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# MICROBIOME ENGINEERING FOR SUSTAINABLE AGRICULTURE AND FOOD SECURITY

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# MICROBIOME ENGINEERING FOR SUSTAINABLE AGRICULTURE AND FOOD SECURITY

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*ABSTRACT: Microbiome engineering is one of the revolutionary approaches being applied in sustainable agriculture and therefore very crucial for soil health development and food security. This review underlines the key contributions of bacteria, fungi, and archaea toward soil fertility enhancement, plant growth optimization, and improvement of ecosystem resilience. Confronted with the twin challenges of soil degradation and climate change, a management approach that utilizes microbial communities offers strongly implementable viable options toward appropriate agricultural practices which are genuinely sustainable. Herein, we review strategies aimed at improving nutrient cycling, coupled with increased yields using low chemical input through a range of approaches: soil amendments, biofertilizers, microbial consortia, and genetic interventions. In addition, the use of microbiome-based biocontrol techniques comprises a non-polluting alternative to conventional pesticides, while soil restoration approaches contribute to ecosystem health and stability. The review also highlights the potential of microbiome engineering to contribute to mitigation strategies in climate change through enhancement in carbon sequestration and reduction of greenhouse gas emissions. Therefore, the focus of the paper is on the likely application of microbiome engineering in agriculture and environmental matters globally through the integration of microbiome science into agricultural practices to advance sustainability and resilience in food production systems.*
*KEYWORDS: Microbiome Engineering, Sustainable Agriculture, Food Security, Agricultural Microbiome, Soil Health*

## 1. Introduction

The improvement of our knowledge in microbiomes has become a popular topic not only in scientific circles but also among the general public, increasingly in particular as an area of great promise for new medical treatments. In fact, today, the human microbiome is even considered to be our "last organ" [1]. Human microbiome research has evolved from a fledgling field to a burgeoning area of medical research, with more than US$1.7 billion having been spent solely in the past decade [2]. Also, promising results from microbiome research gave yet another boost to the whole "microbiome market" and private investments into firms and startups (www.globalengage.com). Besides human health, microbiome research forms the basis for a much broader scope of applications [3]. The development of the engineering of environ mental microbiomes will, in future replace toxic chemicals in agri-horti and aquaculture, and will stimulate a more sustainable use of our environmental resources and also improve our food processing methods [4][5][6]. One of the fastest-growing sectors in agronomy, recording CAGR at 15-18%, will have a projected value of over 10 billion US dollars by 2025 [7]. Moreover, research into microbiomes may provide answers on how Homo sapiens and other life forms on Earth can survive one of our most crucial issues: anthropogenically driven climate change [8]. Historically, the research area Microbiome has emerged from environmental microbiome research (microbial ecology) and represents an interdisciplinary platform for many disciplines, e.g., agriculture, food science, biotechnology, bioeconomy, mathematics-informatics, statistics, modeling-plant pathology, but in particular human medicine. The new research field already provided new and key concepts on how to describe host-microbial interactions: the holobiont theory or meta-organism concept [9][10][11].

According to Nemergut et al. (2013), soil microbial communities are among the most abundant and diverse biological groups in nature [12]. A single gram of soil is home to a teeming and diverse population of bacteria (including actinomycetes), fungi, viruses, archaea, algae, and protozoa. So, it says by Pepper and Gentry (2015), Islam et al. (2020), and Sokol et al. (2022) [13][14][15]. Among these, bacteria, fungi, and archaea are the key components of soil microorganisms. Bacteria represent the most abundant type of microorganism with 70-90% of the total biomass in the soil. Fungi rank second in abundance after bacteria. Both take part in nearly all ecological processes affecting soil and plants. Archaea, which colonize highly critical environments, form a significant fraction of the soil microbiota. They were therefore named the third form of life, for their structural features were quite different from those of bacteria and eukarya. This will go a long way in encouraging more studies into microbial biodiversity, considering how archaea affect plants and soil. As compared to bacteria, fungus, and archaea, algae and protozoa are much less represented and have lesser effects on soil and plants. Among these three ways, it mainly establishes a relationship with the plant in the underground ecosystem of plant-soil: i) plant residues such as roots and leaves along with other secretions are considered the main source of carbon for supplying microbes in soil; ii) metabolic activities of soil microorganisms release nutrients that support development of soils, promote growth and development of plants, and maintain stability of soil carbon cycling; and iii) mycorrhizal symbiosis, release of hormones, and stress signals can directly impact plant growth and development. On the other hand, microorganisms can develop soil structure and form soil aggregates through gas exchange and production of organic acids [16]. Decomposition of organic matter and minerals, release of nutrients, as well as inorganic compounds, by microbial organisms are the other ways that microorganisms can improve soil fertility. Hence, microorganisms play a role in driving ecological processes to alter plant-soil interactions for the stability of the plant-soil ecosystem [17].

Land degradation is not being adequately addressed, but it is of vital importance to raise awareness so that future decisions on land management can be made to arrive at more sustainable and resilient agricultural systems. Of India's total geographical area, 328.7 Mha comprises the reporting area with 264.5 Mha being used for agriculture, forestry, pasture and other biomass production. Several agencies have assessed the severity and extent of soil degradation in the country earlier (Table 1). According to the National Bureau of Soil Survey and Land Use Planning about ~146.8 Mha is degraded. In India, water erosion is the most serious form of degradation, causing loss of topsoil and terrain deformation. With a first approximation, analysis of existing data on soil loss yielded an average soil erosion rate of approximately 16.4 ton $ha^{-1}$ $year^{-1}$, with an annual total soil loss in the entire country at 5.3 billion tons [18]. Of the total eroded soil, 29% is lost permanently to sea, and 61% accounts for mere transportation from one place to another, while the remaining 10% is deposited in reservoirs.

**Table 1: Extent of land degradation in India, as assessed by different organizations.**

| Organizations | Assessment Year | Reference | Degraded Area (Mha) |
|---|---|---|---|
| National Commission on Agriculture | 1976 | [19] | 148.1 |
| Ministry of Agriculture-Soil and Water Conservation Division | 1978 | [18] | 1 75.0 |
| Department of Environment | 1980 | [20] | 95.0 |
| National Wasteland Development Board | 1985 | [21] | 123.0 |
| Society for Promotion of Wastelands Development | 1984 | [22] | 129.6 |
| National Remote Sensing Agency | 1985 | [23] | 53.3 |
| Ministry of Agriculture | 1985 | [24] | 173.6 |
| Ministry of Agriculture | 1994 | [25] | 107.4 |
| NBSS&LUP | 1994 | [26] | 187.7 |
| NBSS&LUP (revised) | 2004 | [27] | 146.8 |

Soil degradation is now becoming a serious problem in both the rainfed and irrigated areas of India. India is losing a huge amount of rupees from degraded lands (Table 2). This cost is documented by declining crop productivity, land use intensity, changing cropping patterns, high input use, and declining profit [28][29][30][31]. Reddy estimated the loss of production in India to be Rupees (Rs) 68 billion in

1988–1989 based on the dataset prepared by the National Remote Sensing Agency (NRSA) [32]. Further losses due to salinization, alkalinization and waterlogging were estimated at Rs 8 billion. Of late, in an extensive study made on the effect of water erosion on crop productivity, it has been reported that soil erosion by water caused an annual crop production loss of 13.4 Mt in cereal, oil seeds, and pulse crops, which is equivalent to ~US$ 162 billion [33].

Table 2: Estimates on the annual direct cost of land degradation in India [34].

| Parameters | NRSA | ARPU | Sehgal and Abrol |
|---|---|---|---|
| Area affected by soil erosion (Mha) | 31.5 | 58.0 | 166.1 |
| Area affected by salinization, alkalinization and waterlogging (Mha) | 3.2 | - | 21.7 |
| Total area affected by land degradation (Mha) | 34.7 | 58.0 | 187.7 |
| Cost of soil erosion in lost nutrients (Rs billion) | 18.0 | 33.3 | 98.3 |
| Cost of soil erosion in lost production (Rs billion) | 67.6 | 124.0 | 361.0 |
| Cost of salinization, alkalinization, and waterlogging in lost production (Rs billion) | 7.6 | - | 87.6 |
| Total direct cost of land degradation (Rs billion} | 75.2 | - | 448.6 |

Microbiome engineering is an emerging frontier for solutions with benefits for human health, productivity in agriculture, and climate management. In this sense, microbiome engineering means improving ecosystem functionality through the alteration of microbial composition. Two major challenges for successful microbiome engineering are the design of an engineered microbiome with improved function and establishment of an improved microbiome in a recipient system of interest. Although many articles and reviews have aimed at functional design [35][36][37], much less has been written about microbiome establishment. We provide a framework for developing microbiome engineering through the need to focus on the process of microbial establishment and by looking to the examples of macrobial ecology. There are two general strategies for engineering: adding members [38]. The latter involves the design and application of inoculants, also known as probiotics, in medical and agricultural contexts, and constitutes one of the fastest growing biotechnology areas. In their most general form both practices have been crudely implemented for thousands of years in both human health and [39] agriculture [40]. However, despite current technical advances inoculants often still fail to establish or confer long lasting, i.e., months to year, modifications to ecosystem function [41]. We feel that this is in part due to the fact that there is repeated failure because of the emphasis not being put upon the establishment of inoculants.

## 2. Understanding the Agricultural Microbiome

During their development, plants are in intimate and continuous contact with microorganisms present in the root vicinity, known as the rhizosphere. Microbes living in the rhizosphere of several plants and having several positive effects on the host plant through various mechanisms are usually termed plant growth-promoting rhizobacteria (PGPR) [42][43]. In the rhizosphere, plant roots secrete a number of exudates that act as attractants for microbes, which eventually improve the physicochemical properties of the surrounding soil. On the other hand, these exudates maintain the function and structure of microbial communities near plant roots [44]. Plants and bacteria form symbiotic associations to alleviate abiotic stresses [45][46][47][48]. PGPR can assist plants in their growth by fixation of atmospheric nitrogen, producing siderophores, generating phytohormones (auxins, gibberellins, cytokinins), solubilizing phosphorus (P), or synthesizing stress-relieving enzymes [49]. Moreover, certain bacteria improve the accessibility of essential nutrients, improve root progression, and lessen stress-induced damage by modifying plant defense systems [50][51]. Furthermore, PGPR indirectly help plant symbionts by initiating induced systemic resistance, exerting an antibiosis effect, and potentially improving the content of plant cell metabolites [50][51][52]. PGPR can withstand hostile natural conditions such as shortage of water, salt stress, weed invasion, lack of nutrients, and heavy metal pollution [53]. The use of PGPR could help to enhance and improve sustainable agriculture and natural stability. These PGPR can be found in association with roots (in the rhizosphere), which enhance plant growth in the absence of pathogens or lessen the harmful effects of pathogens on crop yield by antibiosis, competition, induced systemic resistance, and siderophore production [54][55][56]. Several mechanisms used by PGPR in plant growth promotion are described in detail in the following section

## 3. Microbiome Engineering for Sustainable Agriculture and Food Security

### *3.1. Microbiome Engineering Strategies*

#### *3.1.1. Soil amendments:*

Organic soil amendments are used by farmers to enhance production and control the interactions between plants and microbiomes [57]. Organic additions to the soil have the potential to maximize yield and promote stable agroecosystem functioning by adjusting the biophysical characteristics of the soil. The heterogeneous distribution of microbial species, and plant features, by starting a chain reaction that affects several ecosystem trophic levels. The distribution, composition, and organization of the microbial community are all impacted by the application of organic supplements [58] for they propagate with notable modifications in soil fertility, biomass of plants and microorganisms, root characteristics, tissue elemental composition, substrate utilization, and decomposability, offering a multiplicity of advantages [59]. Compost, charcoal, and manure are examples of organic materials that are frequently employed in soil amendment procedures to enhance microbial health and soil fertility [60]. These strategies are especially crucial for microbiome engineering, which controls soil microbes to raise agricultural yield and maintain ecosystem sustainability [61].

#### *3.1.2. Biochar*

Biochar is when biomass such as wood, manure, or agricultural residues is burned in a closed container with minimal to no air circulation, a carbon-rich byproduct is produced. Its exceptional nutrient-retention qualities and soil-persistence make it a perfect soil supplements with many applications to enhance both agriculture and the environment. Like, carbon-negative biochar sequestration can be utilized to actively remove carbon dioxide from the atmosphere when combined with sustainable biomass production which has the potential to have a significant impact on mitigating climate change. By using the gases released during the pyrolysis process, the generation of biochar and bioenergy can coexist [62].

#### *3.1.3. Compost*

One significant type of organic amendment that helps to improve soil characteristics and crop growth is compost [63]. Using organic waste (such as animal dung, straw, and sewage sludge), microorganisms with certain roles combine to create bio-compost [64]. Bio-compost is thought to be more effective than conventional compost because it has a higher concentration of physiologically active chemicals (including indoleacetic acid, gibberellin, vitamins, and amino acids) and helpful microbial flora [63]. The utilization of bio-compost raised the proportion of metabolism within the six biological metabolic pathway types. The increased ratios of metabolism involving lipids, carbohydrates, biodegradation and metabolism of xenobiotics, and amino acid metabolism. This outcome might be the result of increased soil nutrients, particularly organic carbon, abundant bacterial metabolic substrates, and other modifications to the metabolic processes of bacterial populations brought about by fertilization [63].

*3.1.4. Manure*

Applying manure is also a method to adding soil amendment that increases microbial activity by providing organic matter and vital nutrients [65]. Nitrogen, phosphorus, and other nutrients that are essential for microbial development and activity are easily obtainable from manure. It has been shown that manure is use to boost the diversity of microorganisms, especially those engaged in the cycling of nutrients, such as fungus and bacteria [66].

*3.1.5. Biofertilizers*

It consists of living microorganisms that enhance the nutritional status of the plant to encourage plant growth [67]. This involves the application of mycorrhizal fungi, nitrogen-fixing bacteria, and phosphorus-solubilizing bacteria, each of which has a unique function in improving soil fertility and plant health [68]. The choice of plant growth-promoting rhizobacteria (PGPR) to colonize the rhizosphere, the area surrounding plant roots where microbes interact with the plant [68]. The bacteria like Azotobacter, Bacillus, and Rhizobium are chosen because of their capacity to fix nitrogen from the atmosphere, solubilize phosphorus, and generate hormones that promote growth [69]. By injecting them into the soil, they improve the conditions for plant root development and nutrient uptake. By utilizing mycorrhizal fungi which helps to develop symbiotic associations with plant roots to improve nutrient absorption and stress resistance. The introduction of arbuscular mycorrhizal fungus (AMF) into soils is a commonly used technique to increase plant resistance to salinity, drought, and soil pathogens [70].

*3.1.6. Microbial consortia:*

The goal of utilizing microbial consortia is to increase the stability and resilience of the soil microbiome by utilizing the synergistic effects of several microorganisms that carry out complementary tasks [67]. The choice of microbial species that can coexist and interact in a favourable way within the soil environment is a key element of this strategy. These consortia facilitate the cycling of nutrients, strengthen the structure of the soil, and increase plant resistance to environmental stresses [71]. The capacity of microbial consortia is to boost plant disease resistance [72] and it has the potential to mitigate the occurrence of soil-borne diseases by introducing beneficial microorganisms that either outcompete or inhibit harmful species [73]. By using this biocontrol approach, the requirement for chemical pesticides is decreased while crop health and productivity are improved.

*3.1.7. Genetic engineering:*

This strategy includes adding new genes to microbial strains or changing existing ones in order to increase their ability to promote plant development, regulate nutrients, or act as biocontrol agents. Genetically engineered bacteria can create chemicals that promote plant growth, such as gibberellins, cytokinins, and auxins [74]. Since, these phytohormones promote stress tolerance like temperature, high light, flood, salinity, and drought, strengthen root development, and accelerate plant growth, genetically modified microorganisms are useful instruments for raising crop productivity [75].

## 4. Applications of Microbiome Engineering

*4.1. Enhanced nutrient cycling:*

Enhanced nutrient cycling is a key component of microbiome engineering, which attempts to improve soil health, plant development, and sustainable agricultural methods. This involves manipulating microbial communities to optimize the biogeochemical cycles of essential nutrients such as nitrogen (N), phosphorus (P), carbon (C), and sulfur (S). Improved plant growth and sustainable agro-ecosystems result from conservation agriculture techniques such as zero-tillage, crop residue retention, and fertilizer delivery, which increase the number of nitrogen-cycling bacterial populations [76]. Vermicompost and farm yard manure are two examples of microbe-mediated integrated nutrient management which enhances crop output and soil health without depending on chemical fertilizers [77]. Soil fertility, microbial community structure, lettuce production, and quality were significantly enhanced by the combined application of bio-organic fertilizer and decreased chemical fertilizer [78]. In agroecosystems, organic and chemical-organic fertilization may also successfully preserve bacterial diversity and improve soil fertility, with changes intimately correlated with soil pH [79].

*4.2. Improved crop productivity*

Plant microbiome engineering can increase agricultural yields and resistance by promoting plant growth and reducing the effects of pathogens and abiotic stressors. Enhancing agricultural production and responsiveness to changing environmental circumstances can be achieved by designing rhizosphere microbiomes through the use of prebiotics, crop breeding, host-mediated microbiome engineering, and synthetic microbial consortia [80]. Crop yield can be increased and agronomic solutions can be provided through microbiome engineering using synthetic microbial communities. In sustainable agriculture, plant growth-promoting rhizobacteria (PGPRs), can improve plant growth and resilience to abiotic stressors such as salt, drought, heavy metal toxicity, and nutritional imbalance [81]. In addition to promoting plant development and efficient nutrient use, an efficient microbiome can also help its host by controlling pests and phytopathogens.

*4.3. Biocontrol of pests and diseases:*

Biocontrol microorganisms have the potential to improve plant productivity and efficiency, providing environmentally friendly substitutes for pesticides in the management of plant diseases and other agricultural pests [82]. By influencing pest characteristics, supplying untapped chemical reserves for innovative biopesticides, and enhancing mass-reared insect performance for autocidal programs, microbiomes have the potential to provide sustainable insect pest control. To control disease agents and invertebrate pests, genetic engineering of microbial and viral biological control agents provides affordable, ecologically safe solutions. Integrating microbial community studies into biocontrol research offers novel prospects for the development of inventive techniques to combat plant infections [83]. Compost microbiomes can be used for plant protection by integrating functional assays, metagenomics, and genomics techniques to discover helpful microbes and provide accurate diagnostic tests. Compost that suppresses disease improves the inherent suppressiveness of soil against soil-borne pathogens by adding beneficial bacteria to soils that are suitable to their growth. Beneficial microbes also cooperate with host immunity to provide colonization resistance to pathogens through competition for nutrients and antimicrobial secretion.

*4.4. Soil health restoration*

For sustainable horticulture, forestry, and agriculture, soil mycobiomes are essential because they support soil bioremediation, plant health, and biogeochemical cycles [84]. New technologies for studying the microbiome may increase the variety and amount of organic matter in the soil, which would increase the effectiveness and reliability of restoration results. Reducing soil deterioration and increasing agricultural productivity while enhancing the environment can be achieved by restoring soil quality through conservation agriculture, nitrogen management, and cover crops. By breaking down contaminants, bioengineered microbes can aid in restoring soil health; nevertheless, their introduction may impact native microbial populations [85]. In degraded soils, soil microorganisms can restore ecosystem services and hydraulic performance, perhaps enhancing nutrient cycling and water retention. By shielding crops from soil-borne diseases, soil microbiomes can support plant growth and health, promoting food security and agricultural sustainability. Microbially Induced Calcite Precipitation (MICP), for instance, is a bio-mediated soil improvement technique that has great potential for enhancing soil engineering efficacy and accomplishing multifunctionality while preserving ecological equilibrium and environmental sustainability [86]. Reversing the trends of global soil degradation and mitigating their effects may be achieved best by implementing sustainable land management and agriculture practices.

### *4.5. Climate change mitigation:*

Targeted carbon management by environmental microbiome engineering, which modifies ecosystem processes with microbial inoculate, has the potential to mitigate climate change [87]. Microbial biotechnology can play a major role in mitigating climate change by lowering nitrous oxide emissions through the use of biochemical, cellular, and genome-editing techniques. To decrease the pathogenic effects of climate change-related microorganisms in terrestrial, oceanic, and urban ecosystems and to reduce greenhouse gas emissions, microbial research is essential. Using renewable resources like lignocellulose, $CO_2$, and methane, microorganisms can manufacture sustainable biofuels, providing a climate-friendly answer to energy demands. Engineering microorganisms can support microbial $CO_2$ sequestration as an environmentally friendly and long-term solution to global warming by improving the effectiveness of microbes in fixating $CO_2$, lowering emissions, and raising the carbon yield of products with added value [88]. By modifying cyanobacteria in photobioreactor systems by using genetic engineering, $CO_2$ may be efficiently and sustainably sequestered, lowering greenhouse gas emissions and slowing down global warming. For the purpose of reducing greenhouse gas emissions over the long run, the bioconversion of $CO_2$ by terrestrial plants, microalgae, and other microorganisms is a viable and affordable option. Future developments in carbon capture, sequestration, and utilization technologies based on microbes have the potential to reduce greenhouse gas emissions and alleviate environmental issues.

## 5. Microbiome Engineering Strategies

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## 6. Conclusion

Microbiome engineering promises to open up new horizons for sustainable agriculture by improving soil health, crop productivity, and reducing the use of chemicals. The review covers biofertilizers, microbial consortia, organic amendments, among others, to study their potential for better nutrient cycling, plant resilience, and biocontrol of pests. It ropes in agricultural sustainability while it improves environmental protection toward the mitigation of greenhouse gases and enhances carbon sequestration; hence, it plays a role in the amelioration of climate change.

Despite all these potentially clear benefits, there are significant challenges in the way of consistent establishment and long-term functioning of engineered microbiomes. Substantially greater research efforts, therefore, will be required for tuning microbial inoculants toward site-specific environments and within the diversity of agricultural sy stems. Such achievements would require interdisciplinary collaboration so that the advances could be translated into practical applications in service to farmers and ecosystems.

That is, microbiome engineering forms such a futuristic and environmentally friendly approach to bettering agricultural gains against pressing global issues like food security and climate change. It is in this further development and research that a possible future will be outlined in terms of the development of an ever-more resilient and sustainable agricultural system in caring for an incrementally growing population without compromising ecosystem health.

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## 8. Author Contributions

S.J. and P.D. outlined and drafted the main sections. S.H. contributed text to the Understanding the Agricultural Microbiome section. P.K. contributed text to the Microbiome Engineering Strategies section. L.T. contributed text to the Challenges and Future Directions section. J.K offered comments, edited and arranged the reference of the manuscript.

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