IJPSR Vol. 2 Issue 2 Apr - Jun (2026) 29–33

eISSN: 3139-342X

International Journal of Primary and Secondary Research (IJPSR)

International, Double-Blind, Quarterly, Peer-Reviewed, Refereed, Edited and Open Access Research Journal
Journal homepage: ijpsr.co.in

Bioformulations: A Sustainable Alternative to Agrochemicals for Food Productivity and Security

Sangeeta Yadav[1], Suhani[1] and Devesh Kumar*[1]

[1]*Department of Botany, RBS College, Agra Affiliated to Dr. Bhimrao Ambedkar University, Agra, Uttar Pradesh, India*

* Corresponding author. E-mail address: drdeveshjadon@gmail.com

DOI- https://doi.org/10.59436/ijpsr.v2i2.6.3139-342X

A R T I C L E I N F O

Article history:
Received 11 March 2026
Received in revised form
2 1 April 2026
Accepted 01 June 2026
Available online 16 June 2026

Keywords:

Formulation, Sustainable agriculture, Productivity

A B S T R A C T

Bioformulations are carrier-based preparations that improve soil health and plant growth by adding helpful microbes like Rhizobium, Trichoderma, or Plant Growth-Promoting Rhizobacteria. Microbial viability, shelf life, and field performance are all determined by the formulation process, which has a significant impact on a bioformulation's effectiveness. The main stages of developing bioformulations are described in this review. Elite microbial strains are first isolated and screened for desired characteristics such as phosphate solubilization, nitrogen fixation, or antagonism against pathogens. To obtain high cell density, certain strains are mass multiplied in appropriate liquid media under ideal pH, temperature, and aeration conditions. After that, the microbial biomass is combined with carrier ingredients that offer nourishment and protection while being stored. Common carriers include peat, lignite, charcoal, vermiculite, and liquid formulations containing glycerol, CMC, or trehalose. To avoid contamination, the formulation step requires maintaining the correct moisture content, pH, and sterility levels. Efficacy is measured in laboratory, pot, and field experiments, with measures such as germination rate, plant biomass, nutrient uptake, yield growth, and disease suppression compared to uninoculated controls. Factors influencing efficacy include the strain's compatibility with the crop, carrier qualities, storage conditions, and soil environment. Recent improvements in encapsulation, lyophilization, and polymer-based formulations have increased bioinoculants' shelf life and stress resistance. Standardized formulation techniques are crucial for bridging the gap between laboratory achievement and farmer adoption of sustainable agriculture.

Introduction

The worldwide increase in both environmental damage and human population pressure have the unfortunate consequence that global food production may soon become insufficient to feed the world's people. It is, therefore, essential that agricultural productivity should be significantly increased within the next few decades. To this end, agricultural practice is moving towards a more sustainable and environmentally friendly approach to overcome the loss caused by the chemical fertilizer. Kloepper and Schroth (1978) identified the potential of PGPR to reveal a holistic approach to beneficial microorganisms in soil. Rhizospheric bacteria can impact plant growth both directly and indirectly. Research suggests that treating crops with these microbes improves productivity and reduces the need for synthetic chemicals (Adesemoye *et al*. 2009). To be used on a large scale, bioformulations must be stable, have a long shelf life, and provide desired results when applied in the field with the right delivery system at the lowest effective dose.

A suitable carrier substance, which is inert in nature, helps the active components (viable cells), ensuring that the cells are safely delivered to the vicinity of the plant or within the plant body and that they work efficiently for promoting plant growth or neutralizing specific pests; it also extends the shelf life of the formulation (Burges and Jones 1998). A variety of substances can be used as carriers, including soils, useless plant biomass, inert substances (polymers, vermiculite, and liquids (Bashan *et al*. 2014). Additives like gums, silica gel, methyl cellulose, and starch are added to improve the physicochemical and nutritive characteristics of bioformulations (Schisler *et al*.2004). Jeyarajan and Nakkeeran (2000) listed the following characteristics of a perfect formulation:

1. It ought to be long-lasting.
2. It should not be hazardous to the growing crop.
3. It must transport the bacteria and dissolve efficiently in water.
4. It needs to survive adverse environmental conditions.
5. It needs to be affordable and offer reliable plant disease control.
6. It must be compatible with other agrochemicals.
7. It must be affordable and freely available for formulation development.

2. Preparation of Bioformulation-The components utilized to construct the bioformulation, which include potentially advantageous microbial strains, an appropriate carrier, and an adjuvant, are crucial to the development of an effective and efficient bioformulation (Aamir *et al*., 2020). The following is a summary of the steps taken in developing the bioformulation:

2.1 Selection of microbes-One of the most important steps in the bioformulation development process is the selection of microorganisms. Microbial strains are chosen primarily based on their antagonistic, degrading potential, plant growth promoting (PGP), and other beneficial characteristics (Wong *et al*., 2019; Singh *et al*., 2020). A variety of microbial sources, including soil, water, and any other particular substance used for isolation, were tested for a number of characteristics that make them a potential candidate for bioformulation development, such as the production of siderophores and lytic enzymes, nutrient solubilization, phytohormone and antibiotic production, xenobiotic degradation or heavy metal bioremediation, etc. (Vassilev *et al*., 2015).

For the manufacture of bioformulations, multiple microbial strains are utilized in place of a single microbe. Acetobacter, Arthrobacter, Azotobacter, Azospirillum, Bacillus, Burkholderia, Clostridium,

This is an Open Access article published under the Creative Commons Attribution 4.0 International License (CC BY 4.0)

Enterobacter, Flavobacterium, Frankia, Hydrogenophaga, Kluyvera, Microcoleus, Phyllobacterium, Pseudomonas, Serratia, Streptomyces, Rhizobium, Trichoderma, and other species have already been reported to have remarkable PGP potential and are being considered for bioformulation preparation (Soni *et al*., 2017; Alawiye and Babalola, 2019; Suyal *et al*., 2019; Jeyakumar *et al*., 2020). Additionally, a variety of microorganisms with different plant growth and biocontrol properties, including Rhizobium leguminosarum, Bradirhizobium japonicum, Bacillus amyloliquefaciens, Trichoderma virens, and Penicillium bilaiae, have been commercialized as biofertilizers through various organizations.

2.2 Selection of carrier and Bioformulation assembly

An essential component of bioformulation preparation is an appropriate carrier. It serves as a means of transporting live microbial strains from the lab to the field. To promote microbial growth and efficiently deliver desired microbes into the field, appropriate inorganic/organic or synthetic carriers, such as peat, coal, clays, talc, vermiculite, charcoal, cellulose, sawdust, wheat bran, alginate beads, rice husk, polyacrylamide gel, calcium sulfate, silica gel, etc., can be used singly or in combination (Vishwakarma *et al*., 2018). The shelf life, bio-availability, release rate and general performance of a bioformulation based on bioinoculants can all be greatly impacted by the carriers utilized in its manufacture. Therefore, while choosing the carrier material, compatibility with the microorganisms, potential toxicity, or immunological reaction from the carrier should be given first priority. Additionally, the carrier should shield bioactive substances from deterioration caused by outside factors including heat, light, and moisture. The sterilization of carriers is a crucial step in the manufacture of bioformulations.

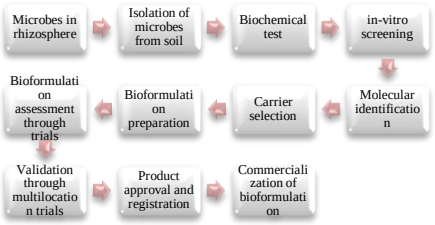


Fig. 1 Diagrammatic illustration of steps in the preparation of bioformulation.

The best method for sterilizing certain carriers, such as rice husk, wheat bran, clay, peat moss, and a mixture of peat moss and vermiculite, is gamma radiation at a dose rate of 4.0 kGy for one hour or autoclaving at 121°C for twenty to thirty minutes (El-Fattah *et al*., 2013; Sahai *et al*., 2019). In order to maintain a moisture content of 15–20%, which is necessary to reduce the microbial metabolic activities, the sterilized carrier is combined with actively growing microbial strains and air dried overnight (Samavat *et al*., 2014). Additionally, the mixture is maintained at room temperature with 80% relative humidity after being packed and sealed in polypropylene bags that have been previously sterilized by autoclaving or gamma irradiation (Arora *et al*., 2010; Suryadi *et al*., 2013; Namsena *et al*., 2016; Bargaz *et al*., 2018). According to Jambhulkar and Sharma (2014) and Samavat *et al*. (2014), an effective bioformulation has to have at least 107 CFUs per gram of microbial cells.

2.3 Storage stability assessment- An important and crucial component of bioformulation efficacy is determining the bioformulation's storage capacity. The product's microbiological stability and self-life are typically anticipated to last between six and twelve months (Berninger *et al*., 2018). The bioformulation's survival and stability depend on the additives and low-temperature storage. Colony forming units (CFUs), that must not be less than 104 CFUs per gram sample, are estimated during the stability test using standard serial dilution plating at various time intervals (Wong *et al*., 2019). The bioformulation sustenance capability, which establishes the bioformulation's shelf life, is being tested using a variety of encapsulating materials, a broad temperature range, and various environmental circumstances.

2.4 Validation, Approval and Commercialization-After the production of the bioformulation and its successful field demonstration, it undergoes additional processing for validation, which involves testing the same bioformulation through multi-location field trials. Before being commercialized, the bioformulation must be registered through patent and risk-related approval following validation.

3. Categorization of Bioformulation Methods-A bioformulation is a biologically active mixture of metabolites and microbial biomass with a carrier material (Aamir *et al*., 2020). According to Khan *et al*. (2023) and Tewari *et al*. (2020), these formulations are categorized as solid, liquid, encapsulated, cell-free culture supernatant (CFCS) and metabolites.

3.1 Solid Bioformulation-Solid formulations increase storage efficiency and provide tailored microbial inoculants with a safe and nourishing habitat. Included are granules, water-dispersible granular and powdered formulations comprising chemicals, carrier materials, and active binders. Soil-derived carriers like charcoal, fine clay, and turf; organic carriers like sawdust, cork compost, soy, oat bran, wheat, sewage sludge, vermicompost, and animal manure; and inert carriers like peat, talc, vermiculite, perlite, bentonite, alginate, silicates, kaolin, charcoal, polyacrylamide beads, and so forth are examples of solid formulation materials (Mishra & Arora, 2016). Furthermore, solid bioformulation is categorized into the following:

(i) Granule formulation: This is made up of granular carrier, binder, and dry particles with active ingredients (5%–20%) (Brar *et al*., 2006). Granules are coarse, non-dusty particles that are safe to breathe in. Among the most often used granules are maize meal baits (Tamez-Guerra *et al*., 1996), wheat granules (Navon, 2000), gluten, gelatine, cottonseed flour, wheat flour, semolina, sodium alginate, and pesta granules (Khan *et al*., 2023; Wong *et al*., 2019). According to earlier studies, inoculants with granular bioformulation performed better under stressful conditions in terms of nitrogen fixation, nodule formation, and total biomass than peat carriers and liquid formulation (Zaidi *et al*., 2017). The inactivation of active substances in the presence of UV radiation is one of the major limitations of granular bioformulations, despite their efficacy. Granules are easier to handle, store, and transport since they contain living bacteria and may be coated with silica, marble, or calcite.

(ii) Wettable powdered (WP) formulations: Wettable powdered (WP) formulations consist of 50%–80% powder, 1%–10% dispersant, 3%–5% surfactant, and 15%–45% filler (Brar *et al*., 2006; Nagaraju & Mohan, 2021). The formulations are easily miscible with water and have an 18-month shelf life. WP formulations offer a number of benefits, including uniform distribution of required gradients, good active gradient retention, residual control, less skin risks, and minimal sedimentation issues. Carriers used in WP creation include charcoal, fly ash, talc, sawdust-molasses mixtures, organic cakes, wheat bran-sand mixtures, and farmyard manure.

(iii) Wettable or water-dispersible granular (WDGs) formulation: Wettable/water-dispersible small granules are solid, free-flowing, and non-dusty. They contain dry dispersible substances that are easily soluble with water and safe for the environment. Ninety percent of nematode-based products on the market are based on this formulation, which is essential to nematode treatment (Mishra & Arora, 2016).

3.2 Liquid Bioformulation-According to Rai *et al*. (2023) and Schisler *et al*. (2004), liquid formulations are aqueous suspensions made of biomass in water, oil, or both. It consists of 1%–3% suspender, 10%–40% microorganisms, 3%–8% surfactant, 35%–65% carrier fluids, and 1%–5% dispersant (Rai *et al*., 2023). Liquid bioformulations are used to maintain the stability of organisms during manufacturing, storage, and transportation. It encourages perseverance and protects against abiotic environmental effects.

Liquid formulations are categorized as oil dispersions (Mbarga *et al*., 2014), oil-ultralow volume suspensions, miscible flowable concentrates (Khan *et al*., 2023), and suspension concentrates (Ijaz *et al*., 2019). Potential liquid carriers include jaggery syrups, water, fruit juices, broth, and polyvinylpyrrolidone. Solid active ingredients that are resistant to hydrolysis and poorly soluble in water were combined to form the suspension concentrates (Ijaz *et al*., 2019). This mixture is measured, doesn't dust, and pours easily for spraying. Organic liquids with active ingredients are suspended in an oil-miscible flowable concentration. The ultralow volume suspension is used in their related equipment. This device uses either aerial or ground spray for fine spray treatments (Aamir *et al*., 2020).

As a result, liquid formulations provide a better way to stable the bioinoculants during manufacturing, transportation, and long-term storage while also increasing the shelf life of agricultural products. However, it is crucial to remember that factors like temperature,

This is an Open Access article published under the Creative Commons Attribution 4.0 International License (CC BY 4.0)

contamination, and light exposure can all have an impact on the survival of microorganisms in liquid formulations. Compared to solid formulations, it could be less stable, particularly in harsh surroundings.

3.3 Encapsulated Bioformulation-Limitations of both liquid and solid formulations include long-term storage and the survivability of microbial spores. In these situations, encapsulation and immobilization have increased the bioinoculants' shelf life and simplified field application (Rojas-Sánchez *et al*., 2022; Vassilev *et al*., 2020). Encapsulation offers a novel method for enhancing soil microflora and promoting sustainable agriculture by enabling the controlled release of dynamic target microbial cells and their metabolites into the rhizosphere (Wu *et al*., 2020). Microbial cells are encapsulated in polymeric materials to form beads that are permeable to nutrients, gases, and metabolites, enabling cell survival inside the beads (Khan *et al*., 2023). Active microbial components are shielded by encapsulated formulation from environmental or unfavorable stimuli like pH, mechanical damage, biochemical variables, temperature and ionic strength.

The long-term consequences of encapsulated formulations on soil, water, or other ecosystems are currently little understood. Over time, residues from the encapsulated formulations may build up in the environment, possibly having unexpected consequences, such altered soil structure or disruption of the nutrient cycle (Iqbal *et al*., 2023).

3.4 Cell-free Culture Supernatant Bioformulation-Enzymes, poisons, and other metabolites released by desired microbial cells may be used to create the CFCS bioformulation. According to Tewari *et al*. (2020), the CFCS bioformulation is created by centrifuging the cell pellet to extract the supernatant, sifting the mixture through a 0.22 µm filter, and then mixing it with a suitable carrier. The CFCS has been thoroughly identified and used in numerous studies to improve soil fertility and agricultural output. According to reports, they include metabolites and nutrients like P and N that can benefit plants in withstanding biotic and abiotic stressors (Rai *et al*., 2023).

3.5 Metabolites-Microorganisms release a variety of secondary metabolites that act as phytopathogen antagonists, plant growth promoters, and bioregulators. These beneficial microorganisms produce a variety of bioactive compounds and proteins that help promote plant growth and protect plants from diseases. These include enzymes such as ACC deaminase (Onofre-Lemus *et al*., 2009) and β-1,3-glucanase (Confortin *et al*., 2019), as well as several antimicrobial substances like phenazines (Biessy & Filion, 2018), pyrrolnitrin (Pawar *et al*., 2019), pyoluteorin (Keswani *et al*., 2020), viscosinamide, tensin, pyochelin (Ho *et al*., 2018), tetracenomycin (Gurusinghe *et al*., 2019), rhizoxins, peptide antibiotics (Gross & Loper, 2009), phenazine-1-carboxylic acid (Morrison *et al*., 2017), orfamide A and H (Khan *et al*., 2023), brabantamide A (Strehmel *et al*., 2014), furanomycin (Masschelein *et al*., 2017), safracins (Santos Kron *et al*., 2020), rimid (Matilla *et al*., 2016), and kalimantacin (Thistlethwaite *et al*., 2017). These compounds contribute to the plant growth-promoting and disease-suppressing abilities of the microorganisms. These metabolites exhibit a variety of traits, such as the capacity to mobilize nutrients, operate as biosurfactants, have insecticidal effects, and trigger plant defense mechanisms. Most of the microbial metabolites mentioned above are secreted by the soil rhizosphere.

Table 1: List of some bioformulations available in India

Name of Company	Name of Product	Active ingredient	Use on the crops	References
T. Stanes & Company Limited, Tamil Nadu	Symbion-N	*Azospirillum, Rhizobium, Acetobacter*, and *Azotobacter*	Cereals, legumes, and vegetable crops	http://www.tstanes.com/products.html
	Symbion-P	*B. megaterium* var. *phosphaticum*		
	Symbion-K	*Frateuria aurantia*		
	Symbion-S	*Thiobacillus thiooxidans*		
	Symbion-VAM	*Glomus fasciculatum*		
Camson Bio Technologies Limited, Karnataka	CALOBIUM	*Rhizobium* sp.	Legume crops, cereal crops, vegetable crops	http://www.camsonbiotechnologies.com/products/bio_fertilizers_and_stimulants.htm
	CALMONAS	*Pseudomonas* sp.		
	CALSPIRAL	*Azospirillum* sp.		
	CALZOTO	*Azotobacter* sp.		
	CALTASH	K solubilizer		
	CALPHOROUS	PSB		
Ajay Biotech, Maharashtra	BIOPHOS	PSB	Various crops	http://www.ajaybio.in/prodpro.htm
Gujarat State Fertilizers and Chemicals, Gujarat	Sardar Biofertilizers	*Azotobacter, Azospirillum*, and PSB	All types of crop	http://www.gsfclimited.com/bio_fertilizers.asp?mnuid¼3&fid¼32

4. Factors Affecting the efficacy of Bioformulation-The performance of a bioformulation depends on several biological and environmental factors. These factors influence the survival, stability, and effectiveness of microorganisms used in the formulation Mawar *et al*., 2021; Rojas-Sánchez *et al*., 2022):

4.1. Selection of Microbial Strains-One of the most crucial aspects of creating a bioformulation is selecting the right microbial strain. Different microorganisms vary in their ability to survive, colonize, and function under different environmental conditions. Therefore, it is best to choose strains with high adaptability and advantageous traits.

4.2. Carrier Materials and Additives-Carrier materials are essential for safeguarding microorganisms during application and storage. They help maintain microbial viability, facilitate transportation, and ensure the gradual release of microbes into the target environment. Suitable additives can enhance formulation performance even more.

4.3. Storage Conditions-The viability of the microorganisms in the formulation depends on the right storage conditions, which include temperature, humidity, and packaging.

4.4. Shelf Life-Shelf life can have a significant impact on the formulation's efficacy. Formulations with longer shelf lives reduce the need for frequent reapplication, while those with shorter shelf lives can necessitate more frequent application.

4.5. Environmental Influences-The ability of microbes to stick to surfaces and grow in their target environment is very important. Microbes in formulations may face challenges such as UV light, chemicals, and competition from naturally occurring microorganisms. Their effectiveness can also be influenced by interactions with native microbes or other introduced microbial strains.

4.6. Application Method-The distribution and efficacy of the formulation in the target area can be affected by the application technique, including spraying, irrigation, injection, and other methods.

4.7. Climatic Conditions-The effectiveness of microbial formulations can be impacted by external environmental factors, such as seasonal alterations and climate shifts that influence both the biotic and abiotic parameters (pH, salinity, temperature, soil type, microbiota, etc.) of such places.

4.8. Quality Control-Strict quality control procedures must be followed throughout the production process to guarantee consistency and dependability in microbial formulations because contamination by any foreign microorganisms significantly reduces the effectiveness of bioformulations.

4.9. Genetic Stability-In certain situations, the formulation's microbial strains' genetic stability should be taken into account to make sure they retain the necessary characteristics throughout time.

5. Role of Bioformulation-Beneficial bacteria known as "plant growth promoting microorganisms" (PGPM) aid in the growth and development of plants by shielding them from biotic and abiotic challenges and regulating the availability of nutrients.

5.1 Increase in agricultural productivity and nutritional value-The ongoing use of chemical fertilizers after the green revolution was able to meet food quality requirements, but it is reducing the nutritional content of soil and plants. Due to their critical roles in plant metabolism, growth, and development, nitrogen (N), phosphorus (P), and potassium (K) are macronutrients that are necessary for healthy plant growth and serve as significant crop production limiting factors. The "BioGro" inoculant is a blend of microbial strains that were separated from the soils of rice crops. Rice's grain yield and nutrient content, such as N and P, are increased when this inoculant is applied (Nguyen *et al*., 2017).

5.2 As biocontrol agents-Biocontrol Agents (BCA) can either directly or indirectly suppress plant pathogens by forming a nonphysical interaction with the host. Competition for micronutrients and space to colonize and thrive in the rhizosphere is another strategy to shield the plant from biotic stressors (Upadhayay *et al*., 2021). According to Lindow's (1987) research, foliar colonization of a Pseudomonas

This is an Open Access article published under the Creative Commons Attribution 4.0 International License (CC BY 4.0)

syringae strain on pear plants reduced Erwinia amylovora infection compared to untreated plants. Inducing an Induced Systemic Response (ISR) defensive system in plants is one strategy to manage plant infection against harmful microbes and insects (Pieterse *et al*., 2014). According to reports, Bacillus species create cyclic lipopeptide compounds that raise plant ISR mechanisms against phytopathogens via salicylic acid (SA) and jasmonic acid (JA)/ethylene pathways.

5.3 Reducing abiotic stress-According to Singh *et al.* (2021), the application of microbial bioformulations is frequently regarded as a practical substitute for increasing crop output under various abiotic stressors. Plant growth, production, and the nutritional quality of seeds are all adversely affected by abiotic stressors such as drought, waterlogging, low or high temperatures, salinity stress, and insufficient or excessive mineral content. A recent study found that using silicon dioxide and a starch-based P. putida bioformulation enhanced cowpea biomass and crop output in water-deficient settings (Rocha *et al*., 2019).

6. Conclusion and Future Prospects-By increasing plant growth, increasing nutrient availability, and promoting environmental health, microbial bioformulations offer a viable and sustainable substitute for traditional agricultural inputs. Careful strain selection, strong carrier materials, extended shelf life, biosafety, and effective delivery methods are all necessary for their successful utilization. Future studies should concentrate on creating metabolite-based, stable, and reasonably priced bioformulations that function consistently in a variety of field scenarios. Microbial inoculants can greatly contribute to sustainable agriculture, food security, and environmental conservation by lowering reliance on chemical pesticides and fertilizers through realistic large-scale use and improved formulation methods. According to Brar *et al*. (2006), the effectiveness of a bioformulation depends on its impact on field conditions, market availability, reliability, and cost-efficiency. Production of bioformulation requires understanding of both microbial and plant physiology, as well as technological barriers such as fermentation, formulation, microbe population, and delivery methods (Malusa' *et al*. 2012).

References

Aamir, M., Rai, K. K., Zehra, A., Dubey, M. K., Kumar, S., Shukla, V., & Upadhyay, R. S. (2020). Microbial bioformulation-based plant biostimulants: A plausible approach toward next generation of sustainable agriculture. In Microbial endophytes (pp. 195-225). Woodhead Publishing.

Abd El-Fattah, D. A., Eweda, W. E., Zayed, M. S., & Hassanein, M. K. (2013). Effect of carrier materials, sterilization method, and storage temperature on survival and biological activities of Azotobacter chroococcum inoculant. Annals of Agricultural Sciences, 58(2), 111-118.

Adesemoye, A. O., Torbert, H. A., & Kloepper, J. W. (2009). Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. Microbial ecology, 58(4), 921-929.

Alawiye, T. T., & Babalola, O. O. (2019). Bacterial diversity and community structure in typical plant rhizosphere. Diversity, 11(10), 179.

Arora, N. K., Khare, E., & Maheshwari, D. K. (2010). Plant growth promoting rhizobacteria: constraints in bioformulation, commercialization, and future strategies. In Plant growth and health promoting bacteria. Berlin, Heidelberg: Springer Berlin Heidelberg. (pp. 97-116)

Bargaz, A., Lyamlouli, K., Chtouki, M., Zeroual, Y., & Dhiba, D. (2018). Soil microbial resources for improving fertilizers efficiency in an integrated plant nutrient management system. Frontiers in microbiology, 9, 1606.

Bashan, Y., de-Bashan, L. E., Prabhu, S. R., & Hernandez, J. P. (2014). Advances in plant growth-promoting bacterial inoculant technology: formulations and practical perspectives (1998–2013). Plant and soil, 378(1), 1-33.

Berninger, T., González López, Ó., Bejarano, A., Preininger, C., & Sessitsch, A. (2018). Maintenance and assessment of cell viability in formulation of non-sporulating bacterial inoculants. Microbial biotechnology, 11(2), 277-301.

Biessy, A., & Filion, M. (2018). Phenazines in plant-beneficial Pseudomonas spp.: biosynthesis, regulation, function and genomics. Environmental Microbiology, 20(11), 3905-3917.

Brar, S. K., Verma, M., Tyagi, R. D., & Valéro, J. R. (2006). Recent advances in downstream processing and formulations of Bacillus thuringiensis based biopesticides. Process biochemistry, 41(2), 323-342.

Burges, H. D. & Jones, K. A. (1998). Formulation of microbial biopesticides: beneficial microorganisms, nematodes and seed treatments. Kluwer Academic, Dordrecht, p 411.

Confortin, T. C., Spannemberg, S. S., Todero, I., Luft, L., Brun, T., Alves, E. A., ... & Mazutti, M. A. (2019). Microbial enzymes as control agents of diseases and pests in organic agriculture. New and future developments in microbial biotechnology and bioengineering, 321-332.

Gross, H., & Loper, J. E. (2009). Genomics of secondary metabolite production by Pseudomonas spp. Natural product reports, 26(11), 1408-1446.

Gurusinghe, S., Brooks, T. L., Barrow, R. A., Zhu, X., Thotagamuwa, A., Dennis, P. G., ... & Weston, L. A. (2019). Technologies for the selection, culture and metabolic profiling of unique rhizosphere microorganisms for natural product discovery. Molecules, 24(10), 1955.

Ho, Y. N., Lee, H. J., Hsieh, C. T., Peng, C. C., & Yang, Y. L. (2018). Chemistry and biology of salicyl-capped siderophores. Studies in Natural Products Chemistry, 59, 431-490.

Ijaz, M., Ali, Q., Ashraf, S., Kamran, M., & Rehman, A. (2019). Development of future bioformulations for sustainable agriculture. Microbiome in plant health and disease: challenges and opportunities, 421-446.

Iqbal, B., Li, G., Alabbosh, K. F., Hussain, H., Khan, I., Tariq, M., ... & Ahmad, N. (2023). Advancing environmental sustainability through microbial reprogramming in growth improvement, stress alleviation, and phytoremediation. Plant stress, 10, 100283.

Jambhulkar, P. P., & Sharma, P. (2014). Development of bioformulation and delivery system of Pseudomonas fluorescens against bacterial leaf blight of rice (Xanthomonas oryzae Pv. oryzae). Journal of Environmental Biology, 35 (5), 843–849.

Jeyakumar, S. P., Dash, B., Singh, A. K., Suyal, D. C., & Soni, R. (2020). Nutrient cycling at higher altitudes. In Microbiological advancements for higher altitude agro-ecosystems & sustainability (pp. 293-305). Singapore: Springer Singapore.

Jeyarajan, R., & Nakkeeran, S. (2000). Exploitation of microorganisms and viruses as biocontrol agents for crop disease management. In Biocontrol Potential and its Exploitation in Sustainable Agriculture: Crop Diseases, Weeds, and Nematodes (pp. 95-116). Boston, MA: Springer US.

Keswani, C., Singh, H. B., García-Estrada, C., Caradus, J., He, Y. W., Mezaache-Aichour, S., ... & Sansinenea, E. (2020). Antimicrobial secondary metabolites from agriculturally important bacteria as next-generation pesticides. Applied microbiology and biotechnology, 104(3), 1013-1034.

Khan, A., Singh, A. V., Gautam, S. S., Agarwal, A., Punetha, A., Upadhayay, V. K., ... & Goel, R. (2023). Microbial bioformulation: a microbial assisted biostimulating fertilization technique for sustainable agriculture. Frontiers in Plant Science, 14, 1270039.

Kloepper, J. W. (1978). Plant growth-promoting rhizobacteria on radishes. In Proc. of the 4th Internet. Conf. on Plant Pathogenic Bacter, Station de Pathologie Vegetale et Phytobacteriologie, INRA, Angers, France, 1978 (Vol. 2, pp. 879-882).

Lindow, S. E. (1987). Competitive exclusion of epiphytic bacteria by Ice− Pseudomonas syringae mutants. Applied and Environmental Microbiology, 53(10), 2520-2527.

Malusá, E., Sas-Paszt, L., & Ciesielska, J. J. T. S. W. J. (2012). Technologies for beneficial microorganisms inocula used as biofertilizers. The scientific world journal, 2012(1), 491206.

Masschelein, J., Jenner, M., & Challis, G. L. (2017). Antibiotics from Gram-negative bacteria: a comprehensive overview and selected biosynthetic highlights. Natural product reports, 34(7), 712-783.

Matilla, M. A., Nogellova, V., Morel, B., Krell, T., & Salmond, G. P. (2016). Biosynthesis of the Acetyl-CoA carboxylase-inhibiting antibiotic, andrimid in Serratia is regulated by Hfq and the LysR-type transcriptional regulator, AdmX. Environmental Microbiology, 18(11), 3635-3650.

Mawar, R., Manjunatha, B. L., & Kumar, S. (2021).

This is an Open Access article published under the Creative Commons Attribution 4.0 International License (CC BY 4.0)

Commercialization, diffusion and adoption of bioformulations for sustainable disease management in Indian arid agriculture: prospects and challenges. Circular Economy and Sustainability, 1(4), 1367-1385.

Mbarga, J. B., Begoude, B. A. D., Ambang, Z., Meboma, M., Kuaté, J., Schiffers, B., ... & Ten Hoopen, G. M. (2014). A new oil-based formulation of Trichoderma asperellum for the biological control of cacao black pod disease caused by Phytophthora megakarya. Biological Control, 77, 15-22.

Mishra, J., & Arora, N. K. (2016). Bioformulations for plant growth promotion and combating phytopathogens: a sustainable approach. In Bioformulations: For sustainable agriculture (pp. 3-33). New Delhi: Springer India.

Morrison, C. K., Arseneault, T., Novinscak, A., & Filion, M. (2017). Phenazine-1-carboxylic acid production by Pseudomonas fluorescens LBUM636 alters Phytophthora infestans growth and late blight development. Phytopathology, 107(3), 273-279.

Nagaraju, M. C., & Mohan, M. (2021). Recent advances in Bacillus thuringiensis formulations. Biopesticides in Horticultural Crops, 139-151.

Namsena, P., Bussaman, P., & Rattanasena, P. (2016). Bioformulation of Xenorhabdus stockiae PB09 for controlling mushroom mite, Luciaphorus perniciosus Rack. Bioresources and Bioprocessing, 3(1), 19.

Navon, A. (2000). Bacillus thuringiensis application in agriculture. In Entomopathogenic bacteria: from laboratory to field application (pp. 355-369). Dordrecht: Springer Netherlands.

Nguyen, H. M., Sako, K., Matsui, A., Suzuki, Y., Mostofa, M. G., Ha, C. V., ... & Seki, M. (2017). Ethanol enhances high-salinity stress tolerance by detoxifying reactive oxygen species in Arabidopsis thaliana and rice. Frontiers in plant science, 8, 1001.

Onofre-Lemus, J., Hernández-Lucas, I., Girard, L., & Caballero-Mellado, J. (2009). ACC (1-aminocyclopropane-1-carboxylate) deaminase activity, a widespread trait in Burkholderia species, and its growth-promoting effect on tomato plants. Applied and Environmental Microbiology, 75(20), 6581-6590.

Pawar, S., Chaudhari, A., Prabha, R., Shukla, R., & Singh, D. P. (2019). Microbial pyrrolnitrin: Natural metabolite with immense practical utility. Biomolecules, 9(9), 443.

Pieterse, C. M., Zamioudis, C., Berendsen, R. L., Weller, D. M., Van Wees, S. C., & Bakker, P. A. (2014). Induced systemic resistance by beneficial microbes. Annual review of phytopathology, 52(1), 347-375.

Rai, S., Mago, Y., Aggarwal, G., Yadav, A., & Tewari, S. (2024). Liquid bioformulation: a trending approach towards achieving sustainable agriculture. Molecular Biotechnology, 66(10), 2725-2750.

Rocha, I., Ma, Y., Vosátka, M., Freitas, H., & Oliveira, R. S. (2019). Growth and nutrition of cowpea (Vigna unguiculata) under water deficit as influenced by microbial inoculation via seed coating. Journal of Agronomy and Crop Science, 205(5), 447-459.

Rojas-Sánchez, B., Guzmán-Guzmán, P., Morales-Cedeño, L. R., Orozco-Mosqueda, M. D. C., Saucedo-Martínez, B. C., Sánchez-Yáñez, J. M., ... & Santoyo, G. (2022). Bioencapsulation of microbial inoculants: mechanisms, formulation types and application techniques. Applied Biosciences, 1(2), 198-220.

Sahai, P., Sinha, V. B., & Dutta, R. (2019). Bioformulation and nanotechnology in pesticide and fertilizer delivery system for eco-friendly agriculture: a review. Sci Agric, 3, 2-10.

Samavat, S., Heydari, A., Zamanizadeh, H. R., Rezaee, S., & Aliabadi, A. A. (2014). Application of new bioformulations of Pseudomonas aureofaciens for biocontrol of cotton seedling damping-off. Journal of Plant Protection Research, 54(4).

Santos Kron, A., Zengerer, V., Bieri, M., Dreyfuss, V., Sostizzo, T., Schmid, M., ... & Pelludat, C. (2020). Pseudomonas orientalis F9 pyoverdine, safracin, and phenazine mutants remain effective antagonists against Erwinia amylovora in apple flowers. Applied and environmental microbiology, 86(8), e02620-19.

Schisler, D. A., Slininger, P. J., Behle, R. W., & Jackson, M. A. (2004). Formulation of Bacillus spp. for biological control of plant diseases. Phytopathology, 94(11), 1267-1271.

Singh, A. V., Khan, A., & Joshi, M. (2020). Plant–microbe interaction: A sustainable strategy to elevate salinity tolerance in plants. In Microbes and signaling biomolecules against plant stress: strategies of plant-microbe relationships for better survival (pp. 37-54). Singapore: Springer Singapore.

Singh, J., Singh, A. V., Upadhayay, V. K., & Khan, A. (2020). Comparative evaluation of developed carrier based bioformulations bearing multifarious PGP properties and their effect on shelf life under different storage conditions.

Soni, R., Kumar, V., Suyal, D. C., Jain, L., & Goel, R. (2017). Metagenomics of plant rhizosphere microbiome. In Understanding Host-Microbiome Interactions-An Omics Approach: Omics of Host-Microbiome Association (pp. 193-205). Singapore: Springer Singapore.

Strehmel, N., Böttcher, C., Schmidt, S., & Scheel, D. (2014). Profiling of secondary metabolites in root exudates of Arabidopsis thaliana. Phytochemistry, 108, 35-46.

Suryadi, Y., Susilowati, D. N., Kadir, T. S., Zaffan, Z. R., Hikmawati, N., & Mubarik, N. R. (2013). Bioformulation of antagonistic bacterial consortium for controlling blast, sheath blight and bacterial blight diseases on rice.

Suyal, D. C., Joshi, D., Debbarma, P., Soni, R., Das, B., & Goel, R. (2019). Soil metagenomics: unculturable microbial diversity and its function. In Mycorrhizosphere and pedogenesis (pp. 355-362). Singapore: Springer Singapore.

Tamez-Guerra, P., McGuire, M. R., Medrano-Roldan, H., Galan-Wong, L. J., Shasha, B. S., & Vega, F. E. (1996). Sprayable granule formulations for Bacillus thuringiensis. Journal of economic entomology, 89(6), 1424-1430.

Tewari, S., Pooniya, V., & Sharma, S. (2020). Next generation bioformulation prepared by amalgamating Bradyrhizobium, cell free culture supernatant, and exopolysaccharides enhances the indigenous rhizospheric rhizobial population, nodulation, and productivity of pigeon pea. Applied Soil Ecology, 147, 103363.

Thistlethwaite, I. R., Bull, F. M., Cui, C., Walker, P. D., Gao, S. S., Wang, L., ... & Willis, C. L. (2017). Elucidation of the relative and absolute stereochemistry of the kalimantacin/batumin antibiotics. Chemical Science, 8(9), 6196-6201.

Upadhayay, V. K., Singh, A. V., Khan, A., & Pareek, N. (2021). Influence of zinc solubilizing bacterial co-inoculation with zinc oxide supplement on rice plant growth and Zn uptake. Journal of Pharmaceutical Innovation, 10, 113–116.

Vassilev, N., Vassileva, M., Lopez, A., Martos, V., Reyes, A., Maksimovic, I., ... & Malusa, E. (2015). Unexploited potential of some biotechnological techniques for biofertilizer production and formulation. Applied microbiology and biotechnology, 99(12), 4983-4996.

Vassilev, N., Vassileva, M., Martos, V., Garcia del Moral, L. F., Kowalska, J., Tylkowski, B., & Malusá, E. (2020). Formulation of microbial inoculants by encapsulation in natural polysaccharides: focus on beneficial properties of carrier additives and derivatives. Frontiers in plant science, 11, 270.

Vishwakarma, K., Kumar, V., Tripathi, D. K., & Sharma, S. (2018). Characterization of rhizobacterial isolates from Brassica juncea for multitrait plant growth promotion and their viability studies on carriers. Environmental Sustainability, 1(3), 253-265.

Wong, C. K. F., Saidi, N. B., Vadamalai, G., Teh, C. Y., & Zulperi, D. (2019). Effect of bioformulations on the biocontrol efficacy, microbial viability and storage stability of a consortium of biocontrol agents against Fusarium wilt of banana. Journal of applied microbiology, 127(2), 544-555.

Wu, Z., Li, X., Liu, X., Dong, J., Fan, D., Xu, X., & He, Y. (2020). Membrane shell permeability of Rs-198 microcapsules and their ability for growth promoting bioactivity compound releasing. Rsc Advances, 10(2), 1159-1171.

Zaidi, A., Khan, M. S., Saif, S., Rizvi, A., Ahmed, B., & Shahid, M. (2017). Role of nitrogenfixing plant growth-promoting rhizobacteria in sustainable production of vegetables. In: Zaidi A, Khan MS, editors. Current perspective in microbial strategies for vegetable production. Cham: Springer. p. 49–79.

This is an Open Access article published under the Creative Commons Attribution 4.0 International License (CC BY 4.0)