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REVIEW ARTICLE

Advancing Circular Bioeconomy Through Waste Valorisation: Synergistic Roles of Microbial Biofertilizers and Biochar in Climate-smart Agriculture

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Abstract: Despite extensive research on microbial biofertilizers and biochar as individual soil amendments, a critical knowledge gap remains regarding their integrated production from organic waste streams and their synergistic contribution to climate-smart agriculture. This review aims to consolidate current advances in waste valorization pathways that convert agricultural, municipal, and industrial residues into microbial inoculants and biochar, and to elucidate the biochemical and soil-plant mechanisms underpinning their combined functionality. Evidence across studies indicates that waste-derived microbial biofertilizers enhance soil nutrient dynamics through biological nitrogen fixation, phosphorus solubilization, siderophore-mediated micronutrient acquisition, phytohormone synthesis, and pathogen suppression, with liquid formulations offering superior microbial stability and activity. Concurrently, thermochemically produced biochar provides recalcitrant carbon for long-term sequestration, improves soil physicochemical properties, enhances cation exchange capacity, and serves as a protective microhabitat that sustains beneficial microbial communities. Their co-application consistently results in higher nutrient-use efficiency, soil enzymatic activity, plant biomass, and resilience to abiotic and biotic stressors compared to single amendments. Persistent constraints-including variable field performance, limited microbial survivability, quality inconsistencies, economic barriers, and inadequate extension support-limit widespread deployment. Emerging innovations such as omics-guided strain optimization, engineered microbial consortia, biochar functionalization, and regulatory frameworks provide promising avenues for overcoming these limitations. Overall, integrating microbial biofertilizers and biochar within circular bioeconomy strategies offers a robust, scalable pathway for enhancing soil health, reducing chemical fertilizer dependency, and advancing climate-adaptive agricultural systems.

Keywords: Circular bioeconomy, waste valorisation, biofertilizers, biochar, liquid biofertilizers, climate-adaptive agricultural systems.

1. INTRODUCTION

The circular bioeconomy is an interdisciplinary economic model based on the principles of sustainability, circular economy, and bioeconomy. Unless the bioeconomy develops biocircularity, which is based on sustainable biomass production, reuse, recycling, and design for degradation, it could still be wasteful and harmful to resources and ecosystems. It is unique and valuable because it lays out a way to address the challenges of circularity in a bioeconomy, especially where resource limits, environmental harm, and its relationship with food systems are considered [1]. Issues like climate change, limited resources, and environmental damage have become so serious.A circular economy (CE) can be one of the solutions as it enables the long-term use of materials and resources through reuse, repair, recycling, and redesigning products to create less waste and pollution [2, 3].While a lot of countries worldwide have committed to climate action, only 55% of major emitters are trying to set exact targets for reduction for 2030, and most are targeting net-zero emissions from 2050 - 2070 [4, 5].CE replaces the "take-make-dispose" model and reduces the need for new materials, reducing pollution and greenhouse gas emissions. A linear economy consumes resources, produces products, and disposes of them as waste, which has negative environmental effects like pollution and resource loss. A circular economy extends the lifecycle of resources through reuse, repair, and recycling of goods and renewable energy options to minimize waste, avoid loss of ecosystems, and create long-lasting environmental, social, and economic benefits [6]. The circular bioeconomy aims to get the most value from biological resources like agricultural residues, forestry by-products, and organic waste by designing processes and products that cap-

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ture value from every part of these materials, returning waste streams back into the production process, and recycling products at the end of their usefulness. For example, food and agricultural waste can be turned into biofertilizers, bioenergy, compost, bioplastics, preventing landfilling and associated greenhouse gas emissions, while reducing reliance on fossil fuels [7]. It highlights the closed-loop nature in which the by- product and waste of one process are inputs for another area. This interlinking provides an efficient organization with zero waste and extends the lifespan of materials multiple times over [8]. Through technological advances, including biorefineries, biotechnology, and smarter supply chains, we can now transform biological materials into a higher-value product-fuels, chemicals, fibers, and thus achieve further waste and environmental impact reductions [9]. The circular bioeconomy aims to ensure that biological resources and wastes can be reused, valued, and converted into value-added products in sustained closed-loop systems. Waste valorisation in the circular bioeconomy refers to the process of converting agricultural, food, and other organic waste into usable resources like biofertilizers, biochars, and reducing their reliance on non-renewable raw materials and landfill storage [10]. Microbial biofertilizers are the products that contain living beneficial microorganisms, and are fundamental to this transition. They can be produced through the bioconversion of organic waste such as food waste, crop residuals, and forestry waste by using microbial fermentation or composting. Once produced, these biofertilizers can be applied to fields to improve soil fertility, replace synthetic fertilizers, and promote healthy and resilient agroecosystems. Beneficial microorganisms that are used include different species of *Bacillus*, *Trichoderma*, *Cyanobacteria*, and mycorrhizal fungi. Microbes contribute to nutrient cycling, nitrogen fixation, phosphorus solubilization, and organic matter degradation; they facilitate the closure of nutrient loops and contribute to improved soil health [11, 12]. Using microbes for waste valorization helps recover nutrients from organic matter that has decomposed and creates biofertilizers that contain essential elements and physiological activity [13]. Biofertilizers can greatly reduce greenhouse gas emissions and sequester carbon in soils while promoting soil health, increasing water retention, and enhancing plant stress tolerance, making plants more resilient to climate change. The circular bioeconomy converts biological waste into goods, which minimizes environmental impact and promotes sustainability. Waste valorization is an integral part of this system, and one of the most well-known and impactful products of waste valorization for agricultural application is biochar. Biochar refers to a stable, carbon-rich product, created through a low-oxygen thermal process called pyrolysis of organic waste materials like agricultural and forestry residues, food waste. This conversion to biochar can provide significant environmental, agricultural, and economic advantages [14]. Biochar provides lots of environmental and agricultural benefits. It enhances soil quality by improving soil structure, fertility, and water holding capacity, and acts as a microbial habitat for beneficial microbes, which increase crop production by fixing nitrogen, solubilizing phosphorus, and producing plant hormones even in poor quality soils. Also, it acts as a long-term carbon sink, decreasing the greenhouse gases such as CO_2, methane, and nitrous oxide. The porous structure of biochar can trap heavy metals and other harmful pollutants and keep the soil safe. Biochar also enhances the resilience of crops to drought and climate variability through its ability to hold nutrients and moisture, while promoting efficient nutrient cycling for a more circular, climate-smart farming system [14, 15]. Innovation hubs in India, such as the Circular Bio Economy Innovation Hub, are enabling the adoption of biochar to stop crop residue burning, improve soil health, enhance the income opportunities for farmers, and achieve sustainable outcomes. Around the world, biochar is being used with practices like precision agriculture and composting to increase the sustainability of farming, restore degraded land, and increase sustainable food and water security [16]. Combined application of biochar and biofertilizers had a greater impact on soil quality, plant growth, and nutrient cycling than either amendment applied alone. Biochar has a porous structure that will provide a safe habitat for beneficial microbes to survive, reproduce, and perform their beneficial functions in the soil. This leads to a more stable and effective microbial community. Biochar increases nutrient retention for a longer period. It prevents the leaching of nutrients. This enables the nutrients to be stored and released more gradually. Microbes in the biofertilizers further mobilize and mineralize these nutrients, making them more available to plants. Increased soil health and nutrient use efficiency result in higher crop productivity due to significant cooperative relationships [17, 18]. Microbial biofertilizers increase the diversity of beneficial microorganisms in the soil, while biochar maintains a favorable environment, creating a healthier soil ecosystem [19]. Research has demonstrated that the co-application of biochar and microbial biofertilizer has a cumulative effect on biomass, crop yields, and growth of plants in the presence of stress, including drought and saline-alkali situations, compared to when applied separately. In many field and lab studies, combined biochar and biofertilizer have led to increased plant biomass up to 91% compared to untreated controls, and substantially more than either biochar or biofertilizer used alone [17, 20].Implementing this combination can also remediate soil contaminants, sequester more soil carbon, and help contribute to sustainable agriculture by reducing the use of chemical fertilizers and avoiding resulting environmental impacts [21].Utilizing biochar and microbial biofertilizer in a synergistic way is a sustainable, environmentally friendly means for improving soil health and crop productivity and supporting resilient systems of agriculture.The biochar acts as a carrier and habitat for the biofertilizer microbes and enhances their positive effects on the soil nutrient cycles, biological activity, and plant health while delivering benefits that are significantly greater than those from using either of the products alone.The novelty of this review lies in integrating circular bioeconomy-based waste valorisation with a quantitative synthesis of liquid microbial biofertilizers and biochar. It highlights how these inputs work together, outlines the practical challenges involved, and identifies key research and policy priorities needed to advance climate-smart agriculture. This review aims to bring together existing knowledge on microbial biofertilizers and waste-derived biochar, examine how they can work together to support climate-smart agriculture within a circular bioeconomy, and outline the major research gaps and future priorities needed for their sustainable, large-scale adoption.

2. METHODOLOGY

This review was conducted through a systematic search of literature focusing on microbial biofertilizers and biochar in the context of waste valorization and climate-smart agriculture. Relevant peer-reviewed articles, books, and conference proceedings were collected from major scientific databases, including PubMed, Scopus, ScienceDirect, SpringerLink, and Google Scholar. The primary search covered the period 2006-2025, with the inclusion of key foundational studies published between 1971 and 2005 to support early concepts of circular bioeconomy, microbial biofertilizers, and biochar science.

As per the keyword searching through databases between 2006 and 2025, a total 2,19,315 no of articles were published in books, conference proceedings, and peer-reviewed journals. The keywords included in the search ware circular bioeconomy and waste valorization (16,800), Microbial biofertilizers from organic wastes (17,700), Production of liquid biofertilizers (18,300), Microbial diversity in fruits and vegetable wastes and its agricultural benefits (401), Biochar production and its properties (1,09,000), Biochar as microbial habitat (17,000), Properties of biochar obtained from different feed stocks (18,300), Synergistic benefits of biochar and biofertilizers in agriculture (7,250), Environmental and agronomic benefits of biochar and biofertilizers over conventional fertilizers (14,600).

2.1. Screening Process

The collected literature underwent a multi-step screening procedure:

- Title screening to remove duplicates, non-scientific sources, unrelated topics, and papers outside the agricultural or environmental scope.
- Abstract screening to assess relevance to microbial biofertilizers, biochar production, waste-derived feedstocks, soil health improvements, and plant response studies.
- Full-text screening for methodological validity, clarity of experimental design, and relevance to the review objectives.

2.2. Inclusion Criteria

- Peer-reviewed articles, experimental studies, field trials, and laboratory investigations
- Research on microbial isolation, characterization, or biofertilizer formulation
- Studies on biochar production, feedstock characterization, or soil-plant interactions
- Publications addressing circular economy, waste valorization, or climate-smart agriculture
- Review articles, policy reports, and case studies offering contextual or regulatory insights

2.3. Exclusion Criteria

- Non-scientific publications, short communications without data, or papers lacking methodological detail
- Studies unrelated to agricultural applications or soil health
- Articles focusing solely on bioenergy or non-microbial waste technologies
- Reports without an accessible full text

After applying the above criteria, 256 high-quality articles were selected for detailed analysis. Foundational studies from 1971 to 2005 (11 papers) were included where essential for defining early concepts of microbial biofertilizers, waste-derived microbial diversity, and fundamental biochar principles.

3. CIRCULAR BIOECONOMY AND WASTE VALORISATION

The world food system is increasingly faced with pressure from growing populations, climate change, pandemics, and wars that pose threats to food security. To produce more food in response to mounting demands sustainably, the agricultural industry will need to adopt digitalisation, smart agriculture, and circular bioeconomy principles. These technologies have the potential to make resource utilisation more efficient, decrease waste, and increase productivity while keeping environmental footprints to a minimum. A shock-resistant, sustainable food system that uses natural resources, as well as high technology to adjust according to changing conditions to provide food for the long term to everyone, is needed for the future [22]. Over the last few years, the concept of the Circular Economy (CE) has received increasing attention globally. The aim is to leave resources in use for as long as possible, generating less waste and consuming fewer raw materials. This serves to preserve the environment and make the economy more sustainable in the long run. It provides a superior alternative to the existing model of economic growth that involves taking resources, producing products, and discarding them. This results in a significant amount of waste and damages the environment. The Circular Economy is a new model that attempts to address this challenge [23]. The theory of the circular economy (CE) draws its origin from several previous concepts and theories. Environmental economists Pearce and Turner (1989) facilitated its introduction based on Boulding's (1966) concept that the economy must be like a closed system where materials are recycled to maintain life on the planet. Pearce and Turner (1989) described that we must go from the conventional manner of resource use-where we use materials, consume them, and discard them (an open system)-to a circular mode of resource use, where we recycle and reuse materials [24]. This was what they founded their concept on, leveraging the laws of thermodynamics, particularly as clarified by Georgescu-Roegen (1971) [25]. These laws state that when we consume energy and materials, they tend to lose their quality and become more difficult to reuse over time. Simply put, the more we utilize resources, the more they deteriorate and produce waste. Therefore, to minimize waste and utilize resources more efficiently, we require a process that keeps materials in circulation for as long as possible-such is the principle of a circular economy [26]. The main principle of the circular economy is based on the 3R principle. The 3R principle is the fundamental strategy of international waste management and addresses climate change. This includes - Reduce, Reuse, and Recycle. It facilitates the development of a material cycles society based on resource efficiency and minimized environmental load [27]. Reduce aims at reducing waste generation at the source and is given the highest priority. Reuse maximizes product lifetimes without significant processing. Recycling transforms waste materials into new products, saving resources and preventing pollution. Worldwide, waste management policies have increasingly moved towards adopting 3R approaches to ensure sustainability [28]. The circular economy (CE) is theoretically connected to sustainability as a subdomain that is mainly concerned with the environmental and economic dimensions through measures such as resource efficiency, waste minimization, and material recycling. Although CE helps meet sustainability objectives, it tends to be insensitive to the social dimension and long-term sustainability at the heart of sustainability. Sustainability, on the other hand, constitutes a harmonious blend of environmental sustainability, economic viability, and social cohesion. If it is to assist sustainable development at all, CE must be integrated with other approaches that address all three pillars of sustainability: environmental, economic, and social [29].

The bioeconomy is a sustainable means to utilize renewable biological resources-such as crops, trees, and organic waste-to create food, energy, and valuable materials. The European Union adopts this method to ensure food security, decrease fossil fuel dependence, save the environment, and generate jobs. There are varying emphases in the bioeconomy: some are to rapidly develop new technologies, others are to utilize natural resources sustainably, and others emphasize conserving biodiversity and ecosystems. Circular economy and bioeconomy are similar yet distinct ideas that have common objectives, especially in enhancing sustainability, waste minimization, and efficient utilization of resources. The bioeconomy complements the circular economy by providing technological solutions that utilize renewable biological resources (*e.g.*, agriculture, forestry, and organic waste) for food, energy, and material production. It promotes resource productivity and environmental sustainability, which are fundamental concepts of the circular economy. Although bioeconomy is distinct from the circular economy. While it helps support circularity objectives, it is more about innovation, industrial application of renewables, and economic competitiveness, instead of closing resource loops entirely. The circular economy adopts a systems-level ecological perspective, whereas the bioeconomy tends to focus on technological progress and economic productivity. Both must be combined with demand-side management and ethical regulation to achieve real sustainability [30]. The bioeconomy also has challenges, including scarce natural resources, unequal access to information, and policy and ownership concerns. For it to be sustainable, it has to utilize resources within natural limits, promote ethical and inclusive research, and observe well-balanced regulations [31].

Circular Economy and Industrial Ecology are interconnected. By emphasizing material and energy fluxes, industrial ecology (IE) sees industry and the environment as a single, interconnected system. By encouraging closed-loop cycles, in which trash is recycled as a resource, it seeks to lessen its negative effects on the environment, much like natural ecosystems do. This method aids in the planning of sustainable development by policymakers, particularly in Asian developing nations, where it ought to be viewed as a strategic goal rather than merely a technological solution. These ideas are expanded upon by the Circular Economy (CE), which applies them across the whole economy. It focuses on creating systems and products that minimise waste, use resources efficiently, and prolong the life of materials. By promoting resource efficiency, waste minimisation, and life cycle thinking, IE essentially lays the groundwork for CE [32]. Municipal Solid Waste (MSW) refers to the everyday waste comprising domestic and commercial refuse that is similar in nature to domestic waste. It is produced because of the level of industrial development, the economic and social conditions of a society, and the local climate. Municipal Solid Waste (MSW) includes various types of materials like paper, leftover food, plastic items, and metals. A large part of this waste-about 46%-is made up of organic materials, such as food and garden waste, which can decompose naturally. This portion is known as the Organic Fraction of Municipal Solid Waste (OFMSW) [33].

Food Supply Chain Waste (FSCW) is the waste that occurs at every stage of food production and use-from farming to processing, transportation, selling, and consumption. It includes food that is lost before it reaches the consumer, as well as waste that could be avoided (like leftovers) and waste that cannot be avoided (like fruit peels or bones). Both households and industries contribute significantly to this type of waste. In developing countries, common methods used to treat waste include composting, anaerobic digestion, burning (incineration), and burying in landfills. However, these traditional methods often cause environmental problems, such as the release of greenhouse gases and bad smells. More modern and sustainable approaches that support a circular economy include advanced techniques like pyrolysis and gasification (which use heat to break down waste) and biological methods like microbial fuel cells and fermentation. These newer technologies can turn waste into valuable products like bioenergy and useful chemicals [34].

Biochar is a porous substance rich in carbon, produced by heating organic waste under low oxygen levels [35]. With its ability to improve soil quality, increase nutrient and water retention, lower greenhouse gas emissions, and carbon sequestration, it promotes sustainable agriculture and works well with the circular economy concept [36]. Through recycling agricultural waste, increasing crop yields, lowering the demand for artificial fertilisers, and enhancing soil health, biochar promotes the circular economy. It is particularly helpful in areas with limited resources, helps restore land, and safeguards natural ecosystems by boosting productivity on already-existing agriculture [37]. Organic biodegradable waste is one of the most significant contributors to pollution and loss of soil health in the environment. Soils are frequently subjected to a combination of limitations: physically, they are sandy and impermeable; chemically, they are acid, of low cation exchange capacity, low in cation exchange capacity, and have toxic levels of aluminum and manganese; biologically, they are insufficiently microbiologically active [38]. Normally, organic matter would enrich the soil structure and fertility, but in tropical Africa, the natural process is slowed down by adverse climate conditions, deforestation, and unethical farming processes such as monoculture. Converting organic waste into useful products like biofertilizers and biopesticides offers a green option over chemical farm inputs. Three main methods are applied for the restoration of soil fertility and environmental conservation: pyrolysis, composting, and mycorrhization (symbiotic association between plant roots and beneficial fungi). All these processes transform organic waste into useful soil amendments. One of these products is Kahambwe Biochar, produced by pyrolyzing bamboo (*Bambusa vulgaris*) at high temperatures. The bamboo is cultivated in hedgerows, and the bamboo is converted into charcoal. It is crushed, sieved, and chemically washed to clean its pores. It makes the soil more alkaline, water-holding, and stores important nutrients such as nitrogen, phosphorus, and potassium. It also maintains healthy soil microbes like *Azotobacter and* mycorrhizal fungi, which contribute to soil fertility as well as enhance plant productivity. When biochar is enriched further with compost as well as arbuscular mycorrhizal fungi (AMF) (root-colonizing fungi that enhance plant nutrient uptake), its potency becomes drastically increased. This enhanced product, still referred to as Kahambwe Biochar, becomes denser, more nutrient-dense, more stable, and capable of resisting drought as well as heat.

Though untreated biochar may be toxic to plants when used alone, mixing it with compost and AMF renders it harmless and incredibly valuable to agricultural applications. This upgraded form has 46.5% carbon, is alkaline in pH with a reading of 8.6, and possesses a high cation exchange capacity of 46.3%, providing the all-important nutrients like nitrogen (3.8%), phosphorus (0.59%), and potassium (0.20%), as well as enhancing the moisture-retaining capacity of the soil [39]. Biorefineries are advanced facilities utilizing biological and chemical transformations to convert various forms of waste-such as agricultural residues, food waste, municipal solid waste, and sewage sludge-into useful products like biofuels, biogas, organic fertilizers, and bio-based chemicals. They base their feedstocks on numerous alternatives, such as crop residues like straw and husks, and employ a range of processes to treat them, such as thermochemical (pyrolysis, gasification, combustion) and biochemical (composting, fermentation, anaerobic digestion) processes. Although the biochemical processes are slower, the thermochemical processes can yield more product varieties. The selection of an appropriate feedstock and process is most important for achieving higher efficiency and lower costs. Biorefineries reduce pollution, landfill waste, and the use of synthetic fertilizers, as well as generating economic benefits [40]. Through the conversion from single-product systems to multifunctional biorefineries, we can recover more valuable materials, increase environmental and economic sustainability, and foster a circular economy Fig. (**1**) [41].

4. MICROBIAL BIOFERTILIZERS FROM ORGANIC WASTE

4.1. Sources and Microbial Diversity

The concept of biofertilizers-natural substances that assist in supplying necessary nutrients to plants-began as early as 1834. A French farming chemist, J. B. Boussingault, observed at that time that the cultivation of legume crops (such as peas or beans) contributed to the nitrogen levels in the soil. This observation indicated that plants could enrich the fertility of soil naturally. Soon after, in 1886, scientists Hellriegel and Wilfarth, and later Beijerinck in 1888, assisted in confirming how the process occurred. They demonstrated that some microbes in soil assist plants, particularly legumes, in absorbing nitrogen from the atmosphere-a process referred to as biological nitrogen fixation. After this, in 1896, scientists Hiltner and Noble created the first known commercial biofertilizer product named Nitragin, which consisted of nitrogen-fixing bacteria of the *Rhizobium group*. Ever since, further discoveries and advancements by other scientists have resulted in mass-scale production and application of biofertilizers. Presently, these products are a valuable part of sustainable agriculture by enhancing soil quality naturally and minimizing the usage of chemical fertilizers [42]. Utilising living microorganisms like bacteria, fungi, or algae, biofertilizers are eco-friendly products that enhance soil fertility and plant growth by colonising the plant's rhizosphere. In order to support healthy crop development, they fix nitrogen from the atmosphere, solubilise vital nutrients, and produce substances that promote growth [43, 44]. Microbial biofertilizers from organic waste provide an environmentally friendly and sustainable option compared to chemical fertilizers, promoting agricultural production while reducing ecological damage. The growing need to address the adverse effects of chemical fertilizers and an ensuing demand for more sustainable agriculture have increased efforts to use biofertilizers from organic waste. These wastes-for instance, crop residues, food waste, animal dung, and agro-industrial residues-are easily accessible and, if not properly managed, can cause a lot of pollution and waste management problems. Food waste is a nutrient-rich waste, and its mix of different types makes it an extremely good candidate to produce biofertilizers. Readily available sources are potato and sugarcane wastes, juice and fruit wastes, wheat and rice waste, used cooking oil, bakery and dairy wastes, meat, fish, poultry, and vegetable trimmings. All these wastes have been successfully utilized to produce useful products such as biofertilizers and biogas using microbial means. Microorganisms including bacteria, actinomycetes, yeasts, and molds, are responsible for this conversion by executing functions such as nitrogen fixation, ammonification, nitrification, and denitrification-processes guided by specialized enzymes [45]. The process of turning food waste into useful products like biofertilizers, biofuels, and biochar using a variety of processes, such as hydrolysis, dehydration, composting, and anaerobic digestion, is known as food waste valorisation. Anaerobic digestion and composting are the two most widely utilised of these. Nutrients (N, P, and K) and beneficial bacteria found in food waste-derived products enhance soil fertility, structure, water retention, and biological activity. They also assist in cleaning up contaminated soils, particularly with compost and biochar, which can lower the amounts of pollutants and heavy metals [46].

Important factors that must be carefully regulated to guarantee the best possible conversion of waste into beneficial outputs like biofertilizers, biogas, or nutrient-rich materials include temperature, moisture content, and the length of

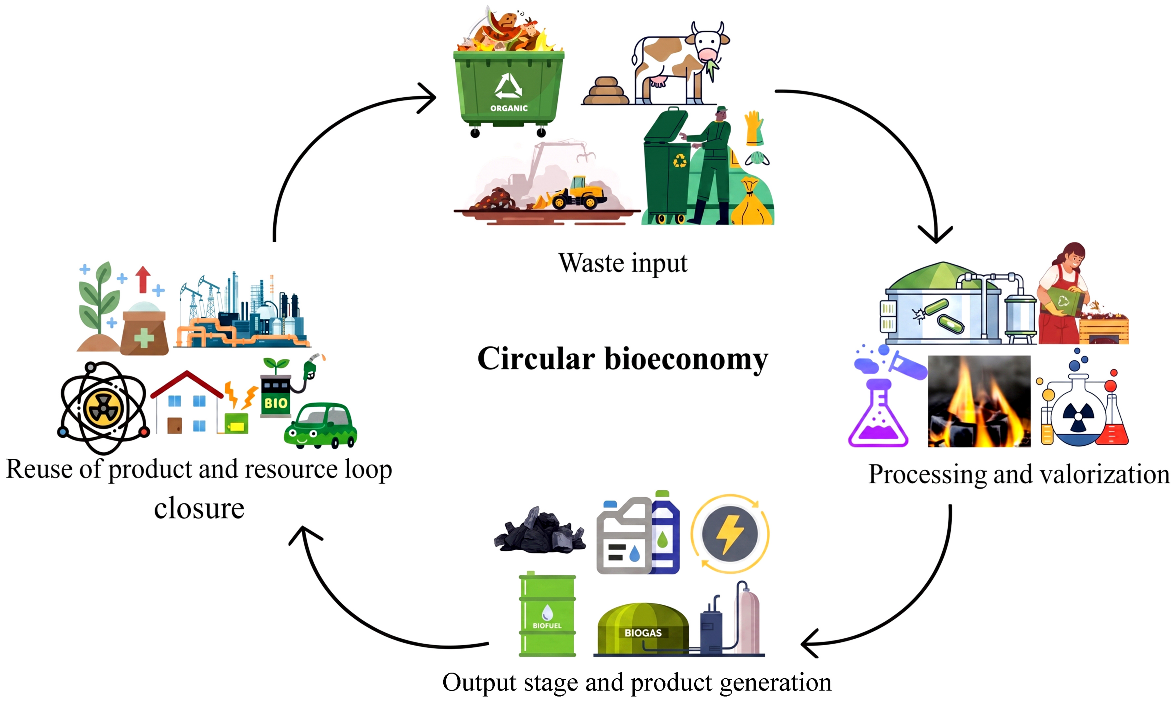

Fig. (1). Conceptual framework of the waste-to-input pathway under circular bioeconomy. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

treatment (incubation period) [47]. Organic materials such as food scraps, agricultural residues (such as straw and crop husks), and animal manures are frequently utilised as raw substrates to produce microbial biofertilizers. Despite being high in nutrients and organic matter, these materials must break down into simpler forms that plants can absorb [44, 48]. This is done by adding helpful microbes-particularly organisms such as *Bacillus* sp.-that possess robust degradative and plant growth-promoting properties. In the process of microbial breakdown, other useful bacteria and fungi also grow, leading to a diverse microbial population in the biofertilizer [49]. Microbialbiofertilizers produced from organic waste carry diverse groups of beneficial bacteria and fungi, making them effective. The most common bacterial groups are Proteobacteria, Bacteroidota, and Actinobacteria, with important plant-beneficial forms such as *Rhizobium, Bacillus*, and *Sphingomonas*. Bacteria are typically more diverse in the root zone (rhizosphere). For fungi, important groups are *Ascomycota*, *Glomeromycota*, and *Basidiomycota* [50]. Based on their capacity to fix nitrogen, solubilise phosphorus and potassium, and promote plant growth, microbial biofertilizers are varied and divided into different categories. Microbial biofertilizers are classified according to the nutrients they assist plants with. Nitrogen-fixing microorganisms may be free-living (such as *Azotobacter*, *Anabaena*, and *Clostridium*), symbiotic (such as *Rhizobium* and *Frankia*), or associative (such as *Azospirillum*, *Herbaspirillum*, and *Klebsiella*). For phosphorus, some microbes solubilize phosphate (such as *Bacillus*, *Pseudomonas*, and *Aspergillus*), and others that assist in mobilizing it through mycorrhizal fungi (such as *Glomus* and *Rhizoctonia*). Some microbes also solubilize micronutrients such as potassium (*Bacillus edaphicus*) and zinc/silicate (*Thiobacillus*, *Saccharomyces*). Then, plant growth-promoting rhizobacteria (PGPR), including *Pseudomonas fluorescens*, *Bacillus*, *Erwinia*, and *Streptomyces* contribute to the promotion of plant growth through multiple mechanisms such as hormone biosynthesis and the enhancement of nutrient acquisition [51]. In legumes, symbiotic N-fixers like *Rhizobium*, *Bradyrhizobium*, and *Frankia* produce root nodules and use the nitrogenase enzyme complex to transform atmospheric N_2 into ammonia [52]. Particularly in crops like wheat and rice, free-living N-fixers such as *Azotobacter* and *cyanobacteria* (*Anabaena*, *Nostoc*) fix nitrogen on their own. They also release phytohormones and antifungal substances [53].

In addition to fixing up to 40 kg of nitrogen per hectare annually, associative N-fixers-primarily *Azospirillum* sp.-also produce plant hormones, enhance root shape, and increase tolerance to stress [54, 55]. Because phosphorus is frequently insoluble in soil, phosphorus-solubilizing microorganisms such as *Bacillus*, *Pseudomonas*, *Aspergillus*, and *Penicillium* release it through enzyme secretion and acidification [56]. Phosphorous-solubilizing microorganisms also increase plant growth by producing siderophores and IAA [57]**.** In addition to helping with disease prevention and root development, arbuscular mycorrhizal fungi (AMF) like *Glomus* and *Gigaspora* enhance phosphorus uptake and boost yield, particularly in low-phosphorus soils [58]. As biofertilizers, soil-dwelling microorganisms can enhance plants' uptake of nutrients other than nitrogen and phosphorus, including potassium, zinc, iron, copper, and silica. Certain rhizobacteria have been shown to increase biomass output and potassium uptake in crops such as cucumber, eggplant, black pepper, and wheat. *Paenibacillusglucanolyticus*, *Bacillus edaphicus*, and *Bacillus mucilaginosus* (when co-inoculated with phosphate-solubilizing *Bacillus megaterium*) are among them [59-61]. Microorganisms such as *Bacillus subtilis*, *Thiobacillus thiooxidans*, and *Saccharomyces* sp. can mobilize zinc, often used in expensive soluble forms, through the solubilization of cheaper zinc compounds such as zinc oxide and zinc carbonate [62]. Many microbes support plant growth by generating hormones and preventing disease, in addition to providing nutrients. Growth hormones like gibberellins and cytokinins are produced by species like *Bacillus* and *Azospirillum*, and *Paenibacilluspolymyxa* fixes nitrogen, solubilises phosphorus, and improves soil health [63].

By generating antibiotics, siderophores, and enzymes that inhibit pathogens like *Fusarium*, *Pythium*, and *Rhizoctonia*, certain microorganisms-particularly *Pseudomonas* species-protect plants. By producing antibiotics, *Azotobacter* also aids in the management of soilborne illnesses. These characteristics make these microorganisms useful biofertilizers [64]. Microbial biofertilizers, especially plant growth-promoting rhizobacteria (PGPR), promote plant growth by fixing nitrogen, phosphorus solubilization, nutrient uptake promotion, and hormone production [65]. Using 16S rRNA sequencing, two auxin-producing Bacillus strains (P4 and S6) from the rhizosphere were found to promote plant growth. After 48 hours, both strains produced the most auxin (IAA) at 37 °C, which was boosted by higher tryptophan concentrations. Auxin levels, shoot and root length, root number, leaf count, and chlorophyll and carotenoid content all increased noticeably when the bacterial inoculation was applied to *Solanum tuberosum* (potato) sprouts. These *Bacillus* strains that produce auxin have the potential to be used as environmentally friendly biofertilizers in agriculture and can effectively promote plant development [66]. The impact of plant growth-promoting rhizobacteria (PGPR) on common bean (*Phaseolus vulgaris* L.) growth, nodulation, and biological nitrogen fixation (BNF) was assessed. *Rhizobium tropici* (CIAT 899), either alone or in combination with other PGPR strains (different *Bacillus* and *Paenibacillus* sp.), was used to inoculate the beans. The findings demonstrated a more effective symbiotic relationship by showing that co-inoculation with *P. polymyxa* (DSM 36) significantly increased nitrogenase activity, nitrogen fixation efficiency, and leghemoglobin (LHb) content. Nitrogen accumulation was increased by the co-inoculation with *P. polymyxa* strain *Loutit* (L), which specifically stimulated nodulation and specific nodulation (number of nodules per gram of root). Certain PGPR strains encouraged nitrogen fixation even though they inhibited root growth. The bacterial treatments affected phytohormones such as cytokinin and IAA, whose balance is crucial for nodulation and root development. PGPR, especially when co-inoculated with *rhizobia*, enhance nodulation and nitrogen fixation in beans through complex hormonal and microbial interactions [67].

The impact of two plant growth-promoting rhizobacteria (PGPR) - *Bacillus* OSU-142 (N_2-fixing) and *Bacillus* M3 (both N_2-fixing and phosphate-solubilizing) - on the growth, yield, and nutrient content of *Rubus idaeus* (red raspberry) was assessed under organic farming conditions. Plant yield, cane length, berry count, and nutrient uptake (particularly nitrogen and phosphorus) were significantly enhanced by *Bacillus* M3 and OSU-142 + M3. These bacteria improved soil nutrient content by fixing nitrogen, solubilizing phosphate, and reducing soil pH by producing organic acids. OSU-142 alone was weak with limited and sometimes inhibitory effects (presumably due to the overproduction of auxins), but M3 and the combined treatment were effective and safe, indicating possible use as biofertilizers in green sustainable raspberry production [68]. Beneficial microorganisms, including cyanobacteria, fungi, and bacteria, are present in microbial biofertilizers. These microorganisms can occasionally be found inside plant tissues or in the rhizosphere, the area of soil close to plant roots. Once there, they perform several functions that increase the plant's availability of nutrients like phosphorus and nitrogen. For instance, they might produce natural substances that facilitate the plant's easier absorption of nutrients, fix nitrogen from the air, or break down minerals in the soil. Plants are therefore better able to obtain vital nutrients, which promotes healthier development and higher harvests [52]. They are environmentally friendly, support soil diversity, and provide a low-cost substitute for chemical fertilizers, particularly for marginal and small farmers. The most common types supply essential nutrients, particularly nitrogen and phosphorus, through microbial processes [69]. The impact of eight microorganisms-three fungi and five bacteria-on the development of robust tomato plants grown hydroponically with rockwool and organic media was assessed. Among these, *Trichoderma atroviride* and Pseudomonas *putida* subgroup B strain 1 markedly increased fruit yield in both media. These microorganisms generate the plant hormone indole-3-acetic acid (IAA), which promotes plant growth, particularly in response to substances such as tryptophan. These microbes lessened the detrimental effect of excessive IAA, which can damage roots. Both enhanced root growth and plant health, which resulted in increased fruit yield [70]. These microorganisms reduced the negative effects of excessive IAA. They worked by two mechanisms. Both Trichoderma *atroviride* and *Pseudomonas putida* partially degraded IAA [71] and exhibited the activity of an enzyme ACC deaminase, which decreases ethylene content (a stress hormone) in plants [72].

4.2. Formulation of Liquid Biofertilizers:

An eco-friendly and natural substitute for chemical fertilisers is biofertilizers, which contain beneficial microorganisms like fungi, bacteria, and algae. They promote better plant growth, enhance nutrient availability, and enhance soil health [73]. Governments and citizens are searching for safer substitutes, such as biofertilizers, as they are increasingly concerned about the effects of chemical fertilisers on the environment. The use and market value of biofertilizers have increased because of this preference change [74]. Although there are several forms of biofertilizers, including liquid, solid, polymer-encapsulated, and fluidised dry types, liquid formulations are becoming increasingly popular due to their many advantages. The effectiveness of traditional solid-based biofertilizers is often limited by their short shelf life and low number of viable microbial cells. Liquid biofertilizers have been developed to address these problems. These formulations provide longer stability and improved performance by providing higher concentrations of active microbes, usually more than 10^9 colony-forming units (CFU) per millilitre [75, 76]. Liquid biofertilizers, or aqueous or flowable suspensions, are concentrated microbial products of 10-40% active microorganisms with stabilizers like surfactants, dispersants, and carriers of water or oil to ensure stability and efficacy. Liquid biofertilizers are found in four basic forms, each suited for application techniques. Suspension concentrates are less difficult to deal with, do not cause much dust, and need dilution before application. Ultralow volume suspensions are pre-diluted fine sprays and can be applied directly by specialized equipment. Oil-miscible flow concentrates are microbes suspended in oil liquids and need to be diluted before application. Oil dispersions, however, employ oil or water-immiscible solvents to provide longer contact time on plant surfaces because of the lower rate of evaporation of oil, thus making them more effective. This range of liquid formulations presents tangible benefits in the form of ease of application, greater shelf life, and more effective microbial performance, which makes them a choice in sustainable agriculture [77].

Liquid biofertilizers also possess some practical benefits compared to conventional solid formulations. They are stable for a shelf life of 1.5 to 2 years, are contamination-free, and can tolerate high temperatures of up to 45°C, making them ideal for storage and application in varied environmental conditions [78]. Moreover, they are simpler to use with current agricultural equipment and involve smaller amounts than solid biofertilizers, yet they provide equal effectiveness [79]. Nevertheless, microorganisms can undergo stress while being stored due to conditions such as a lack of oxygen and nutrient degradation, which lowers their viability. To counter this, protective additives like sucrose, glycerol, Arabic gum, and polyvinylpyrrolidone (PVP) are added to the mixture. These materials extend microbial survival, enhance seed adhesion, and increase environmental stress tolerance, ensuring the effectiveness of the biofertilizers over a prolonged period [78]. The six key steps in their production are: choosing microbial strains, identifying functional characteristics (such as nutrient solubilisation and nitrogen fixation), creating carriers, growing strains, evaluating their effectiveness, and scaling up for commercial use [80]. Liquid biofertilizers hold beneficial microbes and the natural compounds that they secrete. They also possess special preservative additives that protect the microbes by causing them to enter dormant spore or cyst stages. These processes enhance the product's shelf life and its efficiency when applied in the field, making them more effective than solid carrier-based biofertilizers [81, 82]. Identification and extraction of beneficial, non-toxic microorganisms that promote plant growth constitute the first stage of the production of biofertilizer. Usually, these microbes come from their natural habitats, which include soil, the rhizosphere (the area surrounding plant roots), or the tissues of plants, such as the roots, stems, leaves, seeds, and flowers [83]. Scientists conduct routine laboratory tests to assess their utility, frequently utilising specialised culture media or straightforward qualitative techniques. Before conducting more thorough testing, these initial evaluations concentrate on the functional capabilities of the microorganisms, such as growth hormone production or nutrient solubilisation, and offer a rapid and economical means of screening for promising strains Fig. (**2**) [84, 85].

In the next phase of biofertilizer production, scientists are concerned with isolating and selecting pure microbial strains that demonstrate beneficial characteristics like nutrient solubilization, atmospheric nitrogen fixation, or phytohormone production. These strains are subjected to a series of tests in the laboratory (*in vitro*) to ascertain their efficacy-like growth performance on the respective media and determining their functional strength Following successful laboratory testing, the strains are subjected to greenhouse conditions to check how effectively they facilitate plant growth prior to being introduced in real field tests [86, 87]. Furthermore, researchers utilize sophisticated molecular biology techniques-such as genomics (analysis of DNA), transcriptomics (gene expression), proteomics (protein profiling), and metabolomics (chemical study of metabolites)-to identify the ways through which these strains augment plant growth [88, 89]. These approaches combined develop stable biofertilizers that can effectively operate under a variety of farming systems. To determine whether the biofertilizers will be in liquid or solid form, the appropriate formulation materials are chosen. The proper liquid such as water, organic oils, or water in oil emulsions is selected for liquid biofertilizers to prolong the life and activity of the microorganisms [90]. These substances aid in keeping the proper quantity of microorganisms and guarantee their continued efficacy until they are deployed in the field [91]. Then choose the optimal method to cultivate and replicate the selected microbes in the laboratory. It is crucial to maintain ideal conditions during this process to preserve the natural properties of the microbes and ensure their effectiveness in real-world applications. These conditions are identified by observing how the microbes grow in different environmental settings. Typically, their multiplication is carried out using specialized equipment called fermenters. The two main fermentation techniques used for this purpose are solid-state fermentation and submerged fermentation [92]. The product is then developed and tested in a variety of forms. The objective is to determine which version is most effective and appropriate for real-world applications. Following the selection of the best prototype, it undergoes extensive testing in actual agricultural fields with varying soil types and climates. This aids in assessing the product's performance both in the lab and in real-world settings.

A final, standardised process for producing the product on a commercial scale is developed based on these findings [86, 93]. In an experiment liquid biofertilizers is made in two steps. In the first step, a microbial nutrient solution is prepared by combining 2 liters of morass and milk or whey with 10 liters of non-chlorinated water, gently stirred to suspend microbes. Then, in a 1000-liter plastic pot, a fermentation mixture is made up of 100 liters non-chlorinated water, 20 liters fresh rumen, 40-50 liters fresh cow dung, 3 kg silica and phosphorus, 2 kg basalt rock dust, and 0.5 kg fermi pan. Microbial solution is added, well mixed, and with an airlock system sealed for 15 days of fermentation. The product is analyzed by serial dilution, microbial culture methods, gram staining, and various biochemical tests which ascertain the presence of useful bacteria such as *Rhizobium* and *Azotobacter*. An experiment on maize growth indicated that this biofertilizer increases plant growth and height comparably with

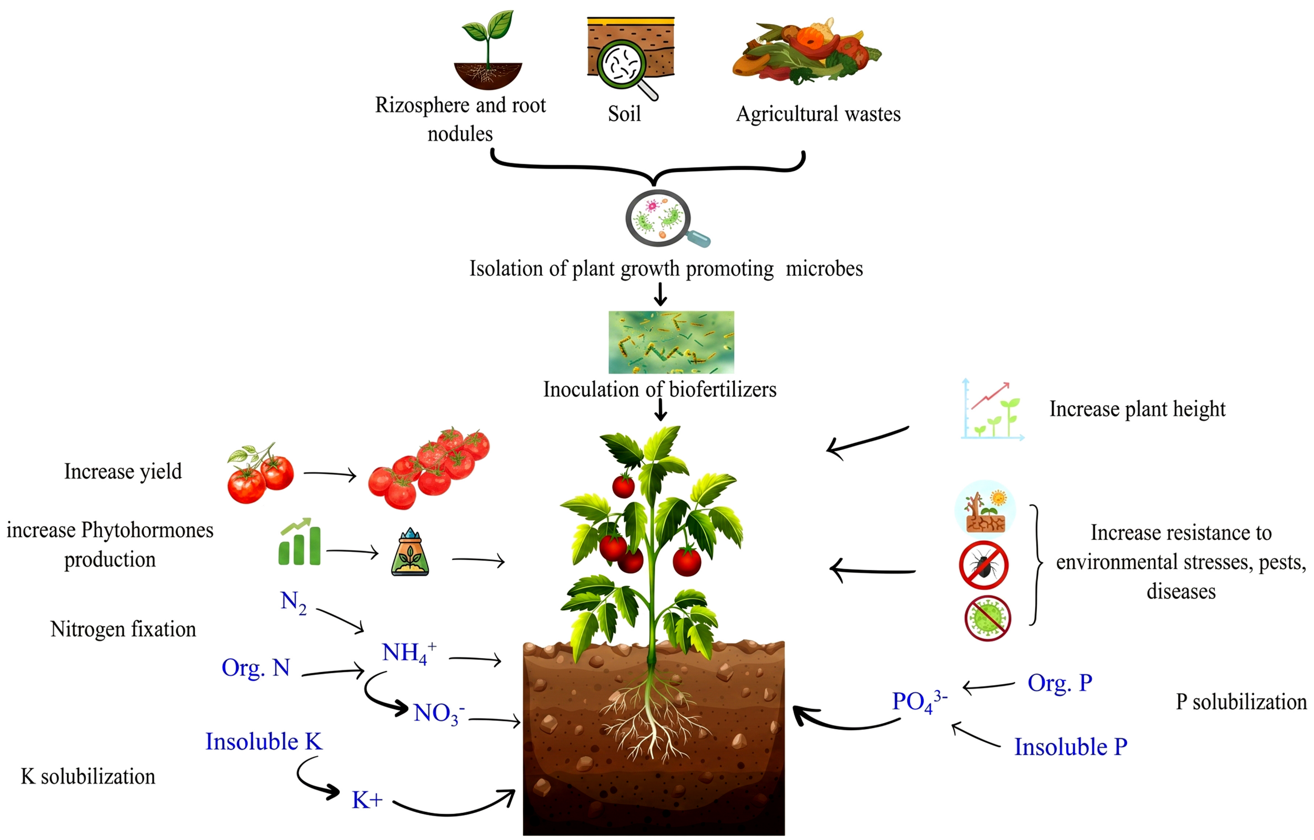

Fig. (2). Effects of microbial biofertilizers on plants and soil. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

chemical fertilizers while providing a more environment-friendly and sustainable option [94]. liquid biofertilizer, fermented banana waste biofertilizers was prepared from banana waste, cow dung, and cow urine. For preparation, take 1 kg cow dung and 1 liter cow urine and mix with 10 liters of water and ferment for 24 hours. Next, add 1 kg mashed banana waste and ferment for 5 additional days, stirring daily.The obtained fertilizer is rich in valuable nutrients (N, P, K, Ca, Fe) and useful microbes, such as phosphate-solubilizing bacteria (5×10^5 CFU/ml), with a complete load of bacteria being 4.48×10^7 CFU/ml. No pathogenic fecal coliforms were detected. It enhances soil quality, increases nutrient content, promotes root and shoot elongation, and inhibits diseases in plants. It also enhances seed germination and plant growth, particularly at a 1:100 concentration. This is safe, reliable, and encourages sustainable agriculture as well as organic waste management Table **1** [95].

5. BIOCHAR: A CARBON-RICH SOIL AMENDMENT

5.1. Production and Properties

The pyrolysis of organic biomass or agricultural residues, which entails heating the feedstock at high temperatures in a closed system with little to no oxygen, produces biochar, a material rich in carbon [162]. The biomass's chemical makeup is changed by this thermal breakdown, producing a carbon-dense product that is applied as a soil amendment [162, 163]. During pyrolysis, the organic materials decompose rather than burn or decompose yielding three primary products - biochar, liquid or oils (tars, water, *etc*.), volatile gases like carbon dioxide *etc*. About70% of the biochar is stable carbon. It is a solid, black, lightweight, and highly porous substance.And the high carbon content makes it effective for carbon sequestration [164].The elements that make up biochar include carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S), and ash, all of which are present in different proportions. Enhancing the soil's nutrient content and absorbing and storing carbon from the atmosphere are its main applications [165]. Biochar is gaining increasing global attention for its significant environmental benefits, especially in sustainable agriculture and climate change mitigation. It plays a vital role in improving soil fertility and structure while also serving as an effective solution for managing organic waste. A key characteristic of biochar is its high content of stable, or recalcitrant, carbon, which is highly resistant to decomposition and remains in the soil for extended periods. This property enables biochar to function as a long-term carbon reservoir, slowing the degradation of organic matter and reducing carbon dioxide emissions. By storing carbon in the soil, biochar could potentially cut global greenhouse gas emissions by up to 12% [166]. Also, it is an excellent option for long-term soil enhancement due to its extremely porous structure. It helps improve water retention by increasing the soil's overall surface area, which increases

Table 1. Common microbial isolates from organic waste and their functional traits.

Microorganism	Source (Fruit/ Vegetable Waste)	Functional Traits	Target Nutrient	Plant Benefits	References
Bacillus sp.	Tomato, Potato, Onion, Coriander, Cabbage, Beet, Capsicum, Cauliflower, Brinjal, Peas,Papaya,Spinach,Banana, Apple, Orange, Chikoo, Lemon, grapes, sweet lime	Phosphate Solubilisation, nitrogen fixation, Siderophore production, Phytohormone production, Enzyme production, biocontrol.	P, N, Fe	Stress tolerance enhancement, Phytohormone production, root elongation, boost crop yield, enhances nutrient cycling, and pathogen suppression.	[96]
Escherichia sp.	Apple, Banana, grapes, pineapple, onion, papaya, Tomato, Cabbage, pepper,Cashew, orange, kola nut.	Endophytic colonization, Phosphorus solubilisation,Siderophore production, Phytohormones production,potassium solubilisation,Nitrogen metabolism,Sulfur metabolism,Ornithine biosynthesis,Acetoin production,ACCD production.	P, K, N, S, Fe.	Increase plant growth, increase shoot and root length, biomass, chlorophyll content, leaf number, stress tolerance, and nutrient uptake.	[97]
Staphylococcus sp.	Apple, Banana, pineapple, Cashew, orange, Pawpaw, star apple, kola nut, tomato, papaya,	Phosphate solubilisation, Production of phytohormones,Siderophore production,ACC deaminase activity,Ammonia, exopolysaccharide (EPS), and HCN production,Drought and pH tolerance,	P, N, Fe	Stress tolerance, promotes root and shoot growth, increases phosphorus availability, increases chlorophyll content, increases fresh and dry weight of root and shoot, drought tolerance,nutrient mobilization, and improves iron accessibility	[98]
Salmonella sp.	Cucumber, hog plum, guava, apple, jujube, cashew, pawpaw, watermelon, carrot, tomato, cabbage, onion, pepper,	Persistence in soils,Forms biofilms and adapts metabolically to plant environments, plant colonization, and carbon metabolism.	C	Interacts with plant stress and immune pathways, activating plant defence mechanisms.	[99, 100]
Pseudomonas sp.	Lemon, sweet lime, banana, chikoo, apple, cucumber, hog plum, guava, jujube, tomato, spinach, coriander, potato, cabbage, beet, capsicum, cauliflower, brinjal, peas, carrot,	Rhizosphere colonization, Production of phytohormones, Siderophore production,Phosphate and potassium solubilisation, Nitrogen fixation, biocontrol of soil pathogens, and stress tolerance.	P, K, N, Fe.	Shoot and root growth, increase yield, biomass and nutrient uptake. protect from pathogens, abiotic stress tolerance.	[101-103]
Lactobacillus sp.	Cucumber, hog plum, guava, jujube, carrot, tomato.	Nitrogen fixation, Phosphate and potassium solubilisation, Siderophore production, biocontrol agent, and defence enzyme production.	P, K, N,Fe.	Improve growth, antimicrobial agent, stimulate germination, and resistance to pathogens.	[104]
Vibrio sp.	Cucumber, hog plum, guava, jujube,carrot, tomato.	Carbohydrate metabolism,Biofilm formation,Siderophore formation.	Carbohydrate, Fe	indirect effect	[105-107]
Klebsiella sp.	Banana, pineapple, tomato, papaya, carrot.	Nitrogen fixation, phosphatesolubilisation, phytohormones production, drought and salinity tolerance, and biological control.	N, P	Increase yield, stress tolerance, increase dry plant biomass, increase nitrogen content, promote plant growth,	[108-110]
Shigella sp.	Orange, tomato, cabbage, onion, pepper.	Pathogenic bacteria	-	No plant benefit	[111]
Enterobacter sp.	Carrots	Nitrogen fixation,salt stress tolerance, phosphate solubilisation, phytohormones production, production of polymer-hydrolyzing enzymes and ammonia.	N, P.	Increases root length, plant height, fresh and dry weight of plant, salt stress tolerance, seed germination, nitrogen accumulation, and plant growth.	[112-114]
*Erwinia*sp.	Carrots	Phosphate solubilisation,Siderophore production,IAA production,Nitrogen fixation,ACC deaminase activity, salt tolerance activity.	N, P, Fe.	Increase seed germination, improve nutrient uptake, promote plant growth, increase root and leaf area as well as weight, increase leaf number, improve tolerance to salinity.	[115, 116]

(Table 1) Contd….

Microorganism	Source (Fruit/ Vegetable Waste)	Functional Traits	Target Nutrient	Plant Benefits	References
*Rothia*sp.	Tomato	Nitrogen fixation,Phosphate solubilisation, Siderophore production, ammonia production.	N, P, Fe.	Improve nutrient availability and nutrient cycling, improve plant growth.	[117]
Mucor sp.	Apple, grapes, tomato, potato.	Heavy metal tolerance, nutrient acquisition.	N, P	Increase biomass, root elongation and nutrient uptake, toxic metals induce stress tolerance.	[118, 119]
Aspergillus sp.	Apple, grapes, Banana, orange, pawpaw, kola nut, tomato, potato,	Phosphate solubilisation, potassium solubilisation, phytohormones production, especially IAA, Siderophore production,	P,K,Fe	Improve nutrient uptake, increase fresh and dry biomass of root and shoot, increase root, shoot, stem length and diameter, enhance seedling growth, and stress tolerance.	[120-123]
Penicillium sp.	Apple, Banana, Grapes, Blackberries, Blueberry, Raspberry, Strawberries, Minneola Oranges, Temple Oranges, Sunkist Lemons, Limes, Lemon, Apple, Tomato, Pomegranate, Pawpaw.	Phosphate solubilisation, toxic metal resistance, phytohormones production and regulation, symbiotic relationship with host plant, ammonia production, biocontrol of plant pathogens, insecticidal, resistance to soil salinity, drought stress tolerance.	P	Increase plant biomass, provide resistance to metal contamination, improve nutrient uptake, reduce toxic metal accumulation, improve growth, root and shoot elongation, seed germination, flowering induction, control plant pathogen, protect crop from insects, protect from the stress of soil salinity, increase the content of chlorophyll, protein, lignin, and amino acids.	[124-126]
*Monilinia*sp.	Banana, tomato, potato, onion	Plant pathogen	-	Produce plant disease, causing brown rot disease in different pome and stone fruits, resulting in significant crop losses.	[127, 128]
Eurotium sp.	Grapes	Biocontrol agent	-	Degrades complex compounds, antimicrobial activity against plant pathogens.	[129]
Botrytis sp.	Apple, banana.	Plant pathogen, a destructive fungal pathogen.	-	Damage fruits and vegetables.	[130, 131]
Plasmo-paraviticola	Grapes, apple	Plant pathogen	-	Causes grapevine downy mildew disease, crop destruction.	[132]
*Phytopthora*sp.	Apple, tomato, potato.	Plant pathogen	-	Crop damage and crop loss	[133]
Sclerotinia sp.	Apple, tomato, potato, onion.	Plant pathogen	-	Crop damage and crop loss. Decrease yield.	[134]
Rhizopus sp.	Grapes,banana, cashews, pawpaw,kola nut, blackberries, raspberries, strawberries, tangerines, tomato, potato, and onion.	Soil erosion resistance, plant pathogen.	-	Prevent soil erosion, Fruit rot, and produce Rhizopus rot symptoms.	[135, 136]
Fusarium sp.	Banana, apple, blackberries, raspberry, strawberries, grapes, minneola Oranges, Sunkist Lemons, limes, tangerines,tomato, potato, turnip.	plant pathogen	-	Produce disease in plants, causing crop damage.	[137]
Bipolaris sp.	Banana, apple, onion,	Plant pathogen,Phosphate solubilisation,phytohormones production such as IAA,gibberellic acid, abiotic stress tolerance, biocontrol agent, potential mycoherbicide.	P	Produce disease in plants, crop damage, plant growth, and tolerance to different stresses such as salinity, drought, heat, and heavy metal stress.	[138, 139]
Cladosporium sp.	Blackberries, raspberries, strawberries, grapes, blueberry, minneola oranges, temple oranges, sunkist lemons, limes, tangerines, okra, melon, pumpkin, carrot, turnip, radish,	Prevent biotic and abiotic stress, biostimulants, phosphate solubilisation, phytohormones production (IAA), hydrolytic enzymes secretion, biomass production, and inhibit pathogen.	N, P	Promote seedlings' growth, provide stress tolerance, increase the weight and height of stems as well as roots, increase the fresh weight of the plant, increase chlorophyll content, and protect plants from pathogen.	[140, 141]

(Table 1) Contd….

Microorganism	Source (Fruit/ Vegetable Waste)	Functional Traits	Target Nutrient	Plant Benefits	References
Trichoderma sp.	blueberry, strawber-ries,minneola oranges, limes,	Biocontrol agent, disease control, biotic and abiotic stress tolerance, root coloniza-tion,bioremediation,phytohormones production, production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase enzyme,Siderophore produc-tion,Phosphate solubilisa-tion,solubilisation of iron, manganese, and magnesium, plant growth regulator.	Fe, P, Mn, Mg, Cu, Zn, N,Ca	Control soil derived diseases, control leaf and panicle diseases, promote plant growth, improve nutrient utilization, induce defence response to plants, in-crease weight and height of stems as well as roots, fresh weight, dry weight and total weight of the plant increases, pro-vide resistance to drought, salini-ty,alkalinity, nutrient deficien-cies,Bioremediation of inorganic , organ-ic pollutants and agrochemicals,restore deteriorated soil, provide resistance to pathogen,	[142-144]
Aureobasidium pullulans	Blueberry	Produce enzymes, polysaccharides, bio surfactants, biofilm, biocontrol agent, stress tolerance,Siderophore produc-tion,phytoremediation agent, phytohor-mones production (IAA),Plant Growth Regulator.	Mn, Cu, Zn, Fe	Promote plant growth, protect crops and woods, prevent plant pathogens, increase nutrient uptake, provide tolerance to drought, heavy metal and salinity, in-crease root and stem diameter and length, increase content of chlorophyll a and b and carotenoids	[145]
Alternaria sp.	Blackberries, raspberries, straw-berries, grapes, blueberries, minneola oranges, navel orang-es, citron lemons,tangerines, papaya.	Potential plant pathogen	-	Causes disease in plants,causes leaf spot or blight diseases, potato foliar and leaf blotch diseases, premature leaf fall, decrease fruit size, quality, and quantity.	[146-149]
Ulocladium sp.	Grapes	Plant pathogen and biocontrol agent.	-	Causes disease in plants, and disease suppression.	[150]
Geotrichum sp.	Eggplant, minneola oranges, navel Sunkist, guava, lemon, okra, bell pepper, papaya, mel-on, pumpkin, carrot, turnip.	Weak plant pathogen.	-	Causes sour rot disease.	[151, 152]
Drechslera sp.	Guava, tomato, bell pepper, pumpkin, radish,	Plant pathogen	-	Causes diseases in crops, producing leaf spot disease.	[153, 154]
Candida tropi-calis	Orange, pawpaw, tomato	Production of IAA,ACC deaminase. Phosphate solubilisation, plant growth Regulator.	N, P	Increase seedling growth, increase yield, increase leaf area, root length, and chlo-rophyll content.	[155, 156]
Phoma sp.	potato	stress resistance, plant pathogen,produce gibberellins.	-	drought tolerance,causes diseases in crops and vegetables, increases shoot length, produce gibberellins.	[157-159]
Saccharomyces sp.	tomato	Biocontrol agent, Plant growth Regulator,Phosphate solubilisa-tion,nitrogen fixation	N, P	seed germination, seedling development, and prevent *Fusarium* infection,	[160, 161]

the soil's capacity to hold moisture [167]. To produce biochar, a wide variety of raw materials or feedstocks can be used. These include agricultural residues (like crop stalks), woody materials (such as branches and sawdust), food waste, animal manure, litter, and other types of solid waste [168, 169]. The most widely used materials are lignocellulosic biomass, such as agricultural and forest waste, due to their high carbon content [170]. In addition to plant-based materials, researchers have also been investigating using non-lignocellulosic sources such as algae, manure, and sewage sludge [171]. Biochar can enhance soil porosity by 1-64% and decrease bulk density by 3-11% (with an average reduction of 12%). By strengthening the soil's physical structure, these modifications improve the flow of heat, air, and water through it [172]. By increasing porosity, water retention, and conductivity, biochar strengthens soil structure. However, the effects of biochar vary depending on the material type, production temperature, and pore structure. Reduced moisture and unstable soil changes over time can result from improper or excessive use, particularly in sandy soils. An analysis revealed that biochar can increase saturated hydraulic conductivity by 25%, water-holding capacity by 15.1%, and soil porosity by 8.4% [173]. It raises the pH of the soil due to its high alkaline contents, potent buffering capability and functional groups. It also delivers vital cations including potassium, magnesium, calcium, and salt. Thus, improves nutrient availability [174, 175]. The amount of surface negative mineral charge and soil organic matter (SOM) enhances the soil's cation exchange capacity (CEC), which is the capability of the soil to hold onto cations in an exchangeable form that plants may use [176]. When newly added biochar encounters oxygen and soil water, it conducts surface oxidation processes that raise the CEC and net negative charge. The high reactivity of the biochar surface is a result of the presence of several reactive functional groups, some of which are pH-dependent (COOH, OH, CO, C-O, N, siloxane) [177].

The pyrolysis temperature and the type of feedstock utilised have a major impact on the yield and important physicochemical characteristics of biochar, including surface area, pore volume, ash content, elemental composition, carbon content, and functional groups. Because more volatile compounds are released at higher temperatures, surface area and porosity often rise while yield decreases. The performance of the biochar is directly impacted by these pyrolysis-induced changes in its content and structure. Therefore, pyrolysis conditions must be understood and controlled in order to customize biochar properties for application [178, 179]. When biomass is heated at the same temperature for a longer time during pyrolysis, it produces less biochar. Prolonged heating causes more volatile compounds in the biomass to decompose and release as vapours or gases. As these volatiles are released over time, the remaining solid material becomes more carbon-rich but also reduces in mass, resulting in less biochar being produced overall. Although prolonged heating improves the carbon quality of the biochar, it reduces its overall quantity [180]. The type of feedstock and the circumstances of the process determine how much biochar, bio-oil, and gas are produced during pyrolysis. Gases such as CO, CO_2, H_2, and light hydrocarbons are emitted during pyrolysis, along with molecules in bio-oil that are rich in oxygen. As a result, the biomass's oxygen-to-carbon (O/C) and hydrogen-to-carbon (H/C) ratios are reduced, producing biochar that is more aromatic and richer in carbon [181]. The yield and characteristics of biochar are affected by a range of pyrolysis variables, such as residence time, particle size, heating rate, temperature, reactor height, pressure, carrier gas flow rate, and catalyst usage. Feedstocks that contain more lignin tend to yield more biochar, whereas those containing cellulose and hemicellulose tend to yield more volatile products. Furthermore, employing bigger feedstock particles may increase the production of biochar.A bigger pyrolyzer's height increases the output of biochar by extending the vapour residence period and enabling re-polymerization. Biochar yields are also said to be improved by higher pressure and lower carrier gas flow rates.The yield of biochar is affected differently by the catalysts used in pyrolysis. In general, the yield of biochar is increased by acidic catalysts and decreased by basic catalysts [182].

A variety of methods are used to produce biochar. Mainly, there are four types of methods including - pyrolysis, gasification, torrefaction, and hydrothermal carbonization. These are the thermochemical processes of biochar production [183-186]. Pyrolysis, the most common method for producing biochar, is a process where organic materials are heated above 400 °C in the absence of oxygen. This is typically done using electric heating or other high-temperature systems in an inert environment. Mainly three types of hydrolysis are used in biochar production including slow pyrolysis, intermediate pyrolysis and fast pyrolysis. Slow pyrolysis is a commonly used technique for producing biochar due to its high yield and beneficial surface properties. This process involves heating biomass slowly-typically at a rate of less than 10 °C per minute-for extended periods, usually an hour or more, in an environment with little or no oxygen. The slow heating allows volatile compounds released during pyrolysis to undergo re-polymerization, which enhances the structural stability and quality of the resulting biocha [187, 188]. Additionally, compared to fast pyrolysis and intermediate pyrolysis, slow pyrolysis is more effective, with lower biomass pretreatment costs [189]. In intermediate pyrolysis, biomass is heated at a low to moderate temperature for a moderate amount of time. In contrast, fast pyrolysis involves rapidly heating the biomass at a rate of 200 to 1000 °C per minute, but only for a few seconds, to produce biochar. This difference in heating rate and duration leads to variations in the yield and properties of the resulting biochar. The yield of biochar is comparatively lower in fast pyrolysis than in slow pyrolysis [182]. This method, often referred to as conventional carbonization, is one of the oldest known techniques for producing charcoal and has been practiced for thousands of years. Historical evidence suggests that knowledge of charcoal production dates back as far as 38,000 years.People have developed and improved the process over this long time, gaining a thorough understanding of how to effectively produce and use charcoal [190]. A novel and promising technique for producing biochar is microwave-assisted pyrolysis. More than 60% of the initial biomass can be converted into biochar, and the biochar has a large surface area (450-800 m^2/g) [191]. The yield of the biochar is comparatively low in the gasification process of biochar production. Gasification is a process that is operated at high temperature, typically 700 °C to 1000 °C. In this process, organic materials, including biodegradable waste, are heated for a few seconds to a minute at a moderate to high heating rate. Additionally, the biomass is mostly transformed into syngas, a mixture of flammable gases made with biochar. With trace amounts of methane (CH_4), this gas is mostly composed of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and nitrogen (N_2). Carried out under limited oxygen or with oxidizing agents like air, oxygen, steam, or CO_2. The high temperatures and oxidative conditions lead to lower biochar yields due to extensive decomposition [192, 193]. As a kind of mild pyrolysis or thermal pretreatment, torrefaction involves gradually heating biomass to temperatures, usually between 200 and 300 °C. The process takes a few minutes to several hours, and the heating rate is typically less than 10 °C per minute [194]. Hydrothermal carbonization (HTC) is a method that converts waterlogged biomass to biochar, known as hydrochar, by heating it within supercritical water at moderate conditions (175-300 °C) at high pressure for long periods (30 minutes to 16 hours) with a gradual heating rate. As it eliminates the need for drying, which consumes a lot of energy, this method is particularly beneficial for feedstocks with a high moisture content. In comparison to biochar produced by other methods, the resulting hydrochar has a higher concentration of alkyl compounds and oxygen-containing functional groups, which enhances its biodegradability [195, 196]. Compared to conventional pyrolysis, hydrothermal carbonisation (HTC) usually produces biochar with a greater energy densification ratio and a large volume of solid product (40-70% of the initial biomass). Due to HTC's ability to retain more of the biomass' energy and eliminate oxygen-rich components, which concentrates carbon and raises its fuel value, the resulting biochar has more energy per unit mass [194]. Since their chemical characteristics do not meet the requirements for biochar, these materials are not accepted under the European Biochar Certificate (EBC) standards. Their efficacy for long-term carbon storage is diminished by their generally low total organic carbon content. Their low surface area and porosity restrict their ability to retain water and nutrients, which are essential characteristics for enhancing soil health, and their high ash content reduces their energy value. Even though they have high nutrient levels [197, 198].

5.2. Biochar as a Microbial Habitat

Due to the unique physical and chemical properties, biochar acts as an excellent habitat for soil microbes like bacteria, actinomycetes, and arbuscular mycorrhizal fungi, and offers an ideal atmosphere to grow and colonize. Porous characteristics of biochar give many tiny pores and broad surface areas. These enables to take up and exchange of organic matter, gases, and nutrients [199]. The variability of the pore sizes is brought about through different biomass sources and pyrolysis conditions. Microbial colonization is mostly influenced by the size of the pores in biochar since only the microbes that are suitable for the size of the pores can pass through the spaces. These pores act as microhabitats or shelters, safeguarding microorganisms from predatory organisms and facilitating the establishment of less competitive species. It also protects from desiccation and temperature fluctuations. Small pores facilitate the growth and colonization of beneficial microbes like bacteria, fungi, protozoa *etc*. but block large-sized predators such as arthropods [200, 201]. Compared to materials like pumice or activated carbon, biochar retains more water, which keeps soils moist for longer periods. This enhanced moisture retention supports better microbial activity. Over time, the porosity of ash increases as it washes away, improving the retention of water and nutrients. Microbes prefer biochar because of its smaller pores. Its fine pores are particularly beneficial, as they store water effectively, providing a steady and protective environment for microbes to grow and survive [202]. Biochar has the ability to trap and retain gases such as oxygen (O_2) and carbon dioxide (CO_2) within its porous structure. The type of microbial activity that occurs inside these pores depends on the availability of oxygen. When sufficient oxygen is present, microbes carry out aerobic respiration, resulting in the production of CO_2 and water. However, if oxygen is limited, microbes shift to anaerobic processes, which lead to the formation of gases like methane (CH_4), nitrous oxide (N_2O), and hydrogen sulfide (H_2S) [190]. Strong microbial adherence and colonization are facilitated by biochar's many surface functional groups, which include hydroxyl, carboxyl, sulfonic acid, and amino groups. Biochar is an efficient medium for delivering microbial inoculants and a sustainable substitute for non-renewable carriers such as peat. This improves plant growth, nitrogen cycling, and pollutant degradation in addition to increasing microbial survival and activity in soil [203]. Enzymes are used by microbes to break down nutrients, and these enzymes must remain near their release site. Depending on how the enzymes adhere to the surface, biochar surfaces can either increase or decrease their activity [204]. As biochar confines enzymes in its porous structure, it can help strengthen soil enzymes. This prolongs the activity of enzymes like arylsulfatase and β-glucosidase by shielding them from degradation brought on by heat or water. The efficiency of these enzymes may also be affected by the biochar. By promoting microbial development and raising the supply of organic matter-which acts as feed for both microorganisms and enzymes-it can occasionally increase enzyme activity.

However, by obstructing substrate availability or altering the soil's microbial and nutritional balance, some forms or excessive concentrations of biochar may lower enzyme activity [205, 206]. Because of its distinct properties, biochar functions as an efficient microbial home and carrier. Also, numerous microbial colonization niches are made possible. These characteristics help microorganisms survive and flourish over time in soil settings and plant rhizospheres, in addition to supporting their initial attachment. These characteristics make biochar especially appropriate for improving soil microbial populations and encouraging plant-microbe interactions [207]. Because it retains moisture along with crucial elements including organic carbon, nitrogen, phosphorus, and potassium, biochar aids in the development of an optimal atmosphere for beneficial microbial populations. These characteristics help microorganisms endure and stay active, even in harsh or nutrient-deficient environments. Biochar improves the resilience and metabolic processes of microorganisms by preserving a stable and resource-rich microenvironment, which benefits soil ecosystems [208]. Furthermore, the rhizosphere-the area surrounding plant roots where microbial activity is highest-beneficial bacteria benefit from a stable and favorable environment that is maintained by biochar's neutral to slightly alkaline pH and potent buffering ability [209]. Because of these combined benefits, biochar is a useful soil supplement for maintaining microbial communities and improving soil performance, such as the breakdown of contaminants, nutrient cycling (such as the transformation of nitrogen and phosphorus), and the decomposition of organic waste, all of which enhance soil fertility and health [210]. Biochar is used as an alternative to peat for carrying beneficial bacteria (*Bradyrhizobium japonicum*) in solid inoculants and seed coatings. It was examined how well both materials preserved bacterial viability during storage at 4°C and 21°C. They also created a seed coating using biochar mixed with guar gum. Results showed that the effectiveness of biochar in maintaining bacterial survival depended on its type, but it did not interfere with seed germination. Greenhouse tests revealed that biochar-based inoculants boosted soybean growth, root development, and nutrient uptake, especially in the absence of nitrogen fertilizer. Overall, biochar appears to be a sustainable and effective microbial inoculant [211], Fig. (**3**). It has been found that some forms of biochar can prolong the shelf life of microbial

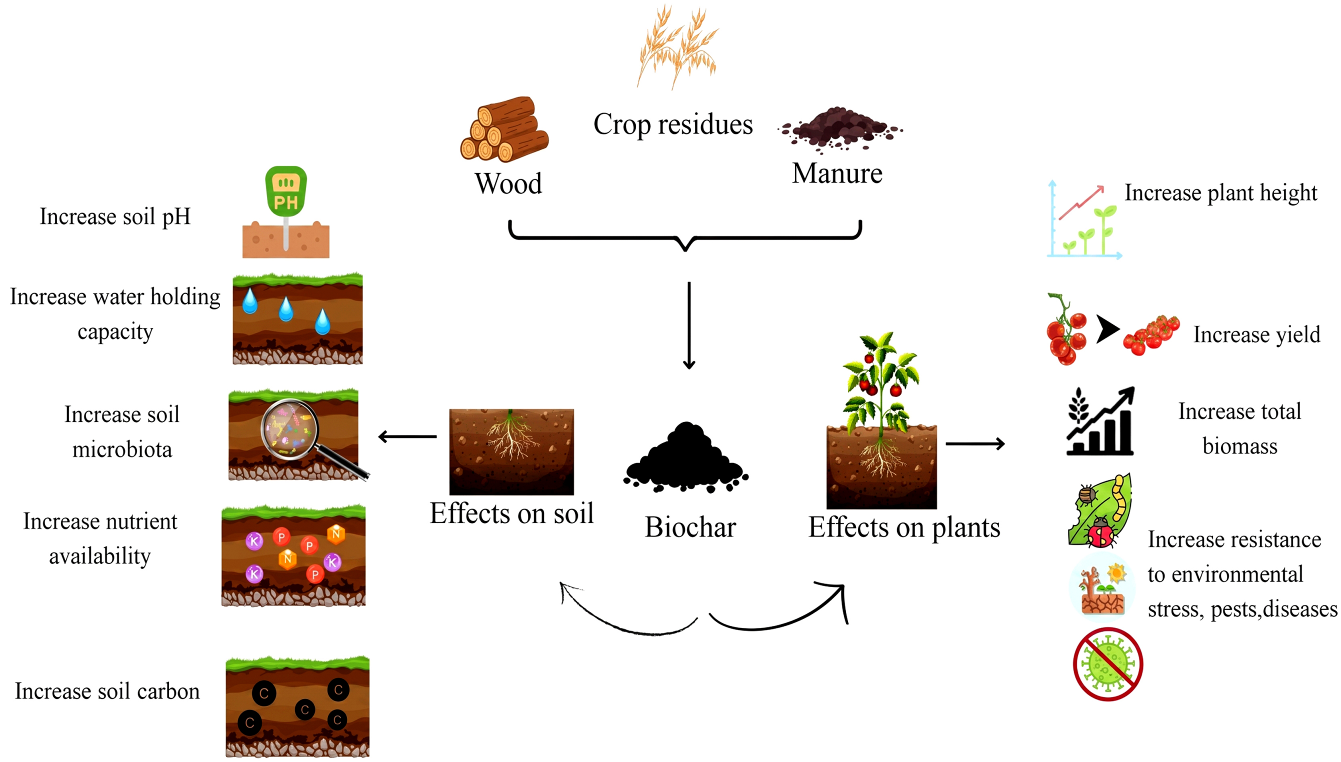

Fig. (3). Various effects of biochar on soil and plant health. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

inoculants by up to a year, which makes them more useful for storage and use in agricultural environments. *Bradyrhizobium* strains last for one year in a biochar prepared from pine bark. But not all biochars are made similarly; some can have characteristics such as high pH or dangerous impurities that prevent them from being used as microbial carriers.

By offering a safe, nutrient-rich environment that improves the longevity and functionality of advantageous inoculation microorganisms, biochar functions as an efficient and renewable microbial carrier in the sectors of agriculture and the environment [212]. Biochar serves as a great microhabitat, providing native soil microbiota and inoculated bacteria such as *Bacillus subtilis* and other species with shade and protection. Microbes can live longer, reproduce more successfully, and remain safe from predators and adverse environmental circumstances in the safe spaces provided by the pores of biochar. Combining biochar with biofertilizers, which include living microorganisms that improve nutrient availability, can have a synergistic impact, which means that the combined advantages of the two products are more than they would be if they were applied separately. For instance, research has indicated that combining the two can result in a 91% increase in plant biomass. One of the main causes of this synergy is that biochar keeps microorganisms that promote plant growth viable and active. These microorganisms help with nitrogen fixation, phosphorus solubilization, and hormone synthesis, all of which have a direct impact on plant growth[20]**.** Research indicates that the quantity and variety of soil microorganisms are often increased by biochar. For instance, it decreases some beneficial groups, such as *Acidobacteria*, by 14.6% while increasing others, such as *Gemmatimonadetes*, by 19.8%. The amount of biochar utilized its carbon-to-nitrogen ratio, pH, and manufacturing temperature are some of the variables that affect these changes. The pH and carbon-to-nitrogen ratio of the soil have an impact on the outcomes as well. Compared to lab studies, field investigations typically reveal more bacterial richness. By increasing the consumption of carbon substrate, biochar may improve nutrient cycling and microbial activity. All things considered, carefully chosen biochar can maintain microbial biodiversity, promote climate-smart agriculture, and enhance soil health [213], Table **2**.

Fig. (**4**) presents a comparative overview of key biochar properties generated at different pyrolysis temperatures across multiple feedstocks. The horizontally stacked bars show how parameters such as ash content, cation exchange capacity (CEC), surface area, pH, and feedstock type vary with temperature. Higher pyrolysis temperatures generally increase biochar surface area and pH while reducing CEC and influencing ash accumulation. The figure highlights the wide variability in biochar characteristics, demonstrating that both feedstock composition and pyrolysis temperature critically determine its functional properties and suitability for agricultural or environmental applications.

6. SYNERGISTIC APPLICATIONS IN CLIMATE-SMART AGRICULTURE

As a soil amendment, biochar-which is made by pyrolyzing organic biomass-improves the soil's structure, ability to hold water and nutrients, and capacity to exchange ions.

Table 2. Comparison of biochar from different feedstocks.

Feedstock	Pyrolysis Temp (°C)	pH	Surface Area (m^2/g)	Cation Exchange Capacity (CEC) (cmol/kg)	Ash Content (%)	Suitability	References
Residual bamboo biomass	450-550	8.2	-	37	-	Alkaline soil with low buffer capacity	[214]
Bamboo	600	7.9	470.4	-	-	Acidic soil	[215, 216]
Hickory wood	600	8.4	401.0	-	-	Acidic soil	[216]
Peanut hull	600	6.9	27.1	-	-	Most soils are slightly acidic to neutral soils.	
CornStover	600	9.42	527	25.21	16.7	Highly acidic soil	[217]
	350	9.39	293	41.93	11.4	Highly acidic soil	
Oakwood	600	7.90	642	7.57	1.3	Slightly acidic or neutral soil	
	350	5.18	450	29.42	1.1	Alkaline soil	
Poultrylitter	600	10.3	94	5.87	55.8	Highly acidic soil	
	350	9.65	47	12.13	51.2	Highly acidic soil	
Cow manure	500	10.2	21.9	149	67.5	Highly acidic soil	[179]
Pig manure	500	10.5	47.4	82.8	48.4	Highly Acidic soil	
	350	9.65	4.26	49.0	37.2	Highly acidic soil	
	650	10.8	42.4	132	69.6	Highly acidic soil	
	200	8.22	3.59	23.6	35.7	Acidic soil	
Grass	500	10.2	3.33	84.0	20.8	Highly acidic soil	
Sawdust	500	10.5	203	41.7	9.94	Highly acidic soil	
Peanut shell	500	10.5	43.5	44.5	10.6	Highly acidic soil	
Wheat straw	350	8.69	3.48	87.2	14.7	Acidic soil	
	500	10.2	33.2	95.5	18.0	Highly acidic soil	
	650	10.2	182	146	16.2	Highly acidic soil	
	200	5.43	2.53	32.1	7.21	Most soils, including slightly acidic to neutral soils	
Wastewater sludge	500	8.82	71.6	168	61.9	Acidic soil	
Shrimp hull	500	10.3	13.3	389	53.8	Highly acidic soil	
Bone dregs	500	9.75	113	87.9	77.6	Highly acidic soil	
Chlorella	500	10.8	2.78	562	52.6	Highly acidic soil	
Waterweeds	500	10.3	3.78	509	63.5	Highly acidic soil	
Waste paper	500	9.88	133	516	53.5	Highly acidic soil	
Japanese cedar chip (*Cryptomeria japonica*)	400	7.7	-	-	0.1	Acidic soil	[218]
	600	8.8	-	-	1.7	Highly acidic soil	
	800	8.4	-	-	2.6	Acidic soil	
Japanese cypress chip (*Chamaecyparis obtusa*)	400	5.4	-	-	2.1	Alkaline soil	
	600	8.3	-	-	2.8	Acidic soil	
	800	9.1	-	-	4.0	Highly acidic soil	

(Table 2) Contd….

Feedstock	Pyrolysis Temp (°C)	pH	Surface Area (m^2/g)	Cation Exchange Capacity (CEC) (cmol/kg)	Ash Content (%)	Suitability	References
Moso bamboo chip (*Phyllostachys edulis*)	400	7.4	-	-	6.1	Most soils, including slightly acidic to neutral soils	
	600	10.3	-	-	8.3	Highly acidic soil	
	800	9.7	-	-	6.7	Highly acidic soil	
Ricehusk (*Oryza sativa*)	400	6.7	-	-	47.9	Most soils, including slightly acidic to neutral soils	
	600	10.2	557.4	-	54.9	Highly Acidic soil	
	800	10.4	-	-	57.7	Highly Acidic soil	
Sugarcane bagasse *(Saccharum officinarum)*	400	5.0	-	-	12.4	Alkaline soil	
	600	7.7	-	-	18.6	Acidic soil	
	800	9.8	-	-	16.1	Highly acidic soil	
Domestic wastewater sludge	400	7.3	-	-	37.1	Most soils, including slightly acidic to neutral soils	
	600	8.3	-	-	52.0	Acidic soil	
	800	8.0	-	-	57.0	Acidic soil	
Poultry manure	400	10.8	-	-	48.4	Highly acidic soil	
	600	12.0	-	-	56.7	Highly acidic soil	
	800	12.2	-	-	68.2	Highly acidic soil	
Algaeresidues	300-700	-	-	-	4.8	Nutrient-poor soils	[219]
Grass *(Festucaarundinacea)*	400	-	8.7	-	16.3	Improve soil quality for carbon sequestration.	[220]
Wood (*Pinusponderosa)*	400	-	28.7	-	1.4	Improve soil quality, for carbon sequestration.	
Municipal sludge	500	8.8	-	76.8	74.2	Highly acidic soil	[221]
	900	2.2	67.6	247.5	88.1	Highly acidic soil	
Wheat Straw	450 (High heating rate)	alkaline	184	-	3.6	Sandy and acidic soil	[168]
	450 (slow heating rate)	Highly alkaline	178	-	3.9	Highly acidic soil	
Timothy grass	450 (High heating rate)	alkaline	203	-	3.1	Sandy and acidic soil	
	450 (Slow heating rate	Highly alkaline	179	-	3.5	Highly acidic soil	
Pine wood	450 (High heating rate)	alkaline	185	-	4.1	Neutral to slightly acidic soils	
	450 (slow heating rate)	Highly alkaline	166	-	4.6	Highly acidic soil	
Turkeylitter	700-800	10.9	21.8	24.4	64	Highly acidic soil	[222]
Walnut shell	900	9.7	227.1	33.4	40.4	Highly acidic soil	

(Table 2) Contd….

Feedstock	Pyrolysis Temp (°C)	pH	Surface Area (m²/g)	Cation Exchange Capacity (CEC) (cmol/kg)	Ash Content (%)	Suitability	References
Rice straw	300	8.0	-	93	31	Acidic soil	[223]
	400	9.7	-	111	40	Highly acidic soil	
	500	10.4	-	77	52	Highly acidic soil	
	300	9.31 in H_2O, 8.55 in KCl	-	60.6	25.4	Highly acidic soil	[224]
	400	9.58 in H20, 9.04 in Kcl	-	63.9	27.6	Highly acidic soil	
	500	10.45 in H20, 10.00 in KCl	-	26.9	30.1	Highly acidic soil	
	600	10.91 in H20, 10.53 in KCl	-	19.0	28.4	Highly acidic soil	
	700	10.77 in H_2O, 10.51 in KCl	-	23.1	28.2	Highly acidic soil	
Wheat straw	300	7.7	-	103	25	Acidic soil	[223]
	400	8.8	-	119	37	Acidic soil	
	500	9.4	-	85	46	Highly acidic soil	
Soybean stover	300	7.27	5.61	-	10.41	Most soils, including slightly acidic to neutral soils	[189]
	700	11.32	420.3	-	17.18	Highly acidic soil	
Peanut shells	300	7.76	3.14	-	1.24	Acidic soil	
	700	10.57	448.2	-	8.91	Highly acidic soil	
	350	10.4	14.0	-	26.5	Highly acidic soil	[225]
	450	11.1	14.0	-	23.7	Highly acidic soil	
	550	10.6	18.6	-	19.7	Highly acidic soil	
	650	10.6	28.1	-	17.4	Highly acidic soil	
Dairy manure	100	8.0	1.8	-	37.0	Acidic soil	[226]
	200	6.8	2.7	-	44.0	Most soils, including slightly acidic to neutral soils	
	350	10.5	7.1	-	62.0	Highly acidic soil	
	500	10.5	13.0	-	95.0	Highly acidic soil	
	350	9.2	1.64	24.2	-	Highly acidic soil	[227]
	700	9.9	186.5	39.5	-	Highly acidic soil	
Feedlot manure	350	9.1	1.34	-	28.7	Highly acidic soil	
	700	10.3	145.2	-	44.0	Highly acidic soil	
Poultry litter	350	8.7	3.9	-	30.7	Highly acidic soil	
	700	10.3	50.9	-	46.2	Highly acidic soil	
Swine solid	350	8.4	0.9	-	32.5	Acidic soil	
	700	9.5	4.1	-	52.9	Highly acidic soil	
Turkey litter	350	8.0	2.6	-	34.8	Acidic soil	
	700	9.9	66.7	-	49.9	Highly acidic soil	

(Table 2) Contd….

Feedstock	Pyrolysis Temp (°C)	pH	Surface Area (m^2/g)	Cation Exchange Capacity (CEC) (cmol/kg)	Ash Content (%)	Suitability	References
Cattle manure	300	8.0	-	66.3	20.2	Acidic soil	[228]
	500	10.2	-	70.9	43.7	Highly acidic soil	
Cattle straw manure	300	10.1	-	65.5	38.3	Highly acidic soil	
	500	10.1	-	58.4	51.3	Highly acidic soil	
Chicken manure	300	8.1	-	137.6	34.8	Acidic soil	
	500	10.6	-	81.4	38.0	Highly acidic soil	
Chicken sawdust manure	300	10.6	-	81.7	34.6	Highly acidic soil	
	500	10.3	-	65.8	35.9	Highly acidic soil	
Pig manure	300	7.8	-	35.6	50.3	Acidic soil	
	500	8.2	-	32.7	73.9	Acidic soil	
Sugarcane bagasse	250	5.02	-	6.40	-	Alkaline soil	[229]
	400	6.98	-	3.82	-	Most soils, including slightly acidic to neutral soils	
	500	7.34	-	9.66	-	Most soils, including slightly acidic to neutral soils	
	600	7.66	-	4.19	-	Acidic soil	
Chicken manure	350	9.7	-	-	52.0	Highly acidic soil	[230]
	450	10.2	-	-	55.3	Highly acidic soil	
	750	11.7	-	-	56.4	Highly acidic soil	
Eucalyptus sawdust	350	5.9	-	-	0.9	Alkaline soil	
	450	8.0	-	-	0.7	Acidic soil	
	750	9.7	-	-	1.1	Highly acidic soil	
Coffee husk	350	9.7	-	-	12.9	Highly acidic soil	
	450	9.8	-	-	12.9	Highly acidic soil	
	750	9.9	-	-	12.9	Highly acidic soil	
Sugarcane bagasse	350	7.2	-	-	1.9	-	
	450	8.8	-	-	2.1	Highly acidic soil	
	750	9.7	-	-	2.2	Highly acidic soil	
Pine bark	350	7.8	-	-	8.3	Acidic soil	
	450	8.3	-	-	7.9	Acidic soil	
	750	9.9	-	-	14.5	Highly acidic soil	
Prosopis africana shell	350	6.5	3.1	-	25.2	Alkaline soil	[231]
Swine manure	400	11.0	4.9	65.6	49.8	Highly acidic soil	[232]
Corn cobs	500	7.8	0	-	-	Acidic soil	[233]
Corn stover	500	7.2	3.1	-	-	Most soils, including slightly acidic to neutral soils	[233]
	300	7.7	3.2	-	5.7	Acidic soil	[234]
	400	8.8	3.2	-	12.5	Highly acidic soil	
	500	9.8	4.6	-	18.7	Highly acidic soil	

(Table 2) Contd….

Feedstock	Pyrolysis Temp (°C)	pH	Surface Area (m²/g)	Cation Exchange Capacity (CEC) (cmol/kg)	Ash Content (%)	Suitability	References
Soybean stover	700	11.3	420.3	59.2	17.2	Highly acidic soil	[235]
Orange pomace	350	9.9	1.2	35.2	11.3	Highly acidic soil	[236]
	600	10.5		25.6	16.3	Highly acidic soil	
Vine pruning	350	10.3	8.1	47.4	8.3	Highly acidic soil	
Cottonseed hull	200	3.5	-	-	3.1	Highly alkaline soil	[237]
	350	7.0	4.7	-	5.7	Most soils, including slightly acidic to neutral soils	
	500	10.1	0	-	7.9	Highly acidic soil	
	650	9.9	34	-	8.3	Highly acidic soil	
	800	9.2	322	-	9.2	Highly acidic soil	
Black wattle	475	9.7	241.0	101.0	4.8	Highly acidic soil	[238]
Vineyard prun-ings	475	6.6	259.0	122.0	12.1	Most soils, including slightly acidic to neutral soils	
Sugarcane ba-gasse	475	10.4	92.0	65.0	8.1	Highly acidic soil	
Canola straw biochar	300	6.48	-	199	10.70	Most soils, including slightly acidic to neutral soils	[239]
	500	9.39	-	210	18.40	Highly acidic soil	
	700	10.76	-	179	28.55	Highly acidic soil	
Cornstraw biochar	300	9.37	-	183	30.15	Highly acidic soil	
	500	10.77	-	304	50.70	Highly acidic soil	
	700	11.32	-	210	73.30	Highly acidic soil	
Soybean straw biochar	300	7.66	-	279	11.15	Acidic soil	
	500	10.92	-	216	17.85	Highly acidic soil	
	700	11.10	-	222	23.70	Highly acidic soil	
Peanutstraw biochar	300	8.60	-	229	20.10	Highly acidic soil	
	500	10.86	-	230	32.50	Highly acidic soil	
	700	11.15	-	254	38.50	Highly acidic soil	
Buckwheathusk	350	9.2	11.4	11.2	4.0	Highly acidic soil	[225]
	450	9.7	10.7	11.5	25.4	Highly acidic soil	
	550	10.0	17.0	10.1	5.8	Highly acidic soil	
	650	9.1	17.8	11.7	33.1	Highly acidic soil	
Mulberrywood	350	10.2	16.6	23.3	7.5	Highly acidic soil	
	450	11.1	31.5	22.1	7.7	Highly acidic soil	
	550	10.6	58.0	19.0	9.8	Highly acidic soil	
	650	10.6	24.5	21.8	9.8	Highly acidic soil	

By acting as a slow-release carrier of nutrients and microorganisms that produce biofertilizer, biochar can maintain long-term fertility by coordinating nutrient release with crop demand. Beneficial microorganisms found in biofertilizers improve nutrient cycling and soil microbial ecosystems [240]. Biochar lowers greenhouse gas emissions and nutrient losses while improving crop output and soil health. It is a promising tactic for climate action and sustainable farming; however, its effects vary depending on variables including fertilizer use, charcoal quality, and soil type [241].According to studies, using biochar and biofertilizers separately or in combination can boost crop yields, albeit the rates vary

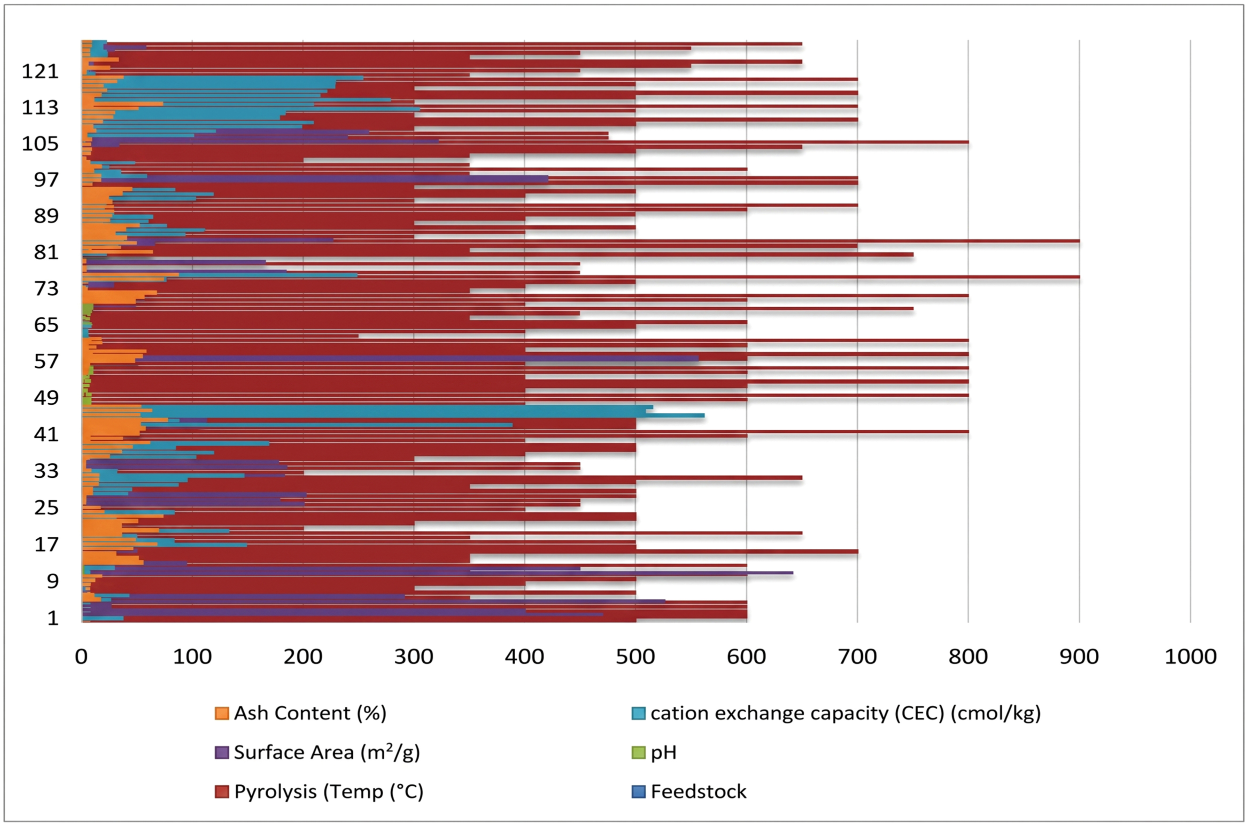

Fig. (4). Biochar properties based on pyrolysis temperature. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

depending on the crop and the circumstances. One field research found that rice output increased by 16.5% to 38.3% [242]. According to the study, the application of biochar and biofertilizers in rice fields increased the amount of nitrous oxide gas emitted due to the increased activity of soil bacteria. The overall effect on global warming was still greater than in untreated soil, even though combining the two helped bring ammonia loss down to normal levels. On the plus side, rice yields increased while the GHGI (greenhouse gas emissions per unit of rice) remained the same. This implies that more rice can be produced without causing greater environmental damage by mixing biochar with biofertilizers. To find out how these treatments impact gas loss over time, more research is necessary [243]. According to the study, biochar and biofertilizers complement each other more effectively than they do separately. Although biochar improves the soil, it may hinder plants' ability to use nitrogen. Together with biofertilizers, particularly inactivated yeast (IY), plants grew significantly better, producing more leaves and more robust roots. In addition to providing trees with additional nitrogen and phosphorus, this mixture also assisted in lowering the levels of toxic copper in the leaves. Simply said, biochar strengthens the soil's structure and biofertilizers supply nutrients, forming a potent combination that can support tree growth in unfavourable urban soils [20].

In a study using a technique called slow pyrolysis, residual bamboo was heated gradually at moderate temperatures (450-550 °C) in a low-oxygen atmosphere to create the biochar. This process produces a porous, carbon-rich substance that is perfect for enhancing soil qualities while preserving a large portion of the carbon in the biomass. Using rabbit feces as a natural microbial starter, leftover pieces of the nopal cactus (*Opuntia ficus-indica*) were fermented without oxygen to create the biofertilizers. Through this process, the organic material is broken down and enhanced with nutrients and helpful bacteria. A greenhouse experiment using tomatillo plants (*Physalis ixocarpa*), also referred to as husk tomatoes, was carried out to evaluate the impact of these two soil additives together. In order to examine both short-term and somewhat longer-term effects on soil and plant health, the experiment was conducted throughout two full crop cycles. In the short term, the combination of biochar and biofertilizer significantly improved the structure, porosity, water-holding capacity, and nutrient availability of the soil. Alkaline ions such as calcium and potassium caused the pH of the soil to rise from 7.6 to 8.5 at the beginning of the second cycle. Because of the increased organic matter, the pH subsequently slightly decreased to 8.1. Important minerals like potassium, calcium, and phosphorus rose dramatically; potassium levels went from 257 mg/kg to over 12,000 mg/kg before stabilizing. However, due to a likely nutritional imbalance, magnesium levels dropped. In certain treatments, iron eventually decreased, but micronutrients like copper, zinc, and iron also improved. Crucially, heavy elements including nickel, cadmium, and lead stayed below detection limits, suggesting no risk of contamination [214]. A study examined the potential benefits of using two types of biofertilizers and varying quantities of biochar on lentil crops for the subsequent crop, maize, without the need for additional fertilizer. Babul tree wood biochar was crushed to create biochar in three different sizes: less than 2 mm, 2-5 mm, and 5-10 mm. Before growing lentils, it was incorporated into the soil. Additionally, the lentil seeds were treated with either Rhizogold or Biozote-N, two biofertilizers that include beneficial nitrogen-fixing bacteria and rhizobacteria that promote plant growth, respectively. In order to determine how well maize will grow from the residual effects of the previous treatments, it was planted in the same soil after the lentil harvest. The results demonstrated that the succeeding maize crop's growth and productivity were greatly enhanced by the combination of Biozote-N and finely powdered biochar (<2 mm).

In particular, this treatment raised the grain weight, biological yield, plant height, and leaf area. Along with a 3% decrease in soil bulk density, it also produced quantifiable increases in grain production from maize (2.5%), nitrogen uptake (15%), nitrogen usage efficiency (17%), grain protein content (15%), and extractable phosphorus (17%) [244]. A study assessed how beneficial microbes, namely plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF), in conjunction with biochar derived from poultry manure, applied at 0, 5, and 10 t/ha, affected soil fertility, chemical characteristics, and Black Cumin *(Nigella sativa* L.) yield. significant improvements ($p \leq 0.05$) in soil properties-pH, electrical conductivity, organic matter, and fertility index - were observed across all biochar and bio-fertilizer treatments. The combined treatment of biochar applied at 10 t/ ha with arbuscular mycorrhizal fungi and plant growth-promoting rhizobacteria resulted in the highest values for electrical conductivity (1.29 dS/m), organic matter (12.22 g/kg), and fertility index (12.74%). Both the application of biochar and microbial inoculants considerably increased the availability and uptake of nutrients, particularly nitrogen, phosphorus, and potassium in Black Cumin plants. In comparison to the control, nutrient availability increased by 186.56% nitrogen, 97.06% phosphorus, and 81.00% potassium when biochar was administered at a rate of 10 t/ha in conjunction with arbuscular mycorrhizal fungi and plant growth-promoting rhizobacteria. Fresh weight, plant height, capsule number, capsule fresh weight, and dry weight increased by 71.79%, 127.19%, 108.28%, 208.84%, and 91.18%, respectively, over untreated plants when a high rate of biochar was applied in conjunction with arbuscular mycorrhizal fungi and plant growth promoting rhizobacteria. It also increases the chlorophyll content in the cumin plants. And the seeds' weight, fixed and volatile oil contents increased from 1606 to 2037 kg/ha 47.12 and 103.18% respectively [245]. The combined effects of biochar and biofertilizer on soybean production, quality, and soil parameters were assessed in one study. Four rates of biochar application (0, 2.5, 8, and 16 t/ha) were employed, together with and without foliar inoculation, a biofertilizer that contained rhizobacteria that solubilized sulfur and phosphorus. Grain yield, cation exchange capacity, soil bulk density, and harvest index all showed significant interactions with biochar and biofertilizers. According to this study, using 8 tons of biochar per hectare coupled with biofertilizer greatly increased the production, oil content, and soil quality of soybeans. A 51% increase in output, an enhanced harvest index, and improved soil characteristics, including pH, electrical conductivity, and cation exchange capacity, were the best outcomes.

The combined treatment worked better than the other biochar levels and the control [246]. Applying biochar in conjunction with *Rhizobium*-based biofertilizers significantly increased groundnut yield, soil health, and environmental advantages, according to two-year field research. 2.30 t/ha of nuts were produced because of this combined treatment's improvements in root nodulation, plant development, and nutrient absorption. By boosting nitrification and decreasing denitrification, it also improved soil microbial activities, increasing the amount of nitrogen accessible to plants Fig. (**5**). It also reduced greenhouse gas emissions by 6.6 kg CO_2eq/ha and increased the soil's organic carbon content to 1.76 t/ha. All things considered, employing biochar as a *Rhizobium medium* promoted eco-friendly farming, improved soil quality, and produced healthier crops [247]. The effects of biochar and biofertilizers on the growth, yield, and soil health of soybeans (*Glycine max*) were investigated in a field experiment conducted during the kharif season. Five treatments, including combinations of biochar with *Azospirillum* and *Rhizobium*, were employed. With the greatest shoot length (52.30 cm), root length (17.30 cm), and average pod number (32.6), the biochar plus *Rhizobium* treatment outperformed the others. All treatments enhanced plant performance when compared to the control; the combination of *Rhizobium* and biochar was noticeably more successful. According to the study's findings, using biochar in conjunction with *Rhizobium* can increase crop yields and enhance soil quality, providing a sustainable substitute for chemical fertilizers, especially for legume crops [248], Table **3**. Fig. (**5**) illustrates the synergistic interaction between biochar and biofertilizers in improving soil health and crop productivity. Organic residues and microbial communities contribute to the development of beneficial biofertilizers, while biomass feedstocks undergo thermochemical conversion to produce biochar. When applied together to soil, biochar enhances nutrient retention, soil structure, and microbial habitat, whereas biofertilizers supply plant-growth-promoting microbes and bioactive compounds. Their combined application results in improved root growth, nutrient uptake, plant vigor, and overall crop yield, demonstrating an integrated approach to sustainable agriculture.

7. ENVIRONMENTAL AND AGRONOMIC BENEFITS

Biofertilizers with biochar give better benefit towards environment and agriculture over conventional fertilizers. Conventional fertilizers rapidly release nutrients after their application and increase nutrient availability immediately. But a significant portion is often lost through runoff and leaching. It causes reduced fertilizer efficiency and environmental pollution. Biofertilizers in combination with biochar, provide nutrient retention and sustained release of nutrients for a long period, creating healthy long-term functionality of the soil [247, 249]. Chemical fertilizers lower the soil pH over time and cause soil acidification. Acidic soils can harm beneficial microbes, reduce nutrient availability,

Table 3. Synergistic benefits of biochar and biofertilizers in agriculture.

Parameter	Plant Name	Biochar Alone	Biofertilizers Alone	Combined Applications	References
Soil Bulk Density (BD) (g/cm^3)	Husk tomato *(Physalisixocarpa)*	1.22 g/cm^3. Decreased by 21%.	-	Decreased more. 0.95 after the first crop cycle, 1.0 after 2nd crop cycle.	[214]
	Maize grain	Reduced to 1.11	-	Significantly reduced to 1.04	[244]
	Soybean (*Glycine max*)	1.54	1.59	1.51	[246]
Soil Water Holding Capacity (WHC)	Husk tomato *(Physalisixocarpa)*	Increased by 6%.	-	Increased more.	[214]
Soil Cation Exchange Capacity (CEC) (cmol/kg)	Husk tomato *(Physalisixocarpa)*	Increased from 16 to 33	-	Not significantly increased	[214]
Electrical conductivity (µS/m)	Husk tomato *(Physalisixocarpa)*	923	-	923 after 1st crop cycle and 517 after 2nd crop cycle.	[214]
	Black cumin (*Nigella sativa*)	118000	103000	129000	[245]
Organic Matter	Husk tomato *(Physalisixocarpa)*	Increased from 2% to 3%	-	Highest increase	[214]
	Black cumin (*Nigella sativa*)	11.24g/kg	9.14g/kg	12.22g/kg	[245]
	Soybean *(Glycine max)*	21.16%	-	21.09%	[248]
Phosphorus content (mg/kg)	Husk tomato *(Physalisixocarpa)*	Increased from 24 to 35	-	Highest phosphorus retention	[214]
	Black cumin (*Nigella sativa*)	8.93	7.50	9.86	[245]
Macronutrients uptake, macronutrient level and availability	*Acer saccharinum* (silver maple)	Slight uptake of macronutrients, especially phosphorus,	Significant uptake of macronutrients-N, P, K, Mg, and Ca.	The highest increases in uptake of all macronutrients. P, K, Mg, and Ca increased significantly	[20]
	Black cumin (*Nigella sativa*)	Increased over control. N (71.31mg/kg), P (8.93 mg/kg), K (312.75mg/kg)	Moderate increased. N(63.16 mg/kg), P(7.50 mg/kg), K(281.61 mg/kg)	Maximum increased. N(82.40 mg/kg), P (9.86 mg/kg), K(339.33 mg/kg)	[245]
Micronutrient uptake, micronutrient level and availability	Husk tomato (*Physalisixocarpa*)	Significantly increased	-	Significantly increased. The highest increase in the Cu and Zn levels	[214]
	Acer saccharinum (silver maple)	moderate uptake of micronutrients	Moderate to high uptake of micronutrients - Fe, B, S, and Zn	The highest increases in uptake of all micronutrients	[20]
Growth of the plant and Plant Height(cm)	Husk tomato (*Physalisixocarpa*)	Increased	-	Increased	[214]
	Acer saccharinum (silver maple)	Minor increase	Moderate increase	Major increase, up to 91%	[20]
	Maize grain	Increased up to 207.	-	Significant increase up to 220.	[244]
	Black cumin *(Nigella sativa*)	Increased up to 109.28	Moderate increase (up to 100.88)	Highest height (up to 133.71)	[245]
	Soybean (*Glycine max*)	Shoot length - 47.44	-	Shoot length - 52.99	[248]

(Table 3) Contd….

Parameter	Plant Name	Biochar Alone	Biofertilizers Alone	Combined Applications	References
Root length	Husk tomato (*Physalisixocarpa)*	Improved	-	Reduced	[214]
	Soybean (*Glycine max*)	15.11	-	17.31	[248]
Fruit Weight	Husk tomato *(Physalisixocarpa)*	Increased	-	An increase in the 2nd crop cycle than in the 1st crop cycle	[214]
	Black cumin *(Nigella sativa*)	Fresh weight increased by 94.51%	Fresh weight increased by 53.05%	Fresh weight increased by 208.84%	[245]
Yield	Husk tomato *(Physalisixocarpa)*	Increased. 730g/plant	-	Decreased. 328 g/plant.	[214]
	Black cumin (*Nigella sativa*)	Seed yield increased. 1807.53 kg/ha	Increased yield by 32.29%. 1429.69 kg/ha	Highest yield. 2037.9 kg/ha	[245]
	Maize grain	Grain yield increased up to 3408 kg/ha	-	Grain yield increased up to 3558 kg/ha	[244]
	Soybean (*Glycine max*)	Grain yield- 677.89 kg/ha. Straw yield- 1211.61 kg/ha.	-	Grain yield- 743.18 kg/ha. Straw yield- 1321.4 kg/ha.	[248]
Soil pH	Husk tomato *(Physalisixocarpa)*	7.2	-	8.5 after 1st crop cycle and 8.1 after 2nd crop cycle.	[214]
	Acer saccharinum (silver maple)	Increased slightly	Increased slightly	No significant change in soil pH	[20]
	Black cumin (*Nigella sativa)*	Increased. Up to 8.22	Slightly increased up to 8.16	Increased up to 8.25	[245]
	Soybean (*Glycine max*)	7.89	7.57	9.70	[246]
Soil Carbon content	*Acer saccharinum* (silver maple)	increased soil carbon by 85-87%	No major effect	Largely increases	[20]
	Soybean (Glycine max)	12.22%	-	12.18%	[248]
Soil Moisture	*Acer saccharinum* (silver maple)	No significant effect	No significant effect	No significant effect	[20]
Heavy Metal Mitigation (Cu)	*Acer saccharinum* (silver maple)	reduce foliar Cu concentrations	reduce Cu accumulation	Greatly reduce Cu toxicity	[20]
Leaf Chlorophyll & Physiology	*Acer saccharinum* (silver maple)	SlightlyIncreased	Moderate increase	Strongly increase	[20]
	Black cumin *(Nigella sativa)*	Increased by 40.78%	Increased by 19.93%	Increased by 58.45%	[245]
Leaf area (cm^2)	Maize grain	Increased up to 449.7	-	Increased up to 483.7	[244]
Fertility index	Black cumin (*Nigella sativa)*	Increased significantly (up to 11.70%)	Moderate increase (up to 10.26%)	Highest increase(12.74%)	[245]

and negatively affect plant growth. In the case of biofertilizers combined with biochar helps maintain and increase soil pH, creating a more balanced soil environment [250, 251]. Long-term use of conventional fertilizers often damages the soil structure by decreasing soil organic matter and disturbing the symbiotic relationship between soil microbes. It also increases soil compaction. But the application of biofertilizers in combination with biochar can improve soil structure, organic carbon content, porosity, and water holding capacity [214, 252, 253]. The production and application of conventional fertilizers produce increased emissions of greenhouse gases. It increases significant amounts of carbon dioxide and

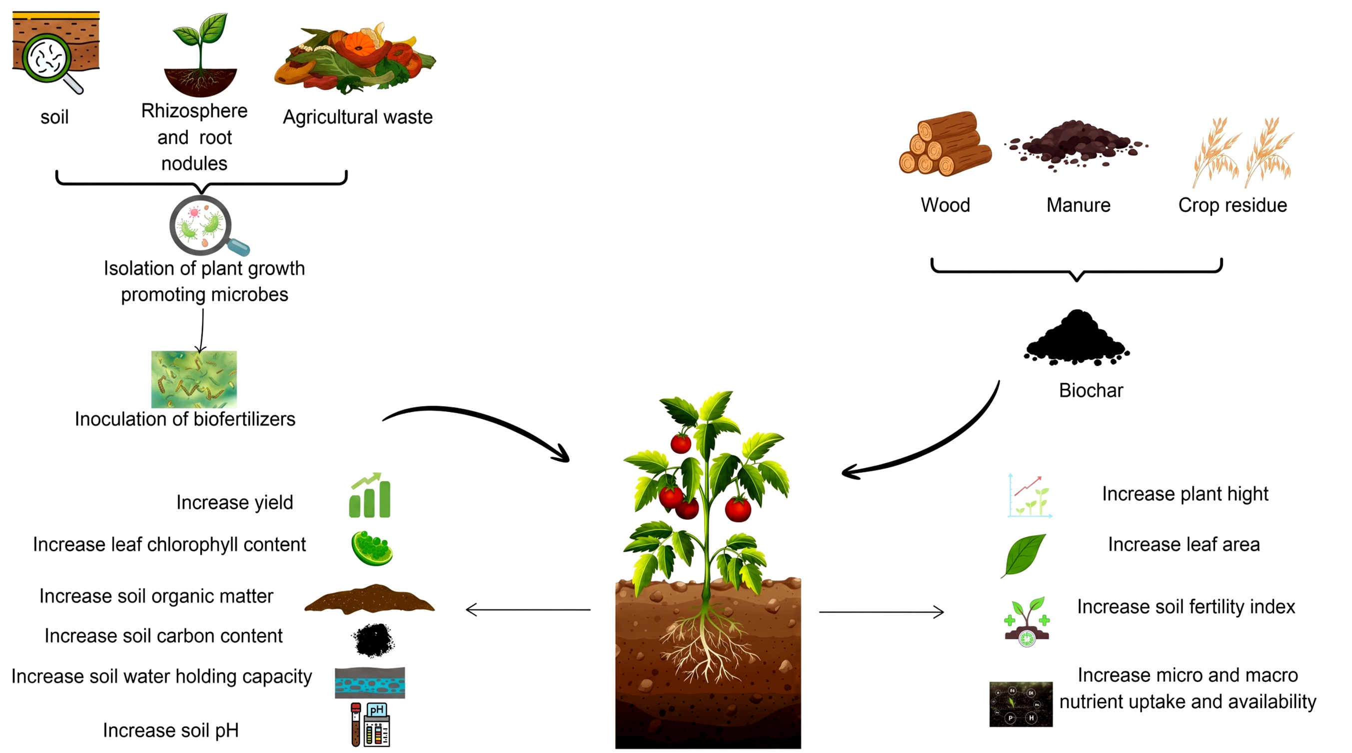

Fig. (5). Synergistic effects of biochar and biofertilizers on soil health and crop performance. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

Table 4. Environmental and agronomic benefitsof conventional fertilizers and biofertilizer + biochar.

Parameter	Conventional Fertilizers	Biofertilizer + Biochar	References
Nutrient Availability	Initially it increases rapidly but causes nutrient runoff and leaching	improves nutrient retention and uptake	[247, 249]
Soil pH	Decreasing soil pH and cause acidification over time	maintain or increase soil pH	[250, 251]
Soil Structure	May degrade soil structure, increase compaction, and reduce soil organic matter after long-term use.	Can improve soil structure, organic carbon content, porosity, and water holding capacity	[214, 252, 253]
GHG Emission	Increases greenhouse gas emissions	Decreases greenhouse gas emissions	[247, 254]
Yield	Decreases yield	Yield increases in the long term	[247, 255]
Cost Efficiency	Production cost is lower, but less cost-efficient in the long term	Production cost is high, but more cost-efficient in the long term.	[256]

nitrous oxide, a potent greenhouse gas. The benefits of using biofertilizers with biochar are a step towards lowering greenhouse gas emissions [247, 254]. Moreover, the use of biofertilizers in combination with biochar increases the yield of crops and is more cost-efficient than conventional fertilizers [247, 255, 256], Table **4**.

8. CURRENT CHALLENGES

Biofertilizers face several interconnected difficulties that limit their effectiveness. Their activity is affected during drought and other stressful conditions, and their performance is dependent on crop, soil type, and weather. Due to seasonal and climatic variations, results achieved in labs or greenhouses are not always reproducible in the field, and there aren't enough large-scale field tests or site-specificity studies to fully assess their effectiveness. Untested parameters are introduced when scaling up from the laboratory to the industry level, such as fermentation parameters, the proper selection of a carrier, and other quality standards. And liquid biofertilizers can require expensive supplies. High viable cell densities (>1×10^8 CFU/ml) are challenging to maintain during long-term storage and transport. The production of biofertilizers, it requires cost-effective and standard quality carrier materials. Though industrial by-products may serve as cheap, nutrient-dense carriers, they require appropriate safety testing. Adding new microorganisms to soil might change the existing soil microflora, quality, and natural cycles, and still, we are not fully aware of the long-term effects. Due to a misconception that all microorganisms are disease-carrying, many farmers are not interested in using biofertilizers. Developing and implementing biofertilizers is further affected by a lack of collaboration as well as knowledge transfer between farmers, researchers, businesses, and governmental organizations. Due to uncontrolled environments, microbial inoculants usually perform well in labs and greenhouses but offer undesirable outcomes in natural environments. Their survival and efficiency may be affected by different parameters such as temperature fluctuations, native microorganisms competing with introduced ones, soil chemistry, and complications like drought or nutrient loss. One microorganism strain that performs well in one type of soil may not work properly in another type of soil due to plant-microbe interaction, and success is more probable in nutrient-poor soils than in nutrient-rich soils. Biochar produced by pyrolyzing organic material, improves soil structure, water holding capacity, provides an ideal environment for microorganisms, and enhances the effectiveness of biofertilizers. Although its effects are unpredictable. Biochar may include toxic substances and interrupt microbial communication, which could affect beneficial processes like nitrogen fixation. These effects are dependent on where it originates and how it is produced. The effects of biochar are dependent on soil types, climates, crops, and the characteristics of biochar. They have different effects, like sometimes they improve nutrient cycling, while other times they immobilize nutrients or promote undesirable microorganisms. Biochar's field performance is unpredictable due to its variable effectiveness in promoting biofertilizers. Production of biofertilizers faces different quality control issues due to various manufacturing methods, limited viability of microbes, and inconsistent microbial concentration. Most manufacturers do not comply with guidelines, leading to contaminated, poor-quality products with limited shelf lives and low efficiency. It becomes worse due to improper storage and shipping. The problem becomes more severe due to insufficient knowledge, technology investment, and the use of ineffective strains. Poor international standards and insufficient monitoring allow low-quality products to reach the market despite certain rules, such as India's Fertilizer Control Order.

9. FUTURE DIRECTIONS

Many microbes in biofertilizers are sensitive to extreme environmental conditions like drought, temperature fluctuations, poor soil quality, salinity, *etc*. We are looking forward to isolating or preparing engineered microorganisms that can tolerate and remain active in stressful conditions. And corps can get consistent benefits. Incorporation of different modified genetically engineered tools and genetic modification of microbes enhances the capability of nitrogen fixation, phosphorus solubilisation, or hormone production. Safety evaluations will be necessary to make sure that genetically modified strains don't cause unintended effects or interrupt natural ecosystems. Advancements in microencapsulation, freeze-drying, and extended shelf-life will make biofertilizers easier to store, transport, and apply. Inducing specific signalling molecules like flavonoids and strigolactones in the formulations can enhance the plant microbe interaction and accelerate root colonization rates and symbiosis, which increase nutrient uptake and stress tolerance. Omics approaches like metabolomics and metagenomics are revolutionizing biofertilizer development. Metagenomics analyses genes of microbial communities from different sources and often reveals novel, unculturable microbes and genes responsible for improving plant growth, soil quality, nutrient cycling, hormone production *etc*. Metabolomics identifies metabolites of the microbes and reveals how they promote soil fertility, plant health, and stress tolerance. By combining these methods, modified, efficient, and environmentally friendly biofertilizers can be produced, increasing crop yields and decreasing the need for chemical fertilizers. Mass application of biofertilizers may change the nutrient cycles or the microbial balance of the soil. there require a long-term monitoring and environmental impact studies to determine the long-term beneficial effects. By using treated wastewater, agro-residues or safe industrial wastes as carrier materials, the environmental impacts and production costs can both be reduced. This approach also creates biofertilizers more affordable for farmers and environmentally friendly by producing value-added products from waste. To scale up effectively, there needs to be cooperation among research institutions, industry, governments, and farming communities. Partnerships provide opportunities to accelerate strain modification and development, field trials, regulatory approvals and distribution networks. Farmers, particularly smallholders, require strong evidence that biofertilizers provide more profitable returns than chemical fertilizers for crops. On-farm economic assessments from various locations will be helpful, as farmers want evidence for their decisions to adopt or invest. A lot of people have the misconception that all microorganisms are disease-carrying. We can change minds and build trust towards biofertilizers through awareness campaigns, field demonstrations, and training programs. Biofertilizers are growing toward multi-strain microbial consortia that are more adaptable and effective than single-strain products, increasing nutrients to crops, enhancing disease resistance, and improving tolerance to stress in native field conditions. To ensure the greatest performance, regional-specific formulations with locally adapted strains are being developed, building on omics tools that connect microbes with specific soil and crop and climate stressors.

Application technologies are also evolving, including slow-release and smart formulations, integration with precision agriculture for the effectiveness of biofertilizers, and utilizing stabilizing additives to extend the shelf life of biofertilizers and overall field effectiveness. Functionalization of biochar changes both its physical and chemical properties to increase nutrient retention and promote microbial adhesion. Thus, improve soil fertility and plant growth. Different processes to modify biochar include steam or gas activation, chemical treatment, and impregnation with metal oxides or nutrients to create more surface area and therefore adsorption sites, provide new functional groups, and create many micropores which also greatly improve its ability to adsorb or slowly release nutrients for crops. Functional biochar can be engineered to provide habitats, moisture-holding capacity, and attachment sites for beneficial microbes. Co-composting or organic coatings will further increase nutrient anchoring and microbial diversity. These technologies are being developed to use biochar as a nutrient carrier and a microbial inoculant substrate, thus promoting sustainable agriculture and soil remediation. Climate-smart agriculture (CSA) strategies are shifting towards integrated methods, where the use of biochar could be combined with microbial biofertilizers or inorganic fertilizers to increase nutrient availability, improve soil health, and enhance climate mitigation. Current research is focused on a better understanding of the interaction between biochar and soil microbes to create region-specific formulations for its effective use. National soil health policies are promoting biochar and biofertilizers to enhance fertility, resilience, and climate benefits. In addition to offering financial incentives and subsidies, soil health missions such as India's Soil Health Mission and the implementation of Soil Health Cards offer recommendations based on local conditions.

CONCLUSION

Integration of microbial biofertilizers and biochar through waste valorisation is essential to transition agriculture towards sustainability, climate resilience, and resource efficiency. Research from a wide range of fields and laboratory studies shows that their combined applications have numerous synergistic benefits for soil health, plant growth, nutrient cycling, and environmental protection. Combine application provides sustained release of nutrients and long-term beneficial effects towards plants and soils. This is more beneficial than the use of single amendments and long-term use of conventional fertilizer. Biochar not only acts as a carbon reservoir and improves soil structure, porosity, and nutrient retention, but also provides a safe and favorable microhabitat for beneficial microbes and improves their effectiveness towards agricultural soil. Microbial biofertilizers produced from organic wastes enhance nutrient availability and uptake, boost plant resistance to biotic and abiotic stresses, and restore soil microbial diversity. Among different forms of biofertilizers, liquid biofertilizers have longer shelf life, stability, improved performance, and higher concentrations of active microbes. While biochar and biofertilizers can contribute to sustainable agriculture, they have quality control, scale-up, and awareness challenges. Addressing their needs, innovation, and collaboration. Advancing biochar and biofertilizers is essential to achieving resilient systems for food production in a circular bioeconomy.

AUTHORS' CONTRIBUTIONS

The authors confirm contribution to this work as follows: Study conception and design: SD. Data collection: AJ, AS, Sk. M. Analysis and interpretation of results: LS, SM, BD, SD. Draft manuscript preparation: SKM LS, AJ, SM. All authors reviewed the manuscript, contributed to revisions, and approved the final version for publication.

LIST OF ABBREVIATION

AMF	=	Arbuscular Mycorrhizal Fungi
CE	=	Circular Economy
FSCW	=	Food Supply Chain Waste
IE	=	Industrial Ecology
MSW	=	Municipal Solid Waste
OFMSW	=	Organic Fraction of Municipal Solid Waste
PGPR	=	Plant Growth-promoting Rhizobacteria

CONSENT FOR PUBLICATION

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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