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REVIEW ARTICLE

Valourizing agricultural farm waste with bioinoculants for plant growth promotion and disease management

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Abstract

Soilborne pathogens such as *Fusarium* spp., *Pythium* spp., *Phytophthora* spp., *Verticillium* spp. causes significant yield loss to various agricultural and horticultural crops. These diseases are difficult to control by chemicals which are harmful to environment and crop health. On the other hand, continuous usage of pesticides leads to the development of pesticides resistance by the pathogens. Valourizing the farm waste by microbial bioinoculants is an alternative and promising approach for controlling soilborne diseases. Farm waste releases bioactive compounds with antifungal and antibacterial properties. Farm waste utilization reduces pesticide dependence by enriching soil, enhancing microbial diversity and promotes sustainable agriculture. Microbial bioinoculants serve as alternatives to synthetic pesticides for the management of plant pathogens. Beneficial microbes like nitrogen-fixing bacteria, phosphate-solubilizing microbes and biocontrol agents play a crucial role in strengthening the plant immunity against pathogens. These beneficial organisms not only improve soil biodiversity but also ensure better plant growth and development. This review focuses on the enrichment of agricultural farm wastes such as fruits and vegetable waste, coir pith, farm yard manure, biochar and chicken manure with bioinoculants for soil borne disease management. Harnessing microbial bioinoculants for farm waste valorization presents a promising pathway toward sustainable agriculture, ensuring environmental protection and long-term soil health.

Keywords: bioinoculants; disease management; farm waste; soil borne pathogens; soil organic carbon; valourization

Introduction

Agricultural activities generate a significant amount of waste, inclusive of crop residues, animal waste and agro-industrial by-products. Agricultural waste management is essential for maintaining soil health and ensuring a sustainable farming system. These activities result in large quantity of the agricultural residue, including crop residues, straw and organic waste. To reduce greenhouse gas emission, smoke from residue burning and soil deterioration, it is important to manage this biomass effectively. Globally, agricultural waste accounts for approximately 998 million tons (1). According to the World Wildlife Fund (WWF), 26 % of fruits and vegetables from total food production end up as waste, followed by 15 % from roots, tubers and oil crops, 12 % from animal waste and 14 % from cereals and pulses (2). The quantity and value of the organic waste production are depicted in Fig. 1. Effective management and utilization of this waste are essential to reduce environmental impact and enhance sustainable farming practices. An innovative approach for addressing this challenge is the valorization of biomass using potential bioinoculants. The valorization process includes the decomposition and enrichment of organic biomass with beneficial organisms *viz*., plant growth promoting rhizobacteria (PGPR) and biocontrol agents to manage the soil borne plant pathogens (3). In this bioconversion involves transforming organic waste into compost and then enriched with crop specific bioinoculants through biological processes. Valorization of farm waste not only aids in waste management but also contributes to improved soil health, reduced use of chemical pesticides and supports environmentally responsible farming practices. Bioinoculants play a pivotal role in this process for colonization and inhabiting plant root system (4). They act as a shield and protecting the roots from soil borne pathogens *viz*., *Pythium*, *Phytophthora*, *Sclerotinia*, *Macrophomina*, *Rhizoctonia*, etc (5). The diversity of plant growth-promoting microorganisms plays an important role in disease reduction (6). Valorization of farm waste using microbial bioinoculants and disease controlled are listed in Table 1. Adopting this integrated approach can lead to more sustainable and productive farming systems, contributing to long-term agricultural sustainability and environmental conservation. In this review valorization of biochar, fruits and vegetable waste, coir pith, farm yard manure and chicken manure are discussed in detail.

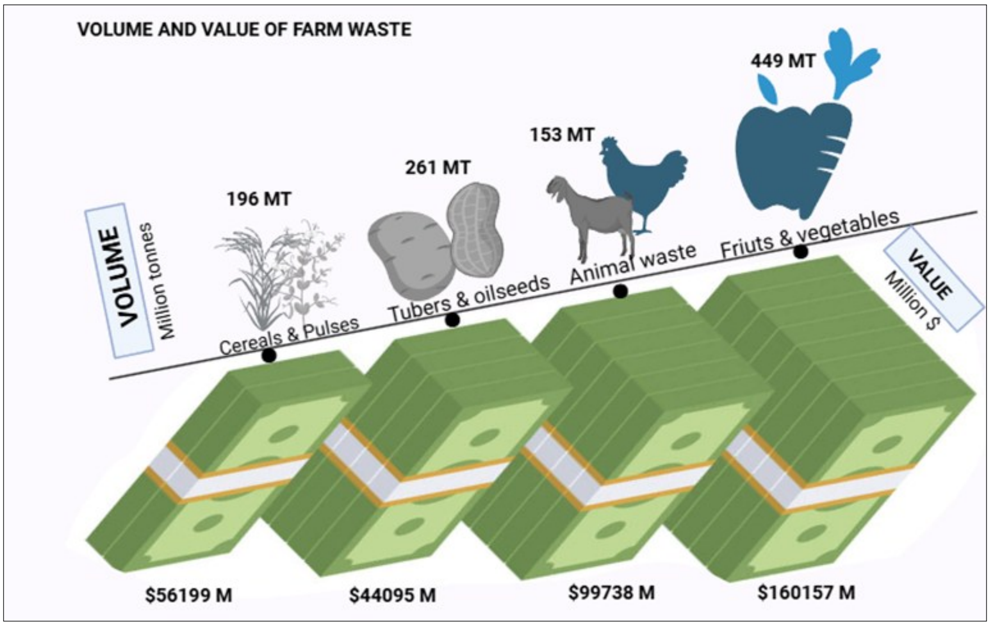

Fig. 1. Quantum of agricultural farm waste and its value.

Table 1. Valorization of farm waste using microbial bioinoculants and disease controlled

Sl. No.	Nature of farm waste	Bioinoculants multiplied	Disease controlled	Crop	Disease reduction (%)	Reference
1	Green waste biochar	*Bacillus subtilis*	Early blight (*Alternaria solani*)	Tomato	>50 %	(62)
2	Biochar	*Pseudomonas*, *B. subtilis*	Wilt (*Fusarium oxysporum* f. sp. *lycopersici*)	Tomato	40-42 %	(58)
			Wilt (*Fusarium* spp.)	Radish	60-70 %	(63)
			Root rot (*Rhizoctonia solani*)	Cucumber	40-60 %	(60)
3	Rice husk biochar	*Pseudomonas* sp, *Azotobacter chroococcum* and *Azospirillum brasilense*	Bacterial wilt (*Ralstonia solanacearum*)	Banana, eggplant, peanut, potato, tobacco, tomato	45-65 %	(86)
4	Spent Mushroom biochar	*P. fluorescens*, *B. subtilis*	*Fusarium oxysporum*, *Pythium aphanidermatum*, *Rhizoctonia solani*, *Phytophthora palmivora*, *Sclerotium rolfsii* and *Ralstonia solanacearum*	Tomato	60-70 %	(74)
		Trichoderma asperellum	Wilt (*Fusarium oxysporum* f. sp. *lycopersici*)	Tomato	70-75 %	(78)
5	Dried banana leaf and pseudostem	*T. harzianum*	Wilt (*Fusarium oxysporom* f. sp. *cubense*)	Banana	>60 %	(87)
6	Mango processing industry	*T. asperellum*	Anthracnose (*Colletotrichum gleosporoides*)	Mango	55-60 %	(34)
7	Coco peat	*Trichoderma harzianum*	Damping off (*Fusarium oxysporum* f. sp. *lycopersici*) Root rot (*Phytophthora capsica*)	Tomato, chilli	60-65 %	(88)
8	Coconut fibre	*T. asperellum*	*Fusarium* wilt (*Fusarium oxysporum* f. sp. *lycopersici*)	Cherry tomato	60–70 %	(37)
9	FYM	*Bacillus* spp.	Wilt (*Ralstonia solanaecearum*)	Egg plant	50–60 %	(42)
		B. subtilis, *Trichoderma asperellum*	Late blight (*Phytophthora infestens*)	Potato	50-55 %	(43)
10	Chicken manure	*T. harzianum*	Seedling mortality - damping off, wilt (*Fusarium oxysporum* f. sp. *phaseoli*, *Ralstonia solani* and *Sclerotium rolfsii*)	Bush Bean	>60 %	(89)
		Bacillus spp.	Root knot Nematode (*Meloidogyne incognita*)	Cucumber	65-70 %	(85)

PGPR bioinoculants for valorization

The plant growth promoting rhizobacteria (PGPR) are potential microorganism, which conquer plant roots act as protective wall against soil-borne pathogens (7). The promising genera of PGPR *viz*., *Bacillus subtilis*, *B. amyloliquefaciens*, *Pseudomonas fluorescens*, *P. striata*, *Azotobacter*, *Rhizobium*, *Acinetobacter*, *Serratia*, *Actinoplanes*, *Enterobacter*, *Cellulomonas*, *Thiobacillus*, *Flavobacterium* and various taxa are under PGPR (8). They synthesize chemical compounds that are beneficial for growth and defense mechanism of plants (9). The plant growth promoting activities of PGPR was given in Fig. 2. PGPR also contributes to induced systemic resistance in plants and is often utilized as a biological agent to suppress plant diseases and pests (10). To function effectively in the rhizosphere, PGPR must be both competitive and compatible with native microbial communities.

The PGPR has a significant impact on soil properties and fertility. In addition to that, these microbes exhibit a synthesis of a variety of biochemical compounds such as exopolysaccharides and phytohormones, siderophores, hydrogen cyanide and antibiotics promote plant growth (11). It also has a role in absorption of nutrients, nitrogen fixation, phosphate and potassium solubilization (12). Several studies have reported that these microbes are used for partially decomposition of farm waste and manures. The ideal carriers such as compost, biogas slurry, crushed corn cobs, biochar, press mud, fruit peels, peat, zeolite, perlite, lignite and talc can be utilized as substrate for PGPR (13). They found that the various types of vegetable waste, crop residues and animal feces can be effectively utilized as carrier materials. The native PGPR strains are becoming more significant as economical and ecofriendly microbes that can be applied for management of crop diseases (14). PGPR controls phytopathogens by triggering systemic resistance through metabolic pathways (15).

Fungal inoculants for valorization

Apart from bacterial inoculants fungal bioinoculants play a major role in enhancing plant growth and reduction of disease progression in crops. *Trichoderma* has a high rate of multiplication, high nutrient uptake capacity, root colonizing ability and triggered systemic resistance of plant (16). According to Bettiol (17) *Trichoderma* species such as *T. harzianum*, *T. atroviride*, *T. stromaticum*, *T. asperellum*, *T. lignorum*, *T. koningiopsis* and *T. fertile* are the commercialized strains used worldwide. *Trichoderma* spp., synthesize mycolytic enzymes such as β-1, 3 glucanases, β-1, 4 endo-glucanases, chitinases and proteases are known to broken down the chitin layer of pathogen (18). *Trichoderma* synthesizes a wide range of secondary metabolites, many of which exhibit antifungal activity against plant pathogens. These antifungal metabolites include compounds like 6-pentyl-2H-pyran-2-one, harzianopyridone and various anthraquinones (19). These metabolites often have broad-spectrum activity against fungal pathogens. *Trichoderma* showed antagonistic activity against *Rhizoctonia solani* and *Macrophomina phaseolina* (20). Addition of soil organic matter enriched with biological antagonists develop suppressiveness for managing soil-borne diseases (21).

Soil organic carbon

Intensive farming practices and the continuous use of chemical fertilizers and pesticides have significantly depleted soil organic carbon (SOC), disrupting soil microbial communities and favoring the proliferation of plant pathogens. Recent studies have shown that such conventional agricultural practices reduce SOC due to enhanced microbial respiration and the absence of carbon-returning practices like residue retention. On the other hand, the application of valorized farm waste and bioinoculants has been proven effective in restoring SOC and enhancing microbial diversity. A meta-analysis demonstrated that organic amendments, such as compost and green manure, increased SOC by an average of 18 %, with individual studies showing increases up to 24 % (22). It was further reported that biofertilizers enhanced SOC by 0.44 g C kg^{-1} soil, particularly those involving mycorrhizal fungi and cyanobacteria (23). A recent study in paddy fields showed that bio-organic fertilizers and rice-straw-derived biochar improved SOC content by 26.1 % and 30.7 %, respectively, within just 180 days of application (24). These findings affirm that combining

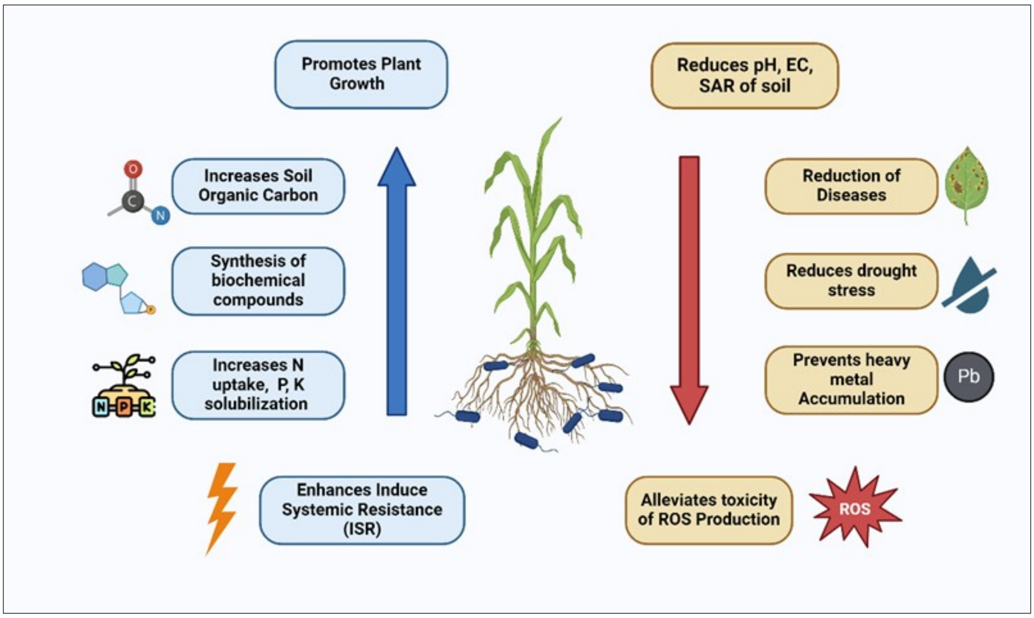

Fig. 2. Plant growth promoting role of PGPR in soil application.

organic waste amendments with bioinoculants can sustainably boost SOC, improve soil health and support resilient agricultural systems.

Valorization of agricultural and agro-industry waste and byproducts

Fruits and vegetables waste

The global production of fruits and vegetables is about 675 million metric tonnes annually and among them, 1.3 billion tonnes of waste are generated (25). It contributes 26 % of fruits and vegetables being wasted and they are beneficially used nowadays for sustainable organic agriculture. They are composted and supplemented to crops for the benefit of nutrient enrichment and biological management of diseases. *Trichoderma* has been found to exhibit a variety of interactions with soil-borne fungal diseases, including *Phytophthora*, *Rhizoctonia*, *Fusarium* and *Pythium* in vegetable crops like tomato, brinjal, cucurbits and okra (26).

Banana farms produce about 4 tonnes of waste for each tonn of bananas, which includes waste fruits, pseudostems, leaves, inflorescences and skins. They are easily degraded and have a suitable carbon-nitrogen fixation ratio. Among them, 40 million tonnes of banana peel are generated every year which accounts for 35 % of the total weight of bananas (27). The banana peel is a novel carrier material for bioformulation. The presence of tryptophan, a key amino acid precursor for microbial indole-3-acetic acid (IAA) synthesis, in banana peel powder highlights its potential as an effective organic talc based carrier material (28). It increases the shoot length and yield of rice crops. It contains macro and micronutrients and processes tryptophan which are the precursors for indole acetic acid (IAA). IAA producing the ability of microbes depends on the available precursor and it is supplemented by banana peel. It helps microbes with wider multiplication and higher auxin production. The phosphate-solubilizing bacteria multiplied from banana waste support the growth and survival of *Musa paradisiaca*, suggesting promising ecological benefits such as improved soil fertility and reduced dependence on chemical fertilizers. However, further research is necessary to fully understand their long-term effects on soil microbiota, nutrient cycling and overall ecosystem stability (29).

Orange peel, known for its high pectin content, has been used as a composting material that supports the growth of *Bacillus velezensis*. This bacterium, when cultured using orange peel compost, has shown potential in promoting drought stress tolerance and nodulation in soybeans, as well as contributing to the biological suppression of root knot nematodes (*Meloidogyne* spp.) in cotton and soybean crops (30). Jack fruit seeds along with rice porridge are effectively used as a substrate for the multiplication of *Azospirillum brasilense*, *A. lipoferum*, *Pseudomonas putida*, *P. fluorescence*, *Burkholderia cepacia* which are used for growth promotion of plantation crops (31). The fruits and vegetable waste *viz.*, potato peel, banana, brinjal, papaya, spinach, guava, agroindustry byproducts sugarcane bagasse, used tea leaves and pea husk were used an ideal substrate for the multiplication of *Trichoderma harzianum* and *T. viride* (32).

Experiments were done with the medium made of wheat straw + apple pomace (WsA) and another medium namely T-GRAN made of dried onion rind, apples and strawberry pomaces, rapeseed meal was combined in a 1:1:1:1 ratio. *T. atroviride* and *T. harzianum* were used to treat those mediums. The effect of adding these organic materials to the soil was found to be substantial in lowering *Sclerotinia sclerotiorum* a pathogen causing white mold in vegetables and fruits. The carrier WsA overgrown with *T. virens* was particularly effective regardless of application dose, it entirely stopped the sclerotia of *S. sclerotiorum* from surviving (33). The dry wastes (dw) produced during the processing of mangoes were analysed and found to be primarily composed of soluble carbohydrates (71 ± 2 %) and fibre (16 ± 1 %) in dry weight. These materials were then used as carriers of *Trichoderma asperellum*, effective against the mango anthracnose pathogen *viz.*, *Colletotrichum gloeosporioides* (34).

Coir pith

Coir pith, a byproduct of the coconut-based coir industry and commercially known as coco-peat, is widely utilized as a substrate for raising vegetable seedlings under protected cultivation systems. It has also proven effective as a carrier material for the multiplication of *Trichoderma* spp., which is vital for the biological control of soil-borne diseases. Studies have shown that coir pith enriched with neem cake medium significantly enhances the colony-forming units (CFUs) of *T. harzianum* within seven days of incubation, making it suitable for soil application. However, large-scale extraction and utilization of coir pith raise ecological concerns, including the depletion of organic matter in coconut-growing areas, potential imbalances in soil ecosystems and disposal challenges of spent material post-application (35). Extensive removal of coir pith from coconut husks can lead to the depletion of organic matter in coconut-growing regions, potentially disrupting local soil ecosystems and contributing to soil imbalances. Over time, this may affect soil structure, water retention capacity and microbial diversity.

Sriram studied the suitable substrate for *T. harzianum* multiplication in coco-peat and they are utilized for growth of tomato and chilli seedlings (36). The multiplication of *T. asperellum* in coconut fibre found that the rate of multiplication was 9.053 × 10^5 CFU per gram of coconut fibre after 120 days of inoculation when compared to oil palm fruit bunches which produced the second-highest amount CFU of 7.406 × 10^5 CFU per gram (37). Additionally, the intensive harvesting process may strain natural resources and contribute to environmental degradation. Another concern arises post-application of biocontrol agents like *Trichoderma* spp. although beneficial for plant health, their large-scale use may create disposal issues, especially if residual biomass or microbial load accumulates in the environment.

Farm yard manure

Farm yard manure (FYM) prepared from cattle dung is nutrient enriched compost for plants. Seed treatment with PGPR and FYM prevents seed borne diseases. *Pseudomonas florescence* which has antifungal, antinematode, growth promotion and defense inducing properties are mass multiplied with FYM. They increase the bulb size of onions and prevents wilt, root rot and damping off disease of different crops (38). Farm yard Manure application with potential zinc solubilizing microbes used for integrated soil fertility management (39). Seed inoculation of *Azotobacter*, phosphate solubilizing bacteria multiplied with FYM increase the plant height, cob length and yield of pearl millet (40). FYM, phosphorus and phosphate solubilizing bacteria helps nodulation, growth and yield of kabuli chickpea (41). Microbiome enriched FYM using *Bacillus* spp. results increased yield and suppression of wilt disease caused by *Ralstonia solanaecearum* of eggplant compared to alone application of FYM (42). Compared to other treatments, combinations of FYM + *B. subtilis* and FYM + *Trichoderma asperellum* were more successful in managing potato late blight. In terms of disease incidence, the plants treated by FYM + *T. asperellum* and FYM + *B. subtilis* revealed lowest rates, at 16 % and 17 %, respectively. The experiment was conducted with three replicates using a randomized complete block design (RCBD). Statistical analysis was done using ANOVA and differences between treatments were tested using LSD at $p \leq 0.05$. The study took place under field conditions with an average temperature of 18–25 °C and humidity between 75 % and 85 %. The soil was loamy with a pH of 6.8. Furthermore, the area under disease progressive curve for FYM + *Trichoderma asperellum* was the lowest (806.62) when compared to the untreated application of FYM alone (2587.86) (43). Treatment with poultry manure and biofertilizers recorded the lowest prevalence of *cercospora* leaf spot (11.18 %) (*Cercospora capsici*) in capsicum and reduced the presence of *Fusarium* root rot (11.42 %), caused by *Fusarium solani* of capsicum and peas (44).

Biochar

The Biochar were developed using organic substrates like wood, dung, or leaves in oxygen limited environment (45). By the process of pyrolysis or dry carbonization, biomass is burnt in anaerobic conditions at temperature between 300 and 700 °C to create biochar, as an activated carbon soil conditioner (46). The addition of biochar significantly stabilizes photosynthetic carbon and raises the amount of chlorophyll, stomatal conductance, photosynthetic rate and relative water content (47). The increased presence of vital nutrients in the soil, such as K+ and the reduction of Na+ absorption are the direct mechanisms of biochar (48). The enhancement of soil enzymatic activity, biological and physiochemical characteristics raised the plant water status represents the indirect mechanism (49). Biochar's high surface area serves as a substrate for PGPR and supplies them with enriched nutrients necessary for its existence (50).

The colonizing effectiveness of PGPR with charcoal is a beneficial strategy to improve soil quality (51). In salt-affected soil, biochar decreased Na+ uptake while boosting K+ uptake when combined with PGPR. Another well-known feature of biochar is its capacity to lower pesticides and heavy metals, which can have negative effects on crops, soil and human health (52). Combination of biochar and PGPR in plant growth promotion has been studied in soybean (53), chickpea (54), French beans (55) and wheat (56). The combined effect of biochar and PGPR on maize and rice are used for the management of abiotic stresses such as drought and salinity respectively (57). The combination of PGPR and biochar represents a promising strategy to improve soil quality. However, its effectiveness is influenced by variables including soil texture, the origin of the biochar feedstock and the quantity applied, as excessive biochar may lead to nutrient imbalances.

The application of biochar has been reported for the reduction of *F. oxysporum* f. sp. *lycopersici* on tomato (58), *Podosphaera aphanis* on strawberry (59), *Rhizoctonia solani* on cucumber (60), *Botrytis cinerea*, *Leveillula taurica* on tomato and pepper (61). The green waste biochar was also found to be effective in suppressing *Alternaria solani* in tomato (62). In addition to that, the combination of *B. subtilis* and biochar application in tomato crop was highly effective against *A. solnai* and *F. oxysporum* f. sp. *lycopersici* when compared biochar alone. It was observed that *B. subtilis* along with biochar effectively control the *Fusarium* wilt in radish and promote plant growth (63).

Biochar and bio-inoculum

Rice husk biochar*:* The integration of plant growth-promoting rhizobacteria (PGPR) with agricultural waste products, such as rice husk, is an innovative approach to enhancing soil health and managing soil-borne diseases. Rice husk, the outer shell of rice grains, is a major by-product of rice milling. It is abundant, renewable and rich in organic matter, making it a suitable candidate for valorization. Rice husk ash, which is a source of carbon and silica has porous physical structure, good for sustaining microorganisms and retaining moisture. This indicates the plant can uptake silicon element *via* their root in a soluble state. Moreover, employing rice husk ash can enhance soil structure and increase soil aeration. Researchers found that rice husk ash, peat, vermiculite, alginate, wheat bran and clay are acceptable materials for usage as a carrier (64). Microorganisms can proliferate and survive in these carriers for longer periods.

The application of Rice husk biochar (3.6 g kg^{-1} soil) along with PGPR strains *viz.*, *Pseudomonas* sp., *Azotobacter chroococcum* and *Azospirillum brasilense* significantly enhanced higher grain and straw yield and increased the uptake of nutrients (phosphorous, zinc, iron) in rice (65). Multiplication of beneficial bacteria such as *Bacillus*, *Bradyrhizobium*, *Burkholderia*, *Chlorochromatium*, *Chthoniobacter*, *Geobacillus*, *Leptospirillum*, *Marisediminicola*, *Microvirga*, *Pseudoxanthomonas*, *Telmatobacter in r*ice husk biochar can be applied for different vegetable crops (66). The reduction of the bacterial wilt disease caused by *Ralstonia solanacearum in* different crops *viz*., banana, eggplant, potato, tobacco, peanut, tomato were noticed. Biochar made of rice husk with *Bacillus* spp. showed inhibitory activity against *Phytophthora nicotianae*, reduced the survival of pathogens in soil and decreased the disease severity of tobacco black shank disease (67). The rice husk biochar was combined with biocontrol agents such as *B. subtilis* and *Trichoderma harzianum* which can control root knot nematode *Meloidogyne incognita* in tomato (68). Interestingly *B. subtilis* with 3 % rice husk biochar increased overall plant growth and decreased *Meloidogyne incognita* losses. However, while RHB presents numerous agronomic and biological benefits, certain limitations must be considered. These include the risk of silicon toxicity at high concentrations, alterations in soil pH that may affect nutrient availability, potential heavy metal contamination depending on the rice husk source and a possible reduction in microbial diversity due to selective promotion of specific microbial populations. Therefore, careful assessment of soil conditions, biochar quality and appropriate application rates is essential to optimize the benefits of rice husk biochar in sustainable agriculture.

Spent mushroom substrate: Spent mushroom substrate (SMS) is a byproduct from mushroom cultivation using *Agaricus bisporus* and *Pleurotus* spp. after mushroom harvesting (69). These edible mushroom fungi are mainly cultivated in agricultural raw wastes such as paddy and millet straw and bagasse (70). Adding SMS-biochar along with pig manure and rice straw lowered the compost's organic matter loss and enhanced the calcium, potassium, phosphorus and nitrogen contents. Recent studies demonstrate, biochar prepared from spent black fungus substrates and spent Shiitake mushroom has enhanced surface area and high porosity. SMS biochar offers advantageous properties that allow for improved microbial attachment and growth that promote plant growth, including as adequate surface area, pore size and functional groups (71). Among the beneficial uses of SMS, the application of SMS along with different bioinoculants in soil and its disease controlling property is quite interesting. Larkin and Fravel demonstrated the reduction of bacterial wilt and damping off diseases in tomato which are serious soil borne diseases (72). SMS extract of *Hericium erinaceus* showed high antagonistic activity against some phytopathogenic bacteria (73). Under *invitro* condition fortified SMS by *P. fluorescens* and *B. subtilis* effectively reduced incidence of *Ralstonia solanacearum*, *Fusarium oxysporum*, *Phytophthora palmivora*, *Pythium aphanidermatum*, *Sclerotium rolfsii* and *Rhizoctonia solani* and tomato (74). Application of both PGPR and SMS significantly reduced the abundance of *Fusarium oxysporum* in the rhizosphere (75).In addition, SMS along with compost, chicken manure significantly reduced the abundance of pathogenic fungi, specifically *Magnaporthe grisea* in rice seedlings (76). SMS from *Pleurotus florida* and *P. sojar-caju* with the antagonist *Pseudomonas aeruginosa* and *B. subtilis* are used to control the nursery disease of black pepper (77). SMS of *Pleurotus ostreatus* was biofortified with *Trichodrema asperellum* shows higher multiplication rate of 12.37×10^{13} conidia/g substrate and effectively controls *F. oxysporum* f. sp. *lycopersici* in tomato (78). SMS with *Serratia* sp., *Bacillus cereus and B. subtilis* controls rice sheath blight and root knot nematode disease (79). Furthermore, the high carbon-to-nitrogen (C:N) ratio in SMS can cause nitrogen immobilization, leading to nutrient deficiencies and reduced crop performance. In some cases, fungal secondary metabolites present in SMS may exhibit allelopathic effects, potentially inhibiting the growth of certain crops or disrupting beneficial microbial communities. Therefore, while SMS holds significant potential as a sustainable agricultural input, its use must be carefully managed through appropriate pre-treatment, dosage regulation and regular monitoring to ensure environmental safety and agronomic efficacy.

Chicken manure: Rural poultry production technology, one of the components of integrated farming systems, has been estimated to increase the benefit–cost ratio by 2.5 times, significantly improving the small and marginal farmer income by diversifying revenue streams and lowering input cost (80). In addition, it can be effectively utilized by farmers as organic fertilizer because of its high macro and micronutrient content (81). For macro and micronutrients, particularly N, P, K and S, chicken dung is a valuable resource (82). Soil physical qualities are improved by using chicken dung. Furthermore, it minimizes the danger of nutrient loss and preserves soil fertility (83). Adding chicken manure helps the soil's physical characteristics, giving it a crumb structure and enhancing soil aeration by increasing the porosity, or pore space, which influences root development. This chicken manure is effectively used as a substrate for the multiplication PGPR. Chicken manure and PGPR are used for shallot plants (*Allium ascalonicum* L.) which can increase the growth of the plant, number of bulbs per hill and number of leaves per clump (84). Under greenhouse conditions, the application of animal (cow, sheep and chicken) manures mixed with *Bacillus* spp. decreases galls and reproduction of root knot nematode *Meloidogyne incognita* in cucumber (85). However, despite its agronomic potential, chicken manure presents several health and environmental risks if not properly treated or applied. Pathogen contamination is a major concern, as raw manure can harbor harmful microorganisms such as *Salmonella*, *Escherichia coli* and *Clostridium perfringens*, posing threats to food safety and human health. Improper application may also lead to excessive ammonia emissions, contributing to air pollution, odor issues and soil acidification. Moreover, chicken feed additives can introduce heavy metals into the manure, which may accumulate in soils and be taken up by crops, impacting food safety. Over-application of manure can result in nutrient overload, especially nitrogen and phosphorus, leading to runoff, water pollution and eutrophication of nearby water bodies. The absence of proper drying, composting, or treatment measures may exacerbate these risks. Therefore, while chicken manure is a valuable input for sustainable agriculture, its application should be guided by best practices including composting, dosage regulation and periodic soil and water quality assessments to ensure environmental safety and crop productivity.

Conclusion

The post-Green Revolution era has seen tremendous strides in agricultural productivity, yet it has also brought serious ecological consequences due to the overuse of chemical inputs and intensive farming practices. Valorizing agricultural waste such as crop residues (rice straw, sugarcane trash, maize stalks) and agro-industrial byproducts (press mud, paddy husk, peanut shells) offers an innovative path toward improving soil health and managing soil-borne pathogens in a sustainable manner. Biofertilizers and microbial bioinoculants, when combined with organic substrates like biochar, spent mushroom substrate and animal manures, have shown promise in enhancing soil fertility, nutrient availability and microbial diversity. These eco-friendly inputs represent a potential alternative to synthetic agrochemicals, aligning with the goals of sustainable agriculture. However, this approach is not without challenges. Many agricultural and agro-industrial wastes may contain residual pesticides, heavy metals, or pathogens if not properly treated or composted. Such contaminants pose a risk to soil, crops and human health. Moreover, overapplication of organic inputs may lead to nutrient imbalances, altered soil pH, or disrupted microbial equilibrium. The effectiveness of biofertilizers also varies with environmental factors such as soil type, climate and existing microbial communities. In some cases, introduced PGPR strains may compete with or suppress native soil microbiota, while their slow-release nature demands consistent, long-term application to achieve noticeable improvements. Therefore, the promotion of biofertilizers and waste-derived soil amendments should be coupled with strict quality control, scientific validation and region-specific application strategies. Government support, public awareness programs and farmer training are essential to ensure the safe and effective use of these materials. Financial assistance and incentives can further encourage entrepreneurship in biomass valorization. A SWOT analysis (Fig. 3) has been included to summarize the key strengths, weaknesses, opportunities and threats associated with using bioinoculants and agricultural waste. This holistic perspective will help guide future research, inform policy frameworks and support the transition toward sustainable, climate-resilient farming systems.

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Authors' contributions

SJ and VS conceived the concept and wrote the manuscript. VS and MS gave ideas for the design of the diagrams and tables. SJ designed the diagrams and tables. SJ, VS, VG, SKM, PM and MS revised and finalized the manuscript. All authors read and approve the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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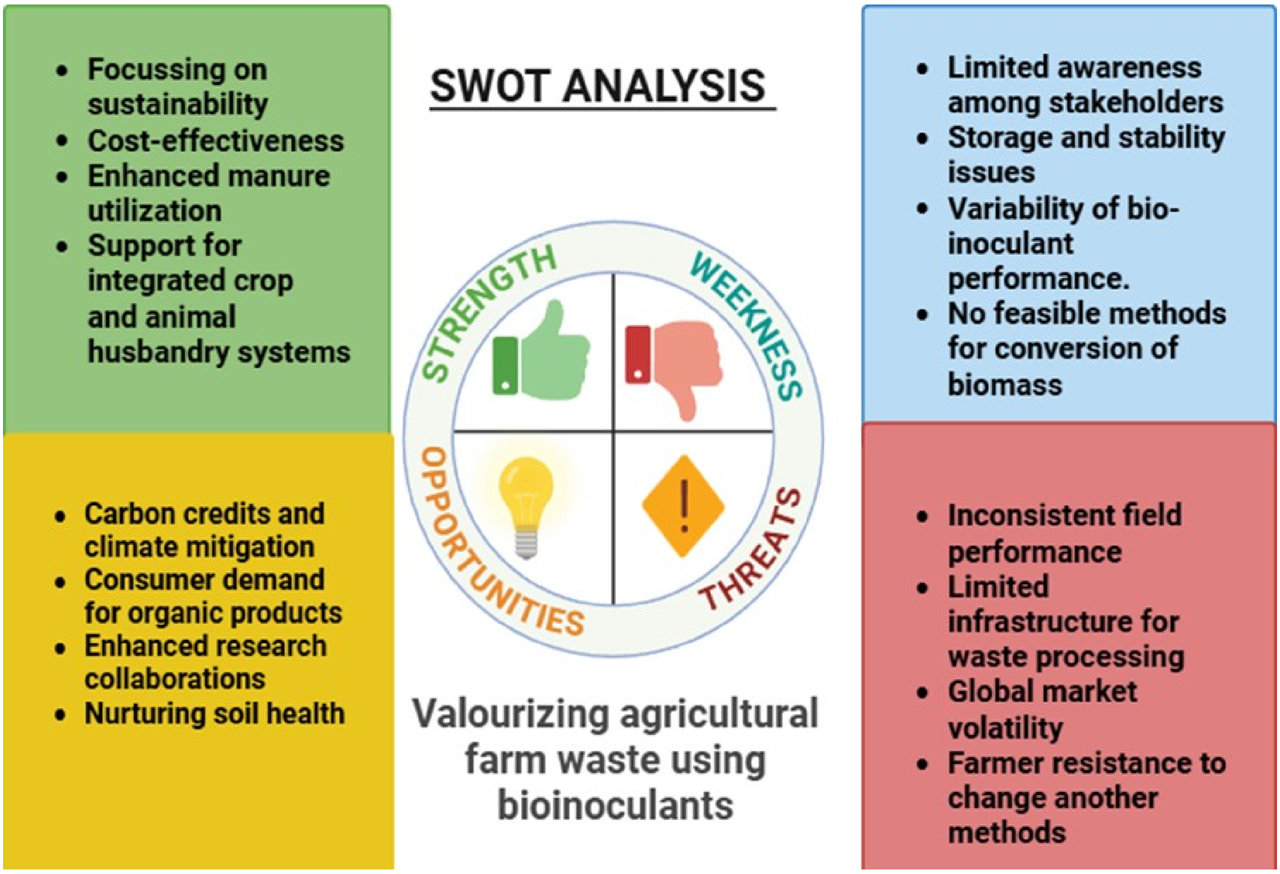

Fig. 3. SWOT (strengths, weaknesses, opportunities and threats) analysis for valourizing agricultural farm waste.

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