

FERMENTATION-DERIVED RESIDUES AS METABOLITE-RICH FUNCTIONAL BIOFERTILIZERS: MECHANISMS, SOIL HEALTH IMPACTS, AND CIRCULAR BIOECONOMY APPLICATIONS

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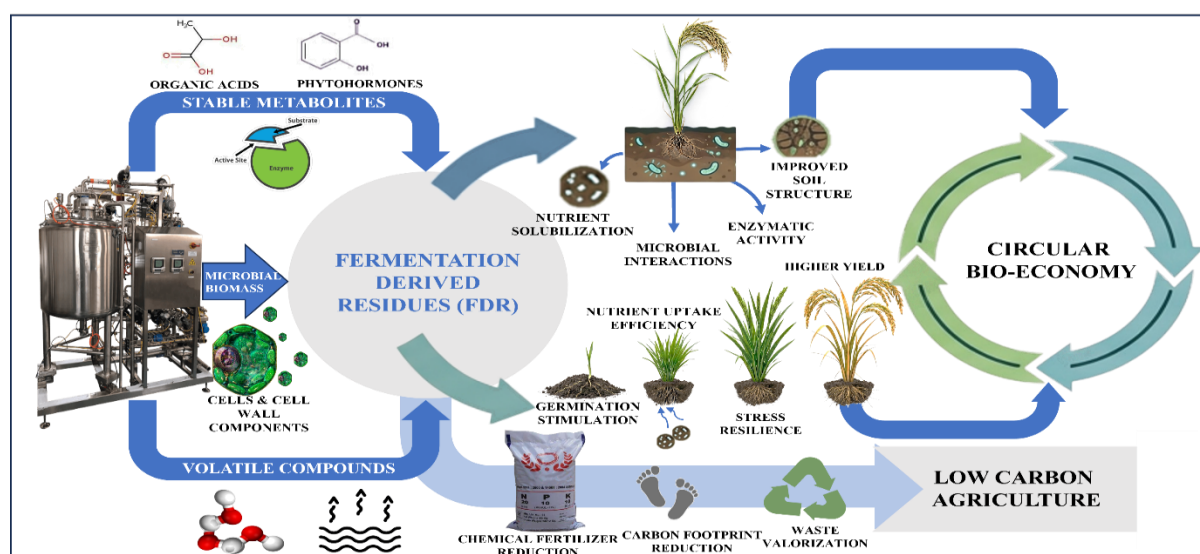
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ABSTRACT

Fermentation-derived residues (FDRs) are gaining attention as metabolite-rich functional biofertilizers for sustainable agriculture and circular bioeconomy applications. The conventional biofertilizers that rely primarily on the survival and colonization of live micro-organisms, FDRs function through stable bioactive metabolites including organic acids, amino acids, peptides, phytohormones, exopolysaccharides, phenolics, enzymes, volatile organic compounds, and microbial biomass components. This review comprehensively examines the origins, biochemical composition, mechanisms of action, soil health impacts, agronomic performance, formulation strategies, and sustainability implications of FDRs. Fermentation-derived metabolites enhance nutrient solubilization, rhizosphere microbial interactions, soil enzymatic activity, plant growth promotion, and stress resilience while improving soil physical, chemical, and biological properties. Applications across cereals, millets, and horticultural crops demonstrate significant improvements in germination, nutrient uptake efficiency, biomass accumulation, yield stability, and soil fertility. The usage of FDRs contributes to waste valorization, reduction in chemical fertilizer dependency, carbon footprint mitigation, and climate-smart agriculture through circular nutrient recycling systems. Advanced formulation approaches such as encapsulation, controlled-release technologies, and hydrogel-based stabilization improve shelf life and field performance. Despite their strong translational potential, challenges related to metabolite standardization, large-scale production, regulatory frameworks, and techno-economic feasibility remain. Overall, FDRs represent a promising strategy for developing resilient, regenerative, and low-carbon agricultural systems.

KEYWORDS: Fermentation-derived residues; Metabolite-based biofertilizers; Soil health; Rhizosphere microbiome; Circular bioeconomy.



GRAPHICAL ABSTRACT

1. INTRODUCTION:

Unustainable agricultural practices have intensified the extent of soil degradation in recent years, this includes excessive tillage, monocropping, and heavy usage on synthetic fertilizers. These lead to declining soil organic matter, disruption of microbial ecosystems, and deterioration of soil structure, ultimately reducing agricultural productivity and resilience, posing a major threat to food security(Li et al., 2023a). The over usage of nitrogen and phosphorus fertilizers has increased the environmental problems. Notably, nitrogen-based fertilizers lead to nitrous oxide release a powerful greenhouse gas while phosphorus runoff drives algal blooms in water bodies(X. Zhang et al., 2025). The long-term fertilizer usage led to soil acidification, less microbial diversity, and impaired nutrient cycling, thereby posing serious threat to soil health. These challenges highlight the urgency in the need for sustainable nutrient management strategies that helps to restore soil while minimizing environmental impacts. Biological inputs, particularly those derived from microbial processes, are increasingly being explored as viable alternatives. Conventional biofertilizers, consisting of live microbial inoculants such as N-fixing, P-solubilizing microorganisms, and plant growth-promoting rhizobacteria (PGPR), have been widely used as eco-friendly alternatives to chemical fertilizers. While these inputs can enhance nutrient availability and plant growth under controlled conditions, their practical field performance often remains inconsistent. A key limitation of conventional biofertilizers is dependence on microbial viability and successful colonization of the rhizosphere. Environmental stresses such as temperature fluctuations, soil pH variability, moisture deficits, and competition with native microbial communities significantly reduce their survival and efficacy(Zhang et al., 2025). There are also other issues like shelf-life, storage stability, and formulation which further constrain their large-scale usage. Another concern is the variability in performance. The effectiveness is often influenced by soil type, crop species, and agronomic practices, leading to inconsistent agronomic outcomes.

Regulatory and quality control challenges, including contamination and lack of standardization, limit their reliability. These constraints highlight the need for next-generation biofertilizer approaches that are less dependent on microbial survival and more focused on stable, functional bioactive compounds. Traditional biofertilizers rely on live microbial activity, FDRs exert their effects through postbiotic metabolites, such as organic acids, peptides, exopolysaccharides, and secondary metabolites. This has advantages, including enhanced stability, reduced sensitivity to environmental conditions. The fermentation residues derived from agricultural wastes can significantly improve soil fertility, enhance microbial diversity, and promote plant growth. The application of fermented organic residues has shown increased root activity, biomass accumulation, and nutrient uptake efficiency while improving soil enzymatic activity and microbial network complexity(Deng et al., 2025). The use of FDRs fulfils the principles of sustainable agriculture and circular bioeconomy by enabling the valorization of agro-industrial waste streams into high-value agricultural inputs.

2. Conceptual Distinction: Probiotics vs Postbiotics vs Fermentation Residues

A clear conceptual distinction between probiotics, postbiotics, and fermentation-derived residues is essential for understanding their roles in agricultural systems.

1. Probiotics: defined by the FAO/WHO as "live microorganisms which when administered in adequate amounts confer a health benefit on the host". Their efficacy in agriculture is dependent on survival, adaptation, and interaction with the native microbiome.
2. Postbiotics: defined as non-viable microbial products or metabolic by-products that exert biological effects. Postbiotics offer advantages such as safety, stability, and consistent activity due to the absence of live cells(Panghal et al., n.d.).
3. Fermentation-derived residues (FDRs): it is a broader category that includes postbiotics also with residual biomass and fermented substrates. These function as complex bioactive matrices, where metabolites, structural components, and organic matter collectively contribute to soil and plant health.

Probiotics rely on biological activity of live cells, postbiotics and FDRs function through biochemical and physicochemical mechanisms, making them more robust under field conditions.

3. Scope and Novelty:

This review aims to provide a comprehensive and mechanistic understanding of fermentation-derived residues as metabolite-rich functional biofertilizers within the context of sustainable agriculture and environmental management. Specifically, the review: 1. Examines the sources, composition, and bioprocessing strategies involved in generating fermentation residues. 2. Elucidates the biochemical and molecular mechanisms through which these residues influence soil properties, microbial communities, and plant growth. 3. Synthesizes current evidence on soil health impacts and agronomic performance across different cropping systems. 4. Explores formulation strategies, environmental implications, and circular bioeconomy integration. 5. Identifies knowledge gaps and future research directions, particularly in relation to metabolomics, multi-omics integration, and AI-driven optimization. The novelty of this review lies in its integrated perspective, linking fermentation, soil microbiology, and circular bioeconomy frameworks to position FDRs as next-generation biofertilizers. By directing on metabolite-mediated mechanisms rather than microbial inoculation alone, this work provides a forward-looking framework for the development of stable, efficient, and scalable bio-based agricultural inputs.

4. Fermentation-Derived Residues: Origins and Bioprocessing

The production of metabolite-rich residues is much linked with the type of fermentation systems, shaping their biochemical makeup and soil functional performance. Key platforms include submerged fermentation (SmF), solid-state fermentation (SSF), and mixed-culture fermentation which differ in process behavior and metabolite profiles(Perwez & Al Asheh, 2025; Sokra et al., 2025). 1. Lactic Acid Fermentation: Driven mainly by lactic acid

bacteria (LAB), yields residues rich in organic acids, antimicrobial peptides, and exopolysaccharides. LAB-based systems produce metabolites including lactic and acetic acids along with bacteriocins that aid nutrient solubilization and control pathogens. These systems are well suited for fermenting carbohydrate-dense substrates like molasses, cereal byproducts, and food waste(Sokra et al., 2025). Additionally, LAB-based fermentation residues contribute to soil acidification at the microscale, enhancing phosphorus solubilization and micronutrient availability, improving nutrient use efficiency. 2. Fungal/Yeast Fermentation: Fungal and yeast fermentation systems like *Trichoderma*, *Aspergillus*, and *Saccharomyces*. are characterized by their ability to degrade complex organic substrates and produce a wide range of extracellular enzymes and secondary metabolites. These systems are particularly effective in solid-state fermentation, where lignocellulosic materials are converted into value-added products. Fungal fermentation enhances the production of enzymes such as cellulases, ligninases, and proteases, along with secondary metabolites including phenolics and biosurfactants, which can contribute to soil organic matter transformation and plant growth promotion(Perwez and Al Asheh, 2025; Sokra et al., 2025). 3. Mixed-culture fermentation: Mixed-culture fermentation contains consortia of bacteria, fungi, and yeasts, facilitating synergistic metabolic exchanges that boost metabolite variety and functional performance. These systems compete with natural microbial communities and yield a wider array of bioactive compounds than single-strain approaches. Genome-resolved analyses of fermented consortia reveal functional genes tied to nutrient cycling, secondary metabolite production, and stress resilience, showing their ecological importance for soil restoration(Walia et al., 2025). These systems are progressively recognized as next-generation platforms for biofertilizer development.

5. Feedstocks and Substrates

The sustainability and scalability of fermentation-derived residues are strongly linked to the diversity and availability of feedstocks used in fermentation processes.

1. Agro-industrial byproducts: Agro-industrial byproducts including bran, molasses, whey, and crop residues offer nutrient-dense substrates for microbial fermentation. These low-cost materials are rich in carbohydrates, proteins, and minerals, which supports microbial growth and metabolite synthesis. Solid-state fermentation of such residues enables efficient conversion into biofertilizers, mitigating waste management challenges while producing functional agricultural inputs(Perwez & Al Asheh, 2025). 2. Food Processing By-products: Wastes from the food processing units offer a substantial resource base for biofertilizer production. Microbial fermentation converts these wastes into nutrient-dense products enriched with organic acids, amino acids, and bioactive compounds. Such bioconversion not only promotes nutrient recycling but also enhances soil fertility and crop yields(Kolawole et al., 2025; Zaini et al., 2023). 3. Lignocellulosic Biomass: Lignocellulosic crop residues like straw, husk, and stover were complex substrates that require enzymatic breakdown. Fungal and mixed microbial fermentation systems are instrumental in degrading cellulose, hemicellulose, and lignin into simpler constituents. This transformation yields bioactive metabolites and partially decomposed organic matter, thereby enhancing soil organic carbon and microbial activity(Perwez & Al Asheh, 2025).

6. Residue Composition Spectrum

Cell-Free Supernatants (CFS): Cell-free supernatant (CFS) the cell-free liquid fraction post-fermentation has diverse soluble metabolites such as organic acids, peptides, enzymes, and signaling molecules. These compounds drive the bioactivity of fermentation residues, functioning as postbiotic agents that modulate soil chemistry and microbial interactions. The microbial fermentation broths enhance root metabolism and rhizosphere microbial diversity, underscoring the functional relevance of soluble metabolites(Deng et al., 2025). Microbial Biomass (Dead/Inactive Cells): Inactive microbial biomass consists structural biomolecules including cell wall constituents like peptidoglycans and lipopolysaccharides along with other intracellular nutrients. These components serve as sustained slow-release nutrient reservoirs and microbial signaling agents, shaping soil microbial communities and plant responses, such biomass augments soil organic matter and offers substrates for indigenous microbial populations, promoting ecological stability.

TABLE 1: TYPES OF FERMENTATION RESIDUES

FERMENTA- TION PLAT- FORM / RESI- DUE TYPE	MAJOR FEED- STOCKS / SUB- STRATES	DOMINANT METABO- LITES / BIOACTIVE COMPONENTS	FUNCTIONAL PROPERTIES IN SOIL AND PLANTS
LACTIC ACID FERMENTA- TION RESI- DUES	Molasses, cereal by-products, food waste, millet sub- strates	Lactic acid, acetic acid, bacte- riocins, exopolysaccharides (EPS), peptides	Phosphorus solubilization, pathogen suppression, micronutrient mobili- zation, rhizosphere acidification, im- proved nutrient use effi- ciency(Cheng et al., 2026; Sokra et al., 2025).
FUNGAL FER- MENTATION RESIDUES	Lignocellulosic bi- omass, crop resi- dues, straw, husk	Cellulases, ligninases, prote- ases, phenolics, biosurfac- tants, citric acid	Organic matter degradation, carbon turnover, nutrient mobilization, soil conditioning(Perwez and Al Asheh, 2025; Sokra et al., 2025).
YEAST FER- MENTATION RESIDUES	Agro-industrial wastes, sugar-rich substrates, whey	Amino acids, peptides, vita- mins, volatile organic com- pounds (VOCs), enzymes	Plant growth promotion, microbial stimulation, stress tolerance

			enhancement(Perwez and Al Asheh, 2025).
MIXED-CULTURE FERMENTATION RESIDUES	Food processing waste, agro-industrial residues, mixed organic biomass	Diverse organic acids, secondary metabolites, signaling molecules, microbial biomass	Enhanced microbial diversity, nutrient cycling, ecological stability, stress resilience (Walia et al., 2025).
CELL-FREE SUPERNATANTS (CFS)	Fermentation broths from bacterial and fungal systems	Organic acids, enzymes, peptides, signaling molecules, soluble metabolites	Root stimulation, rhizosphere modulation, enhanced microbial diversity(Deng et al., 2025).
FERMENTED AGRO-INDUSTRIAL RESIDUES	Bran, molasses, whey, crop residues	Organic acids, amino acids, minerals, microbial metabolites	Waste valorization, nutrient recycling, improved soil fertility (Perwez and Al Asheh, 2025).
FERMENTED FOOD PROCESSING RESIDUES	Fruit and vegetable wastes, food industry by-products	Phenolics, flavonoids, amino acids, organic acids	Antioxidant activity, nutrient enrichment, improved crop productivity(Kolawole et al., 2025; Zaini et al., 2023).
LIGNOCELLULOSIC FERMENTATION RESIDUES	Straw, stover, husk, agricultural biomass	Partially degraded cellulose, hemicellulose derivatives, lignin metabolites	Soil organic carbon enhancement, microbial activation, improved aggregation (Perwez and Al Asheh, 2025).
MICROBIAL BIOMASS RESIDUES (INACTIVE CELLS)	Fermented microbial cultures	Peptidoglycans, lipopolysaccharides, intracellular nutrients	Slow-release nutrient reservoir, microbial signaling, soil organic matter enrichment (Deng et al., 2025).
LAB-DERIVED POSTBIOTIC RESIDUES	Lactic acid bacterial fermentations	Bacteriocins, antimicrobial peptides, organic acids, EPS	Soil disease suppression, microbial balance, plant defense stimulation (Cheng et al., 2026).
EPS-RICH FERMENTATION RESIDUES	LAB and mixed microbial fermentations	Exopolysaccharides, biofilm-forming polymers	Soil aggregation, water retention, moisture regulation, biofilm formation (Cheng et al., 2026; Panek et al., 2026).
VOC-RICH FERMENTATION RESIDUES	Bacterial and yeast fermentations	Alcohols, aldehydes, ketones, esters, sulfur compounds	Plant signaling, induced systemic resistance, pathogen inhibition(Cheng et al., 2026)
FERMENTED PADDY STRAW RESIDUES	Paddy straw and cereal residues	Organic carbon fractions, microbial metabolites, decomposed lignocellulose	Carbon sequestration, microbial biomass enhancement, nutrient cycling(Rathore et al., 2026).
BIOCHAR-INTEGRATED FERMENTATION RESIDUES	Fermentation waste subjected to pyrolysis	Recalcitrant carbon, mineral ash, porous carbon matrix	Carbon sequestration, cation exchange enhancement, microbial carrier function(Shahzaib, n.d.)

7. Processing Parameters Influencing Metabolite Profiles

The biochemical composition and functional performance of fermentation-derived residues are dependent on process parameters.

1. pH, Temperature, and Oxygen: Environmental conditions such as pH, temperature, and oxygen availability regulate microbial metabolism and enzymatic activity. For instance: Low pH favors organic acid production in lactic acid fermentation, temperature influences microbial growth kinetics and metabolite synthesis, oxygen availability determines aerobic and anaerobic metabolic pathways. Optimization of these parameters is essential for maximizing metabolite yield and functional efficacy(Sokra et al., 2025).
2. Fermentation Duration: Time taken for fermentation affects metabolite buildup and conversion. Initial phases favor primary metabolites, while extended periods drive the accumulation of secondary metabolites and complex bioactive compounds. Longer fermentation periods further enhance substrate breakdown and the enrichment of functional biomolecules, boosting the agronomic value of the resulting residues.
3. Microbial Consortia Design: Microbial community composition and interactions critically shape metabolite diversity. Mixed consortia enhance synergistic relationships, resulting in elevated bioactive compound yields and superior functional performance. The synthetic microbial communities (SynComs) underscore the value of rational consortium design in optimizing biofertilizer effectiveness and stability(Singh et al., 2025).

8. Biochemical Composition and Functional Metabolites

Fermentation-derived residues (FDRs) represent chemically complex systems comprising primary metabolites, secondary metabolites, and structural biomolecules, which together govern their ecological function in soil. This biochemical diversity has its base from microbial metabolism, substrate type, and fermentation parameters, yielding a metabolite-dense matrix that modulates nutrient dynamics, microbial communities, and plant physiological processes.

1. **Primary Metabolites:** Primary metabolites from the active microbial growth phase and are associated to central metabolic routes, including glycolysis and the tricarboxylic acid (TCA) cycle. These constitute to the biochemical backbone of fermentation-derived residues. **Organic Acids:** Organic acids rank among the most functionally important metabolites in fermentation systems. Lactic acid bacteria (LAB) primarily generate lactic acid, whereas heterofermentative routes produce acetic acid and additional short-chain acids, aiding in the environmental acidification and microbial suppression (Cheng et al., 2026). These organic acids have several functions: reducing pH which facilitates phosphate solubilization, chelating the micronutrients like Fe and Zn, and suppressing pathogens via membrane disruption. Citric acid which is commonly generated by fungal systems such as *Aspergillus* aids nutrient mobilization and metal chelation in soil environments. Organic acids are the biochemical drivers of nutrient accessibility and soil chemical transformation, making them as important to the functional efficacy of FDRs. **Amino Acids and Short Peptides:** Proteolysis during fermentation yields free amino acids and bioactive peptides, which act as both nitrogen sources and signaling agents in soil. Microbial protein breakdown produces peptides exhibiting various functional traits, such as antimicrobial, antioxidant, and plant growth-promoting activities (Fitsum et al., 2025; Seol & Yeo, 2026). These compounds boost microbial growth in the rhizosphere, aid nitrogen mineralization, and serve as precursors for phytohormone production. Low-molecular-weight peptides directly affect plant metabolic routes and stress responses.

2. **Secondary Metabolites:** Secondary metabolites from the microbial stationary phase, remaining outside primary metabolism while serving key ecological and functional roles. **Phenolics and Flavonoids:** Fermentation promotes the release and modification of phenolic compounds and flavonoids from complex substrates, thereby boosting their bioavailability and functional potency. These molecules possess strong antioxidant and antimicrobial activities, supporting soil health and plant defence against pathogens (Künili et al., 2025). In soil, phenolic compounds shape microbial community composition, serve as signaling agents in plant–microbe interactions, and alleviate oxidative stress in plants. **Bacteriocins and Antimicrobial Peptides:** Bacteriocins are antimicrobial peptides from bacteria, notably LAB that has selective activity against competing or pathogenic microbes, boosting soil disease suppression. LAB-derived metabolites, like bacteriocins and other antimicrobial peptides, suppress diverse Gram-positive and Gram-negative pathogens, supporting a more balanced soil microbial community (Cheng et al., 2026). **Volatile Organic Compounds (VOCs):** Volatile organic compounds (VOCs) generated during fermentation including alcohols, aldehydes, ketones, esters, and sulfur-containing molecules can act as bio-signaling agents that enhances plant growth, root architecture, and microbial interactions. LAB-driven metabolism of amino acids and lipids yields VOCs like phenylethanol and short-chain aldehydes, which contribute to ecological signaling and antimicrobial effects (Cheng et al., 2026). Volatile organic compounds (VOCs) are known for their functions in triggering systemic resistance in plants, facilitating plant–microbe signaling, and inhibiting soil-borne pathogens.

9. Macromolecules and Structural Components

1. **Exopolysaccharides (EPS):** Exopolysaccharides (EPS) are the high-molecular-weight polymers secreted by microbes during fermentation that contribute crucially to soil aggregation, structural stability, water retention, moisture regulation, and biofilm formation. Lactic acid bacteria and other fermentative microorganisms produce EPS as part of their metabolism, thereby improving soil architecture and aiding microbial colonization (Cheng et al., 2026).

2. **Cell Wall Fragments (Peptidoglycan, Teichoic Acids):** Cell wall-derived structural components such as peptidoglycans and teichoic acids remain in fermentation residues even after cell inactivation. These molecules can act as slow-release nutrient reservoirs, microbial signaling agents, and improves the plant defence responses. Such constituents enrich soil organic matter and promote beneficial microbial interactions, strengthening soil ecological stability.

10. Metabolomics Approaches for Profiling

Advanced analytical techniques help in the characterization of fermentation-derived metabolites, enabling high-resolution profiling and functional interpretation. LC–MS/MS for polar and semi-polar metabolites, GC–MS for volatile and derivatized compounds, NMR spectroscopy for structural elucidation and quantitative analysis. These techniques allow comprehensive identification of metabolites, including organic acids, amino acids, lipids, and secondary compounds, providing insights into fermentation-driven biochemical transformations. Databases such as KEGG (metabolic pathways), HMDB (metabolite structures and functions), and METLIN (mass spectral data) support metabolite identification and annotation, enabling accurate compound profiling and pathway mapping. Pathway enrichment and functional annotation tools further analyze metabolomics data to pinpoint key fermentation pathways, the functional roles of metabolites in soil–plant systems, and links between microbial metabolism and ecological outcomes. Fermentation reshapes pathways related to amino acid metabolism, organic acid synthesis, and lipid transformation, showing its systemic influence on biochemical networks (Akanni & Adebo, 2024).

11. Mechanisms of Action in Soil Systems

Fermentation-derived residues (FDRs) affect agronomic and ecological factors by various biochemical and microbiological pathways involving nutrient cycling, microbial ecology, plant signaling, and enzymatic activity. Distinct from conventional biofertilizers, their functionality is primarily metabolite-dependent, allowing a stable performance across different soil types. A key mechanism involves the solubilization of insoluble phosphorus by organic acid generation. Gluconic, citric, lactic, and oxalic acids lower soil pH and chelate cations (e.g., Ca^{2+} , Fe^{3+} , Al^{3+}), making phosphate into plant-available forms (Yadav, 2022). Phosphate-solubilizing microorganisms (PSMs) and their metabolites can convert up to 50–60% of bound phosphorus into available forms, showing the efficiency of acid-mediated mechanisms (Ghimirey et al., 2024).

Enzymatic mineralization (phosphatases, phytases) contributes to the conversion of organic phosphorus pools into inorganic phosphate, enhancing nutrient availability (Yadav, 2022). Along with phosphorus, fermentation metabolites aid potassium and micronutrient mobilization by organic acid-driven mineral dissolution, chelation by siderophores and low-molecular-weight ligands, and redox changes that alter metal valence states. These mechanisms boost the bioavailability of Fe, Zn, and other micronutrients essential for plant metabolism. Organic acids and related metabolites bind heavy metals, reducing heavy metal toxicity through precipitation or complexation (Feng et al., 2023). FDRs function as substrate-rich amendments, that deliver amino acids, organic acids, and carbon sources that selectively promote beneficial microbial taxa, this leads to enhanced microbial diversity, enrichment of nutrient-cycling functional groups, and stabilization of microbial networks. These actions resemble prebiotic effects, where non-living compounds shape microbial community composition and activity. Certain fermentation metabolites such as organic acids and secondary compounds can disrupt quorum sensing (QS), the microbial communication system that governs virulence and biofilm formation. Interfering with QS pathways reduces pathogenicity and restricts colonization by harmful microorganisms. While mechanistic understanding remains incomplete, evidence suggests that metabolites like cyclic dipeptides and organic acids modulate signaling routes involved in microbial competition and cooperation. FDRs enhance beneficial microbial communities that suppress pathogens by nutrient competition, niche occupancy, and antimicrobial metabolite production.

Phosphate-solubilizing and plant growth-promoting microbes generate bioactive compounds that inhibit pathogenic bacteria and improve plant defence mechanisms (Feng et al., 2023). Fermentation residues harbor metabolites with plant hormone-like activity, like indole-3-acetic acid (IAA) and related compounds. These molecules stimulate cell elongation and division, enhance nutrient uptake, and regulate root–shoot signaling. Microbes and their metabolites in biofertilizers are known to produce auxins, gibberellins, and other growth-promoting substances, thereby directly influencing plant physiological processes. Metabolite-mediated signaling promotes a better root length and surface area, enhanced lateral root development, and improved rhizosphere interactions.

These effects lead to superior nutrient uptake efficiency and better plant establishment, especially under nutrient-limited conditions. FDRs improve plant tolerance to abiotic stresses by promoting osmoprotectant accumulation regulating stress-responsive pathways, and modulating antioxidant systems. Metabolites like organic acids and peptides further aid ionic balance and control oxidative damage under stress. Fermentation-derived metabolites contribute to induced systemic resistance (ISR) by activating plant defence mechanisms, including enhanced defence enzyme production, cell wall reinforcement, and stimulation of jasmonic and salicylic acid signaling routes. Additionally, microbial metabolites directly suppress pathogens through antimicrobial action, offering dual protection (Feng et al., 2023). Soil enzymes play a vital role in nutrient cycling, and FDRs markedly boost their activity by microbial stimulation and substrate supply. Dehydrogenase activity, a proxy for overall microbial activity and oxidative metabolism, rises significantly following biofertilizer application, indicating enhanced microbial respiration and soil biological function. Phosphatases facilitate the hydrolysis of organic phosphorus, liberating inorganic phosphate for plant absorption. Elevated phosphatase activity closely aligns with greater microbial abundance and improved phosphorus availability. (Chen et al., 2026). Urease drives nitrogen cycling by converting urea to ammonia, thereby rendering nitrogen accessible for plant uptake. Elevated urease activity reflects enhanced nitrogen turnover and soil fertility.

Soil enzymes function as biochemical catalysts of nutrient cycling, breaking down organic matter and governing carbon, nitrogen, and phosphorus dynamics in terrestrial ecosystems.

12. Soil Health Impacts

Fermentation-derived residues (FDRs) enhance soil health by improving physical structure, chemical equilibrium, and biological function, thereby restoring soil as a dynamic, self-regulating system. Soil health is now understood as an integration of these three domains, with microbial processes driving most nutrient transformations and ecosystem stability (Q. Chen et al., 2024; Iqbal et al., 2025). EPS generated during fermentation serve as key biological binding agents, linking soil particles into stable aggregates. Their adhesive and complexing properties promote the formation of both micro- and macro-aggregates, thereby strengthening soil structural integrity. These aggregates enhance soil porosity, aeration, erosion resistance, and stability under environmental stress. Aggregation correlates directly with improved pore architecture, which regulates water infiltration, gas exchange, and root penetration (M. Zhang et al., 2024). Biofilm-forming microbial communities further enhance aggregate stability and nutrient retention in degraded soils.

EPS and linked microbial metabolites markedly improve soil water-holding capacity by their hygroscopic and gel-forming traits. EPS matrices retain water within soil pores and biofilms, mitigating evaporation losses and enhancing moisture accessibility for plants (Panek et al., 2026). Microbial communities which are influenced by FDRs further improve water dynamics by enhancing pore connectivity, increasing capillary water retention, and

stabilizing soil aggregates. Such improvements are vital under drought conditions, where greater water retention aids plant survival and productivity. Fermentation-derived metabolites like organic acids and their salts aid in soil pH regulation. Organic acids initially reduce soil pH, subsequent microbial breakdown and buffering processes stabilize pH within ranges favorable for nutrient availability. The buffering capacity improves nutrient solubility, prevents excessive shifts in soil pH, and supports microbial enzymatic activity. Such pH regulation is key to sustaining balanced soil chemistry and maximizing nutrient uptake. FDRs raise cation exchange capacity (CEC) by supplying organic matter and functional groups such as hydroxyl moieties that bind cations. Elevated CEC enhances retention of essential nutrients (e.g., K^+ , Ca^{2+} , Mg^{2+}), reduces nutrient leaching, and improves nutrient buffering. EPS and humified organic fractions from fermentation residues further support ion exchange by offering reactive surfaces for nutrient adsorption (M. Zhang et al., 2024).

FDRs provide substantial amounts of both labile and stable organic carbon, aiding soil carbon sequestration and fertility. Microbial biomass residues and partially broken-down substrates enrich soil organic matter pools, supplying energy for soil microbes and improving soil structure. Biofertilizer application has been observed to raise soil organic carbon levels and stimulate nutrient cycling, thereby supporting long-term soil productivity (Pradmiardi Mushalin et al., n.d.). FDRs enhance soil microbial diversity and functional complexity by supplying metabolite-rich substrates that sustain a wide range of microbial taxa. Fertility inputs act as a primary driver of microbial community assembly, shaping both bacterial and fungal populations (Mo et al., 2024). Increased microbial diversity promotes more efficient nutrient cycling, better ecosystem resilience, and functional redundancy that ensures stability under stress. The soil microbiome is central to regulating key processes such as organic matter decomposition, nutrient transformation, and stress tolerance (Iqbal et al., 2025).

The application of fermentation-derived residues markedly elevates soil enzyme activities, which serve as key indicators of biological soil health. Enzymes including dehydrogenase reflecting overall microbial activity, phosphatase involved in phosphorus cycling, and urease driving nitrogen cycling are stimulated as a result of increased microbial biomass and substrate availability. Elevated enzymatic activity speeds up organic matter breakdown and nutrient mineralization, thereby enhancing soil fertility and plant nutrient accessibility (Q. Chen et al., 2024). FDRs aid in the biological suppression of soil-borne pathogens via several routes: enrichment of beneficial microbes, generation of antimicrobial metabolites, and competitive exclusion through niche occupation. Biofilm-forming microbial communities alongside metabolite-rich residues render conditions unfavorable for pathogen persistence, thereby lowering disease occurrence and promoting plant health (Pradmiardi Mushalin et al., n.d.).

13. Agronomic Performance and Crop Responses

FDRs act as metabolite rich biofertilizers that supply organic acids, amino acids, peptides, phytohormone analogs, and signaling molecules to the rhizosphere region. This mechanism shifts the functional basis from microbial colonization to direct biochemical engagement, yielding consistent agronomic benefits across diverse crops and environments. The FDR-based formulations can improve seed germination, biomass, yield stability, and nutrient use efficiency, within integrated nutrient management frameworks (Li et al., 2023a) (Zhao et al., 2024). Seed germination is sensitive to biochemical signals, and FDRs supply various metabolites that speeds the seed metabolism, enzyme induction, and early developmental pathways. Fermentation-derived liquid biofertilizers shown improvements in germination rates, root elongation, and seedling vigor indices across various crops, including legumes, cereals, and vegetables.

Under controlled conditions, germination rates rose by 15–30%, alongside 20–50% increases in root and shoot length, pointing good physiological stimulation during early developmental stages (Satyanarayana et al., 2025). The physiological basis for enhanced germination involves several mechanisms like activation of hydrolytic enzymes (e.g., amylases and proteases) mobilizing seed reserves; organic acids that enhance membrane permeability and nutrient accessibility; amino acids and peptides as signaling agents for metabolic activation; and antimicrobial metabolites that lower seed-borne pathogen pressure. Furthermore, auxin-like compounds (IAA analogs) present in fermentation residues promote radicle emergence and lateral root formation, thereby improving seedling establishment (Zhao et al., 2024). Seed priming with metabolite-enriched biofertilizers enhances germination under abiotic stresses such as salinity and drought by boosting antioxidant enzyme activity and maintaining osmotic equilibrium (Iqbal et al., 2025).

FDRs can boost both vegetative growth and reproductive output, improving photosynthetic performance, nutrient accessibility, and hormonal balance. A broad synthesis of biofertilizer trials reveals yield gains between 10% and 40%, with more pronounced effects when FDRs are applied alongside organic amendments or under reduced chemical fertilizer application (Zhao et al., 2024). A field investigation reported that bio-organic fertilizer application raised soil total nitrogen by approximately 16.7%, available phosphorus by roughly 10.9%, and crop yield by nearly 29% (Pei et al., 2025). Fermentation-based biofertilizers enhanced plant height, leaf area index, and dry matter accumulation, leading to increased grain and fruit yields in various crops, including maize, wheat, and legumes (Demir et al., 2023). At the mechanistic level, biomass enhancement results from several factors: elevated chlorophyll content and photosynthetic rates, which increase carbon assimilation; improved root architecture that boosts water and nutrient uptake; phytohormone-like activity that modulates growth and development; and reduced disease pressure, allowing greater resource allocation toward growth. Additionally, fermentation-derived metabolites optimize source–sink dynamics, improving the translocation of assimilates to reproductive tissues, thereby enhancing yield quality (Li et al., 2023b). In stress-prone environments, FDRs help sustain yield stability by alleviating oxidative damage and enhancing water-use efficiency, positioning them as valuable tools for climate-resilient agricultural systems (Iqbal et al., 2025). Enhanced nutrient use efficiency (NUE) represents a key

agronomic benefit of fermentation-derived residues, leading to lower reliance on synthetic fertilizers without compromising crop productivity. FDRs improve nutrient acquisition via several pathways:

1. **Increased Nutrient Accessibility:** Organic acids and related metabolites solubilize phosphorus and mobilize micronutrients, raising their availability in the rhizosphere region (Li et al., 2023c).
2. **Root System Expansion:** Phytohormone like compounds stimulate root proliferation, increasing the surface area of root and nutrient absorption.
3. **Microbial Stimulation:** FDRs support beneficial microbial communities involved in nitrogen fixation, phosphorus solubilization, and nutrient cycling, thus enhancing overall nutrient fluxes.
4. **Activation of Transport Systems:** Metabolites modulate the expression of nutrient transporter genes, improving uptake efficiency at the cellular level. Empirical evidence indicates that biofertilizer application significantly raises plant nutrient content, with nitrogen uptake increasing by 15–25%, phosphorus by 10–20%, and potassium by 10–18% (Demir et al., 2023).

Moreover, integrated nutrient management strategies shows that FDR-based amendments can replace 25–30% of synthetic fertilizers with no yield penalty, enhancing soil fertility and lowering environmental footprint (Zhao et al., 2024). Metabolome and microbiome analyses shows that bio-organic fertilizers reconstruct rhizosphere metabolic pathways, improving the nutrient cycling efficiency and plant nutrient acquisition (Li et al., 2023).

14. Case Studies Across Crops

The agronomic efficacy of fermentation-derived residues (FDRs) has been confirmed across a range of crop, including cereals, millets, and horticultural species. These case studies offer crop-specific evidence of increased yield, physiological gains, and improved nutrient use efficiency, highlighting the practical applicability of metabolite-based biofertilizers under field conditions.

Cereals (Rice, Wheat, Maize):

Cereal crops, characterized by high nutrient demands, shows good responses to metabolite-enriched biofertilizers owing to enhanced nutrient cycling and rhizosphere activity. In rice production systems, fermentation-derived bio-organic fertilizers notably increased grain yield, nitrogen assimilation, and soil microbial activity, with yield gains of 15–35% observed under integrated nutrient management (Li et al., 2023). These gains were linked to complex rhizosphere metabolite profiles and microbial network architectures, pointing to robust interactions among plants, microbes, and metabolites. In wheat, the application of fermented organic amendments showed greater tillering, longer spikes, and increased grain weight, largely driven by enhanced phosphorus solubilization and nitrogen mineralization. Reported outcomes include a 10–25% rise in biomass and grain yield, elevated soil enzyme activity and organic carbon content (Q. Chen et al., 2024). Maize - a widely used model for assessing biofertilizer performance. Fermentation-derived organic fertilizers and biofilm-based systems have been shown to increase biomass and grain yield by 20–30%, improve root elongation and nutrient acquisition, and enhance soil aggregation alongside microbial activity (Oyebamiji et al., n.d.). Additionally, biofertilizer-based systems have been shown to reduce chemical fertilizer requirements by up to 30–50% in cereal production systems, while maintaining or improving yield stability (Zhao et al., 2024). These results affirm that FDRs can effectively sustain high-input cereal cropping systems, boosting productivity while reducing environmental harm.

Millets:

Millets such as finger millet (*Eleusine coracana*), pearl millet (*Pennisetum glaucum*), and foxtail millet (*Setaria italica*) are gaining value as climate-resilient crops owing to their tolerance for marginal soils and low water requirements. Their productivity remains limited by poor soil fertility, inadequate nutrient availability, and weak rhizosphere activity. Microbial and metabolite-based bio-stimulants have been shown to enhance seedling establishment, nutrient use efficiency, and stress tolerance in climate-resilient cropping systems, including millets and other dryland cereals. (Carletti et al., 2021; Rouphael & Colla, 2020) In fermented millet-based systems especially those employing lactic acid fermentation residues become enriched with organic acids and phenolic compounds that increases phosphorus availability and rhizosphere microbial exchanges. These metabolites also bolster antioxidant defense routes and osmotic adjustment in plants, thereby improving drought resilience and water-use efficiency under rainfed agricultural conditions (Brown & Saa, 2015; Rouphael & Colla, 2020). The incorporation biofertilizer-based strategies into millet farming supports long-term soil sustainability by increasing soil biological activity, accelerating carbon turnover, and lowering reliance on synthetic fertilizers (Ruzzi et al., 2024).

Horticultural crops

Horticultural crops exhibit strong responsiveness to metabolite-enriched biofertilizers owing to their elevated nutrient requirements and sensitivity to rhizosphere conditions. Fermentation-derived residues have shown considerable advantages in vegetables, fruits, and controlled-environment horticulture by enhancing nutrient uptake, modulating hormonal activity, and influencing microbial communities. In leafy vegetables and fruit-bearing crops, both microbial and non-microbial bio-stimulants enhance biomass buildup, chlorophyll production and photosynthetic performance, mineral nutrient acquisition, as well as fruit quality and antioxidant levels (Rouphael & Colla, 2020). Research on horticultural crops indicates that protein hydrolysates and microbial metabolites induce the lettuce growth, increase nitrogen use efficiency, and promote beneficial epiphytic microbial communities. Microbial bio-stimulants applied to pepper and other vegetable crops modulate hormonal balances and plant metabolic

pathways, leading to improved yield and stress resilience(Bonini et al., 2020). In fruit crops and greenhouse production systems, fermentation-derived formulations enhance flowering and fruit set, root biomass and nutrient uptake, post-harvest quality characteristics, and resistance to abiotic stresses such as salinity and drought. The observed improvements in horticultural crops are closely linked to enhanced microbial signaling, metabolic reprogramming, and greater nutrient use efficiency(Rouphael & Colla, 2020; Yakhin et al., 2017). Fermentation-derived liquid preparations are well suited for use in foliar application and fertigation, enabling rapid metabolite absorption and faster physiological responses in high-value horticultural crops.

15. Formulation Approaches and Product Development

The effective commercialization and field deployment of fermentation-derived residues (FDRs) heavily depend on formulation techniques that ensure stability, extended shelf life, metabolite preservation, controlled release, and farmer-friendly application. Many bioactive metabolites are easily prone to environmental breakdown, so there is a need for advanced formulation methods for preserving their functionality under field conditions. Bio-fertilizer formulation needs to fulfil several objectives: improving metabolite stability, ensuring compatibility with diverse soil systems, enabling sustained and targeted release, enhancing storage and transport stability, and minimizing environmental losses. Among these strategies, encapsulation using biodegradable polymers particularly sodium alginate has emerged as a leading technology for the development of next-generation biofertilizers(Colin et al., 2024)(Khaliq et al., 2023). Fermentation-derived biofertilizers are typically prepared as either liquid or solid formulations, each with distinct physicochemical and agronomic attributes. Liquid Formulations: Liquid preparations generally consist of cell-free supernatants (CFS), fermentation broths, soluble metabolite concentrates, or suspensions containing microbial biomass along with metabolites. These can offer rapid metabolite availability in soil, ease of application and faster plant physiological responses.

Liquid biofertilizers are especially effective in horticultural systems and protected cultivation, where metabolites can be quickly absorbed and utilized by plants. They also integrate well with precision agriculture and drip irrigation setups. Liquid formulations have drawbacks, including reduced shelf stability due to metabolite breakdown, sensitivity to temperature shifts and UV exposure, and a higher contamination risk during storage. To address these issues, stabilizers, preservatives, and encapsulation techniques are being increasingly incorporated into liquid biofertilizer technologies. Solid Formulations: Solid formulations are manufactured as carrier-based powders, granules, pellets, or fermented organic matrices. Common carriers include peat, lignite, vermiculite, biochar, compost, and clay minerals. These formulations provide extended shelf life, environment friendly, easier transport and storage, and sustained nutrient and metabolite release. Fermented solid matrices also enhance soil organic matter content and water retention following application. Products derived from solid-state fermentation are particularly well suited for field-scale cereal and millet cultivation, as they are compatible with conventional fertilizer application methods. The solid formulations may exhibit slower metabolite release, lower immediate bioavailability, and possible uneven distribution of active compounds, hybrid systems that combine liquid metabolites with solid encapsulating matrices are being increasingly explored to maximize both stability and bioactivity. The formulation strategy profoundly influences the field efficacy and consistency of biofertilizers, often determining their commercial success more than microbial composition alone(Zhao et al., 2024). Encapsulation methods provide protection for labile metabolites and microbial constituents against oxidative breakdown, UV exposure, desiccation stress, and premature release in soil, encapsulation enables controlled and sustained release, thereby improving product persistence and its agronomic effectiveness. Sodium Alginate Beads: Sodium alginate the most commonly used encapsulation polymers owing to its biocompatibility, biodegradability, non-toxic nature, mild gelation conditions, and excellent hydrogel-forming capacity. Alginate forms hydrogels with divalent cations such as Ca^{2+} via the "egg-box" crosslinking mechanism, generating stable beads capable of entrapping metabolites, microbial cells, enzymes, and nutrients(Colin et al., 2024).

Alginate bead encapsulation offers several benefits: protection of metabolites against environmental breakdown, extended shelf life and storage stability, controlled delivery of bioactive compounds, and greater persistence within the rhizosphere. The physicochemical behavior of alginate beads depends on factors such as alginate molecular weight, the mannuronic to guluronic acid ratio (M/G ratio), the type of crosslinking ion, and bead size and porosity. A high guluronic acid content yields firmer and denser hydrogels, whereas a higher mannuronic acid content enhances swelling and release characteristics(Phùng et al., 2025). Micro-encapsulation and Controlled Release: Microencapsulation techniques entrap bioactive compounds within microscopic polymer matrices, enabling highly tunable release profiles. Major methods include ionic gelation, spray drying, emulsion-based encapsulation, coacervation, and nanoencapsulation. Controlled-release systems enhance biofertilizer efficiency by reducing nutrient leaching, minimizing volatilization losses, prolonging metabolite persistence in soil, and matching release timing with plant nutrient demand.

Recent progress in alginate hydrogel engineering demonstrates that release kinetics can be precisely adjusted by modifying crosslinking density, employing polymer blends (e.g., alginate–chitosan or alginate–gelatin), incorporating nanoparticles, or designing multilayer capsules(Colin et al., 2025).Chitosan-coated alginate matrices have shown considerable promise for slow-release fertilizer applications, as the chitosan layer minimizes initial burst release and enhances overall structural integrity(Szopa et al., 2025).Controlled-release formulations hold particular value in sustainable agriculture by enhancing nutrient use efficiency, reducing environmental pollution, lowering the required frequency of fertilizer applications, and supporting long-term soil fertility. Emerging smart encapsulation systems are also being designed as stimuli-responsive release platforms triggered by factors such

as soil pH, moisture levels, enzymatic activity, or root exudates. Such technologies may represent the next generation of precision biofertilizer delivery systems.

16. Shelf-Life Stabilization

Ensuring adequate shelf life remains a major hurdle in the commercialization of fermentation-derived biofertilizers, as bioactive metabolites, microbial constituents, and organic matrices are highly affected by environmental factors including temperature, humidity, oxidation, and UV exposure. Deterioration during storage can lead to diminished metabolite activity, reduced microbial viability, phase separation, and inconsistent field performance.(Malusá et al., 2012) The storage stability of biofertilizer formulations is affected by moisture content, storage temperature, oxygen availability, carrier material properties, metabolite composition, and packaging conditions. Liquid formulations derived from fermentation are especially prone to instability, since soluble metabolites undergo hydrolysis, oxidation, and enzymatic breakdown over extended storage. Additionally, liquid systems are susceptible to contamination and sedimentation, which affects the formulation uniformity and agronomic efficacy(Bashan et al., 2014). To address these limitations, several stabilization approaches have been developed. 1. Carrier materials serve as protective matrices that adsorb metabolites and microbial components, thereby reducing environmental stress and improving storage stability. Substances such as peat, biochar, vermiculite, lignite, clay minerals, and compost-derived matrices have been extensively studied for their high adsorption capacity and moisture-buffering properties. Biochar-based carriers are especially promising, as their porous structure enhances the retention of metabolites and microbial cells while also improving soil conditioning after field application. Carrier systems further help mitigate oxidative degradation and enable gradual metabolite release under field conditions(Bhattacharyya et al., 2022). 2. Polymeric matrices and hydrogels have become advanced stabilization platforms for fermentation-derived biofertilizers. Hydrogels based on sodium alginate, chitosan, starch, and gelatin create protective micro-environments that reduce desiccation stress, limit oxygen diffusion, prevent rapid metabolite breakdown, and improve thermal stability. Encapsulation within hydrogel systems greatly prolongs storage duration by shielding metabolites from external environmental variations. The polymeric encapsulation can preserve microbial viability and metabolite activity for several months to over a year, depending on the formulation parameters (Colin et al., 2024). 3. Drying methods are commonly employed to stabilize biofertilizer formulations by lowering water activity. Key techniques include lyophilization, spray drying, and fluidized-bed drying. Freeze drying preserves labile metabolites and microbial structures more effectively than thermal drying methods, though it is relatively costly. Spray drying offers industrial scalability but may lead to degradation of heat-sensitive compounds. Thus, optimizing drying parameters is essential to balance metabolite retention, microbial survival, and production expenses(Ferreira-Suarez et al., 2024). Packaging materials affect storage stability by controlling oxygen exposure, moisture transfer, and light penetration. Vacuum-sealed and multilayer barrier packaging systems are increasingly employed to preserve bioactivity during storage and transport. Refrigerated storage further enhances formulation stability, especially for metabolite-rich liquid products.

Additionally, quality control protocols focusing on cell density, metabolite retention, moisture content, and contamination prevention are critical for maintaining commercial consistency(Matura et al., 2023). Recent studies are increasingly directed toward nanobiofertilizer systems, stimuli-responsive polymers, nanocomposite encapsulation matrices, and smart controlled-release platforms. Nanostructured encapsulation enhances stability by shielding metabolites from biological degradation while enabling slow and targeted release in soil environments. These systems also minimize nutrient losses and improve product persistence under field conditions(Das et al., 2026). Shelf-life stability continues to be a major constraint limiting the large-scale commercialization of fermentation-derived biofertilizers. Future efforts must therefore integrate materials science, polymer engineering, and fermentation biotechnology to develop formulations that are both stable and resilient under field conditions.

17. Compatibility with Conventional Fertilizers and Soil Amendments

The compatibility of fermentation-derived biofertilizers with synthetic fertilizers and soil amendments is critical for their effective integration into modern farming systems. Rather than seeking complete replacement of chemical fertilizers, most current approaches focus on integrated nutrient management (INM), wherein biofertilizers are applied alongside reduced rates of inorganic inputs to enhance nutrient use efficiency and agricultural sustainability. The combined applications of biofertilizers with synthetic fertilizers such as urea, diammonium phosphate (DAP), and NPK blends promote crop growth more effectively than either input used alone(Zainuddin et al., 2022).

These synergistic benefits arise because synthetic fertilizers supply immediately accessible nutrients, fermentation-derived metabolites enhance nutrient solubilization and uptake, biofertilizers stimulate microbial activity and root development, and soil amendments improve nutrient retention and structural integrity. Integrating biofertilizers with reduced rates of chemical fertilizers typically leads to greater nutrient use efficiency, increased plant biomass and yield, diminished fertilizer losses, and lower environmental pollution. In maize production, for instance, the combined application of biofertilizers with DAP and urea significantly improved plant height, leaf area, and grain yield compared to synthetic fertilizers alone(Wadria et al., 2024). The integrated use of biofertilizers and chemical fertilizers in oil palm systems improved nutrient acquisition, microbial diversity, root development, and biomass accumulation, while lowering the overall demand for synthetic fertilizers(Zainuddin et al., 2022).

Compatibility is highly dependent on fertilizer type and concentration. Excessively high levels of inorganic fertilizers may destabilize metabolites through osmotic stress and chemical interactions. Fermentation-derived biofertilizers show strong compatibility with organic amendments such as compost, vermicompost, biochar, farmyard

manure, and crop residue composts. These materials supply additional organic carbon and microbial niches, thereby enhancing the persistence and functionality of biofertilizer metabolites. Biochar is especially beneficial due to its high porosity, water-holding capacity, nutrient adsorption properties, and ability to support microbial colonization. Integrated systems that combine biochar with fermentation-derived biofertilizers improve nutrient retention, reduce leaching, and support long-term soil fertility (Khan et al., 2023). Despite the benefits of integrated systems, several compatibility issues persist. Potential problems include antagonistic interactions with pesticides and fungicides, metabolite degradation under strongly alkaline or acidic fertilizer conditions, reduced microbial activity due to salt stress, and physical incompatibility during tank mixing. Certain agrochemicals may also suppress beneficial microbial populations and diminish biofertilizer efficacy (Woolridge, 2024). Consequently, compatibility assessment should encompass physicochemical stability testing, metabolite retention analysis, microbial survival evaluation, and field-level agronomic validation.

Emerging formulation strategies are increasingly focusing on multi-component nutrient systems, co-formulated biofertilizer–biostimulant blends, precision fertigation-compatible products, and smart release platforms that align with crop nutrient demand. These integrated technologies are expected to substantially lower reliance on synthetic fertilizers while sustaining agricultural productivity and environmental sustainability.

18. Environmental and Sustainability Implications

Waste Valorization and Zero-Waste Fermentation

Fermentation-derived residues (FDRs) from agro-industrial processes including brewery waste, dairy fermentations, and bioethanol production are increasingly viewed as valuable resources rather than mere waste streams, which are abundant in microbial metabolites, extracellular enzymes, organic acids, amino acids, peptides, phytohormones, polysaccharides, and mineral nutrients, making them suitable for reuse as functional biofertilizers within circular bioeconomy frameworks. The valorization of fermentation residues aligns closely with zero-waste biorefinery principles by converting low-value organic by-products into agriculturally beneficial inputs and reducing environmental pollution (Orlandella & Fiore, 2025; Polipalli et al., 2025). Conventional disposal methods for fermentation residues such as landfilling or uncontrolled dumping led to methane emissions, eutrophication, odor problems, and nutrient loss. By contrast, the bio-transformation and agricultural reuse of these residues promote nutrient recycling and resource efficiency. Given their high organic carbon content and bioactive compounds capable of stimulating rhizosphere microbial activity and enhancing nutrient mobilization, fermentation residues offer a sustainable alternative to synthetic agrochemicals (Orlandella & Fiore, 2025).

Modern zero-waste fermentation systems combine upstream biomass utilization with downstream residue recovery, ensuring complete valorization of agricultural wastes. These systems use methods such as composting, anaerobic digestion, vermicomposting, microbial enrichment, and biochar production from post-fermentation residues. Integrating these into biorefinery frameworks enables the concurrent production of bioenergy, bio-stimulants, organic fertilizers, and soil conditioners while markedly reducing waste output (Polipalli et al., 2025). Fermented agricultural residues can act as an effective substitute for conventional organic amendments enhancing soil biological functions and crop productivity.

It is shown that fermented paddy straw and cereal residues improve soil organic carbon, microbial biomass, and nutrient cycling efficiency. Such valorization strategies also help reduce crop residue burning, a significant environmental problem in many farming regions. The circular economy framework emphasizes cascading biomass utilization, wherein fermentation residues are repeatedly converted into value-added agricultural products. This strategy enhances sustainability indicators by reducing raw material extraction, lowering waste management expenses, and maximizing nutrient recovery. Consequently, the conversion of agricultural biomass into biofertilizers and biomaterials is emerging as a cornerstone of sustainable waste management systems (Almeida et al., 2025).

Zero-waste biorefineries utilize thermo-chemical conversion methods such as pyrolysis and gasification to transform fermentation residues into biochar and syngas. Biochar derived from these residues enhances soil structure, water retention, cation exchange capacity, and long-term carbon sequestration, while simultaneously serving as a carrier for beneficial microorganisms (Shahzaib, n.d.). Thus, the valorization of fermentation-derived residues constitutes a transformative approach for sustainable agriculture, concurrently addressing waste management, nutrient recovery, renewable resource utilization, and environmental protection.

Reduction in Chemical Fertilizer Dependency

Over dependence on synthetic fertilizers has led to serious environmental consequences, including soil acidification, nutrient imbalances, groundwater pollution, biodiversity decline, greenhouse gas emissions, and reduced soil microbial diversity. Fermentation-derived functional biofertilizers provide an ecologically sustainable alternative by partially substituting for chemical fertilizers simultaneously improving nutrient use efficiency and soil biological health (Orlandella & Fiore, 2025). Fermentation residues supply bioavailable nutrients alongside microbial metabolite including organic acids, siderophores, amino acids, enzymes, phytohormones, and exopolysaccharides that enhance nutrient solubilization and uptake. These bioactive compounds facilitate phosphorus mobilization, nitrogen mineralization, and micronutrient availability, thereby lowering the demand for synthetic fertilizer inputs (Polipalli et al., 2025).

Biofertilizers derived from fermented agro-industrial residues have been shown to markedly improve nutrient use efficiency while sustaining crop productivity. Compared to highly soluble mineral fertilizers, the sustained nutrient release patterns of organic fermented residues reduce losses from leaching and volatilization. This slow-release property supports enhanced soil fertility sustainability and long-term nutrient cycling (Orlandella & Fiore, 2025).

Microbial metabolites in fermented residues stimulate native soil microbiota and foster beneficial rhizosphere interactions. This microbial enrichment enhances nutrient acquisition efficiency and suppresses soil-borne pathogens, in which indirectly reducing the need for synthetic fertilizers and pesticides. Fermentation-derived bio-stimulants have also been linked to improved root architecture and greater nutrient uptake efficiency under nutrient-limited conditions (Gabriele et al., 2026).

Circular farming models that use crop residues to produce organic fertilizers have been shown to significantly reduce the environmental burdens associated with synthetic fertilizers. The circular organic fertilizer systems based on agricultural residues lowered overall environmental and economic costs by roughly 57% relative to conventional, fertilizer-intensive agricultural practices (Sukuman et al., 2025). The substitution of synthetic nitrogen fertilizers with biofertilizers reduces fossil fuel use linked to the Haber–Bosch ammonia synthesis process. The production of mineral fertilizers is highly energy-demanding and a major contributor to global greenhouse gas emissions. The widespread adoption of fermentation-derived biofertilizers could lower the reliance on fossil-based inputs and improve the sustainability of agro-ecosystems (Orlandella & Fiore, 2025). The incorporation of fermentation-derived biofertilizers into nutrient management strategies is increasingly acknowledged as a critical pathway toward regenerative and sustainable agriculture.

Carbon Footprint and Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) has become a critical methodology for evaluating the environmental sustainability of biofertilizer production systems based on agricultural and fermentation residues. LCA studies provide a comprehensive analysis of environmental impacts across all stages, including feedstock acquisition, fermentation, residue processing, transportation, field application, and end-of-life disposal. Biofertilizers derived from agricultural and fermentation wastes show considerably lower environmental impacts compared to synthetic fertilizers. Notable reductions have been seen across several categories, including global warming potential, acidification, eutrophication, ecotoxicity, and fossil resource depletion (Orlandella & Fiore, 2025). Microalgae and fermentation-based biofertilizer systems have achieved environmental impact reductions of up to 38.65%, with mitigation efficiencies exceeding 50% when waste water reuse and integrated cultivation methods are employed. Key environmental hotspots identified in these systems include biomass cultivation, harvesting, drying, and transportation, pointing to opportunities for further process optimization (Havukainen et al., 2018). The application of fermentation-derived residues aids substantially in lowering carbon footprints by diverting organic waste from landfills and replacing energy-intensive mineral fertilizers.

Recycling organic residues encourages soil carbon sequestration through enhanced soil organic matter buildup and greater stabilization of microbial biomass. Moreover, biochar generated from fermentation residues further promotes long-term carbon storage in soils owing to its recalcitrant carbon structure (Shahzaib, n.d.). In Thailand, circular agriculture systems based on residue recycling demonstrated substantial reductions in disability-adjusted life years (DALY), ecosystem degradation, and resource depletion relative to conventional practices reliant on synthetic fertilizers and open residue burning (Sukuman et al., 2025). The shift toward circular agriculture in the Indian states of Punjab and Haryana has the potential to lessen Delhi's smog during winter by replacing residue burning with valorization techniques such as composting and feed production. Evidence from Thailand indicates that such systems significantly reduce health burdens (measured in disability-adjusted life years, DALY) and ecosystem damage while converting agricultural waste into economic assets. By moving policy focus from fire suppression to resource recovery, India could achieve a 50–60% reduction in environmental costs, alongside improvements in soil health and farm incomes. Even though there's a promising environmental advantage of biofertilizers, methodological inconsistencies have challenges in LCA studies.

Differences in functional units, system boundaries, allocation approaches, and impact assessment categories hinder direct comparisons across studies. Consequently, harmonization of LCA methodologies is increasingly advocated to enhance standardization and comparability of environmental evaluations for bio-based fertilizers (Vikki et al., 2026). Future LCA research should also incorporate socio-economic assessments, techno-economic analysis (TEA), water footprint evaluation, and circularity metrics to enable a more holistic sustainability assessment of fermentation-derived biofertilizer systems.

Role in Climate-Smart Agriculture

Climate-smart agriculture (CSA) aims to boost agricultural productivity, strengthen resilience to climate change, and lower greenhouse gas emissions. Fermentation-derived, metabolite-rich biofertilizers are highly consistent with CSA principles, as they enhance soil health, improve nutrient use efficiency, reduce environmental pollution, and support climate adaptation strategies (Gabriele et al., 2026). A key contribution of fermentation-derived biofertilizers to climate-smart agriculture lies in their ability to raise soil organic carbon levels and microbial diversity. Greater soil organic matter enhances aggregate stability, water retention, nutrient buffering, and resilience to drought and extreme climatic events. These attributes are especially critical under climate change scenarios marked by irregular rainfall and rising temperatures (Rathore et al., 2026). Fermentation-derived metabolites including phytohormones, amino acids, antioxidants, osmoprotectants, and exopolysaccharides enhance plant tolerance to abiotic stresses. These beneficial microbial compounds also activate systemic stress responses and improve root architecture, thereby increasing crop adaptability under unfavorable environmental conditions (Gabriele et al., 2026). As human-driven climate change is challenging the global agricultural output, sustainable nutrient management strategies with circular bioeconomy principles will grow ever more critical. Fermentation-derived biofertilizers thus offer a promising route toward developing resilient, low-carbon, and climate-adaptive farming systems (Ortiz-Bobea et al., 2021).

19. Circular Bioeconomy Integration

Closed-Loop Agricultural Systems

Closed-loop farming systems represent a foundational principle of the circular bioeconomy, in which agricultural wastes and fermentation-derived residues are continuously recycled as value-added inputs. Fermentation-derived residues (FDRs) can function as regenerative biofertilizers that restore nutrient cycles while reducing waste output. These systems shift agriculture from a linear "take–make–dispose" model toward a regenerative nutrient-cycling framework (Kurniawan, n.d.; Nguyen et al., 2025). In this, crop residues, agro-industrial by-products, livestock manure, food processing waste, and fermentation effluents are reused through microbial fermentation, composting, anaerobic digestion, and bioconversion technologies to produce biofertilizers and soil conditioners. These integrated approaches improve nutrient recovery efficiency and reduce environmental losses linked to synthetic fertilizers and waste disposal (Arsic et al., 2025). Fermentation-derived biofertilizers significantly enhance nutrient cycling by supplying both macro- and micronutrients in biologically active forms. In conventional fertilizers, these residues also stimulate microbial nutrient mineralization and rhizosphere activity, thereby improving nutrient retention and recycling within agroecosystems. Nutrient recycling from fermented residues lessens dependence on external chemical inputs and supports sustainable soil fertility management (Mahmoudi et al., 2025). Recent circular bioeconomy models increasingly integrate anaerobic digestion and fermentation processes with crop production. In such systems, agricultural residues are converted into biogas and digestate, while residual fermentation biomass is recycled as biofertilizer. This integration generates renewable energy and recovers nutrients, creating economically and environmentally sustainable agricultural loops (Rathore et al., 2026). Closed-loop systems also enhance soil organic carbon accumulation and microbial biodiversity. Frequent applications of metabolite-rich fermentation residues improve soil aggregation, moisture retention, enzymatic activity, and nutrient buffering capacity. These benefits contribute to long-term soil resilience and regenerative agriculture objectives (Orlandella & Fiore, 2025). Zero-waste biorefinery concepts further strengthen closed-loop agriculture by ensuring complete biomass valorization. Fermentation residues can be thermochemically converted into biochar, syngas, and bio-oil, while residual nutrients are returned to soils. Such systems maximize resource efficiency while lowering greenhouse gas emissions and landfill burdens (Shahzaib, n.d.). The integration of fermentation-derived residues into circular nutrient loops represents a promising pathway for sustainable agriculture, regenerative soil management, and climate-resilient food production systems.

Policy Frameworks and Economic Feasibility

The gradual shift toward circular bioeconomy-based biofertilizer systems depends heavily on supportive policy frameworks, regulatory alignment, financial incentives, and market development mechanisms. Governments and international bodies increasingly acknowledge the importance of organic waste valorization and nutrient recycling for achieving sustainability goals, climate mitigation targets, and food security objectives (Arsic et al., 2025). Several international policies encourage the use of waste-derived fertilizers and circular agricultural systems. The European Union's Circular Economy Action Plan and its Fertilising Products Regulation (EU 2019/1009) promote nutrient recovery from organic waste streams and facilitate the commercialization of bio-based fertilizers. These policies support the reuse of agricultural residues, digestates, composts, and fermentation by-products as sustainable agricultural inputs (Orlandella & Fiore, 2025). The Nordic Circular Economy Programme (2021–2024) established goals for diverting organic waste from landfills and encouraged biofertilizer production from biodegradable waste streams. Such initiatives bolster nutrient circularity and sustainable waste management infrastructure (Aborisade et al., 2026). Economic feasibility studies show that fermentation-derived biofertilizers can lower production costs by utilizing low-cost waste feedstocks. Agro-industrial residues are often abundant and inexpensive, making them rich substrates for microbial fermentation and biofertilizer manufacturing. Cost reductions are especially significant when savings from waste management and carbon mitigation benefits are factored into economic analyses (Garimella, n.d.). Despite promising economic potential, market feasibility of biofertilizers remains limited due to inconsistent regulations, a lack of standardized quality criteria, limited farmer awareness, and competition from subsidized synthetic fertilizers. Regulatory uncertainties concerning microbial safety, contaminant limits, shelf life, and efficacy validation further restrict commercialization (Shahzad et al., 2025). Carbon credit programs, green subsidies, circular economy incentives, and sustainable agriculture policies could substantially improve the economic competitiveness of fermentation-derived biofertilizers. Future policy frameworks should therefore integrate environmental externalities, climate mitigation benefits, and ecosystem services into fertilizer pricing structures to encourage the adoption of circular bioeconomy practices (Nguyen et al., 2025).

20. CONCLUSION

Fermentation-derived residues (FDRs) are emerging as next-generation functional biofertilizers with the potential to transform sustainable agriculture through metabolite-mediated mechanisms rather than reliance on live microbial inoculation alone. As highlighted throughout this review, FDRs contain diverse bioactive compounds including organic acids, amino acids, peptides, exopolysaccharides, phytohormones, phenolics, antimicrobial compounds, and microbial biomass components that collectively enhance nutrient mobilization, rhizosphere interactions, soil enzymatic activity, and plant physiological responses. These residues improve soil physical, chemical, and biological properties by increasing soil aggregation, water retention, cation exchange capacity, microbial diversity, and nutrient cycling efficiency, ultimately contributing to improved crop productivity and stress resilience. Beyond their agronomic benefits, FDRs represent an important strategy for agro-industrial waste valorization and circular bioeconomy integration. The reutilization of food processing wastes, lignocellulosic biomass, dairy

residues, brewery wastes, and fermentation effluents into metabolite-rich agricultural inputs supports zero-waste biorefinery concepts and closed-loop nutrient cycling systems.

Their ability to partially replace synthetic fertilizers can significantly reduce greenhouse gas emissions, nutrient losses, fossil fuel dependency, and environmental pollution associated with conventional fertilizer production and use. Despite substantial progress, challenges related to formulation stability, metabolite standardization, large-scale production, regulatory harmonization, and field-level consistency remain critical barriers to commercialization. Future research should focus on metabolomics-guided characterization, AI-assisted fermentation optimization, advanced encapsulation technologies, multi-omics integration, and long-term field validation across diverse agroecosystems. Overall, fermentation-derived residues represent a promising pathway toward regenerative agriculture, climate-smart farming, and resilient low-carbon food production systems capable of supporting global sustainability goals.

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Author contribution

SE – conceptualization, original draft, UT – supervision.

Declaration of generative AI use

During the preparation of this work, the authors used ChatGPT 4.0 to improve the grammar and clarity of the text. After using this tool/service, the authors/ reviewed and edited the content as needed and take full responsibility for the content of the published article.

Conflict of interest

The authors declare there is no conflict of interest.

Data Availability Statement

All the data are mentioned in the manuscript.

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