Microencapsulation: Futuristic Approach to Bioformulations

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The formulation of microbial inoculants is an industrial process that involves transforming laboratory-proven microorganisms into commercially viable products for field application. The primary objective of inoculant formulation is to maintain microbial cells, or their active components, in a metabolically and physiologically competent state so that they can deliver the intended benefits after application, while also providing a favorable microenvironment for their survival. Various microbial formulations have been developed using either liquid or solid carriers. Liquid inoculants consist of microbial cultures supplemented with water, oils, or polymeric additives that enhance suspension viscosity, stability, and dispersal efficiency. In contrast, solid formulations utilize inorganic or organic carrier materials and are produced in solid, granular, or powder forms, which are further classified based on particle size or method of application. However, a major limitation of these products is the rapid decline in microbial population and metabolic activity once cell suspensions are introduced into specific environmental conditions.

However, the activity of beneficial microbes diminishes over time due to decreased survival rate in soils, environmental factors and interactions with the indigenous microbial diversity in soil. The prime problem that exists is to inhibit bioactivity degradation under various environmental conditions and to maintain its function in soil ecosystems. Bioencapsulation serves as an effective delivery system for preserving and sustaining the functional activity of beneficial microorganisms. It involves the formation of a hardened layer or membrane around aqueous particles containing biocatalysts, resulting in the production of hydrogel beads or microcapsules. Initial approaches relied on dropping a pre-gel emulsion containing the immobilizing material into a hardening solution to form gel beads. Subsequently, finer dispersions were achieved by emulsifying the gel within an oil phase and solidifying the droplets through internal gelation. Membrane microencapsulation involved introducing droplets of an ionically charged gel solution into a polymer solution carrying an opposite charge. Further research has focused on cell entrapment through interfacial polymerization, where a polymeric shell is formed around dispersed droplets emulsified in a non-aqueous hydrophobic medium.

Microbial encapsulation is a method of enclosing solids, liquids, or gaseous tiny droplets surrounded by a coating material, resulting in the formation of small capsules on a micrometric scale. The basic requirements for encapsulation of microbial inoculants are

1. selection of core material/active ingredient which is done based on application, 2. selection of a shell/wall coating material and 3. the technique. The shell/wall coating involves the varied kinds of synthetic and natural polymers as its outer capsular material. The basis of selection is the mechanisms of delivery and release of microcapsules in particular environmental conditions, such as high/low pH, moisture and temperature. Biopolymers (including carbohydrates and proteins) are used for the encapsulation process, obtained from natural sources such as algae (ϰ-carrageenan and alginate), plants (gum Arabic and starch), insects (Chitosan) and animal proteins (gelatin). Each polymer has certain disadvantages which can be overcome by the usage of certain additives such as starch, milk protein, clay minerals *etc*. These combinations enhance the stability, improve the shelf life, protect against various environmental conditions and also act as a carbon source for microbial encapsulated products.

The choice of encapsulation technique is equally critical for microcapsule formation. Over the past 10–15 years, several encapsulation technologies have been developed, ranging from simple extrusion or dripping of homogenized core–coating mixtures into cross-linking agents to more complex methods such as coacervation. Emulsification involves the dispersion of core material and polymer in the oil/organic phase (dispersed phase) and crosslinking agent in the aqueous phase (continuous phase). Congelation of the dispersed phase is initiated by cooling or the addition of a crosslinking agent to the emulsion. Coacervation technique involves the gelling by the phase separation of one or more incompatible polymers as a result of specific pH, temperature or the composition of the solution (Eghbal *et al.,* 2022).

Microcapsules with diverse morphologies have been widely studied for applications across various industries, including agriculture. Microencapsulation technology originated in the 1950s within the enzyme and pharmaceutical industries for controlled and sustained release. In recent years, its application has expanded to sectors such as food, flavors, essential oils, construction materials, and agriculture. In the food industry, probiotics and biofortification of various products have developed. Numerous studies also reported the use of microencapsulated microbes in the waste management industry. In agriculture, bioencapsulation has been applied for plant growth-promoting microorganisms and alleviating biotic and abiotic stress. From a formulation perspective, the integration of smart or stimuli-responsive polymers offers new opportunities for developing next-generation microbial inoculants with enhanced adaptability to fluctuating field conditions. Advances in nano- and micro-fabrication techniques have further enabled precise control over capsule size, porosity, and degradation rate, which directly influence microbial release kinetics and efficacy. Such innovations not only improve inoculant performance but also contribute to reducing application frequency and dosage, thereby lowering production and operational costs.

Microencapsulation of beneficial microbes displayed prolonged shelf life and better application in each industry. However, the problems with commercialization and scaling up of these formulations are to be evaluated. Further research should be carried out to find out more promising new polysaccharides for bio microencapsulation to enrich the selection range of wall material and expand the application area for these formulations.

Conclusion

The development and commercialization of biofertilizers have progressed significantly since their inception, highlighting their crucial role in sustainable agriculture. Plant growth–promoting microorganisms offer multiple agronomic benefits through diverse mechanisms such as nitrogen fixation, phytohormone production, nutrient solubilization, and suppression of phytopathogens. However, the inconsistent performance of microbial inoculants under field conditions, largely due to poor survival, environmental stresses, and competition within complex soil ecosystems, remains a major limitation to their widespread adoption. Bioencapsulation has emerged as an effective formulation strategy to overcome these challenges by protecting microbial cells, enhancing their shelf life, and improving their functional stability in soil. Among the various encapsulating materials explored, alginate-based biopolymers have gained prominence due to their biocompatibility, biodegradability, ease of gel formation, and cost-effectiveness. Although alginate encapsulation faces certain limitations related to pH sensitivity and chelation, these drawbacks can be mitigated through polymer blending or surface coating with complementary biopolymers.

Overall, bioencapsulation represents a promising technological advancement for improving the delivery and efficacy of biofertilizers. Continued research focused on optimizing encapsulation materials, formulations, and large-scale application methods will be essential for translating laboratory success into consistent field performance, thereby supporting environmentally sustainable and resilient agricultural systems.

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