perennial forage grasses, and particularly fodder oats (*Avena sativa*); and finally pinpointing evidence based research gaps regarding phosphorus enriched soil amendments for fodder oats. Rather than providing an exhaustive global list of INM literature, this review focuses on recent, high depth field and pot studies (2020–2026) that provide directly comparable, quantifiable results.

3. METHODS OF LITERATURE SELECTION

Literature was gathered using targeted searches across key databases, including Web of Science, Scopus, PubMed/PMC, and Google Scholar alongside major publisher portals (Springer Nature, MDPI, Frontiers, Wiley, Science Direct, and Nature Portfolio) and open access repositories like AGRIS and Research Gate. Search strings combined the overarching concept of integrated nutrient management with crop-specific terms (wheat, rice, maize, pearl millet, sorghum, fodder oat, Avena sativa) and targeted amendment inputs (phosphorus, phosphate-solubilizing bacteria, bio fertilizer, vermicompost, biochar, farmyard manure, nutrient use efficiency). Studies were prioritized for inclusion if they reported original field or pot culture data (or synthesized such data in a peer reviewed review article), focused on a Poaceae food or fodder crop, evaluated at least one combination of inorganic, organic, or biological nutrient sources against an appropriate control or comparator, and were published in an indexed, peer reviewed journal. For fodder oats, where the specialized INM literature base is smaller than for major grain cereals, older foundational studies were retained whenever they remained the primary or most direct evidence for a given crop nutrient combination.

I excluded studies that focused on non Poaceae crops without a clear comparative link, centered solely on genetic or breeding mechanisms without practical nutrient management, or lacked verifiable full texts. To maintain strict standards of accuracy, I only included papers whose findings, authors, and publication details could be independently confirmed. Rather than dumping every result from our initial search into the review, I intentionally curated a focused set of high quality, verifiable sources.

4. POACEAE AS THE BACKBONE OF GLOBAL FOOD AND FODDER SYSTEMS

Major cereal grains and most natural and farmed pasture grasses belong to the Poaceae family, which is one of the biggest and most significant plant families in agriculture. A family level approach to nutrition management is scientifically coherent despite significant variation in growth habits due to a number of shared physiological characteristics. Poaceae species are more sensitive to the availability of immobile nutrients like phosphorus in the surface soil horizon because they have a fibrous, adventitious root system instead of a taproot, which allows for effective exploration of the topsoil but relatively limited access to nutrients and moisture at depth (Dutta et al., 2025).

The photosynthetic pathway is a second site of differentiation at the family level. While maize, sorghum, and pearl millet follow the C4 photosynthetic pathway, which offers improved water- and nitrogen-use efficiency at high temperature and light intensity, wheat, rice, oats, and barley are C3 species. This distinction has practical implications for nutrient management, under semi-arid, high radiation conditions, C4 cereals like maize and pearl millet typically exhibit a stronger yield response to combined organic or inorganic phosphorus management, while C3 cereals like wheat and oats, which are primarily grown during the colder seasons, rely more on residual and slow release organic phosphorus sources to make up for decreased microbial and root activity at lower temperatures (Majeed et al., 2025).

Several plant species in this family serve a dual purpose, supplying both human food and animal feed. Pearl millet is a clear example, providing grain as a dietary staple for smallholders in dry regions of Asia and Africa while its remaining stover and specialized forage varieties feed livestock (Majeed et al., 2025). Similarly, oats play a dual purpose role in temperate and subtropical winter farming systems, where growers can manage a single crop for repeated green forage cuttings, harvest it for seed and straw, or combine both approaches based on their cutting schedules and fertilization practices (Koireng et al., 2025; M Kour, 2023), these grasses fulfill both roles, nutrient management approaches developed for grain crops can directly inform strategies for forage grasses, and vice versa.

5. CONCEPT AND COMPONENTS OF INTEGRATED NUTRIENT MANAGEMENT

The broad definition of integrated nutrient management is the balanced use of all potential plant nutrient sources in an integrated way suitable for each cropping system in order to maintain or improve soil fertility and, consequently, crop productivity. INM views organic, inorganic, and biological nutrient sources as complementing parts of a single nutrition-supply system rather than as rivals. (Hasan et al., 2024; M Kour, 2023).

5.1 Inorganic Fertilizer Sources

Inorganic fertilizers remain indispensable within INM because they supply nutrients in immediately plant available forms and permit precise, need based dosing. However, sole reliance on inorganic sources, particularly nitrogen, phosphorus and potassium (NPK) fertilizers applied without organic supplementation, has repeatedly been associated with declining soil organic carbon and microbial biomass carbon relative to integrated treatments, even where crop yields are temporarily sustained (Paramesh et al., 2023; Urmi et al., 2022). Long term rice based and rice wheat cropping system trials indicate that continuous inorganic only fertilization progressively narrows the soil's capacity to buffer nutrient supply during periods of high crop demand, a limitation that integrated approaches are specifically designed to overcome.

5.2 Organic Amendments

Organic amendments used within INM include farmyard manure (FYM), vermicompost, compost, crop residues, green manures, and biochar. These sources typically release nutrients more slowly than inorganic fertilizers but confer substantial co-benefits: improved soil aggregate stability, higher water holding capacity, enhanced cation exchange capacity, and increased microbial biomass and enzymatic activity(Hasan et al., 2024). In wheat grown on floodplain soils, combined vermicompost and biochar amendment measurably improved soil fertility indicators alongside grain productivity relative to inorganic fertilizer alone (Hasan et al., 2024). Similarly, a synthesis of over one hundred peer reviewed studies on compost, vermicompost and biochar concluded that vermicompost in particular substantially increases total soil nitrogen and improves water retention relative to unamended or solely composted soils, translating into more consistent crop performance across seasons (Mahatale et al., 2026).

Biochar, produced through the pyrolysis of crop residues or other organic feedstocks, has drawn particular research interest for its capacity to improve nutrient retention and reduce leaching losses. In cereal systems, biochar amendment, whether alone or combined with compost, has been shown to increase soil phosphorus and organic carbon in ways that correlate directly with grain yield, reinforcing its relevance as a component of integrated phosphorus management in Poaceae crops.

5.3 Bio fertilizers and Microbial Inoculants

The application of microbial bio fertilizers is the third pillar of INM and is especially relevant to phosphorus enriched amendment schemes. Soil phosphorus that is chemically fixed in insoluble mineral or organic forms is transformed into plant available orthophosphate ions by phosphate solubilizing bacteria (PSB), a functionally varied group that includes species of Bacillus, Pseudomonas, Pantoea, and Acinetobacter. This is primarily accomplished by the enzymatic breakdown of organic phosphorus compounds by phosphatases and phytases, as well as the secretion of low molecular weight organic acids that chelate calcium, iron, or aluminum cations bound to phosphate (Sun et al., 2026.).

Several Poaceae crops have field evidence of PSB efficacy. Under field inoculation trials, native rhizosphere PSB strains such as *Acinetobacter sp*. MR5 and *Pseudomonas sp*. MR7 enhanced grain and straw yield by four to seven percent in both Basmati and non Basmati rice(Rasul et al., 2024). Compared to inorganic phosphorus administered alone, the combination of inorganic phosphorus sources and Bacillus cereus MN54 inoculation greatly increased fodder yield, phosphorus use efficiency, and net economic returns in pearl millet cultivated on calcareous, phosphorus fixing soils (Majeed et al., 2025). A PSB consortium consisting of Azospirillum brasilense, Rhizobium leguminosarum, and Herbaspirillum sp. enhanced soil labile phosphorus, acid phosphomonoesterase activity, and, eventually, Kikuyu grass yield and forage quality under eighteen months of field evaluation, even in perennial forage systems (Torres-Cuesta et al., 2023).

In addition to PSB, Azospirillum and Azotobacter species perform complementary roles in fixing nitrogen and creating phytohormones (Rakhmatova et al., 2026). Some strains are also able to solubilize phosphorus, which provides a partially overlapping but reinforcing mode of action to specific PSB inoculants. The biological basis of current INM guidelines for cereal and fodder Poaceae crops is the deployment of these microbial groups in conjunction with organic and reduced dose inorganic fertilizer.

6. CROP-WISE EVIDENCE OF INTEGRATED NUTRIENT MANAGEMENT IN POACEAE CROPS

6.1 Wheat (Triticum aestivum)

Given its significance in the world's diet, wheat is one of the grains that have been studied the most in terms of INM. In Bangladeshi floodplain soils, amendments containing vermicompost and biochar have been demonstrated to improve soil fertility parameters and grain productivity in a synergistic manner when compared to solely inorganic fertilization. The organic amendments also improve soil physicochemical resilience under varying moisture conditions (Hasan et al., 2024). Decades of balanced INM application have produced quantifiable, cumulative improvements in soil organic carbon, nitrogen, phosphorus, potassium, and zinc status in long term rice and wheat systems of the Indo-Gangetic Plains, along with sustained grain yield. This shows that the benefits of integrated management compound over time rather than being restricted to single-season effects (Urmi et al., 2022).

6.2 Rice (Oryza sativa)

When farmyard manure and chemical fertilizer were used together in lowland rice-rice cropping systems, crop yield, microbial biomass carbon, soil carbon stock, energy use efficiency, and net economic return were all considerably higher than when chemical fertilizer was used alone over the course of three cropping years (Paramesh et al., 2023). A biological supplement to organic and inorganic integration strategies in rice based systems, native phosphate solubilizing bacterial strains isolated from rice rhizospheres have shown the ability to boost grain and straw yield through increased phosphorus bioavailability (Rasul et al., 2024).

6.3 Maize (Zea mays)

Maize functions as a versatile crop used as a staple food, animal fodder, and industrial input, with research confirming its favorable response to combined nutrient practices. In Kenya's sub-humid and semi-arid zones, trials in conservation agriculture and integrated soil fertility management show that integrating reduced chemical fertilizer with organic residue retention maintains yield while restoring soil quality over time. These findings offer practical benefits for smallholder farming systems operating under similar resource limits (Mutuku et al., 2020).

6.4 Pearl Millet, Sorghum, and Other Millets

Pearl millet offers compelling evidence for how combined phosphorus management boosts forage yields. A three year trial in a pearl millet with chickpea rotation on alkaline Fluvisol showed that replacing a portion of synthetic phosphorus with manure improved key plant health markers like nitrate reductase activity and chlorophyll levels while keeping overall yields steady. This proves that organic substitution can maintain, or even improve, plant nutrition(Dutta et al., 2025). Furthermore, applying chemical phosphorus alongside Bacillus cereus MN54 in high phosphorus fixing soils significantly increased fodder volume, nutrient efficiency, and profit margins compared to synthetic inputs alone (Majeed et al., 2025). Similar benefits appear in sorghum systems, where mixing mineral fertilizers with manure or bio-inoculants consistently boosts grain yields and financial returns(Prajapati, 2023).

6.5 Fodder Oats (Avena sativa)

Compared to wheat, rice, maize, and pearl millet, fodder oats have a smaller body of INM literature; however, the information that is now available is consistent in both direction and magnitude with findings from other Poaceae crops. A nutrient regime combining 50% of the recommended NPK dose with farmyard manure at 7.5 tonnes per hectare produced significantly higher green fodder yield, dry matter production, seed yield, and crude protein content than either the full recommended inorganic dose or lower organic substitution levels in cutting-schedule and nutrient-management trials carried out under Eastern Himalayan agro climatic conditions. This suggests a clear yield optimum at intermediate levels of organic-inorganic integration rather than at either extreme (Koireng et al., 2025).

Complementary evidence from oat-legume intercropping systems under integrated nutrient management in West Bengal demonstrated that combining oats with grass pea at varying INM levels improved overall system productivity, energy use efficiency, and economic returns while reducing the carbon footprint of the cropping system relative to sole cropped, inorganically fertilized oats(Biswas et al., 2024). In studies specifically targeting fodder quality rather than yield alone, increasing nitrogen, phosphorus, and potassium fertilization moderately above the recommended rate improved fodder yield and nutritional energy status while reducing fiber fractions; conversely, reducing inorganic fertilizer to 75% of the recommended dose and substituting the balance with organic manure and plant growth promoting rhizobacteria markedly improved forage quality parameters (Pyati et al., 2025).
A dedicated review of fodder oat productivity under INM further reported that, treatments combining 75% of the recommended fertilizer dose with vermicompost, manganese and Sulphur amendment maximized nitrogen, potassium, phosphorus, Sulphur and manganese uptake by the crop, while the combination of farmyard manure at five tonnes per hectare with 50% of the recommended fertilizer dose delivered the highest net economic returns among the treatments evaluated (Kour, 2023). Taken together, this body of evidence indicates that fodder oats respond to integrated nutrient management in a manner broadly consistent with other Poaceae fodder and food crops, but that the specific role of phosphorus enriched organic and microbial amendments, as distinct from combined N, P, and K integration remains comparatively under explored for this crop, a gap this review returns to in Section 9.

6.6 Perennial Forage Grasses

Evidence from perennial tropical forage grasses reinforces the cereal-based findings summarized above. In Kikuyu grass (*Cenchrus clandestinus*), a species widely used for dairy cattle grazing in high altitude tropical regions, inoculation with a phosphate solubilizing bacterial consortium combined with low solubility rock phosphate increased soil labile phosphorus and acid phosphatase enzyme activity over an eighteen month field evaluation, translating into higher forage yield and quality than either rock phosphate or bacterial inoculation applied alone (Torres-Cuesta et al., 2023). This finding is particularly instructive for phosphorus enriched amendment strategies in fodder oats, since it demonstrates that the synergy between slow release phosphorus sources and PSB inoculation, rather than either component individually, drives the strongest productivity response in a directly analogous forage-grass system.

7. EFFECTS OF INTEGRATED NUTRIENT MANAGEMENT ON SOIL HEALTH AND NUTRIENT USE EFFICIENCY

A recurring finding across the crop wise evidence reviewed above is that INM benefits extend well beyond the current season's yield to encompass measurable improvements in soil biological and chemical properties. In rice based systems, integrated farmyard manure and chemical fertilizer use produced significantly higher microbial biomass carbon and soil carbon stock than chemical fertilizer alone, alongside improved energy use efficiency (Paramesh et al., 2023). Comparable long term evidence from rice and wheat systems demonstrates a positive correlation between decades of balanced integrated fertilization and multiple soil fertility indicators, including organic carbon, nitrogen, phosphorus, potassium and zinc status (Urmi et al., 2022).

From a nutrient use efficiency perspective, bio fertilizer integration appears to act principally by increasing the bioavailable fraction of an already applied nutrient rather than by directly adding new nutrient mass to the soil. This mechanism is well illustrated in pearl millet, where phosphorus use efficiency and fodder yield improved substantially when Bacillus cereus MN54 was combined with inorganic phosphorus sources on calcareous soils prone to phosphorus fixation, compared with the same phosphorus dose applied without bacterial inoculation (Majeed et al., 2025). Organic amendments contribute a complementary but mechanistically distinct benefit: vermicompost, in particular, has been shown to substantially increase total soil nitrogen and improve soil water holding capacity relative to compost or biochar applied alone, properties that indirectly support more efficient uptake of co applied inorganic nutrients by improving root zone conditions (Mahatale et al., 2026).

8. EFFECTS ON PRODUCE QUALITY AND ECONOMIC RETURNS

Because many of the crops considered in this review, particularly pearl millet and oats, are cultivated explicitly for fodder rather than grain, quality parameters such as crude protein content, fiber fractions and net economic return are as important as gross biomass yield in evaluating INM strategies. In fodder oats, integrated treatments combining reduced inorganic fertilizer with organic manure and plant growth promoting rhizobacteria improved crude protein content and reduced fiber fractions relative to full inorganic fertilization, indicating that INM can enhance nutritional quality even where it does not maximize absolute biomass yield (Pyati et al., 2025). Economic analysis of oat nutrient management trials similarly indicates that the treatment combination delivering the highest net return is not always the one delivering the highest yield. For instance, farmyard manure at five tonnes per hectare combined with fifty percent of the recommended fertilizer dose produced the best net economic returns among treatments evaluated in one review, despite not being the single highest yielding combination (Kour, 2023).

Similar quality economics tradeoffs are evident in pearl millet, where integrated phosphorus and bio fertilizer treatments improved both fodder yield and nutrient use efficiency sufficiently to translate into improved economic returns despite the additional cost of bacterial inoculant application (Majeed et al., 2025). These findings collectively suggest that INM recommendations for fodder oriented Poaceae crops should be evaluated against multiple criteria such as yield, quality and profitability rather than yield alone, since the treatment optimum can differ depending on which criterion is prioritized.

9. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite the broadly consistent picture of INM benefits across Poaceae food and fodder crops, this review identifies several specific gaps relevant to phosphorus enriched amendment research in fodder oats. First, while INM studies in oats have generally evaluated combined N,P and K integration (Koireng et al., 2025; Kour, 2023), comparatively few have isolated the specific contribution of phosphorus enriched organic amendments or phosphate solubilizing bacterial inoculants, in contrast to the more phosphorus focused literature available for pearl millet (Dutta, 2025; Majeed et al., 2025) and perennial forage grasses (Torres-Cuesta et al., 2023). Second, the demonstrated synergy between slow release phosphorus sources (such as rock phosphate or compost) and PSB inoculation observed in Kikuyu grass (Torres-Cuesta et al., 2023) has not yet been systematically tested in fodder oats, despite oats sharing the C3, cool season physiology that might be expected to respond differently to such synergy than the C4, tropical Kikuyu system.

Third, most available oat INM trials have been conducted in the sub tropical and Eastern Himalayan agro climatic zones of India (Biswas et al., 2024; Koireng et al., 2025), leaving open questions about the transferability of these nutrient response optima to other winter oat growing regions with differing soil phosphorus fixation capacities. Finally, few studies have concurrently tracked phosphorus use efficiency, forage quality and soil residual phosphorus status within a single experimental design for fodder oats, even though this combined evaluation has proven informative in pearl millet (Majeed et al., 2025) and would allow a more complete assessment of whether phosphorus enriched amendments deliver genuinely sustainable, rather than merely short term, productivity gains. Addressing these specific gaps through dedicated, phosphorus focused, and multi location field trials in fodder oats represents a clear and justified extension of the broader INM evidence base reviewed here.

10. CONCLUSION

Integrated Nutrient Management, combining inorganic fertilizers with organic amendments and microbial bio fertilizers, consistently improves yield, nutrient use efficiency, soil health and, in several cases, produce quality across major Poaceae food and fodder crops, including wheat, rice, maize, pearl millet, sorghum and fodder oats. The evidence reviewed indicates that intermediate levels of organic and inorganic integration, typically 50% to 75% of the recommended inorganic dose supplemented with organic manure and/or microbial inoculants, generally outperform either sole inorganic or sole organic management. For fodder oats specifically, while the existing evidence base confirms that INM improves both fodder yield and quality relative to conventional fertilization, the specific role of phosphorus enriched soil amendments as demonstrated more thoroughly in pearl millet and perennial forage grasses remains comparatively under investigated. This gap provides a clear scientific rationale for targeted field research on phosphorus enriched soil amendments in fodder oat production, building directly on the principles and mechanisms established across the wider Poaceae literature synthesized in this review.

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CONFLICT OF INTEREST

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REFERENCES

1. *Biswas, S., Das, R., Jana, K., & Puste, A. (2024). Integrated nutrient management on oat + grasspea intercropping system: An evaluation of system productivity, economics, energetics and carbon footprint. Scientific Reports, 14(1), 19414. https://doi.org/10.1038/s41598-024-66107-9*
2. *Dutta. (2025). Assessing integrated phosphorus management practices on crop performance and soil–plant phosphorus dynamics under pearl millet–chickpea system in alkaline Fluvisol—Google Search. https://www.google.com/search?q=Assessing+integrated+phosphorus+management+practices+on+crop+performance+and+soil%E2%80%93plant+phosphorus+dynamics+under+pearl+millet%E2%80%93chickpea+system+in+alkaline+Fluvisol&oq=Assessing+integrated+phosphorus+management+practices+on+crop+performance+and+soil%E2%80%93plant+phosphorus+dynamics+under+pearl+millet%E2%80%93chickpea+system+in+alkaline+Fluvisol&gs_lcrp=EgZjaHJvbWUyBggAEEUYOTIGCAEQRRg8MgYIAhBFGDwyBggDEEUYPNIBCDM4NDJqMGo3qAIAsAIA&sourceid=chrome&source=chrome.ob&ie=UTF-8*
3. *Dutta, A., Hazra, K. K., Nath, C. P., Kumar, N., Singh, R., Praharaj, C. S., & Patra, A. (2025). Assessing integrated phosphorus management practices on crop performance and soil–plant phosphorus dynamics under pearl millet–chickpea system in alkaline Fluvisol. Frontiers in Sustainable Food Systems, 9. https://doi.org/10.3389/fsufs.2025.1583697*
4. *Hasan, A. K., Islam, S. S., Jahan, M., Kheya, S. A., Uddin, Md. R., Islam, Md. S., & Khomphet, T. (2024). Synergistic Effects of Vermicompost and Biochar Amendments on Soil Fertility and Wheat Productivity in Bangladesh Floodplain Soils. Scientifica, 2024(1), 6624984. https://doi.org/10.1155/sci5/6624984*
5. *Imran. (2024). Integration of organic, inorganic and bio fertilizer, improve maize-wheat system productivity and soil nutrients. Journal of Plant Nutrition, 47(15), 2494–2510. https://doi.org/10.1080/01904167.2024.2354190*
6. *Koireng, R. J., Mary, K., Konsam, J., Chanu, T. M., Maheshwari, K., Moirangthem, A., Heisnam, P., Phurailatpam, S., Khangjarakpam, G., & Stina, K. (2025). Performance of oat under different cutting scheduling and integrated nutrient management in Eastern Himalayan agroclimatic conditions of India. Scientific Reports, 15(1), 44441. https://doi.org/10.1038/s41598-025-28099-y*
7. *M Kour. (2023). Productivity and profitability of fodder oat (Avena sativa L.) as affected by integrated nutrient management: A review—Google Search. https://www.google.com/search?q=+Productivity+and+profitability+of+fodder+oat+%28Avena+sativa+L.%29+as+affected+by+integrated+nutrient+management%3A+A+review&sca_esv=f2d48d055a0c39d3&sxsrf=APpeQnskthk5W9OXROwSnr-swqsu1PAz3Q%3A1788884072835&ei=aDSgaoWZLoyci-gPgNyVWA&biw=1183&bih=696&ved=2ahUKEwiF7c29sN-WAxUMzgIHHQBuBQsQ4dUDegQIBhAM&oq=+Productivity+and+profitability+of+fodder+oat+%28Avena+sativa+L.%29+as+affected+by+integrated+nutrient+management%3A+A+review&gs_lp=Egxnd3Mtd2l6LXNlcnAidyBQcm9kdWN0aXZpdHkgYW5kIHByb2ZpdGFiaWxpdHkgb2YgZm9kZGVyIG9hdCAoQXZlbmEgc2F0aXZhIEwuKSBhcyBhZmZlY3RlZCBieSBpbnRlZ3JhdGVkIG51dHJpZW50IG1hbmFnZW1lbnQ6IEEgcmV2aWV3MgcQIxjqAhgnMgcQIxjqAhgnMgcQIxjqAhgnMgcQIxjqAhgnMgcQIxjqAhgnMgcQIxjqAhgnMgcQIxjqAhgnMgcQIxjqAhgnMgcQIxjqAhgnMgcQIxjqAhgnMhYQABiABBiKBRhDGOcGGOoCGLQC2AEBMhwQLhiABBiKBRhDGOcGGMcBGNEDGOoCGLQC2AEBMhYQABiABBiKBRhDGOcGGOoCGLQC2AEBMhYQABiABBiKBRhDGOcGGOoCGLQC2AEBMhYQABiABBiKBRhDGOcGGOoCGLQC2AEBMhYQABiABBiKBRhDGOcGGOoCGLQC2AEBMhYQABiABBiKBRhDGOcGGOoCGLQC2AEBMhYQABiABBiKBRhDGOcGGOoCGLQC2AEBMhYQABiABBiKBRhDGOcGGOoCGLQC2AEBMhYQABiABBiKBRhDGOcGGOoCGLQC2AEBSLJGUIYBWJY2cAJ4AZABBJgBmASgAfkUqgEHMy0yLjIuMrABALgBDMgBAPgBAfgBApgCBKAC1weoAhTCAgoQABhHGNYEGLADwgINEAAYgAQYigUYQxiwA8ICFxAuGNwGGLgGGNoGGNgCGMgDGLAD2AEBwgIXEC4Y2AIYuAYY2gYY3AYYyAMYsAPYAQHCAgcQIxixAhgnwgIMEAAYgAQYChgLGLEDwgIPEAAYgAQYChgLGLEDGIMBwgIJEAAYgAQYChgLwgIEECMYJ8ICCxAAGIAEGIoFGJECwgIOEAAYgAQYigUYkQIYsQPCAhAQABiABBgUGIcCGLEDGIMBwgIIEAAYgAQYsQPCAgUQABiABJgDEeIDBBgAIF3iAwQYACBe4gMEGAAgX-IDBBgAIGDiAwQYACBh4gMEGAAgYuIDBRIBMSBA8QWeWei2_1TR8IgGAZAGFLoGBggBEAEYGZIHBzIuMy0xLjGgB7YxsgcFMy0xLjG4B-IGwgcHMy0zLjYtMcgHkwGACAE&sclient=gws-wiz-serp*
8. *Mahatale, P. V., Rani, M., Chavan, A. A., Kahodariya, J. H., Tk, N., Babu, K. D., Sidharthan, B., & Padhi, A. (2026). The role of organic amendments (Compost, vermicompost, biochar) in improving soil fertility and crop performance: A review. International Journal of Research in Agronomy, 9(3S), 108–119. https://doi.org/10.33545/2618060X.2026.v9.i3Sb.5031*
9. *Majeed, A., Ali, Q., Naveed, M., & Hussain, M. (2025). Integrated Phosphorus Management and Bacillus Cereus MN54 Inoculation Improve Fodder Yield, Nutrient Use Efficiency and Economic Returns in Pearl Millet Grown in Calcareous Soils. Journal of Soil Science and Plant Nutrition, 25(4), 8951–8960. https://doi.org/10.1007/s42729-025-02705-4*
10. *Mutuku, E. A., Roobroeck, D., Vanlauwe, B., Boeckx, P., & Cornelis, W. M. (2020). Maize production under combined conservation agriculture and integrated soil fertility management in the sub-humid and semi-arid regions of Kenya. Field Crops Research, 254, 107833. Https://doi.org/10.1016/j.fcr.2020.107833—Google Search. (n.d.). Retrieved September 9, 2026, from https://www.google.com/search?q=Mutuku%2C+E.+A.%2C+Roobroeck%2C+D.%2C+Vanlauwe%2C+B.%2C+Boeckx%2C+P.%2C+%26+Cornelis%2C+W.+M.+(2020).+Maize+production+under+combined+conservation+agriculture+and+integrated+soil+fertility+management+in+the+sub-humid+and+semi-arid+regions+of+Kenya.+Field+Crops+Research%2C+254%2C+107833.+https%3A%2F%2Fdoi.org%2F10.1016%2Fj.fcr.2020.10783*

3&oq=Mutuku%2C+E.+A.%2C+Roobroeck%2C+D.%2C+Vanlauwe%2C+B.%2C+Boeckx%2C+P.%2C+%26+Cornelis%2C+W.+M.+(2020).+Maize+production+under+combined+conservation+agriculture+and+integrated+soil+fertility+management+in+the+sub-humid+and+semi-arid+regions+of+Kenya.+Field+Crops+Research%2C+254%2C+107833.+https%3A%2F%2Fdoi.org%2F10.1016%2Fj.fcr.2020.107833&gs_lcrp=EgZjaHJvbWUyBggAEEUYOdIBCTExNTBqMGoxNagCALACAA&sourceid=chrome&source=chrome.rb&ie=UTF-8

11. *Paramesh, V., Kumar, P., Bhagat, T., Nath, A. J., Manohara, K. K., Das, B., Desai, B. F., Jha, P. K., & Prasad, P. V. V. (2023). Integrated Nutrient Management Enhances Yield, Improves Soil Quality, and Conserves Energy under the Lowland Rice–Rice Cropping System. Agronomy, 13(6), 1557. https://doi.org/10.3390/agronomy13061557*
12. *Prajapati. (2023). Nutrient management for optimizing fodder production of sorghum—A review | International Journal of Bio-resource and Stress Management | IndianJournals.com. https://indianjournals.com/article/ijbsm-14-1-011*
13. *Pyati, P. S., Bhattacharjee, S., Kumar, R., Ram, H., Meena, R. K., Hindorya, P. S., Bhakuni, K., Kashyap, S., Biswal, B., S. K., M., Yadav, M., Makarana, G., & Min, D. (2025). Optimizing Oat (Avena sativa L.) Production Strategies to Mitigate Nitrate Toxicity Without Compromising Fodder Quality. International Journal of Agronomy, 2025(1), 9767875. https://doi.org/10.1155/ioa/9767875*
14. *Rakhmatova, M., Khusanov, T., Kushiev, K., Tekebayeva, Z., Wang, Z., Temirbekova, A., Amantayeva, A., Abzhalelov, A., Bekshin, Z., Dubey, A. K., Kyzykbaikyzy, F., Abilkhadirov, A., Temirkhanov, A., & Nurbekova, Z. (2026). Harnessing Nitrogen-Fixing and Phosphate-Mobilizing Bacteria for Sustainable Agriculture. Microorganisms, 14(4), 803. https://doi.org/10.3390/microorganisms14040803*
15. *Rasul, M., Yahya, M., Suleman, M., Hakim, S., Mirza, B. S., Mirza, M. S., Reitz, T., Tarkka, M. T., & Yasmin, S. (2024). Diversity and functional traits based indigenous rhizosphere associated phosphate solubilizing bacteria for sustainable production of rice. Frontiers in Microbiology, 15. https://doi.org/10.3389/fmicb.2024.1470019*
16. *Sun, X., Tian, X., Jia, M., Hu, X., Zhang, C., & Zhao, L. (n.d.). Phosphate-solubilizing bacteria: A review of diversity, mechanisms, and applications in sustainable agriculture. Frontiers in Microbiology, 17, 1778470. https://doi.org/10.3389/fmicb.2026.1778470*
17. *Torres-Cuesta, D., Mora-Motta, D., Chavarro-Bermeo, J. P., Olaya-Montes, A., Vargas-Garcia, C., Bonilla, R., & Estrada-Bonilla, G. (2023). Phosphate-Solubilizing Bacteria with Low-Solubility Fertilizer Improve Soil P Availability and Yield of Kikuyu Grass. Microorganisms, 11(7), 1748. https://doi.org/10.3390/microorganisms11071748*
18. *Urmi, T. A., Rahman, M. M., Islam, M. M., Islam, M. A., Jahan, N. A., Mia, M. A. B., Akhter, S., Siddiqui, M. H., & Kalaji, H. M. (2022). Integrated Nutrient Management for Rice Yield, Soil Fertility, and Carbon Sequestration. Plants, 11(1), 138. https://doi.org/10.3390/plants11010138*