Malaysian Journal of Soil Science 2024 Vol. 28: 369-381

Systematic Review of Emerging Trends in Soil-Based Probiotic

Khairul, S.R.[1]; Leong, S.S.[2,3]*; Korel, F.[4]; Lingoh, A.D.[2] & Toh, Seng Chiew[2]

[1]Institute of Ecosystem Science Borneo, Universiti Putra Malaysia Bintulu Sarawak Campus, Nyabau Road, 97008 Bintulu, Sarawak, Malaysia
[2]Department of Animal Science and Fishery, Faculty of Agricultural and Forestry Sciences, Universiti Putra Malaysia Bintulu Sarawak Campus, Nyabau Road, 97008 Bintulu, Sarawak, Malaysia
[3]Laboratory of Sustainable Aquaculture, International Institute of Aquaculture and Aquatic Sciences (I-AQUAS), Universiti Putra Malaysia, 71050 Port Dickson, Negeri Sembilan, Malaysia
[4]Food Engineering Department, Faculty of Engineering, Izmir Institute of Technology, Urla 35430, İzmir, Turkey.

**Corresponding author: leongsuisien@upm.edu.my*

ABSTRACT

Soil-based probiotics (SBPs) are microorganisms originating from soil that have the potential to significantly enhance soil fertility and plant health, similar to the benefits of conventional probiotics in human and animal health. While much is known about the role of SBPs in the animal's gut, the specific mechanisms and long-term impacts of SBPs in soil ecosystems remain underexplored. This review systematically summarizes recent research on SBPs, with a focus on lactic acid bacteria (LAB), including Lactobacillus and Bifidobacterium, and their role in soil and plant ecosystems. A comprehensive literature search was conducted using major databases, including PubMed, Web of Science, Scopus, and Google Scholar, covering the past 20 years. Out of 90 initial studies, 30 were excluded for irrelevance, and a further 60 were omitted based on selection criteria, leaving only the most relevant studies for analysis. The review highlights the multifaceted applications of SBPs in agriculture, focusing on their ability to enrich soil microbiomes, promote plant growth, and suppress pathogens. Additionally, SBPs offer sustainable alternatives in livestock feed. A comparison between SBPs and traditional probiotics underscores the unique advantages of soil-derived strains in agricultural systems. As sustainable agriculture practices grow in importance, SBPs present a natural, eco-friendly approach to improving soil health and plant resilience. Continued research is vital to fully harness the potential of SBPs, contributing to long-term soil health, sustainable farming, and global food security.

Keywords: Pathogen, plant, soil-based probiotics, probiotics

INTRODUCTION

Soil-based probiotics (SBPs) are microorganisms derived from soil that can significantly improve soil and plant health. Besides, SBPs can provide similar benefits that conventional probiotics offer in human and animal health. As the global population continues to grow, there is an increasing need for sustainable agricultural practices and enhanced food production. This has led to heightened interest in the development of bio-products, including SBPs, that offer natural alternatives to chemical pesticides and fertilizers (de Souza Vandenberghe *et al*., 2017). SBPs are particularly valuable in agriculture for their potential to enhance soil fertility, boost plant growth, and contribute to sustainable farming practices (Wang *et al*., 2022).

SBPs are commonly identify as lactic acid bacteria but not limited to *Lactobacillus* or *Bifidobacterium* strains, yet they still provide all the benefits of a probiotic (Jiménez-Gómez *et al.*, 2017). While there is growing recognition of the benefits that SBPs can offer for soil health and integrated into farming practices, they start to use in human or animal supplement. The recognition of SBPs varies significantly across different geographic areas. In tropical regions, where biodiversity is high and agricultural practices often face challenges such as soil degradation and nutrient depletion, the potential of SBPs to enhance soil fertility and support

plant growth is particularly relevant (Furey and Tilman, 2021). However, the level of awareness and understanding of SBPs among farmers, agricultural stakeholders and globally in these regions is still limited. Factors such as access to information, educational resources, and agricultural extension services play crucial roles in shaping perceptions and adoption rates (Jha *et al*., 2024). Furthermore, the research landscape surrounding SBPs is evolving, yet many studies are concentrated in temperate climates. This creates a gap in knowledge about how SBPs perform under tropical conditions, where factors such as humidity, temperature, and diverse microbial communities may influence their efficacy. Addressing these uncertainties is essential for promoting the use of SBPs in tropical agriculture.(Jiménez-Gómez *et al*., 2017; Tahat *et al*., 2020).

Traditional probiotics are often associated with dairy products, such as yogurt, which cater to human health needs. However, the rise in vegetarianism and lactose intolerance has driven a demand for non-dairy probiotic sources (Mariotti and Gardner, 2019). SBPs, sourced from soil environments, present a promising alternative not only for food applications but also for agricultural use. Unlike conventional probiotics, SBPs are resilient to harsh environmental conditions, including stomach acid, allowing them to thrive and exert their benefits in diverse settings, including soil ecosystems (Yanni *et al*., 2023). In the context of agriculture, SBPs have demonstrated significant potential in promoting soil health. They contribute to nutrient cycling, enhance soil structure, and increase organic matter decomposition, thereby optimizing soil fertility and boosting carbon sequestration (Smith and Johnson, 2021). Additionally, SBPs play a crucial role in suppressing soil-borne pathogens and improving plant growth and resilience (Chen *et al*., 2024). For instance, lactic acid bacteria (LAB), a common type of soil-based probiotic, have shown promise in enhancing nutrient availability and stimulating beneficial microbial communities within the soil (Kumar *et al*., 2022; Li *et al*., 2023).

Despite these promising attributes, the safety and efficacy of SBPs, particularly in human and animal health, require further investigation. While much is known about the benefits of probiotics in the animal's gut, the specific mechanisms and long-term impacts of SBPs in soil and plant ecosystems are still being underexplored. As such, SBPs represent an innovative approach to soil management, with the potential to transform agricultural practices by reducing dependence on synthetic inputs and promoting environmental sustainability. This review aims to synthesize recent research on the application of soil-based lactic acid bacteria in soil management and their broader implications for sustainable agriculture and soil conservation. By exploring the health benefits and soil quality improvements associated with SBPs, this paper will provide a comprehensive overview of current literature, highlighting the potential of SBPs as a natural solution for enhancing soil fertility and plant health (Murindangabo *et al*., 2023).

MATERIALS AND METHODS

Literature search

A comprehensive literature search was conducted to gather relevant studies and reviews related to soil-based probiotics. The search strategy involved systematically reviewing literature from major databases, including PubMed, Web of Science, Scopus, and Google Scholar. Initial searches yielded a total of 90 articles. Keywords included "soil-based probiotics," "soil microbiome," "soil health," "plant growth promotion," "soil bacteria," and "lactic acid bacteria." All studies were filtered by publication date (last 20 years) to capture recent trends. Only English-language articles were considered to maintain consistency in the review process.

Inclusion and exclusion criteria

For this review, the inclusion criteria focused on peer-reviewed research articles and comprehensive reviews published within the last 20 years. Relevant studies must have addressed soil-based probiotics, detailing specific probiotic strains, their mechanisms of action, and applications in enhancing soil health and plant growth in either agricultural or medical contexts. Empirical research, such as field trials and laboratory experiments, as well as meta-analyses providing insights into the effectiveness of soil-based probiotics, were included.

During preliminary assessments, 30 articles were excluded due to irrelevance. Subsequently, an additional 60 articles were omitted based on selection criteria, which ruled out studies focusing solely on probiotics isolated from non-soil sources or those lacking empirical data or detailed insights into probiotic mechanisms and impacts. This rigorous selection process ensured a focused and relevant synthesis of current trends and advancements in the field.

Data extraction

In the data extraction and synthesis phase, relevant information was meticulously gathered from the selected studies. Data extraction focused on identifying key elements such as the specific probiotic strains used, their sources, and their characteristics. Additionally, details regarding the applications of these probiotics in soil management and their impacts on plant growth were extracted. This also included the mechanisms through which the probiotics affect soil health, such as nutrient cycling, disease suppression, and microbial interactions. The extracted data were then synthesized into thematic categories to highlight major trends and advancements. These themes included novel probiotic strains and their innovative uses, effectiveness in various soil types, and comparative analyses of different probiotic formulations. By organizing the data into these categories, a comprehensive overview of emerging trends was created, revealing patterns and insights into the evolving field of soil-based probiotics.

Analysis of the database

The collected data were critically examined to identify and understand emerging trends in the field of soil-based probiotics. This involved trend analysis to highlight recent advancements, such as the discovery of novel probiotic strains and the development of innovative application methods. Comparative analysis was conducted to evaluate the effectiveness of different probiotics based on their impact on soil health and plant growth, as reported in the literature. This included assessing variations in efficacy across different soil types and environmental conditions. Additionally, a critical evaluation of the study quality was performed to determine the reliability and robustness of the findings. The analysis aimed to synthesize these insights to provide a coherent understanding of the current state of soil-based probiotics and to pinpoint areas where further research is needed. This comprehensive approach ensures that the review captures both the advancements and the challenges within the field.

RESULTS AND DISCUSSION

Soil based Lactic acid bacteria (LAB)

The SBPs will display same as probiotics, which are defined as live microorganisms that, when administered in adequate amounts, confer a health benefit to the host (Lingoh *et al*., 2020). Among the various SBPs strains, lactic acid bacteria (LAB) are particularly notable for their health-promoting properties, safety profile, and versatility. LAB are characterized as Gram-positive, non-spore forming cocci or rod-shaped bacteria, which are catalase-negative and exhibit fastidious growth requirements. This group of bacteria is known for producing lactic

acid as a major metabolic by-product from the fermentation of carbohydrates, contributing to their beneficial effects (Siraj *et al*., 2017). LAB are widely distributed across different environments including fermented and unfermented foods, the gastrointestinal tracts of animals, soil, water, and sewage (Siraj *et al*., 2017; Leong *et al*., 2023). Their role extends beyond mere survival; these microorganisms contribute to the decomposition of organic compounds and help maintain environmental balance (Gupta *et al*., 2017). LAB bacteria exhibit beneficial properties as shown in **Figure 1**. LAB can be applied in almost all application from agricultural, environment to functional foods in human. Research done by Ramanathan *et al*. (1993) demonstrated that only a fraction of faecal-origin isolates produced alpha-hemolysin, whereas none of the soil isolates did. This finding indicates variability in bacterial properties and their environmental interactions. Thus, SBPs can be considered organic probiotic LAB if they fulfilled minimum criteria as a probiotic and display the function as probiotics.

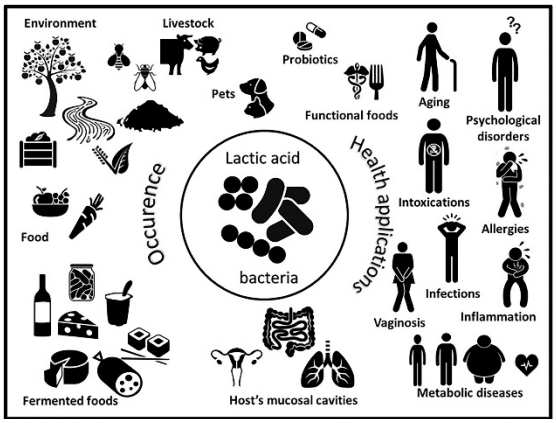

Figure 1. Summary of LAB applications in food, animal health, and agriculture.

*(*George *et al.*, 2018)

Soil microflora

Soil is a complex and dynamic system shaped by a combination of geological parent material, historical glacial and geomorphological processes, biological activity, and land use history (Aislabie and Deslippe, 2013). It serves as a habitat for a diverse array of organisms, including bacteria, archaea, fungi, insects, annelids, and other invertebrates. These microorganisms and invertebrates play critical roles in maintaining soil health and ecosystem functions. Soil microorganisms, such as bacteria, fungi, and archaea, are integral components of soil organic matter, contributing to the colloidal fraction of humus, which consists of both living microbial cells and their decomposed residues. The diversity and activity of these microorganisms are closely linked to the quantity and quality of organic matter present in the soil (Fierer *et al*., 2017).

A diagram illustrating the diversity of microorganisms in soil, including bacteria, fungi, archaea, and invertebrates, is presented in Figure 2, encompassing numerous genera and species. Bacteria are ubiquitous and can thrive in a wide range of environments, including the often-harsh conditions of soil (Aislabie and Deslippe, 2013). The formation and development of soil are driven by a complex interplay of biological, chemical, and physical processes. Soil microbes are essential for many biological transformations and play a pivotal role in the cycling of carbon (C), nitrogen (N), and other nutrients, thereby supporting plant growth and ecosystem stability (Schulz *et al*., 2013; Jones *et al*., 2014).

Figure 2. Overview of the microbial diversity in soil.(Sapkota, 2023)

Soil-based probiotic (SBPs)

Soil-based probiotics (SBPs) are microorganisms naturally occurring in soil that were once prevalent in the human food chain. These beneficial bacteria include LAB strains but not limited to *Lactobacillus* and *Bifidobacterium* (Kim *et al*., 2007). *Lactobacillus* and *Bifidobacterium* are famous probiotics used especially in milk products processing and human consumption. SBPs isolated from soil are consider safe and non-pathogen. SBPs are able to form spore, endospore or capsule which involves replicating their DNA and producing a resilient external spore by pinching off from their plasma membranes between chromosome sets. One of the distinguishing features of SBPs is their remarkable resistance to the acidic environment of the stomach, as noted by Kim *et al*. (2020). This resilience allows SBPs to survive the gastrointestinal tract and reach the small and large intestines intact. Their stability eliminates the need for protective coatings, making them effective probiotics. Traditionally, people think of probiotics, it will be consumed through cultured dairy products such as yogurt, where they contribute to gut health and overall well-being. In this review, we introduce SBPs which has displayed same efficiency as the commercial probiotics. The identified SOPs by previous studies were tabulated in **Table 1**. They are classified into genera such as *Lactobacillus*, *Leuconostoc*, *Pediococcus*, and *Streptococcus* (Mokoena, 2017). Furthermore, soil bacteria produce extracellular enzymes such as phosphatases, which help them utilize organic carbon more efficiently (Pold *et al*., 2017). Among LAB, genera such as *Lactobacillus*, *Lactococcus*, *Enterococcus*, *Leuconostoc*, and *Weissella* are frequently found in soil environments (Chen *et al*., 2006).

Although SBPs offer various benefits, concerns regarding their safety persist. Recent studies have highlighted issues such as the high prevalence of *Escherichia coli* in farm soils, often associated with fecal contamination from wildlife, which contributes to microbial pollution (Leong *et al*., 2018; 2019). Additionally, animals can introduce pathogens and fungi into farm environments, disrupting the balance of the microbial community. For instance, Laus et al. (2016) identified significant microbial burdens in ocular cultures from animals, indicating the need for further investigation into environmental influences. Similarly, Delia *et al*. (2012) noted that the presence of microorganisms in animal feces can adversely affect farm soil microflora. Collectively, these factors raise concerns about potential contamination in agricultural settings.

Table 1. List of identified soil-based probiotic (SBPs).

No.	Soil-based probiotic	Descriptions	Scientific proven effects on each strains	References
1.	*Bacillus coagulans*	Produces lactic acid — a microbial metabolite that supports gut health.	1. **GBI-30, 6086**: reduces symptoms of IBS, enhances immune function, and beneficially modulates the gut microbiome. 2. **Unique IS-2**: improves symptoms of bacterial vaginosis and IBS symptoms in children. Inhibits the proliferation of cancer cells. 3. **MTCC 5856**: reduces bloating, depressive symptoms, abdominal stress in IBS patients.	Jäger *et al*. (2018) Madempudi *et al.* (2019) Majeed *et al*. (2016)
2.	*Bacillus subtilis*	Called the "hay bacillus" or "grass bacillus" because it's found in the gastrointestinal tract of cows (and humans).	1. **DE111** reduces body fat percentage and blood markers of inflammation and improves bowel irregularity. 2. **CU1**: improves immune function. 3. **R0179**: survives passage through the GI tract. 4. **IP 5832**: gives better patient outcomes in Salmonella gastroenteritis.	Townsend *et al*. (2018) Lefevre *et al*. (2015) Hanifi *et al*. (2015) Vuković (2001)
3.	*Bacillus clausii*	Can reduce nitrate in the soil to nitrite.	1. **OC, NR, SIN, and T:** reduce nasal congestion, nasal pharyngeal allergy, and bacterial overgrowth in the small intestine.	Lippolis *et al*. (2013)
4.	*Bacillus indicus*	Produces a distinct yellow-orange pigmentation.	There are no scientific studies of *B. indicus* as a stand-alone probiotic.	
5.	*Bacillus licheniformis*	Found on bird feathers, especially chest and back plumage.	There are no scientific studies on the individual strains of *B. licheniformis*.	
6.	*Enterococcus faecium*	an be commensal in the guts of humans and animals, but it may also cause diseases like neonatal meningitis or endocarditis.	1. **L3:** reduces C. difficile infection. 2. **IS 27526:** increases weight gain in underweight preschool children.	Yermolenko *et al*. (2006) Surono *et al*. (2011)
7.	*Clostridium butyricum*	is widely used as a probiotic in Asia.	1. **MIYAIRI 588:** reduces side effects in H. pylori eradication therapy.	Kato *et al*. (2018)

Applications of Soil-Based Probiotics

SBPs can be applied for multifaceted applications across agriculture and environmental health. By enriching soil microbiomes, SBPs enhance soil fertility and promote sustainable farming practices. They improve plant growth by facilitating nutrient uptake and increasing resilience against environmental stressors. Additionally, SBPs play a critical role in pathogen suppression, helping to protect crops and livestock from diseases without the need for chemical pesticides or antibiotics. As a result, the integration of SBPs into agricultural systems holds promise for improving food security and fostering healthier ecosystems.

Plant growth

In agriculture, *Lactobacillus plantarum*, can be used to treat seeds prior to planting. This practice enhances seed germination and promotes plant health by inoculating seeds with beneficial microorganisms. These treatments help prevent fungal infections and boost nutrient uptake from the soil (Beresford, 2011; Kumar *et al*., 2020). Diagrammatic representations of plant–microbe interactions in the root system and their diverse functions under salinity stress was shown in **Figure 3**. LAB produce various signalling molecules that contribute to plant growth and resilience, particularly in challenging conditions such as high salinity. These signalling molecules play a crucial role in modulating plant responses to stress, promoting development, and enhancing overall plant health. LAB cultures can be combined with various nutrient solutions to treat seeds prior to planting. This treatment enhances seed germination, introduces beneficial microbes to the seeds, and helps prevent fungal issues such as "damping off" (Hamed *et al*., 2011).

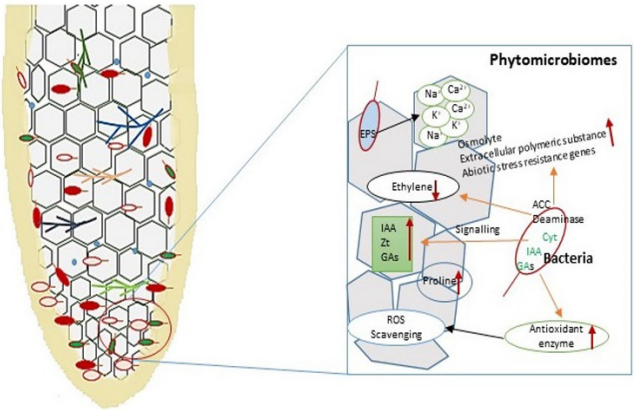

Figure 3. Impact of LAB inoculation on plant germination and growth. (Kumar *et al*., 2020)

Soil health

SBPs are effective in accelerating the decomposition of organic matter, which enhances soil fertility and increases nutrient availability for plants (Ikeda *et al*., 2013; Zhang *et al*., 2022). The SBPs are commonly used alongside Indigenous Microorganisms (IMO) in natural farming practices to prepare composts and compost teas for soil conditioning prior to planting (Park and DuPonte, 2008). The application of bacteria cultures can significantly speed up the breakdown of organic matter in the soil, thereby improving the availability and release of essential nutrients for plant uptake (Lee *et al*., 2021). Recent studies have underscored their potential in promoting plant growth by enhancing nutrient uptake and bolstering plant immune responses against environmental stresses (Kumar *et al*., 2022; Li *et al*., 2023). Additionally, SBPs can help mitigate soil degradation and improve soil structure, both of which are critical for sustainable agriculture and soil conservation (Davis *et al*., 2023). Despite the promising potential of SBPs for enhancing soil health, further research is necessary to fully understand their mechanisms of action, optimal application methods, and long-term effects on soil

ecosystems. Investigating the specific interactions between SBPs, soil, and plant roots will enable more targeted and effective use of these probiotics in agriculture. Ensuring the safety and efficacy of SBPs in soil applications requires careful evaluation of factors such as strain-specific properties, environmental adaptability, and potential impacts on non-target organisms.

Pathogen suppression

In animal husbandry, SBPs contribute significantly to livestock health by promoting healthy gut flora, enhancing immune responses, and improving digestion. SBPs can transform odorous waste from livestock pens into less harmful forms, thereby mitigating environmental impacts (Ikeda *et al*., 2013; Dhama *et al*., 2015). Furthermore, most research has showed SBPs ability to produce bacteriocins helps prevent the growth of spoilage microorganisms during fermentation, improving the quality of fermented products (Silva *et al*., 2018; Hong *et al*., 2019). LAB especially soil based are economically important in the food industry due to their functional characteristics and their ability to enhance product quality. They are commonly used in the production of fermented dairy products like yogurt and can also be found in various vegetarian food products (Wedajo, 2015; Patel *et al*., 2016). For instance, in Malaysia, products such as Nestlé Bliss incorporate live bacteria cultures to promote digestive health (Tee, 2020). Additionally, SBPs are recognized for their role in maintaining human health, particularly in restoring gut microbiota balance during or after antibiotic treatment (Hemarajata and Versalovic, 2013; Jandhyala *et al*., 2015).

Beyond their applications in food and animal health, SBPs are valued for their bio-preservative properties. They inhibit food-borne pathogens, mycotoxigenic fungi, and phytopathogenic bacteria, enhancing food safety and agricultural practices (Seddik *et al*., 2017; Yang *et al*., 2019). SBPs also improve the rheological properties, texture, and sensory qualities of fermented foods through the production of functional oligosaccharides (Patel *et al*., 2012; Raman *et al*., 2013).

All probiotics, including SBPs, are characterized by their ability to establish themselves in the gastrointestinal tract, where they outcompete harmful microorganisms and assist in digestion (Purchiaroni *et al*., 2013). SBPs bacteria facilitate the breakdown of complex hydrocarbons into simpler forms, alleviating constipation and other digestive issues (Roberfroid *et al*., 2010). They support the growth of beneficial gut flora, help prevent the colonization of pathogenic bacteria, regulate intestinal motility, and enhance immune responses. Moreover, probiotics have been shown to reduce the risk of colorectal cancer and manage lactose intolerance by surviving in the acidic environment of the gut (Jones, 2016). In addition to their digestive benefits, probiotics can serve as alternatives to antibiotics in treating enteric infections and mitigating antibiotic-associated dysbiosis (Wedajo, 2015). They help maintain a balanced gut microbiota, offering protection against gastrointestinal diseases, infections, and inflammation (Wedajo, 2015).

Bacteriocins, which are antimicrobial peptides produced by certain LAB and presented in SBPs, play a crucial role in inhibiting harmful microorganisms and possess antimutagenic properties (Lingoh *et al*., 2020). For example, *Bifidobacteria*, known for their anti-tumorigenic activity, can activate immune cells to target and destroy tumor cells (Shi *et al*., 2016). Probiotics isolated from *Bifidobacterium* have also been shown to reduce the incidence of colon cancer and improve overall gut health (Shi *et al*., 2016). Furthermore, SBPs are safe to be apply to livestock and poultry, where they enhance growth performance and act as biocontrol agents against pathogenic microorganisms. Overall, when evaluating the safety and efficacy of probiotic strains, it is essential to consider factors such as pathogenicity, infectivity, and metabolic activity to ensure their beneficial effects while minimizing risks (Shi *et al*., 2016). For instance, bacteria have been used as preservatives in vegetable products and silage due to their ability to inhibit spoilage organisms (Beresford, 2011). The use of probiotic supplements

in animal feed has also been shown to influence the microbial communities within animal feces, potentially affecting soil health (Zhang *et al*., 2020). Additionally, the microbial communities in the rumen of herbivores play a critical role in the overall microbial ecology of farms (Morgavi *et al*., 2015).

Soil-based probiotic (SBPs) vs traditional probiotic

SBPs are a sub-category of probiotics, which grow in warm and moist environment. They have good adaptability to the harsh surroundings; thus, it can grow unharmed by stomach acids and able to travel to the target host cells, creating a better symbiotic relationship with humans. Two main advantages of SBP over traditional probiotic are 1) SBP have a longer or even stable shelf-life; 2) SBP do not require additional preservation.

They appear to survive the first part of their journey through your stomach and small intestine. Some studies suggest traditional probiotics are less likely to survive to the same extent. Some people call SBPs as dirt spores. Researchers assumed SBPs as dirt supplements that are rich in Vitamin B12, zinc, selenium, and calcium, when we ate food, we also ate small amounts of dirt. Human may mitigate the beneficial effect of SBPs that are no longer having access through the food by intentionally ingesting them as supplement (Rawi *et al*., 2020). We help build our immunity to many pathogens, much as a child playing in the dirt does.

According to McNulty *et al.* (2011) test, traditional probiotics had no effect on the long-term microbiome or general health of laboratory mice. Conversely, soil probiotics improved both the ongoing metabolic pathways and general health of mice. Several traditional probiotics were used in treating the irritable bowel syndrome and did not show significant result, however SBPs are proved to be able to reduce their symptoms (Bittner *et al*., 2005). Sensitive individuals who are histamine intolerance or SIBO (small intestinal bacterial overgrowth) can often tolerate SBPs better than traditional probiotics.

CONCLUSION

Soil-based probiotics (SBPs) represent a promising, sustainable approach to enhancing soil health and plant productivity. Unlike traditional probiotics associated with human and animal health, the soil based lactic acid bacteria (LAB), play a crucial role in soil ecosystems by improving nutrient cycling, organic matter decomposition, and pathogen suppression. SBPs are vital microorganisms with diverse applications that enhance human health, agricultural productivity, and environmental sustainability. Their ability to thrive in various environments and their beneficial effects on fermentation and soil health make them an indispensable component of modern food and agricultural systems. These advantages contribute to healthier soils and more robust plant growth, providing an eco-friendly alternative to conventional chemical inputs in agriculture.

The application of SBPs can significantly reduce reliance on synthetic fertilizers and pesticides, aligning with the global movement towards sustainable agricultural practices. While current research highlights the potential of SBPs in improving soil fertility and supporting crop resilience, further studies are needed to fully elucidate their mechanisms of action, optimize their usage, and evaluate their long-term effects across different soil types and environmental conditions. Future research should focus on several key areas, including investigating the long-term impacts of SBPs on various soil types, understanding the interactions between SBPs and indigenous soil microbiota, and exploring their performance in diverse soil conditions, such as varying textures, pH levels, and organic matter content. Additionally, examining how different crops respond to SBP applications can inform tailored practices that maximize benefits across various agricultural systems. Research into how SBPs contribute to soil resilience against climate stressors, such as drought and flooding, will also be crucial for adapting to changing environmental conditions. Lastly, evaluating the cost-effectiveness of incorporating SBPs into

farming practices compared to traditional methods can facilitate broader adoption among farmers. By integrating SBPs into soil management practices, there is potential to transform agricultural systems, promoting more sustainable and resilient farming methods. Continued research and development are essential to realize the full potential of SBPs, enhancing their application in sustainable agriculture and contributing to long-term soil health and food security.

ACKNOWLEDGEMENTS

This review was supported by financial support from TWAS-UNESCO Associateship Scheme (Ref. no: 3240319965) and Grant IPS, Universiti Putra Malaysia (Grant no. 9789900).

REFERENCES

Aislabie, J., & Deslippe, J.R. 2013. Soil microbes and their contribution to soil services. p. 80-89. In: J. R. Dymond (Eds.). Ecosystem services in New Zealand – conditions and trends. Manaaki Whenua Press, Lincoln, New Zealand.

de Souza Vandenberghe, L.P., Garcia, L.M.B., Rodrigues, C., Camara, M.C., de Melo Pereira, G.V., de Oliveira, J., & Soccol, C.R. 2017. Potential applications of plant probiotic microorganisms in agriculture and forestry. *AIMS Microbiology* 3(3): 629-648.

Furey, G.N., & Tilman, D. 2021. Plant biodiversity and the regeneration of soil fertility. *Proceedings of the National Academy of Sciences* 118(49): e2111321118.

Lingoh, A.D., Leong, S.S., & Sarbini, S.R. 2020. Detection of lactic acid bacteria (LAB) from local chicken breed gut as probiotic agent in livestock. *Pakistan Journal of Nutrition* 19: 197-203.

Beresford, T.P. 2011. Lactic acid bacteria: Citrate fermentation by lactic acid bacteria. *Encyclopedia of Dairy Sciences* 2: 166-172.

Bittner, A.C., Croffut, R.M., & Stranahan, M.C. 2005. Prescript-assist™ probiotic-prebiotic treatment for irritable bowel syndrome: A methodologically oriented, 2-week, randomized, placebo-controlled, double-blind clinical study. *Clinical Therapeutics* 27(6): 755-761.

Chen, Y.S., Yanagida, F., & Hsu, J.S. 2006. Isolation and characterization of lactic acid bacteria from suan-tsai (fermented mustard), a traditional fermented food in Taiwan. *Journal of Applied Microbiology* 101(1): 125-130.

Chen, X., Zhang, Y., and Wu, X. 2024. Impact of soil-derived lactic acid bacteria on soil-borne pathogens and plant growth. *Journal of Soil Health* 12(1): 45-58.

Davis, M., Brown, J., and White, A. 2023. Advancements in soil probiotics: applications and benefits for sustainable agriculture. *Environmental Microbiology Reports* 15(3): 210-225.

Delia, E., Tafaj, M., and Manner, K. 2012. Efficiency of probiotics in farm animals. Probiotic in Animals. Intech Open, Brazil.

Dhama, K., Latif, M., and Gani, M. 2015. Probiotics in animal nutrition and health: A review. *Journal of Animal Science and Biotechnology* 6: 23.

Fierer, N., Schimel, J.P., and Holden, P.A. 2017. Variations in microbial community composition through two soil depths. *Soil Biology & Biochemistry* 45(1): 101-108.

George, F., Daniel, C., Thomas, M., Singer, E., Guilbaud, A., Tessier, F.J., Revol-Junelles, A.M., Borges, F., & Foligné, B. 2018. Occurrence and dynamism of lactic acid bacteria in distinct ecological niches: A multifaceted functional health perspective. *Frontiers in Microbiology* 9.

Gupta, A., Gupta, R., & Singh, R.L. 2017. Microbes and Environment. p. 3-7. In: Singh R. (Eds.). Principles and Applications of Environmental Biotechnology for a Sustainable Future. Applied Environmental Science and Engineering for a Sustainable Future. Springer, Singapore.

Hamed, H.A., Moustafa, Y.A., & Abdel-Aziz, S.M. 2011. In vivo efficacy of lactic acid bacteria in biological control against *Fusarium oxysporum* for protection of tomato plant. *Life Science Journal* 8: 462-468.

Hanifi, A., Culpepper, T., Mai, V., Anand, A., Ford, A.L., Ukhanova, M., Christman, M., Tompkins, T.A., & Dahl, W.J. 2015. Evaluation of *Bacillus subtilis* R0179 on gastrointestinal viability and general wellness: a randomised, double-blind, placebo-controlled trial in healthy adults. *Benefitial Microbes* 6(1): 19-27.

Hemarajata, P., & Versalovic, J. 2013. Effects of probiotics on gut microbiota: mechanisms of intestinal immunomodulation and neuromodulation. *Therapeutic advances in gastroenterology* 6(1): 39-51.

Hong, H.A., Duc, L.H., & Cutting, S.M. 2019. Bacteriocins Produced by lactic acid bacteria: Mechanisms of action and applications. *International Journal of Food Microbiology* 290: 82-91.

Ikeda, D.M., Jr., E.W., Chang, K.C.S., McGinn, J.M., Miller, S.A., Keliihoomalu, C., & DuPonte, M.W. 2013. Natural farming: Lactic acid bacteria. Retrieved from netLibrary:

Jäger, R., Purpura, M., Farmer, S., Cash, H.A., & Keller, D. 2018. Probiotic *Bacillus coagulans* GBI-30, 6086 improves protein absorption and utilization. *Probiotics and antimicrobial proteins*, 10(4): 611-615.

Jandhyala, S.M., Talukdar, R., Subramanyam, C., Vuyyuru, H., Sasikala, M., & Nageshwar Reddy, D. 2015. Role of the normal gut microbiota. *World journal of gastroenterology* 21(29): 8787-8803.

Jha, G.K., Velayudhan, P.K., Bhatia, A., Laishram, C., Kumar, D., Begho, T., & Eory, V. 2024. Transitioning towards sustainable agriculture: analysing the factors and impact of adopting multiple sustainable inputs by paddy farmers in India. *Frontiers in Sustainable Food Systems* 8: 1447936.

Jiménez-Gómez, A., Celador-Lera, L., Fradejas-Bayón, M., & Rivas, R. 2017. Plant probiotic bacteria enhance the quality of fruit and horticultural crops. *AIMS Microbiology 3*(3): 483-501.

Jones, M.L., Tompkins, L., & Payne, J. 2014. Soil Microbial diversity and ecosystem functions. *Ecological Monographs* 84(2): 243-261.

Jones, R.M. 2016. Symbiotic Bacteria and gut epithelial homeostasis. *Probiotics, Prebiotics, and Synbiotics*: 605-618.

Kato, M., Hamazaki, Y., Sun, S., Nishikawa, Y., and Kage-Nakadai, E. 2018. *Clostridium butyricum* MIYAIRI 588 increases the lifespan and multiple-stress resistance of caenorhabditis elegans. *Nutrients* 10(12): 1921.

Kim, P.I., Jung, M.Y., Chang, Y.H., Kim, S., Kim, S.J., & Park, Y.H. 2007. Probiotic properties of Lactobacillus and Bifidobacterium strains isolated from porcine gastrointestinal tract. *Applied Microbiology and Biotechnology* 74(5): 1103-1111.

Kim, D. 2020. Probiotic microorganisms: Their health benefits and mechanisms of action. *Microbiology Insights* 12: 1-15.

Kumar, P., Singh, R., & Patel, A. 2022. Soil-based probiotics and their role in enhancing soil quality. *Applied Soil Ecology* 94: 89-102.

Kumar, P., Verma, M., & Sharma, R. 2020. Seed treatment with lactic acid bacteria: Enhancing germination and plant health. *Journal of Soil Science and Plant Nutrition* 20(1): 345-356.

Laus, F., Faillace, V., Attili, A.R., Spaterna, A., Tesei, B., & Cuteri, V. 2016. Conjuctival bacterial and fungal flora in healthy donkeys in central Italy. *Large Animal Review* 22: 137-142.

Lee, S.H., Kim, H.J., & Choi, J.S. 2021. Enhancing soil health and plant growth with lactic acid bacteria and indigenous microorganisms: recent advances and applications. *Environmental Science & Technology* 55(8): 5174-5185.

Lefevre, M., Racedo, S.M., Ripert, G., Housez, B., Cazaubiel, M., Maudet, C., & Urdaci, M.C. 2015. Probiotic strain *Bacillus subtilis* CU1 stimulates immune system of elderly during common infectious disease period: a randomized, double-blind placebo-controlled study. *Immunity & Ageing* 12(1).

Leong, S.S., Ismail, J., Denil, N.A., Sarbini, S.R., Wasli, W., & Debbie, A. 2018. Microbiological and physicochemical water quality assessments of river water in an industrial region of the northwest coast of Borneo. *Water* 10(11): 1648.

Leong, S.S., Korel, F., Lingoh, A.D., Sarbini, S.R., Toh, S.C., Abit, L.Y., & Wong, S.C. 2023. Current probiotics application for aquaculture feed: a review. *Borneo Science Journal* 44(2).

Leong, S.S., Samuel, L., Chia, H.C., Kueh, J.H.R., & Kwan, Y.M. 2019. Biorisk assessment of antibiotic resistant pathogenic bacteria isolated from swiftlet houses in Sarawak. *Pertanika Journal of Tropical Agricultural Science* 42 (1): 285-303.

Li, H., Wang, S., & Zhao, C. 2023. Lactic acid bacteria in soil ecosystems: Functions and applications. *Soil Biology & Biochemistry* 151: 106-119.

Lippolis, R., Siciliano, R.A., Mazzeo, M.F., Abbrescia, A., Gnoni, A., Sardanelli, A.M., & Papa, S. 2013. Comparative secretome analysis of four isogenic *Bacillus clausii* probiotic strains. *Proteome science* 11(1): 28.

Madempudi, R.S., Neelamraju, J., Ahire, J.J., Gupta, S.K., & Shukla, V.K. 2019. *Bacillus coagulans* Unique IS2 in constipation: A double-blind, placebo-controlled study. *Probiotics and Antimicrobial Proteins* 12(2): 335-342.

Majeed, M., Nagabhushanam, K., Natarajan, S., Sivakumar, A., Ali, F., Pande, A., Majeed, S., & Karri, S.K. 2016. *Bacillus coagulans* MTCC 5856 supplementation in the management of diarrhea predominant Irritable Bowel Syndrome: a double blind randomized placebo controlled pilot clinical study. *Nutrition journal* 15: 21.

Mariotti, F., & Gardner, C.D. 2019. Dietary protein and amino acids in vegetarian diets-A Review. *Nutrients* 11(11): 2661.

Tahat, M.M., Alananbeh, K.M, Othman, Y.A., & Leskovar, D.I. 2020. Soil health and sustainable agriculture. *Sustainability* 12(12): 12.

Murindangabo, Y.T., Kopecký, M., Perná, K., Nguyen, T.G., Konvalina, P., & Kavková, M. 2023. Prominent use of lactic acid bacteria in soil-plant systems. *Applied Soil Ecology* 189: 104955.

McNulty, N.P., Yatsunenko, T., Hsiao, A., Faith, J.J., Muegge, B.D., Goodman, A.L., & Gordon, J.I. 2011. The impact of a consortium of fermented milk strains on the gut microbiome of gnotobiotic mice and monozygotic twins. *Science Translational Medicine* 3(106): 106ra106-106ra106.

Morgavi, D.P., Forano, E., & Martin, C. 2015. Microbial ecosystems in the rumen: Their dynamics and functions. *Animal Feed Science and Technology* 219: 1-13.

Mokoena, M.P. 2017. Lactic acid bacteria and their bacteriocins: Classification, biosynthesis and applications against uropathogens: a mini-review. *Molecules* (Basel, Switzerland) 22(8): 1255.

Park, J.H., & DuPonte, M.W. 2008. Application of Indigenous Microorganisms (IMO) in natural farming: compost and compost teas for soil preparation. *Journal of Natural Farming* 7(2): 145-155.

Patel, S., Majumder, A., & Goyal, A. 2012. Potentials of exopolysaccharides from lactic acid bacteria. *Indian Journal of Microbiology* 52(1): 3-12.

Pold, G., Grandy, A.S., Melillo, J.M., & DeAngelis, K.M. 2017. Changes in substrate availability drive carbon cycle response to chronic warming. *Soil Biology and Biochemistry* 110: 68-78.

Purchiaroni, F., Tortora, A., Gabrielli, M., Bertucci, F., Gigante, G., Ianiro, G., Ojetti, V., Scarpellini, E., & Gasbarrini, A. 2013. The role of intestinal microbiota and the immune system. *European Review for Medical and Pharmacological Sciences* 17(3): 323-333.

Raman, M., Ambalam, P., Kondepudi, K.K., Pithva, S., Kothari, C., Patel, A.T., Purama, R. K., Dave, J.M., & Vyas, B.R. 2013. Potential of probiotics, prebiotics and synbiotics for management of colorectal cancer. *Gut microbes* 4(3): 181-192.

Ramanathan, M., Duhamel, G.E., Mathiesen, M.R., & Messier, S. 1993. Identification and partial characterization of a group of weakly beta-hemolytic intestinal spirochetes of swine distinct from *Serpulina innocens* isolate B256. *Veterinary Microbiology* 37(1-2): 53-64.

Rawi, M.H., Zaman, S.A., Pa'ee, K.F., Leong, S.S., and Sarbini, S.R. 2020) Prebiotics metabolism by gut-isolated probiotics. *Food Science Technology* 57: 2786-2799.

Roberfroid, M., Gibson, G., Hoyles, L., McCartney, A., Rastall, R., Rowland, I., & Meheust, A. 2010. Prebiotic effects: Metabolic and health benefits. *British Journal of Nutrition* 104(S2): S1-S63.

Sapkota, A. 2023. Microorganisms found in soil with effects and examples. Access from: https://microbenotes.com/microorganisms-in-soil/.

Schulz, S., Brankatschk, R., Dümig, A., Kögel-Knabner, I., Schloter, M., & Zeyer, J. 2013. The role of microorganisms at different stages of ecosystem development for soil formation. *Biogeosciences* 10(6): 3983-3996.

Seddik, H.A., Bendali, F., Gancel, F., Fliss, I., Spano, G., & Drider, D. 2017. *Lactobacillus plantarum* and its probiotic and food potentialities. *Probiotics and Antimicrobial Proteins* 9(2): 111-122.

Silva, C., Silva, S., & Ribeiro, S.C. 2018. Application of bacteriocins and protective cultures in dairy food preservation. *Frontiers in Microbiology* 9: 594.

Shi, L.H., Balakrishnan, K., Thiagarajah, K., Mohd Ismail, N.I., & Yin, O.S. 2016. Beneficial properties of probiotics. *Tropical Life Sciences Research* 27(2): 73-90.

Siraj, N.M., Sood, K., & Yadav, R.N.S. 2017. Isolation and identification of potential probiotic bacteria from cattle farm soil in Dibrugarh District. *Advances in Microbiology* 07(04): 265-279.

Smith, R., & Johnson, L. 2021. The role of soil probiotics in carbon sequestration and soil health. *Journal of Environmental Management* 278: 111-123.

Surono, I.S., Koestomo, F.P., Novitasari, N., Zakaria, F.R., Yulianasari, & Koesnandar. 2011. Novel probiotic *Enterococcus faecium* IS-27526 supplementation increased total salivary sIgA level and bodyweight of pre-school children: A pilot study. *Anaerobe* 17(6): 496-500.

Tee, E.S. 2020. Probiotic products in Malaysia: market trends and health benefits. *Asian Journal of Clinical Nutrition* 12(4): 234-245.

Townsend, J.R., Bender, D., Vantrease, W.C., Sapp, P.A., Toy, A.M., Woods, C.A., & Johnson, K.D. 2018. Effects of probiotic (*Bacillus subtilis* DE111) supplementation on immune function, hormonal status, and physical performance in division I baseball players. *Sports* (Basel, Switzerland) 6(3): 70.

Vuković, M. 2001. *Bacillus subtilis* IP 5832 (Flonivin BS) shortens the duration of the carrier state in patients with acute non-typhoid *salmonella enteritis*. *Medicinski Pregled* 54(1-2): 62-68.

Wedajo, B. 2015. Lactic acid bacteria: Benefits, Selection criteria and probiotic potential in fermented food. *Journal of Probiotics & Health* 03(02): 129.

Yang, C., Liu, Y., & Zhang, X. 2019. Biopreservative properties of lactic acid bacteria in food safety. *Food Research International* 116: 1085-1093.

Yermolenko, E., Chernish, A., Aleshina, G., Cvetkova, E., Martsinkovskaya, I., Kolodjieva, V., & Suvorov, A. 2006. Antagonistic activity of *Enterococcus faecium* L3 against different groups of pathogenic streptococci. *International Congress Series* 1289: 363-366.

Wang, G., Ren, Y., Bai, X., Su, Y., & Han, J. 2022. Contributions of beneficial microorganisms in soil remediation and quality improvement of medicinal plants. *Plants* 11(23): 3200.

Zhang, Y., Liu, H., & Zhao, M. 2022. Enhancing soil fertility with soil-based probiotics: Mechanisms and benefits. *Environmental Science & Technology* 56(3): 1679-1689.

Yanni, A.E., Iakovidi, S., Vasilikopoulou, E., & Karathanos, V.T. 2023. Legumes: a vehicle for transition to sustainability. *Nutrients*16(1): 98.

Zhang, R., Wang, X., & Zhang, Q. 2020. Effects of probiotic supplementation on soil microbial communities. *Applied Soil Ecology* 148: 103426.