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Advancing Sustainable Agriculture: Bioinputs and Solid-State Fermentation Innovations for Eco-Friendly Farming

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This study explores the growing importance of bioinputs, specifically biological control agents and inoculants, in sustainable agriculture. The escalating environmental concerns linked to synthetic pesticides and fertilizers have led to a shift towards eco-friendly alternatives, focusing on restoring soil biodiversity and mitigating ecological damage. Inoculants, comprising live microorganisms, play a crucial role in enhancing plant growth, nutrient availability, soil fertility, and resistance against pests and diseases. They encompass various plant growth-promoting bacteria and fungi, each contributing unique attributes such as phosphate solubilization, nitrogen fixation, and production of beneficial compounds. Biological control agents, derived from microorganisms, offer effective pest and disease management strategies while minimizing environmental impact. The development of these bioinputs is driven by technological advancements, including biorefinery concepts and molecular biology techniques, coupled with the utilization of lignocellulosic biomass to reduce production costs. Solid-state fermentation (SSF) emerges as a critical process for bioinput production, albeit facing challenges like mass and heat transfer, bioproduct retrieval, and downstream processing. The study underscores the importance of addressing these challenges to scale up SSF operations effectively. Overall, the research highlights the promising role of bioinputs in sustainable agriculture and the need for continued innovation in bioinput production technologies.

Keywords: Biоinputs, Sustainable Agriculture, Biological Control Agents, Inoculants, Soil Biodiversity, Eco-Friendly Alternatives, Solid-State Fermentation.

Introduction:

Anaerobic digestion (AD) and composting have gained significant recognition as the predominant techniques for managing organic waste within the context of the Circular Economy due to their capacity to facilitate the retrieval of materials and energy [1]. The increasing utilization of biological treatments for organic waste can be attributed to stringent global regulations prohibiting dumping and incinerator methods. However, Solid-State Fermentation (SSF) has recently gained prominence as a novel field of research. SSF has been widely utilized for a considerable period; nonetheless, it has recently attained an elevated degree of circularity by employing organic waste as a substrate. The main goal of SSF is to substitute the current, environmentally harmful chemicals with a valued and marketable product derived from renewable resources while ensuring sustainability. In addition, anaerobic digestion (AD) or composting can be employed to extract supplementary nutrients from the disposed materials [2]. In general, the bioproduct generated by SSF is employed as a substitute for a non-biodegradable chemical that possesses similar characteristics but is more cost-effective. The culture technique referred to as "solid-state fermentation" entails the proliferation of microorganisms on solid substrates without the presence of a liquid phase.

In practical terms, the production of the intended bioproduct involves the introduction of a solid substrate into an aerobic bioreactor, followed by the injection of the strain of interest. While the ultimate fermented solid may sometimes be employed as the outcome, this bioproduct can be recovered after its production. Various reactor configurations, including packed bed reactors, tray reactors, mechanically stirred reactors, and plug flow designs, have been employed in the advancement of SSF. During the scaling-up phase, the primary objective of these topologies is to surpass the mass and heat transfer constraints imposed by solid organic materials. These limitations can result in temperatures that pose detrimental effects on the strain under investigation. These challenges are a major barrier to the complete utilization and commercialization of SSF and typically occur as SSF is expanded. Recently, several models have been developed to monitor the mass behavior in SSF reactors. These models utilize advanced techniques such as computational fluid dynamics or traditional approaches such as residence time distributions [3].

The concept of solid-state fermentation is not new; it has been used for a long time, especially in Asian culinary traditions. Moreover, composting is a highly specific type of SSF. However, the utilization of this technique as a prospective biotechnological instrument has only surfaced within the last two decades. To generate the intended bioproducts, researchers initially investigated the SSF technique for synthesizing hydrolytic enzymes. A diverse array of enzyme families, such as cellulases, lipases, and proteases, has been produced by SSF. In addition, SSF is currently under investigation for its potential to develop materials that offer comparable benefits to chemicals in biodegradable products. These phenomena are observed in various contexts, including biopesticides, biosurfactants, perfumes, and bioplastics [4].

Lignocellulosic agricultural waste types are frequently employed as substrates and support materials in SSF. In recent times, alternative organic waste materials have been utilized as substrates tospecific biochemical compositions, hence facilitating the production of targeted bioproducts. In the case of glycolipid biosurfactants, lipids are essential. However, complex mixtures may be used to incorporate additional elements such as the organic component of municipal solid waste or digestate from biowaste. SSF can leverage these resources, which serve no other function, due to the abundant availability, affordability, and significant potential for value restoration of organic wastes. The issues arise from the inherent characteristics of these wastes, namely their heterogeneity, complexity, and dynamic nature [5].

Moreover, due to the solid substrates and reduced humidity levels in SSF, which closely resemble their natural habitat, it can be demonstrated that fungi have a significant impact on SSF. For instance, only SSF generate aerial conidia, which are the primary component in most fungal biopesticides. In the future, it is expected that the isolation of novel strains suitable for SSF systems will lead to an increase in the number of strains, bioproducts, and the diversity of waste materials used as substrates [6].

The SSF technique, which originated in Egypt around 2600 BC, has a long history and has subsequently been used in several regions including Asia, Africa, and Europe. This method was zutilized to produce certain traditional foods and beverages. Its popularity in the Western world began in the mid-19th century, and it was subsequently employed in the production of meals, medications, organic acids, enzymes, and agricultural products. This particular bioprocess employs solid substrates, typically obtained from natural sources, as a nutritive or supportive medium within a low-aqueous environment. This facilitates the proliferation of microorganisms and enables them to direct their metabolic activities towards the intended target. As previously stated, the utilization of SSF is being employed for the production of various bio inputs employed in the field of agriculture [7].

The fundamental tenets of solid-state fermentation:

Agricultural bio inputs encompass a range of products formed from microbial cells and metabolites, plant materials, and animal components, which serve the purpose of combating insects and phytopathogenic microorganisms, enhancing soil fertility, and maintaining plant fitness. The most prominent bioinputs currently in use are biofertilizers, inoculants, and biocontrol agents. Both farmers and consumers can derive several environmental benefits from the utilization of these biological substances. The primary advantages include improved sustainability of the production process, reduced costs associated with application, increased biological fixation of micronutrients like potassium, phosphorus, and nitrogen, and enhanced synthesis of growth-influencing substances, immune modulators, and antimicrobials [8].

Bioinputs can be produced using a diverse range of microorganisms, such as filamentous fungi, yeasts, and bacteria. Microorganisms can be classified into three main categories: rhizospheric, epiphytic, and endophytic. These microorganisms are commonly obtained from natural plant sources. It is necessary to ascertain the specific plant part from which the microorganism is extracted. The utilization of a microorganism in an inoculant formulation is contingent upon its origin, and inoculant formulations possess the capacity to enhance plant lifespan and proliferation. To enhance nutrient availability, many application techniques are employed, such as direct absorption into the soil, foliar treatment, root application, and seed coating application. A diverse range of microorganisms, such as filamentous mycorrhizal fungi like Claroideoglomus, Glomus, and Rhizophagus, are employed in the production of bioinoculants. Additionally, bacteria from the genera Rhizobium, Azospirillum, Bacillus, Streptomyces, Gluconoacetobacter, and Pseudomonas are also involved in promoting plant growth. There has been a recent rise in research conducted on yeasts that have demonstrated the ability to promote plant growth, specifically those classified under the genera Candida, Rhodotorula, Cryptococcus, and Saccharomyces [9].

Several studies are currently focused on the development of plant growth promoters through fermentation processes using low-cost and renewable feedstock. These studies aim to describe bioprocesses that have reduced emissions and are environmentally friendly and sustainable compared to synthetic agrochemicals. The utilization of raw materials in SSF is a key factor that contributes to its flexibility. Lignocellulosic biomasses, brands, and other agricultural residues have the potential to be employed in SSF for the production of various bio-based products, such as bioinputs. SSF refers to the method of fostering microbial growth by culturing microbes on insoluble solid substrates or within a solid matrix that has limited moisture availability, resulting in low water activity [10].

According to [11], SSF offers several advantages in terms of technological-economic, environmental, and biological factors. Submerged fermentation (SmF) provides greater consistency in the system, a broader spectrum of uses, and enhanced regulation of environmental conditions in comparison to SSF. Furthermore, through the utilization of diverse kinetic models and operating mode procedures, these attributes ensure a predictable and reliable level of product quality. Despite these limitations, SSF remains the favored method for on-farm production of agricultural bioinputs due to its cost-effectiveness, ease of implementation, and simplicity of farmer upkeep [12].

Biofertilizers in their entirety:

The utilization of biofertilizers has emerged as a highly promising approach to enhance crop yields while minimizing environmental impact. Biofertilizers consist of living microorganisms, such as bacteria, fungi, or algae, which can be found individually or in combination. These microorganisms settle in the rhizosphere and improve soil productivity by nitrogen fixation and nutrient solubilization. As a result, they have direct or indirect positive impacts on crop growth and yield through various mechanisms. Organic fertilizers, such as animal manure, compost, slurry waste, peat, bones, and blood meal, differ from chemical fertilizers. Certain organisms, such as earthworms, play a crucial role in the conversion of organic fertilizers into readily assimilated nutrients that are beneficial for plants. Plant-growth-promoting rhizobacteria are the predominant bacteria employed in the production of biofertilizers. These bacteria stimulate plant growth by the release of Potassium (K), Nitrogen (N) fixation, Phosphorous (P) solution, and hormone release. [13] have reported that biofertilizers are offered in many formulations, including liquid, solid, polymer-entrapped, and fluidized bed dry formulations. Table 1 presents the differentiations among chemical, organic, and biofertilizers, accompanied by an examination of their advantages and disadvantages. Plants necessitate fourteen essential mineral elements for their growth and development, encompassing micronutrients (Fe, B, Cl, Mn, Zn, Cu, Mo, and Ni) as well as macronutrients (N, P, K, Ca, Mg, and S) [14]. The soil contains a significant proportion of elements; but, due to their inaccessible forms, plants are unable to assimilate and absorb them. Plants only absorb certain elements in specific forms, such as nitrogen, which can be taken up as either nitrate or ammonia. Biofertilizers are classified based on the microorganisms they include and the functional characteristics they have developed through interactions with plants in the rhizosphere, as stated by [15].

Table 1: Comparison between biofertilizers, chemical fertilizers, and organic fertilizers:

Aspect	**Biofertilizers**	**Chemical Fertilizers**	**Organic Fertilizers**
Composition	Contains living microorganisms	Synthetic chemicals	Natural substances, compost, manure
Nutrient Content	Moderate nutrient content	High nutrient content	Moderate to high nutrient content
Nutrient Release	Slow release over time	Rapid release upon application	Slow release over time
Soil Health Impact	Enhances soil health and fertility	This can lead to soil degradation	Improves soil structure and health
Environmental Impact	Environmentally friendly	Can cause pollution and soil erosion	Environmentally friendly
Cost	Generally cost-effective	Can be expensive	Cost-effective or may require processing
Plant Uptake Efficiency	May require multiple applications	High immediate uptake by plants	Moderate to high uptake efficiency
Residual Effects	Beneficial residual effects	Can lead to soil salinity	Beneficial residual effects
Sustainability	Supports sustainable agriculture	May contribute to environmental issues	Supports sustainable agriculture
Application Frequency	Regular applications may be needed	Less frequent applications	Regular applications may be needed

Regulation	May have less stringent regulations	Heavily regulated	Varied regulations depending on the source

This table provides a comparative overview of key aspects between biofertilizers, chemical fertilizers, and organic fertilizers, including their composition, nutrient content, environmental impact, cost, sustainability, and application frequency, among others.

Bioinputs consist of biological regulating agents and inoculants:

The pursuit of environmentally friendly and economically efficient alternatives to synthetic goods derived from petroleum and mineral extraction has become more pronounced as a result of the worldwide expansion of green and circular economy principles. Recently, there has been evidence indicating that the excessive utilization of synthetic pesticides and NPK fertilizers (nitrogen, phosphate, and potassium compounds) in agricultural practices has resulted in adverse consequences for soil biodiversity, as well as the pollution of food, groundwater, and water sources. Consequently, this has given rise to various health concerns for life on our planet. To restore the equilibrium of soil biodiversity, the utilization of biological control agents and inoculants can be considered as a viable substitute for synthetic chemicals [16].

Inoculants are live microorganisms that facilitate the growth of different plant species by increasing the availability of nutrients and improving their absorption capacity. In addition, they enhance soil fertility and enhance plant resistance. The microorganisms included in the preparation of inoculant formulations are plant growth promoters, which consist of bacteria and fungi that are attached to roots (rhizospheric), within plant tissues (endophytic), and in plant leaves. In addition to their role as phosphate solubilizers and nitrogen fixers (diazotrophs), these bacteria possess distinctive characteristics such as the production of siderophores, phytohormones, antibacterial compounds, and enzymes. Inoculant formulations have been observed to incorporate microorganisms, including bacteria from the genera Burkholderia, Pantoea, Enterobacter, Pseudomonas, Massilia, Sphingobium, Sphingomonas, Agrobacterium, Rhizobium, Bradyrhizobium, and Ochrobactrum, as well as fungi from the genera Penicillium and Mycorrhiza. Biological control agents, sometimes referred to as bioproducts derived from micro- or macroorganisms, are utilized to mitigate the impact of both biotic and abiotic factors on agricultural output. They are utilized in notable techniques that have demonstrated efficacy in safeguarding plants against arthropod pests and phytopathogenic microorganisms while minimizing ecological damage. This research will primarily focus on the development of microbial biological control agents, commonly referred to as bioinsecticides. More precisely, the agents will originate from entomopathogenic bacteria and fungi that infect insect pests and possess antagonistic properties against phytopathogenic microorganisms [17].

The most commonly seen types of these biological control agents on the market are formulations that include bacteria from the genera Agrobacterium, Bacillus, Pseudomonas, Streptomyces, and Paenibacillus, as well as fungi from the genera Trichoderma, Metarhizium, and Beauveria. The aforementioned medicines have demonstrated efficacy and extensive study, effectively combating a diverse range of plant diseases. Induction of systemic host resistance and antibiosis can be achieved by biological control agents through many processes, such as hyperparasitism, competition, release of lytic enzymes, and stimulation of plant growth [18].

The increasing amount of research on inoculants and biological control agents can be attributed to various factors from a technological standpoint. These factors include the emergence of biorefinery concepts, advancements in molecular biology techniques and fermentative processes, and the urgent need for alternative agricultural inputs that are more sustainable. The main steps involved in the bioprocess to obtain inoculant formulations and biological control agents include the selection of suitable microbial strains, their morphological, physiological, and biochemical characterization, evaluation of fermentation conditions (optimization of nutritional and physical parameters), and the development of biopinputs using cost-effective reagents, adjuvants, and vehicles to stabilize the bioactive agents in the formulation. Lignocellulosic biomass has emerged as a viable alternative and is being utilized as a primary component in the manufacture of inoculant formulations and agricultural biological control agents, aiming to reduce production expenses. The aforementioned aligns with the principles of sustainability promoted by biorefineries, green initiatives, and circular economies [19].

SSF in the production of biological control agents and inoculants:

The global market share of inoculants is projected to reach USD 3.9 billion by 2025, with a compound annual growth rate (CAGR) ranging from 11 to 12.8%. In 2020, the expected market share was between USD 1.0 and USD 2.3 billion. The current valuation of the market for biological control agents stands at USD 6.6 billion, with a projected compound annual growth rate (CAGR) of 15.8% by 2027, resulting in a market value of USD 13.7 billion. The leading global producers of inoculants and biological control agents include Novozymes (founded in Frederiksberg, Denmark), BASF SE (based in Ludwigshafen am Rhein, Germany), Premier Tech (based in Boizenburg, Germany), Bioceres Crop Solutions (based in Rosario, Argentina), Marrone Bio Innovations Inc. (based in Davis, CA, USA), Bayer CropScience AG (based in Monheim am Rhein, Germany), and Valent Biosciences (based in Libertyville, IL, USA) [20].

The assessment of productivity is a crucial consideration for the large-scale manufacturing and global application of these compounds, particularly in light of advancements in the utilization of inoculants and biological control agents. The appropriate microbial strain for the bioinput is determined by several factors, including the cultivar species, disease type, and intended systemic effect. The intended systemic effect can range from inducing innate plant immunity and direct pathogen antagonistic action to the synthesis of enzymes or enhancement of soil quality. The process parameters and substrate composition have an impact on the kinetics of microbial metabolism. Therefore, it is crucial to exercise caution when choosing the microbial strain to optimize either biomass or metabolite excretion. Both strategies aid in the suppression of infections; however, the optimal approach must be evaluated in real-time and will depend on the frequency with which they yield advantageous outcomes throughout the culture phase or over an extended duration [21].

The content of the medium has an impact on the growth of microorganisms and the synthesis of metabolites, depending on the kind of substrate. Inoculant and biological control formulations commonly utilize microorganisms that predominantly metabolize sugars and polyols, such as glucose, sucrose, xylose, lactose, glycerol, and mannitol, among others. These nutrients are present in a variety of substrates. When considering the cost and availability of raw materials and substrates, agro-industrial byproducts like lignocellulosic biomasses, which primarily consist of a carbohydrate component abundant in cellulose and hemicellulose, are particularly noteworthy. As mentioned earlier, lignocellulosic materials exist as a feasible nutrient source that can be employed in SSF for the production of bioinputs such as control agents and inoculants. In addition to their applications as supports and substrates, lignocellulosic materials have the potential to function as carriers for biological control agents and inoculant formulations.

[22] reported on the utilization of charcoal and fresh wheat straw as supports for the synthesis of Rhizobium leguminosarum biomass through the process of solid-state fermentation (SSF). Following 72 hours of cultivation in solid-state fermentation (SSF) using wheat straw, a significant rise in the number of viable cells was observed. Specifically, the initial concentration of 7.3 log cfu/g substrate was found to have multiplied by almost one thousand. Following a 72-hour incubation period, the introduction of charcoal resulted in a tenfold increase in the

quantity of viable cells. The study's results indicated that although charcoal is a widely recognized inert substrate for the production of biofertilizers, wheat straw exhibited superior performance.

Bacillus thuringensis, a soil-dwelling bacteria, is commonly utilized as a potential bioinsecticide. This bacterium produces distinct proteins called Cry, which exhibit insecticidal properties against Lepidoptera, Coleoptera, and Diptera. [23] documented the proliferation of Bacillus thuringiensis in SSF utilizing solid waste that underwent lytic enzyme treatment, such as cellulases, hemicellulases, pectinases, and amylases, as the primary substrate. After a 100-hour incubation period, a total of 108 viable cells per gram of substrate and 108 spores per gram of substrate were successfully retrieved. Additionally, it was observed that the presence of Cry protein crystals, which are essential for insecticidal activity, was detected. Consequently, this methodology exhibited feasibility at the magnitude of its implementation, functioning as an alternative process including a bioinput that enhances the worth of forthcoming biorefineries.

Several studies have utilized corncobs, food waste, rice husks, and coconut husks as substrates or supports for the cellular biomass synthesis process to achieve biological pest management. The efficacy of specific formulations derived from agricultural waste in facilitating plant growth and development.

Development of a bioformulation using SSF of agricultural wastes:

Table 2 presents the impacts of the five formulations derived from agro waste, which were chosen based on their shelf life, the crop's yield, and yield-related attributes. The application of formulations CSPfBs, VBs, and VPf to soil resulted in yields of 2.85 kg/plant, 2.76 kg/plant, and 2.69 kg/plant, respectively, in brinjal plants after 30 days of transplantation. In comparison to the yields of plants treated with DmPf and DmBs, these yields exhibited statistical significance at a significance level of CD0.05. Similar tendencies were seen in growth metrics, including plant height, number of branches per plant, leaf area, average fruit weight per plant, and number of fruits per plant. Prior research has also shown that the application of vermicompost in combination with a microbial inoculant has resulted in improved plant growth and yield characteristics24. Prior research has demonstrated that the lettuce plant exhibited enhanced plant development features when subjected to inoculation with Pseudomonas and Bacillus strains, either individually or in combination when compared to the control group (25, 26). The simultaneous introduction of B into the organic system has been identified. The presence of P. fluorescens and subtilis has been observed to result in increased biomass in both Gram-positive and Gram-negative bacteria27. This implies that the absence of competitive interactions between the native bacteria and the inoculants may be attributed to the increased availability of resources.

Table 2: Attainment of yield and yield-related traits of crops applied with agro-waste-based bioformulation [24]

Treatments	**Leaf area (cm^2)**	**Average fruit weight (g)/ plant**	**Yield/ plant (kg)**	**No: of fruits/plant**	**No: of branches/ plant**	**Plant height (cm)**
DmBs	164.6	162.96	2.30	14^{fgh}	15^{kl}	73.8
DmPf	156.6	156.96	1.88	13.8^{fgh}	14.2^{l}	72.6
VPf	174.0	169.56	2.69^{bc}	14.2^{fg}	16.4^{jk}	75.4
VBs	187.4	174.2^{a}	2.76^{dc}	14.8^{ef}	17.2^{ij}	79.4
CSPfBs	193.4	176.1^{a}	2.85^{db}	15.6^{e}	18.4^{i}	81.6
Control	100	138.28	1.11	12.4	11.2	69.6
S.Ed.±	2.47	1.83	0.135	0.588	0.889	1.726
$CD_{0.05}$	5.15	3.81	0.28	1.22	1.85	3.6

At a significance level of 5%, there is no significant difference observed between values that have comparable superscripts.

Primary Challenges for SSF:

Mass and heat transfer:

Solid-state fermentation presents a considerable challenge due to the limitations imposed by mass and heat transport in solid organic matter. Given the interconnectedness of the two challenges, it is impractical to do separate studies and analyses on them. The methodology encompasses several variables that exert an influence on these transfer processes. The temperature of the process is of utmost importance in heat transfer processes for two primary reasons. Firstly, the fermentation process generates temperature elevations that necessitate regulation to ensure a satisfactory outcome. Secondly, microbial strains frequently necessitate precise temperature conditions for their growth and development, underscoring the significance of effectively controlling this parameter [80]. The conduction heat transmission in solid-state fermentation (SSF) is hindered due to the low conductivity of organic components and the presence of vacant regions within the reactor. Consequently, convection arises as the most captivating mechanism for heat dissipation, serving to mitigate the accumulation of heat within the solid matrix that may lead to unfavorable temperature gradients. The preference for low levels of aeration over intense aerations may arise due to the presence of additional concerns, such as moisture losses and drying of the solid substrate, that arise from convection during aeration processes.

Hence, it is imperative to effectively administer this approach. Certain SSF systems that employ filamentous fungus may encounter limitations in implementing this cooling strategy due to the necessity of a mixing mechanism. Additional cooling alternatives involve the addition of water throughout the fermentation process. Therefore, it is crucial to conduct research on the most effective heat dissipation methods for each SSF scenario and employ a suitable bioreactor. Heat transmission limitations might result in problems with the moisture content of the reactor, which is essential for the growth and dispersion of nutrients among microorganisms and is also linked to problems with mass transfer. Another notable concern arising from inadequate heat transfer is the inefficiency of sterilization. The exclusion of microorganisms that pose a risk to the pertinent process is necessary. It is important to note that not all sterilization procedures necessitate the use of heat. For instance, the use of chemicals, vapor gas, or chlorine gas streams also involves resolving mass transfer issues. Therefore, when dealing with sterilization, it is necessary to address both transfer operational issues [24].

In addition to the aforementioned concerns, there exist additional factors that can give rise to mass transfer complications, or conversely. To achieve satisfactory development, microorganisms necessitate access to oxygen. Consequently, the implementation of a suitable aeration system becomes imperative for the elimination of carbon dioxide and other volatile compounds. Agitation is an effective strategy for addressing mass transfer issues, including heat transfer. It enhances the transfer of gas or liquid interfaces and ensures a more uniform temperature and gaseous environment. Mass transfer limitations can also hinder the accessibility of nutrients, a crucial factor in microbial growth, and can be significantly improved through the implementation of agitation and aeration techniques. Nevertheless, it has been previously shown that agitation has the potential to cause harm to filamentous fungi and result in the release of nutrients, which may then contribute to an increase in microbial activity and subsequent heat emission. Moreover, it has the potential to diminish the porosity of the substrate or compromise the adhesion between microorganisms and the substrate. Both methodologies must be employed to tackle these issues, occasionally intermittently. Recent research suggests that the presence of unique characteristics such as a high granulometry and a low reactor compressibility index can facilitate efficient air movement, hence enhancing heat transfer.

The aforementioned issues hold considerable importance during laboratory or pilot-scale operations, but they can assume greater significance when the process is expanded for larger-scale production. Therefore, it is imperative to do thorough modeling to effectively build and investigate a reactor with a greater scale. Several studies in the literature, including those that are quite recent, have made efforts to find an appropriate model for expanding the size of SSF reactors. There are various works that focus on the economic modeling of the process. However, a significant portion of these studies focuses on different characteristics that require optimization to enhance production, such as microbial growth or substrate behavior. Due to the direct impact of geometry, mass distribution, and agitation or aeration on heat and mass transfer, it is typical to encounter models specifically designed for a particular reactor type. Tray and packed bed reactors are widely used configurations for SSF operations [25].

Bioproduct retrieval and downstream processing

The challenge associated with solid-state fermentation methods arises from the diverse range of chemicals involved, hence requiring a complex downstream technique. The main challenges related to downstream processes are their exorbitant costs, which constitute over 70% of overall expenditures, and their utilization of environmentally unfriendly solvents. In certain applications, the fermented solid might serve as the final product. Thus, there is no necessity for a costly and ecologically detrimental procedure. If this technique fails, the solid exhaust becomes a new waste that must be managed after the extraction of bioproducts. The handling and management of this trash may lead to an increase in process expenses. Utilizing the end product once more for composting, anaerobic digestion, or animal feed is a highly beneficial method. The augmentation of the exhaust solid's value can be achieved through the coproduction of supplementary low-value molecules, such as proteins and fatty acids.

The process of product recovery in SSF may present greater difficulties compared to submerged fermentation (SmF) due to the diffusion of metabolites within the solid matrix. The utilization of organic solvents is often required for the extraction of secondary metabolites in SSF. This is because it is a straightforward method that has been employed for numerous years to extract a diverse range of materials. However, there are several disadvantages associated with this method, such as its expensive nature due to the extensive use of organic solvents, time constraints, the presence of solvent residue in the exhaust material that can cause disposal problems, and the toxicity that diminishes the waste's potential for reuse. Moreover, there are specific health regulations that are incongruous with this methodology, potentially impeding the promotion of bioproducts designed for human or animal use. As our understanding of SSF production for these bioproducts has expanded, new techniques have been developed to mitigate the cost and environmental impacts of the extraction process. The approaches encompass ultrasound-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, solid-liquid extraction, pressurized liquid extraction, subcritical water extraction, solid-solid extraction, and enzyme-assisted extraction. Achieving a harmonious equilibrium between performance and power consumption is of utmost importance, as a significant proportion of these innovative methodologies necessitate more power consumption compared to conventional solvent extraction methods [26].

It is imperative to uphold the benefits of SSF technology throughout the extraction phase to effectively retrieve bioproducts. The characteristics of the substance to be extracted significantly influence the choice of extraction method. Characteristics such as pH resistance or thermostability may restrict some possibilities. These restrictions are also applicable to other downstream processes. However, in the production of SSF, it is crucial to consider waste materials due to their significant contribution to the system's variability and heterogeneity. These waste materials have the capacity to negatively impact the subsequent process and reduce the financial profits of the SSF. The purification stage for most of these bioproducts is relatively underdeveloped, despite the ongoing challenge of isolating pure natural products from a solid matrix. The commonly utilized silica-packed columns face a problem when they encounter complex compounds derived from natural sources due to the potential risks of obstruction, damage, or irreversible adsorption. Secondary metabolites in the pharmaceutical and health business usually necessitate a significant level of purity.

However, the utilization of waste as raw materials may be influenced by regulatory concerns and public opinion. The costs associated with purification are mostly influenced by the desired level of purity. When evaluating the potential of SSF for industrial applications, it is imperative to consider the stability of the bioproducts. The stability of the bioproducts created by SSF can be evaluated by examining their shelf life, storage stability, and thermal stability. The consideration of pH, temperature, and water activity is crucial in assessing the stability of bioproducts. Studies on enzyme synthesis have shown that SSF can yield bioproducts with high stability and extended shelf-life. Unfortunately, there is a lack of information regarding less popular products. Once the bio-compounds of interest have been extracted, it is necessary to dispose of the spent material. This is the ultimate inquiry that needs to be resolved in the subsequent procedure. The feasibility of the extraction procedure varies depending on its intended utilization. Therefore, it is our contention that additional focus should be given to the extraction strategies and their appropriateness for the aforementioned applications [27].

Conclusion

This study centers on the contemporary and advanced applications of Solid-State Fermentation (SSF) in the production of bioproducts derived from a wide range of organic waste materials. SSF manufactures a diverse array of bioproducts, including those that are crucial for the full advancement of the circular economy. Despite the publication of multiple bench-scale SSF experiments, there is currently a scarcity of studies that specifically tackle and resolve the main challenges in downstream processing and scaled-up manufacturing. The authors contend that the term "SSF" should not be employed to describe experiments conducted in petri dishes with a small amount of substrate. They argue that larger-scale studies are necessary to tackle the issues highlighted in this review, which are not applicable at smaller scales where productivity and yield are the sole considerations. This is crucial for SSF to establish itself as a dependable technology. When conducting any solid-state fermentation (SSF) process that involves organic waste or solid matrices, it is important to consider the heterogeneity of the waste, ensure sufficient oxygen transport within the matrix, and prevent the accumulation of heat.

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