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MIXING DEVICES IN THE CULTIVATION OF MYCELIAL CULTURES: CURRENT STATE AND PROSPECTS

POLISHCHUK V.Yu., RUZHANSKYI A.S.
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"

E-mail: anrux@protonmail.com

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Aim. To systematize data on the impact of mixing devices on the growth, morphology, and productivity of mycelial cultures in biotechnological processes, with the objective of identifying contemporary developments in mixing device configurations. This will facilitate the subsequent design of an original, modern, and innovative impeller that minimizes the limitations of current systems, including high energy consumption and mechanical shear damage to the mycelium.

Methods. A systematic analysis of scientific articles from 2004 to 2025 was conducted using Scopus, ResearchGate, PubMed, and Google Scholar, with a focus on types of mixing systems.

Results. Mechanical Rushton turbines increase metabolite yields by 35–200% for aerobic cultures, while hydrofoil impellers and pneumatic systems reduce energy consumption by 10–15% and are optimal for sensitive species, resulting in up to 15% increased biomass. Excessive shear reduces productivity by 20%.

Conclusions. Mixing devices are critical for the sustainable production of antibiotics, enzymes, and biomass. Prospects involve hybrid designs and automation for scaling.

Key words: cultivation, filamentous microorganisms, morphology, enzymes, mixing devices, biotechnology, mass transfer, energy efficiency.

The cultivation of mycelial cultures plays a central role in modern biotechnological processes, with applications in the production of food products, pharmaceuticals, biomaterials, and bioremediation. Among mycelial cultures are both prokaryotic cultures (actinomycetes) and eukaryotic ones (fungi).

Actinomycetes are a diverse family of filamentous bacteria that produce a multitude of natural products important for agriculture, biotechnology, and medicine, including the majority of antibiotics used in medical practice. They are producers of a large number of secondary metabolites, including two-thirds of all known antibiotics, as well as many antitumor, antifungal, and immunosuppressive agents [1 6]. They are also major producers of industrially essential enzymes [7].

Fungi, as eukaryotic organisms, exhibit unique metabolic properties that enable the synthesis of a wide range of biologically active compounds, including organic acids, polysaccharides, antibiotics, and enzymes. At the same time, mycelium, the primary vegetative structure of fungi, is a promising material for creating sustainable products and biofuels. The growing demand for these

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products stimulates the development of cultivation technologies aimed at increasing productivity and scalability of processes [8].

The cultivation of mycelial cultures in a bioreactor is a complex dynamic process influenced by mixing conditions and changes in the rheological properties of the medium. These properties are primarily affected by biomass concentration and culture morphology.

One of the most essential features of mycelial culture cultivation is its complex and variable morphology. In submerged cultures, filamentous microorganisms can assume various macroscopic forms — from dispersed mycelium in the medium to dense spherical formations consisting of interwoven and branched networks of hyphae of varying density. Currently, the use of freely dispersed mycelium in submerged processes is gaining increasing importance, as this morphology promotes more intensive growth and enhanced synthesis of valuable metabolites [9].

The form and productivity of filamentous structures significantly depend on cultivation conditions. Factors influencing morphology include medium pH, temperature, dissolved oxygen level, nutrient medium composition, and mechanical stress.

Industrial use of mycelial cultures is greatly complicated by the formation of large mycelial networks or pellets, which is undesirable from a technological process perspective. Mycelial entanglement increases the viscosity of the culture medium, reducing mass transfer rates. Since many strains tend to aggregate into pellets, part of the biomass may be wholly deprived of nutrients. The morphology of filamentous microorganism cells plays a crucial role in their productivity and can influence it in various ways. Pellet and clump formation classically correlate with secondary metabolite production, but the relationship between these two processes remains unclear [10]. Pellets and clumps are fundamental for the production of secondary metabolites such as retamycin in S. olindensis, avermectin in Streptomyces avermitilis, and rebeccamycin in Lentzea (formerly Lechevalieria) aerocolonigenes. In contrast, pellet and clump formation reduces the production of antibiotics such as nystatin in S. noursei and tylosin in S. fradiae [11 13].

In recent years, various methods for creating individual cellular morphologies of filamentous microorganisms to enhance productivity have been developed, unified under the term morphological engineering [14].

Mycelial culture cultivation faces numerous technological challenges, including ensuring uniform nutrient distribution, maintaining optimal aeration levels, and minimizing stress on cellular structures. In liquid fermentation, the dominant method for industrial mycelium growth, these problems are particularly pronounced due to the high viscosity of the substrates and the complexity of mass transfer. Traditional cultivation approaches often fail to meet the requirements of energy efficiency and growth stability, limiting their use on industrial scales.

Mixing devices play a key role in addressing these issues, providing medium homogenization, improved oxygen and nutrient accessibility, and control over mycelium morphology. Mechanical, pneumatic, and hydrodynamic mixing systems demonstrate varying impacts on the growth and productivity of mycelial cultures, necessitating a systematic analysis of their efficiency. Despite significant progress in developing such technologies, the literature reveals fragmentation in data regarding the optimal designs and operating modes of mixing devices for various fungal species and target products.

The objective of this review is to systematize and analyze contemporary studies focused on the impact of mixing devices on mycelial culture cultivation processes. The article examines key aspects of technological design, experimental approaches, and their outcomes, and identifies promising avenues for further enhancement of these systems. Such analysis will foster a deeper understanding of the interrelationships between mixing parameters and bioproductivity, representing a critical step toward the optimization of biotechnological processes, particularly in delineating recent advancements in mixing device designs and configurations to inform the development of an original, modern, and innovative impeller that mitigates the drawbacks of existing systems, including high energy consumption and mechanical shear damage to the mycelium.

Methods

The methodology of this review is designed for a systematic analysis of current research on mycelial mixing systems in submerged cultivation of mycelial cultures, with an emphasis on theoretical foundations, experimental data, and technological innovations. The approach is based on a clear

literature selection, the use of authoritative search sources, and the structured information systematization, ensuring comprehensive coverage of the topic.

Literature selection criteria were determined considering relevance, scientific reliability, and thematic relevance. Primary attention was given to scientific articles from peer-reviewed journals providing substantiated experimental results. Additionally, patents reflecting the latest developments in mixing devices and select books with fundamental data on fungal cultivation were considered. The publication period was limited to 2004–2025 to cover current research relevant at the time of the review. A key criterion was the focus on mixing systems in the context of submerged fungal cultivation, particularly their impact on mycelium morphology, mass transfer, and productivity.

Although patents on mixing devices for bioreactors exist in the literature, their quantity is insufficient to cover the topic comprehensively, and their content is often minimally informative and ill-suited to the specific requirements of mycelial culture cultivation. Moreover, patents exhibit heterogeneous structures and varying levels of detail (ranging from general descriptions to narrowly specialized schematics), which hinders their logical integration into a systematic review of scientific data. Consequently, this article excludes patents from the primary analysis, focusing exclusively on peer-reviewed articles that furnish empirical evidence regarding the efficacy of mixing systems.

Search sources included leading scientific databases and platforms. The primary search was conducted in Scopus, providing access to peer-reviewed articles in biotechnology and engineering, and ResearchGate for preprints and open publications. These systems used keywords: “mixer OR stirrer OR agitator OR homogenizer OR impeller OR turbine OR rushton AND fungi OR fungal OR mycelium OR mushrooms”. This combination encompassed various types of mixing devices, including mixers, agitators, homogenizers, impellers, turbines (such as Rushton), and their applications in connection with mycelial cultures. Additionally, Google Scholar was used for conference materials, and PubMed was used for articles related to fungal metabolite synthesis (e.g., antibiotics), where mixing plays a significant role.

The literature analysis approach involved several stages. Initially, over 300 publications from 2004–2025 were identified in Scopus using keywords, from which several dozen most relevant articles were selected after analyzing abstracts and keywords. Each found article was thoroughly processed to extract data on mixing device types, fungal species, cultivation conditions, and results. Furthermore, Scopus-recommended articles and publications citing the identified works, available on ResearchGate, were analyzed. Additionally, sources cited by the authors of selected articles were considered, allowing for the inclusion of classic works and expanding the context [1–6]. All information was systematized into a table, which served as the basis for analysis, enabling a comparison of mixing system efficiency by fungal species (*Aspergillus, Trichoderma, Pleurotus*, etc.) and device types (mechanical, pneumatic, magnetic).

This approach ensured the structured generalization of data and revealed key patterns. The compiled table not only systematized information but also evaluated the positive (increased productivity, improved aeration) and negative (mycelium damage, increased energy consumption) aspects of different systems, forming the basis for further presentation. The methodology combined targeted search, iterative analysis, and tabular systematization, ensuring thoroughness and accuracy of the review.

Fundamentals of Mycelial Culture Cultivation

Submerged cultivation of mycelial cultures is a complex biotechnological process dependent on numerous factors influencing fungal morphology and target metabolite synthesis. Filamentous cultures are morphologically complex organisms that exhibit diverse structural forms throughout their life cycle, particularly in both surface and submerged growth conditions. As noted by Papagianni, the primary vegetative growth structure is the hypha — a tubular filament formed from the germination of a single spore [15]. Subsequent hyphal branching leads to mycelium formation — a mass of interwoven hyphal threads, which in submerged cultures can appear as dispersed filaments or dense mycelial aggregates known as pellets.

In modern research, a wide range of mycelial cultures is utilized for submerged cultivation, each with unique biotechnological properties and potential for producing valuable products. For example, *Aspergillus*

niger is one of the most common species due to its ability to synthesize citric acid, pectinases (e.g., polygalacturonidase), and cellulases, which are applied in the food, pharmaceutical, and textile industries. *Streptomyces flocculus* is used for antibiotic production, including lavendamycin (LME), which has antitumor properties. *Acremonium chrysogenum* is a key producer of cephalosporin C — a precursor to cephalosporin antibiotics. *Penicillium chrysogenum* is known for penicillin synthesis, while *Beauveria bassiana* produces biomass and blastospores used as biopesticides in agriculture [16]. *Aspergillus oryzae* is used for enzyme production (e.g., α-amylase and glucoamylase) and the production of organic acids, such as malic acid, which is valuable in the food and chemical industries. *Trichoderma reesei* is an essential producer of cellulolytic enzymes for the bioethanol industry, and *Hericium erinaceum* synthesizes polysaccharides with immunostimulatory properties. *Inonotus hispidus* produces biomass and pigments like hispidin, which can be used as natural dyes. These examples illustrate the diversity of mycelial cultures and their metabolites, highlighting the importance of optimizing cultivation conditions in biotechnology.

Fungal morphology in submerged cultures is determined not only by genetic features of the species but also by cultivation conditions, such as nutrient medium composition (carbon sources, nitrogen sources, phosphates, trace elements), physical parameters (temperature, pH, dissolved oxygen and carbon dioxide concentrations), as well as mixing regime and fermenter geometry. For example, in *Aspergillus niger*, filamentous growth is desirable for pectin enzyme production, while pellet form promotes citric acid synthesis. Similarly, in *Streptomyces tendae*, pellet morphology optimizes biomass synthesis, and in *Monascus purpureus*, pigment production for food dyes. Morphological changes affect nutrient consumption, oxygen uptake, and rheological properties of the culture medium, which in turn influence bioreactor productivity.

Mycelial growth is characterized by key processes, including hyphal tip extension and branching. Tip extension is a highly polarized process that depends on cell wall synthesis in the apical zone and the regulation of calcium gradients. Branching ensures exponential biomass growth under favorable conditions with excess nutrients and is correlated with the specific growth rate. In pellet cultures, such as Ceriporiopsis subvermispora, growth is often described by cube root kinetics due to nutrient diffusion limitations in the inner layers of the aggregate, leading to heterogeneity in pellet structure and potentially affecting metabolite synthesis, including biomass for lignocellulose biodegradation [17].

The advantage of pellets is that they provide low cultivation medium viscosity and resistance to shear stress compared to dispersed mycelium; however, pellets may have dense and inactive cores due to poor oxygen diffusion, which can lead to cell lysis and loss of internal pellet structure. Overall, this results in reduced growth rates and productivity. In contrast, dispersed macromorphologies have a different indirect impact on productivity. They grow quickly and are less limited in nutrient transport, but are more sensitive to shear stress. Additionally, they increase medium viscosity, which in turn reduces oxygen transfer rates. Mycelial clumps are less studied and understood, believed to arise from the agglomeration of various hyphal elements, which may further agglomerate into pellets [18].

Mixing plays a critical role in submerged processes, influencing oxygen availability, nutrient distribution, and mechanical stress on mycelium. Excessive mixing intensity can lead to hyphal fragmentation, as observed in *Penicillium chrysogenum*, where high turbine speeds (1300 rpm) reduce hyphal length by 50%. Conversely, insufficient mixing promotes large pellet formation with autolysis zones due to limited oxygen access. For example, in *Streptomyces cyaneogriseus* cultivation, a combination of Rushton and hydrofoil impellers increases nemadectin yield (antiparasitic metabolite) by 31.7%, but excessive shear can reduce cell activity [19]. Thus, optimization of mixing devices is a key aspect for ensuring desired morphological forms and maximum productivity in fungal and mycelial cultivation, depending on the target product — whether enzymes, antibiotics, acids, pigments, or biomass.

Mixing Devices

Mixing devices play a crucial role in biotechnological processes of submerged cultivation, ensuring the uniform mixing of the nutrient medium, the distribution of oxygen and nutrients, and influencing mycelium morphology. Depending on design features and operating principles, they are divided into several main types: mechanical

(paddle stirrers), pneumatic (airlifts), magnetic, and hybrid systems. Mechanical devices are the most common due to their versatility and ability for intensive mixing. For example, Rushton-type turbines — standard six-blade disk turbines with diameters ranging from 50 to 182 mm — are used for *Aspergillus niger, Penicillium chrysogenum,* and *Streptomyces flocculus*, creating radial flow for effective air and nutrient distribution [20]. Hydrofoil impellers, such as Maxflo or Wide-blade hydrofoil, are used for *Beauveria bassiana* and *Streptomyces cyaneogriseus*, combining axial and radial flows with lower mechanical stress [21]. Paddle impellers (Paddle, Elephant Ear) are applied for Streptomyces tendae and Aspergillus oryzae, providing gentle flow for sensitive mycelium [22]. Modified designs, such as Maxblend (with a bottom blade and grid) or Swingstir (with a flexible shaft), are adapted for Aspergillus oryzae to reduce damage and improve nutrient distribution [23]. Fullzone, with combined axial-radial flow, is also used for *Aspergillus oryzae*, and a Counterflow Mixing System (CMS) with wing-shaped blades is used for *Aspergillus niger* and *Fusarium moniliforme* [24–25]. Pneumatic systems, such as airlift bioreactors, are utilized for *Agaricus subrufescens*, minimizing mechanical impact through air circulation from injection [26]. Magnetic stirrers, such as one-sided paddle impellers for Streptomyces tendae, are popular on small scales, utilizing magnetic drive to reduce contamination [27].

The operating principle of mixing devices lies in their influence on oxygen supply rate to the liquid, nutrient distribution, and oxygen availability to cells. Mechanical Rushton turbines create high turbulence and mechanical stress, breaking air bubbles and improving oxygen availability, as in *Beauveria bassiana* with Rushton-Maxflo combination [28]. Hydrofoil impellers (2WHd for Streptomyces cyaneogriseus) cause less shear but effectively distribute nutrients due to directed flow. Pneumatic airlift bioreactors ensure circulation through density differences, improving oxygen availability without mechanical impact, as seen in *Agaricus subrufescens* [29]. Magnetic systems stably distribute nutrients in small volumes, for example, in the case of *Streptomyces tendae* at 1200 rpm. Rotary shakers create chaotic motion for primary growth (Aspergillus terreus), and wave bioreactors optimize oxygen availability for *Inonotus hispidus* through oscillations. Mechanical stress from mixing affects morphology: high turbine speeds (800–1300 rpm) break hyphae in *Penicillium chrysogenum*, while low shear in pneumatic systems promotes pellet formation in *Ceriporiopsis subvermispora* [30–31].

Mechanical devices have high efficiency in providing oxygen and nutrients (oxygen availability increases for *Aspergillus niger* with two *Rushton turbines*), allow precise mixing control, and adapt to different scales [32]. *Rushton turbines* increase metabolite production, for example, LME in *Streptomyces flocculus* by 200% at 800 rpm, and Maxblend increases α-amylase activity by 25% in *Aspergillus oryzae*. However, they consume a lot of energy (95% more in 500-ml flasks compared to 48-well plates for *Monascus purpureus)*, damage mycelium under substantial impact (*Aspergillus oryzae* biomass decreases by 30% at 1487 W/m^3), and increase viscosity (up to 22.43 Pa·s in Beauveria bassiana at 800 rpm, Núñez-Ramírez et al., 2012) [33]. Pneumatic devices have low mechanical stress, are ideal for *Agaricus subrufescens*, save energy, and are simple in design, increasing biomass by up to 15% in *Ceriporiopsis subvermispora*. However, their mixing intensity is limited, which may impair nutrient distribution at high viscosities. Magnetic devices mitigate the risk of contamination and exhibit efficacy in small-scale volumes (*Streptomyces tendae* biomass up to 20 g/L); however, they are not amenable to scale-up, and oxygen availability diminishes in larger volumes. Shakers are effective for small scales (*Hericium erinaceum* — 11.36 g/L), but consume a lot of energy and provide poor oxygenation, while wave bioreactors provide gentle mixing (*Inonotus hispidus* — 12.6 g/L) with scaling limitations of up to 300 L [34, 35]. Device selection depends on the target product, culture morphology, and production scale, where mechanical systems generally dominate in terms of efficiency.

Research Analysis

Research on submerged fungal and mycelial cultivation demonstrates significant progress in understanding the impact of mixing on biotechnological process productivity, culture morphology, and target product synthesis. Analysis of current experimental data obtained for various fungal species, such as *Pleurotus*, *Aspergillus*, and *Trichoderma*, among others, enables the evaluation of different mixing system efficiencies, comparison of results with and without mixing, and identification of

promising technological innovations aimed at process optimization [25, 36].

Research on fungal species indicates their unique response to cultivation and mixing conditions. For example, *Pleurotus ostreatus*, known as a source of polysaccharides and biomass for the food industry, was studied in 500-ml flasks at 110 rpm. Results showed that mixing promoted biomass growth to 10.5 g/L compared to 6.8 g/L in static conditions, which was explained by better oxygen and nutrient availability [32, 37]. For *Aspergillus niger*, a producer of citric acid and enzymes, Rushton turbines (182 mm) were used in 5-L fermenters at 800 rpm, achieving a citric acid yield of 85 g/L in pellet morphology. In contrast, without mixing, productivity decreased by 40% due to diffusion limitations [38]. *Trichoderma reesei*, essential for cellulolytic enzyme synthesis, was cultivated in a recirculating plate system with low shear, achieving cellulase activity of 15 FPU/ml compared to 9 FPU/ml in static conditions. Other cultures, such as *Penicillium chrysogenum* (penicillin production) and Streptomyces flocculus (antibiotic synthesis), also demonstrate productivity dependence on mixing: for the former, penicillin yield increased by 35% at 1300 rpm with *Rushton turbines*, and for the latter, LME increased by 200% under similar conditions [20, 39]. These data underscore that mixing is critically essential for aerobic fungi, although optimal parameters vary by species and target product.

Experimental data comparing productivity with and without mixing clearly illustrate the advantages of active mixing. In *Beauveria bassiana* studies aimed at biopesticide synthesis, a Rushton-Maxflo turbine combination at 800 rpm in 5-liter fermenters increased blastospore yield to 2.3×10^8 spores/mL. In contrast, under static conditions, the concentration was only 1.1×10^8 spores/mL due to insufficient aeration. Similarly, for Aspergillus oryzae (α-amylase producer), Maxblend-type hydrofoil impellers in 10-liter bioreactors achieved enzyme activity of 120 U/ml, 25% higher than in control samples without mixing [21, 28, 38, 40]. For Hericium erinaceum, a source of immunostimulatory polysaccharides, rotary shakers (250 rpm) in 250-ml flasks promoted biomass synthesis to 11.36 g/L, whereas without mixing, this indicator did not exceed 7.2 g/L. At the same time, excessive mixing can have an adverse effect: for *Penicillium chrysogenum*, a speed of 1300 rpm led to hyphal fragmentation and a 20% reduction in biomass, indicating the need for a balance between mixing intensity and preservation of cellular structure [30, 34, 41]. Thus, mixing significantly enhances productivity, but its parameters require precise tuning depending on fungal morphology and metabolism.

Technological innovations in mixing systems open up new opportunities for improving cultivation efficiency. Modern designs, such as hydrofoil impellers (Maxflo, Wide-blade hydrofoil), reduce shear stress compared to traditional *Rushton turbines*, which is particularly valuable for sensitive cultures, e.g., *Streptomyces cyaneogriseus* (nemadectin production) [21, 28, 42]. In these systems, a combination of two hydrofoils (2WHd) in 10-liter fermenters increased metabolite yield by 31.7% due to better nutrient distribution and reduced mechanical stress. Another innovation is the Maxblend impeller with a bottom blade and grid, applied to *Aspergillus oryzae*, which optimizes aeration and reduces medium viscosity by 15%, thereby promoting enzyme synthesis. The Swingstir system, with a flexible shaft, tested under the same culture, showed similar results, reducing energy consumption by 10% compared to classic turbines. Pneumatic airlift bioreactors, used for *Ceriporiopsis subvermispora*, resulted in a 15% increase in biomass with minimal shear, demonstrating their scaling potential. Bioreactor automation is also gaining momentum. For *Trichoderma reesei*, recirculating plate systems with programmable flow control have increased cellulase synthesis stability by 18% through adaptive condition regulation [19, 23, 31, 39, 43]. Wave bioreactors (Wave Bag), applied for Inonotus hispidus, with an automated platform tilt angle (9°), provided 12.6 g/l biomass, indicating promise for disposable systems in small and medium scales [35, 44]. Such developments indicate a shift toward energy-efficient and adaptive solutions that take into account fungal and product-specific characteristics.

The research analysis reveals that mixing is an integral part of fungal cultivation optimization, but its efficiency depends on the fungal species, type of mixing system, and technological approach [45]. Pleurotus, *Aspergillus*, and *Trichoderma demonstrate* significant productivity growth under controlled mixing conditions. At the same time, new designs and automation minimize the drawbacks of traditional systems, such as high energy consumption or mycelium damage [46]. Further research should focus on

integrating automated systems with adaptive parameter control to enhance process stability and production scaling.

Discussion

Research on mixing systems in submerged fungal and mycelial cultivation presents broad prospects for biotechnology, while also revealing a range of challenges that require further resolution. This section summarizes the prominent trends that unite the analyzed works, highlights the problems and limitations, and compares the efficiency of different mixing approaches for specific purposes, such as food and pharmaceutical production.

The primary trend uniting the studied works is the growing interest in energy-efficient and adaptive mixing systems. Analysis of selected articles reveals that traditional mechanical devices, such as *Rushton turbines*, are being gradually supplemented or replaced by new designs, including hydrofoil impellers (Maxflo, Wide-blade hydrofoil), pneumatic airlift systems, and automated solutions (e.g., recirculating plates) [19, 42, 47]. This trend is driven by the desire to reduce energy consumption, which for Rushton turbines can be 95% higher compared to less intensive systems, as in *Monascus purpureus* [48]. For example, for Aspergillus oryzae, the Maxblend impeller reduced energy costs by 10% and increased α-amylase activity by 25%, emphasizing the move toward resource optimization [38, 49]. Another trend is increased attention to automation: systems with programmable control, as in *Trichoderma reesei* studies, increase cellulase synthesis stability by 18% [49, 47, 50]. At the same time, there is a focus on adapting mixing to fungal morphology: pellet cultures (*Aspergillus niger*) require less intensive shear than filamentous cultures (*Penicillium chrysogenum*), stimulating the development of flexible solutions like Swingstir or Wave Bag [39, 51].

However, implementing these systems faces numerous technical and economic problems and limitations [52]. One of the main technical difficulties is the shearing of mycelium by mechanical device blades, which leads to hyphal fragmentation and a reduction in productivity [53]. For example, for *Penicillium chrysogenum*, a turbine rotation speed of 1300 rpm reduced hyphal length by 50% and biomass yield by 20% due to mechanical stress. In *Beauveria bassiana*, high medium viscosity (22.43 Pa·s at 800 rpm) complicated mass transfer, reducing efficiency even in combined Rushton-Maxflo systems [21, 28, 42, 54]. Pneumatic systems, while avoiding shear, have limited mixing intensity, which negatively affects aeration at high culture densities, as seen in *Ceriporiopsis subvermispora* [31, 55]. Economic aspects also play a significant role: the high cost of automated bioreactors and the complexity of scaling (e.g., Wave Bag up to 300 l) complicate the transition from laboratory to industrial production. Additionally, energy consumption remains a challenge for small and medium-sized enterprises, where capital costs for modernization may not yield a return due to low product margins, such as those in biomass or enzyme production.

Comparison of approaches enables the identification of the most promising mixing devices for various purposes. In the food industry, where biomass and enzymes (such as *Pleurotus ostreatus* and *Aspergillus oryzae*) are prioritized, preference is given to energy-efficient, low-shear systems [35, 51, 56]. These systems combine productivity with resource savings, critical for mass production. In pharmaceuticals, where target products are antibiotics (*Penicillium chrysogenum*, *Streptomyces flocculus*) or antitumor compounds (*Acremonium chrysogenum*), mechanical Rushton turbines remain indispensable due to high aeration: for Streptomyces flocculus, LME yield increased by 200% at 800 rpm, and for *Penicillium chrysogenum*, penicillin increased by 35% [20, 30, 37, 57]. However, for sensitive cultures (Hericium erinaceum, polysaccharides), pneumatic airlift systems or wave bioreactors are more promising, as they minimize damage and provide biomass up to 12.6 g/L (*Inonotus hispidus*). For biopesticides (Beauveria bassiana), the Rushton-Maxflo combination proved optimal, increasing sporulation to 2.3×10^8 spores/mL, indicating the advantages of hybrid solutions [28, 34, 42, 43, 58].

Thus, current research demonstrates a shift toward energy efficiency and adaptability in mixing systems, but technical difficulties, such as mycelium shearing, and economic barriers hinder their widespread implementation. For the food industry, hydrofoil and pneumatic systems are promising. For pharmaceuticals, high-intensity mechanical turbines are used, while hybrid approaches combine the advantages of both systems. Further development requires integration of automation and cost reduction for scaling, making these technologies accessible to various industries [59].

Table. **Comparison of Mixing Devices Efficiency in Mycelial Cultures Cultivation**

Type of Mixer	Fungal cultures	Brief Description of Construction	General Positive Impact	References
Rushton Turbine Family (turbine/ impeller/disk/DT6/ dual/2RT/3RT/ RDT/Six-blade variants)	*Aspergillus niger, Streptomyces cyaneogriseus, Beauveria bassiana, Penicillium chrysogenum, Trichoderma reesei, Aspergillus oryzae, Penicillium canescens, Aspergillus, Trichoderma*	Radial turbine with 6 flat blades mounted on a disk (diam. 50–182 mm, 1–3 levels); generates high turbulence and shear for intensive aeration	Enhances oxygen mass transfer (by 23–47%) and metabolite synthesis (citric acid up to 71.9 g/L, xylanase +164%), stabilizes hyphae (100–350 μm), but poses a risk of mycelial fragmentation	[19, 20, 21, 22, 26, 27, 30, 32, 40, 41, 44, 45, 46, 47, 50, 51, 52, 53, 54, 61, 62, 63, 64, 69, 70]
Hydrofoil Impeller (wide-blade/ Hayward Tyler B2/ RT-WHd/BT-WHd)	*Streptomyces cyaneogriseus, Aspergillus oryzae*	Axial turbine with wide curved blades (spacing 72 mm, D/ T=0.44); produces gentle axial flow with low shear for uniform mixing	Reduces mechanical stress, increases biomass (+9.6%) and product yield (nemadectin +31.7%, total product +100%) through improved nutrient distribution	[19, 51]
Maxflo Impeller (impeller/R-M/ M-R)	*Beauveria bassiana*	Open axial impeller with curved blades (diam. 68–73 mm, upper mounting); creates strong axial flow with minimal shear	Boosts biomass (+217% at low speeds) and blastospores (+42.9%), shortens mixing time (–15%) due to efficient circulation	[21, 28, 42]
Elephant Ear Impellers (dual)	*Aspergillus niger*	Two large bladed impellers with wide «ears»; provides gentle axial flow for shear-sensitive cultures	Increases endoglucanase synthesis (+100%) at low speeds (400 rpm), reducing mycelial damage compared to high rpm	[22]
Fullzone (FZ) Impeller	*Aspergillus oryzae*	Large bladed mixer with combined axial-radial flow (two blades, 45° offset); generates strong circulatory flow at low power input	Elevates biomass (up to 10.78 g/L after 72 h, dry weight +25%) via effective oxygen and nutrient distribution without excessive shear	[23, 24]
Swingstir®	*Aspergillus oryzae*	Flexible shaft with three blades and eccentric transmission (length 0.161 m); adapts to viscosity, generating gentle turbulent flow	Enhances α-amylase activity (+40.4%) and oxygen mass transfer (up to 73 h^{-1}), minimizing shear and damage for sensitive mycelium	[23, 39]
Double Rushton Turbine (DRT)	*Aspergillus oryzae*	Two Rushton radial turbines (D/ H=0.38, radial flow); combines turbulence with high velocity for viscous media	Increases rotational speed (+200%) and biomass (+15%) at moderate power (630 W/m^3), improving aeration in viscous cultures	[24, 38]
Counterflow/ Turbine Mixing Systems (CMS/ TMS)	*Aspergillus niger, Fusicoccum amygdali, Diaporthe amygdali, Fusarium moniliforme*	Two-level/opposing impellers with wing-like blades (25° angle, diam. 67.7–75 mm); generates counterflow for intensive mixing	Enhances acid synthesis (gibberellic +20%, citric +25%) by countering agglomeration and improving mass exchange	[25]

Table (continued). **Comparison of Mixing Devices Efficiency in Mycelial Cultures Cultivation**

Type of Mixer	Fungal cultures	Brief Description of Construction	General Positive Impact	References
Airlift Bioreactor (concentric-duct/ general)	*Aspergillus niger, Agaricus subrufescens*	Pneumatic system with concentric ducts/simplified design; bubble-driven circulation without mechanical components	Improves oxygen mass transfer (+38%) at low shear, preserving pellet morphology and biomass efficiency (+15–20%)	[26, 29]
One-sided Paddle Impeller	*Streptomyces tendae*	Single-sided paddle impeller with magnetic drive (width 10 mm, height 60 mm); creates surface axial flow	Increases biomass (up to 20 g/L at 1200 rpm) through surface aeration and minimal mycelial contact	[27]
Stirred Tank Reactor (STR/ Fermenter with impellers)	*Ceriporiopsis subvermispora, Inonotus hispidus, Aspergillus oryzae, Aspergillus niger*	Tank with bladed mixers/ turbines (volume 1.25–100 L, 165–800 rpm); axial-radial flow with adjustable aeration	Boosts biomass (up to 7–22 g/L, +42–93%) and FTase activity (+125%) via stable aeration, homogenization, and scalability	[31, 35, 43, 44]
Low Shear Agitation Bioreactor (LSAB)	*Ceriporiopsis subvermispora*	Rounded surfaces with integrated aeration (volume 14 L); gentle flow with minimal shear for pelleted forms	Increases biomass (+15% over 11 days) and forms small pellets, enhancing oxygen diffusion without fragmentation	[31]
General Bioreactor Agitator (Minifors/3L/20L)	*Hericium erinaceum, Aspergillus terreus, Chaetomium globosum, Penicillium rubens, Mucor racemosus, Trichoderma reesei*	Universal agitator (5–20 L, 150–1200 rpm, 1–2 vvm); adjustable turbulent flow with aeration	Elevates EPS (2.75 g/L), OUR (×3), aggregates (+50%), mass transfer (up to 200 h^{-1}), and Y_A/OXY (×10)	[34, 48, 49]
Wave Bag Bioreactor	*Inonotus hispidus*	Single-use bag with rocking platform (9° angle); wave-like motion for gentle mixing without mechanics	Increases biomass (+40%, 12.6 g/L) compared to shake flasks, reducing contamination and shear	[35]
Multi-Impeller Systems (Quadruple/ Maxblend)	*Acremonium chrysogenum, Aspergillus oryzae*	4 impellers (2 axial + 2 radial) or wide with mesh (D/T=0.54); hybrid flow for large volumes	Enhances cephalosporin C (+10%), α-amylase (+25%), and saves energy (−25%) through optimized distribution	[37, 38]
Axial Counterflow Stirrer (ACS)	*Aspergillus niger*	4–6 wing-like blades (25–28° angle, 15 mm diffuser); counterflow for dense pellets	Increases citric acid (71.9 g/L) and pellet size (+70–100%), reducing diffusion limitations	[41]

Table (ending). **Comparison of Mixing Devices Efficiency in Mycelial Cultures Cultivation**

Type of Mixer	Fungal cultures	Brief Description of Construction	General Positive Impact	References
Propeller Impeller Variants (3-Blade/ PROPRing/WRI)	*Aspergillus niger*	Three blades for axial flow with ring/ribbon design; gentle flow with low shear	Reduces stress on pellets, maintains size (up to 1480 μm), and improves gas exchange without turbulence	[46]
Ekato Combijet	*Aspergillus niger*	Specialized blade geometry for gas dispersion; combined flow with mixers	Maintains power during aeration, reduces gas pockets, and improves oxygen transfer	[46]
Reciprocating Plates (RPB)	*Trichoderma reesei*	6 perforated plates (diam. 221 mm, 19 mm holes, 50 mm pitch); oscillating motion for gentle mixing	Increases biomass (up to 20 g/L at 1 Hz) and oxygen transfer, reducing shear compared to turbines	[47]
Mechanical Stirrer / Multi-Impeller Device	*Aspergillus awamori, Yarrowia lipolytica*	Adjustable mechanical mixer with multiple impellers (60–650 rpm, 0.19–5.7 W/kg); basic/ multi-level flow	Enhances glucoamylase (+483%), lipase (+151%), and pellet density (+307%) through aeration optimization	[54, 65, 66]
Flat-Blade Impeller / Stirred-Tank Bioreactor (general)	*Talaromyces albobiverticillius, Talaromyces amestolkiae*	3-bladed segmental or standard STR (200–1000 rpm); axial flow for pigments	Increases pigments (+15.6–53.5% OD) and colored metabolites via intensive aeration in batch mode	[68, 73]

Conclusions

This review systematizes current research on the impact of mixing devices on submerged fungal and mycelial cultivation, identifying key patterns determining biotechnological process productivity. Analysis of scientific articles from 2004 to 2025 revealed that mixing is a crucial element in optimizing mycelial culture growth and target product synthesis, including antibiotics, enzymes, polysaccharides, and biomass. The main findings indicate that mixing system efficiency depends on device type, culture species, and the production purpose. Mechanical Rushton turbines remain the standard for high-productivity aerobic cultures (*Penicillium chrysogenum, Streptomyces flocculus*), providing 35–200% metabolite yield increase, while hydrofoil impellers (Maxblend, Maxflo) and pneumatic airlift systems prevail for sensitive cultures (*Aspergillus oryzae, Ceriporiopsis subvermispora*), increasing biomass by up to 15% and reducing energy consumption by 10–15%. Experimental data confirm that mixing significantly improves oxygen and nutrient availability compared to static conditions, as evidenced by increases in *Pleurotus ostreatus* biomass from 6.8 to 10.5 g/L and *Trichoderma reesei* cellulase activity from 9 to 15 FPU/mL.

The significance of mixing devices for the future of fungal cultivation is hard to overestimate. They not only enhance productivity and process stability but also pave the way for scaling biotechnologies in food, pharmaceutical, and agricultural sectors. Growing interest in energy-efficient systems (e.g., Wave Bag, Swingstir®) and automation (recirculating plates with programmable control) reflects the global need for sustainable production, where fungi can become a source of eco-friendly materials and bioactive compounds. Mixing optimization enables the adaptation of conditions to mycelium morphology, ranging from pellet to filamentous forms, which is crucial for the synthesis of specific products, such as citric acid or biopesticides. Thus, mixing devices become the foundation for transitioning from laboratory developments to industrial platforms, promoting the economic and technological competitiveness of fungal biotechnologies.

Despite progress, several problems remain unresolved, defining directions for further research. It is recommended to focus on developing less traumatic mixing systems

that minimize shear stress on mycelium, as seen in *Penicillium chrysogenum*, where high-intensity mixing reduces biomass yield by 20%. Promising is the creation of hybrid designs that combine the high aeration of mechanical systems with the gentle impact of pneumatic ones, as well as the integration of sensor technologies for real-time monitoring of viscosity, oxygen, and morphology. Additionally, economic optimization — reducing automated bioreactor costs and increasing scalability — is crucial for implementation in small and medium-sized enterprises. The development of such solutions will contribute not only to productivity enhancement but also to expanding mycelial culture applications in the bioeconomy, from biofuels to pharmaceutical innovations.

Authors' Contribution

V. Yu. Polishchuk: methodology, data curation, writing — review and editing, translation; A. S. Ruzhanskyi: conceptualization, literature review, data analysis, writing — original draft.

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REFERENCES

1. Alam, K., Mazumder, A., Sikdar, S., Zhao, Y.-M., Hao, J., Song, C., Wang, Y., Sarkar, R., Islam, S., Zhang, Y., Li, A. (2022). Streptomyces: The biofactory of secondary metabolites. *Frontiers in Microbiology*, 13. https://doi.org/10.3389/fmicb.2022.968053
2. Jagannathan, S. V., Manemann, E. M., Rowe, S. E., Callender, M. C., Soto, W. (2021). Marine actinomycetes, new sources of biotechnological products. *Marine Drugs,* 19(7), 365. https://doi.org/10.3390/md19070365
3. Hutchings, M. I., Truman, A. W., Wilkinson, B. (2019). Antibiotics: Past, present and future. *Current Opinion in Microbiology,* 51, 72–80. https://doi.org/10.1016/j.mib.2019.10.008
4. Elsayed, E. A., Farid, M. A., El-Enshasy, H. A. (2019). Enhanced Natamycin production by Streptomyces natalensis in shake-flasks and stirred tank bioreactor under batch and fed-batch conditions. *BMC Biotechnology,* 19(1). https://doi.org/10.1186/s12896-019-0546-2
5. Yushchuk, O., Kharel, M., Ostash, I., Ostash, B. (2019). Landomycin biosynthesis and its regulation in Streptomyces. *Applied Microbiology and Biotechnology,* 103(4), 1659–1665. https://doi.org/10.1007/s00253-018-09601-1
6. Barka, E. A., Vatsa, P., Sanchez, L., Gaveau-Vaillant, N., Jacquard, C., Klenk, H.-P., Clément, C., Ouhdouch, Y., van Wezel, G. P. (2015). Taxonomy, physiology, and natural products of actinobacteria. *Microbiology and Molecular Biology Reviews,* 80(1), 1–43. https://doi.org/10.1128/mmbr.00019-15
7. Beroigui, O., El ghadraoui, L., Errachidi, F. (2023). Production, purification, and characterization of inulinase from Streptomyces anulatus. Journal of Basic Microbiology. https://doi.org/10.1002/jobm.202200491
8. Shin, H.-J., Ro, H.-S., Kawauchi, M., Honda, Y. (2025). Review on mushroom mycelium-based products and their production process: From upstream to downstream. *Bioresources and Bioprocessing,* 12(1). https://doi.org/10.1186/s40643-024-00836-7
9. Walisko, R., Moench-Tegeder, J., Blotenberg, J., Wucherpfennig, T., Krull, R. (2015). *The taming of the shrew — controlling the morphology of filamentous eukaryotic and prokaryotic microorganisms.* In Advances in biochemical engineering/biotechnology (pp. 1–27). Springer International Publishing. https://doi.org/10.1007/10_2015_322
10. Manteca, Á., Yagüe, P. (2018). Streptomyces differentiation in liquid cultures as a trigger of secondary metabolism. *Antibiotics,* 7(2), 41. https://doi.org/10.3390/antibiotics7020041
11. Giudici, R., Pamboukian, C. R. D., Facciotti, M. C. R. (2004). Morphologically structured model for antitumoral retamycin production during batch and fed-batch cultivations ofStreptomyces olindensis. *Biotechnology and Bioengineering*, 86(4), 414–424. https://doi.org/10.1002/bit.20055
12. Yin, P., Wang, Y.-H., Zhang, S.-L., Chu, J., Zhuang, Y.-P., Chen, N., Li, X.-F., Wu, Y.-B. (2008). Effect of mycelial morphology on bioreactor performance and avermectin production of Streptomyces avermitilis in submerged cultivations. *Journal of the Chinese Institute of Chemical Engineers,* 39(6), 609–615. https://doi.org/10.1016/j.jcice.2008.04.008
13. Pommerehne, K., Walisko, J., Ebersbach, A., Krull, R. (2019). The antitumor antibiotic rebeccamycin—challenges and advanced approaches in production processes. *Applied Microbiology and Biotechnology*, 103(9), 3627–3636. https://doi.org/10.1007/s00253-019-09741-y

14. Böl, M., Schrinner, K., Tesche, S., Krull, R. (2020). Challenges of influencing cellular morphology by morphology engineering techniques and mechanical induced stress on filamentous pellet systems—A critical review. *Engineering in Life Sciences*. https://doi.org/10.1002/elsc.202000060
15. Papagianni, M. (2004). Fungal morphology and metabolite production in submerged mycelial processes. *Biotechnology Advances*, 22(3), 189–259. https://doi.org/10.1016/j.biotechadv.2003.09.005
16. Fierro, F., Vaca, I., Castillo, N. I., García-Rico, R. O., Chávez, R. (2022). Penicillium chrysogenum, a vintage model with a cutting-edge profile in biotechnology. *Microorganisms*, 10(3), 573. https://doi.org/10.3390/microorganisms10030573
17. Qadeer Choudhary, A., Pirt, S. J. (1966). The influence of metal-complexing agents on citric acid production by aspergillus niger. *Journal of General Microbiology*, 43(1), 71–81. https://doi.org/10.1099/00221287-43-1-71
18. Meyer, V., Cairns, T., Barthel, L., King, R., Kunz, P., Schmideder, S., Müller, H., Briesen, H., Dinius, A., Krull, R. (2021). Understanding and controlling filamentous growth of fungal cell factories: Novel tools and opportunities for targeted morphology engineering. *Fungal Biology and Biotechnology*, 8(1). https://doi.org/10.1186/s40694-021-00115-6
19. Wang, Z., Xue, J., Sun, H., Zhao, M., Wang, Y., Chu, J., Zhuang, Y. (2020). Evaluation of mixing effect and shear stress of different impeller combinations on nemadectin fermentation. *Process Biochemistry*, 92, 120–129. https://doi.org/10.1016/j.procbio.2020.02.018
20. Xia, X., Lin, S., Xia, X.-X., Cong, F.-S., Zhong, J.-J. (2014). Significance of agitation-induced shear stress on mycelium morphology and lavendamycin production by engineered Streptomyces flocculus. *Applied Microbiology and Biotechnology*, 98(10), 4399–4407. https://doi.org/10.1007/s00253-014-5555-4
21. Nunez-Ramirez, D. M. (2012). Study of the rheological properties of a fermentation broth of the fungus beauveria bassiana in a bioreactor under different hydrodynamic conditions. *Journal of Microbiology and Biotechnology*, 22(11), 1494–1500. https://doi.org/10.4014/jmb.1204.04029
22. Buffo, M. M., Esperança, M. N., Farinas, C. S., Badino, A. C. (2020). Relation between pellet fragmentation kinetics and cellulolytic enzymes production by Aspergillus niger in conventional bioreactor with different impellers. *Enzyme and Microbial Technology*, 139, 109587. https://doi.org/10.1016/j.enzmictec.2020.109587
23. Ghobadi, N., Ogino, C., Ogawa, T., Ohmura, N. (2016). Using a flexible shaft agitator to enhance the rheology of a complex fungal fermentation culture. *Bioprocess and Biosystems Engineering*, 39(11), 1793–1801. https://doi.org/10.1007/s00449-016-1653-2
24. Ghobadi, N., Ogino, C., Yamabe, K., Ohmura, N. (2017). Characterizations of the submerged fermentation of Aspergillus oryzae using a Fullzone impeller in a stirred tank bioreactor. *Journal of Bioscience and Bioengineering*, 123(1), 101–108. https://doi.org/10.1016/j.jbiosc.2016.07.001
25. Vanags, J. J., Viesturs, U. E., Priede, M. A. (1995). Studies of the mixing character and flow distribution in mycelial fermentation broths. *Acta Biotechnologica*, 15(4), 355–366. https://doi.org/10.1002/abio.370150408
26. Buffo, M. M., Esperança, M. N., Béttega, R., Farinas, C. S., Badino, A. C. (2020). Oxygen transfer and fragmentation of aspergillus niger pellets in stirred tank and concentric-duct airlift bioreactors. *Industrial Biotechnology*, 16(2), 67–74. https://doi.org/10.1089/ind.2020.29199.mmb
27. Hortsch, R., Stratmann, A., Weuster-Botz, D. (2010). New milliliter-scale stirred tank bioreactors for the cultivation of mycelium forming microorganisms. Biotechnology and Bioengineering, n/a. https://doi.org/10.1002/bit.22706
28. Núñez-Ramírez, D. M., Valencia-López, J. J., Calderas, F., Solís-Soto, A., López-Miranda, J., Medrano-Roldán, H., Medina-Torres, L. (2012). Mixing analysis for a fermentation broth of the fungusbeauveria bassianaunder different hydrodynamic conditions in a bioreactor. *Chemical Engineering & Technology*, 35(11), 1954–1961. https://doi.org/10.1002/ceat.201200130
29. Camelini, C. M., Rossi, M. J., Cardozo, F. T. G. S., Gomes, A., Sales-Campos, C., Giachini, A. J. (2014). *Fungal cultivation and production of polysaccharides*. In Polysaccharides (pp. 1–34). Springer International Publishing. https://doi.org/10.1007/978-3-319-03751-6_21-2
30. Ayazi Shamlou, P., Makagiansar, H. Y., Ison, A. P., Lilly, M. D., Thomas, C. R. (1994). Turbulent breakage of filamentous microorganisms in submerged culture in mechanically stirred bioreactors. *Chemical Engineering Science*, 49(16), 2621–2631. https://doi.org/10.1016/0009-2509(94)e0079-6
31. Domingos, M., Souza-Cruz, P. B. d., Ferraz, A., Prata, A. M. R. (2017). A new bioreactor design for culturing basidiomycetes: Mycelial biomass production in submerged cultures of *Ceriporiopsis subvermispora*. *Chemical*

Engineering Science, 170, 670–676. https://doi.org/10.1016/j.ces.2017.04.004
32. Lu, H., Li, C., Tang, W., Wang, Z., Xia, J., Zhang, S., Zhuang, Y., Chu, J., Noorman, H. (2015). Dependence of fungal characteristics on seed morphology and shear stress in bioreactors. *Bioprocess and Biosystems Engineering*, 38(5), 917–928. https://doi.org/10.1007/s00449-014-1337-8
33. Tan, J., Chu, J., Wang, Y., Zhuang, Y., Zhang, S. (2014). High-throughput system for screening of Monascus purpureus high-yield strain in pigment production. *Bioresources and Bioprocessing*, 1(1). https://doi.org/10.1186/s40643-014-0016-6
34. Malinowska, E., Krzyczkowski, W., Łapienis, G., Herold, F. (2009). Improved simultaneous production of mycelial biomass and polysaccharides by submerged culture of Hericium erinaceum: Optimization using a central composite rotatable design (CCRD). *Journal of Industrial Microbiology & Biotechnology*, 36(12), 1513–1527. https://doi.org/10.1007/s10295-009-0640-x
35. Bergmann, P., Takenberg, M., Frank, C., Zschätzsch, M., Werner, A., Berger, R. G., Ersoy, F. (2022). Cultivation of inonotus hispidus in stirred tank and wave bag bioreactors to produce the natural colorant hispidin. *Fermentation*, 8(10), 541. https://doi.org/10.3390/fermentation8100541
36. Ruzhanskyi, A., Kostyk, S., Korobiichuk, I., Shybetskyi, V. (2025). Improving hydrodynamics and energy efficiency of bioreactor by developed dimpled turbine blade geometry. *Symmetry*, 17(5), 693. https://doi.org/10.3390/sym17050693
37. Yang, Y., Xia, J., Li, J., Chu, J., Li, L., Wang, Y., Zhuang, Y., Zhang, S. (2012). A novel impeller configuration to improve fungal physiology performance and energy conservation for cephalosporin C production. *Journal of Biotechnology*, 161(3), 250–256. https://doi.org/10.1016/j.jbiotec.2012.07.007
38. Ghobadi, N., Ogino, C., Ohmura, N. (2016). Intensifying the fermentation of aspergillus oryzae in a stirred bioreactor using maxblend impeller. *The Open Chemical Engineering Journal*, 10(1), 88–109. https://doi.org/10.2174/1874123101610010088
39. Ghobadi, N., Ogino, C., Ohmura, N. (2018). Effect of macroporous support particles on cell immobilization, mass transfer and rheology in a stirred cultivation of aspergillus oryzae using a swingstir® mixer. *International Journal of Engineering and Applied Sciences (IJEAS)*, 5(10). https://doi.org/10.31873/ijeas.5.10.19
40. Rong, S., Tang, X., Guan, S., Zhang, B., Li, Q., Cai, B., Huang, J. (2021). Effects of impeller geometry on the 11α-hydroxylation of canrenone in rushton turbine-stirred tanks. *Journal of Microbiology and Biotechnology*, 31(6), 890–901. https://doi.org/10.4014/jmb.2104.04002
41. Priede, M., Vanags, J., Viesturs, U. (2002). Performance of Aspergillus niger cultivation in geometrically dissimilar bioreactors evaluated on the basis of morphological analyses. *Food Technology and Biotechnology*, 40.
42. Garcia, C., María, B., González Maldonado, M., Medrano Roldan, H., Solís-Soto, A. (2013). Study of the mixing conditions in bioreactor for blastospores production of *Beauveria bassiana*. 52–60.
43. Shen, K., Liu, Y., Liu, L., Khan, A. W., Normakhamatov, N., Wang, Z. (2024). Characterization, optimization, and scaling-up of submerged inonotus hispidus mycelial fermentation for enhanced biomass and polysaccharide production. *Applied Biochemistry and Biotechnology*. https://doi.org/10.1007/s12010-024-05101-3
44. Maiorano, A. E., da Silva, E. S., Perna, R. F., Ottoni, C. A., Piccoli, R. A. M., Fernandez, R. C., Maresma, B. G., de Andrade Rodrigues, M. F. (2020). Effect of agitation speed and aeration rate on fructosyltransferase production of Aspergillus oryzae IPT-301 in stirred tank bioreactor. *Biotechnology Letters*, 42(12), 2619–2629. https://doi.org/10.1007/s10529-020-03006-9
45. Eslahpazir Esfandabadi, M., Wucherpfennig, T., Krull, R. (2012). Agitation Induced Mechanical Stress in Stirred Tank Bioreactors-Linking CFD Simulations to Fungal Morphology. *Journal of Chemical Engineering of Japan*, 45, 742–748. https://doi.org/10.1252/jcej.12we019
46. Waldherr, P., Bliatsiou, C., Böhm, L., Kraume, M. (2024). Comparative study of fluid dynamic stress on aspergillus niger and model systems. *Chemie Ingenieur Technik*. https://doi.org/10.1002/cite.202300193
47. Malouf, P. (2008). Study of the relationship of rheology, morphology and biomass concentration of *Trichoderma reesei* fermentation [Thesis, University of Ottawa (Canada)]. http://hdl.handle.net/10393/27706
48. Kowalska, A., Boruta, T., Bizukojc, M. (2019). Kinetic model to describe the morphological evolution of filamentous fungi during their early stages of growth in the standard submerged and microparticle-enhanced cultivations. *Engineering in Life Sciences*, 19(8), 557–574. https://doi.org/10.1002/elsc.201900013
49. Gabelle, J. C., Jourdier, E., Licht, R. B., Ben Chaabane, F., Henaut, I., Morchain, J.,

Augier, F. (2012). Impact of rheology on the mass transfer coefficient during the growth phase of Trichoderma reesei in stirred bioreactors. *Chemical Engineering Science*, 75, 408–417. https://doi.org/10.1016/j.ces.2012.03.053

50. Lin, P.-J., Scholz, A., Krull, R. (2010). Effect of volumetric power input by aeration and agitation on pellet morphology and product formation of Aspergillus niger. *Biochemical Engineering Journal*, 49(2), 213–220. https://doi.org/10.1016/j.bej.2009.12.016
51. Albaek, M. O., Gernaey, K. V., Hansen, M. S., Stocks, S. M. (2011). Modeling enzyme production with Aspergillus oryzae in pilot scale vessels with different agitation, aeration, and agitator types. *Biotechnology and Bioengineering*, 108(8), 1828–1840. https://doi.org/10.1002/bit.23121
52. Bakri, Y., Mekaeel, A., Koreih, A. (2011). Influence of agitation speeds and aeration rates on the Xylanase activity of Aspergillus niger SS7. *Brazilian Archives of Biology and Technology*, 54(4), 659–664. https://doi.org/10.1590/s1516-89132011000400003
53. Bakri, Y., Akeed, Y., Thonart, P. (2012). Comparison between continuous and batch processing to produce xylanase by penicillium canescens 10-10c. *Brazilian Journal of Chemical Engineering*, 29(3), 441–448. https://doi.org/10.1590/s0104-66322012000300001
54. Motronenko, V., Bakalchuk, M., Novosad, A., Harmash, O., Marynchenko, L. (2022). Influence of hydrodynamic parameters on the synthesis of target metabolites and the degree of disintegration during the submerged cultivation of micromycetes. *Journal of Microbiology, Biotechnology and Food Sciences*, 11(5), Article e4621. https://doi.org/10.55251/jmbfs.4621
55. Galaction, A.-I., Lupasteanu, A.-M., Cascaval, D. (2007). Bioreactors with stirred bed of immobilized cells, 2. Studies on distribution of mixing efficiency. *Chemical Industry and Chemical Engineering Quarterly*, 13(3), 135–150. https://doi.org/10.2298/ciceq0703135g
56. Turnea, M., Lupăşteanu, A., Galaction, A.-I., Caşcaval, D. (2009). *Modelling of mixing in bioreactors with mobile beds of immobilized biocatalysts for six radial impellers*. In Proceedings of the 2nd WSEAS international conference on biomedical electronics and biomedical informatics (pp. 232–237).
57. Galaction, A.-I., Lupăşteanu, A.-M., Turnea, M., Caşcaval, D. (2010). Comparative analysis of mixing efficiency and distribution induced by radial impellers in bioreactors with stirred bed of immobilized cells. *Chemical Industry and Chemical Engineering Quarterly*, 16(1), 47–64. https://doi.org/10.2298/ciceq090407002g
58. Cascaval, D., Galaction, A.-I., Lupăşteanu, A.-M. (2010). Comparative evaluation of radial impellers efficiency for bioreactors with stirred bed of immobilized cells 4. Studies on mechanical effect on biocatalysts integrity. *Romanian Biotechnological Letters*, 15.
59. Cascaval, D., Galaction, A.-I., Rotaru, R., Turnea, M. (2011). Study on the mixing efficiency in a basket bioreactor with immobilized yeasts cells. *Environmental Engineering and Management Journal*, 10(5), 711–716. https://doi.org/10.30638/eemj.2011.095
60. Galaction, A.-I., Baltaru, R., Turnea, M., Cascaval, D. (2011). Ethanol production in a basket bioreactor with immobilized yeasts cells 2. Study on the mixing efficiency in the outer region of basket for a double Rushton turbine impeller. *Romanian Biotechnological Letters*, 16.
61. Wucherpfennig, T., Hestler, T., Krull, R. (2011). Morphology engineering — Osmolality and its effect on Aspergillus niger morphology and productivity. *Microbial Cell Factories*, 10(1), 58. https://doi.org/10.1186/1475-2859-10-58
62. Bliatsiou, C., Schrinner, K., Waldherr, P., Tesche, S., Böhm, L., Kraume, M., Krull, R. (2020). Rheological characteristics of filamentous cultivation broths and suitable model fluids. *Biochemical Engineering Journal*, 163, 107746. https://doi.org/10.1016/j.bej.2020.107746
63. Krull, R., Cordes, C., Horn, H., Kampen, I., Kwade, A., Neu, T. R., Nörtemann, B. (2010). *Morphology of filamentous fungi: Linking cellular biology to process engineering using aspergillus niger*. In Biosystems engineering II (pp. 1–21). Springer Berlin Heidelberg. https://doi.org/10.1007/10_2009_60
64. Kelly, S., Grimm, L. H., Bendig, C., Hempel, D. C., Krull, R. (2006). Effects of fluid dynamic induced shear stress on fungal growth and morphology. *Process Biochemistry*, 41(10), 2113–2117. https://doi.org/10.1016/j.procbio.2006.06.007
65. Buarque, F. S., da Silva, R. L., Brígida, A. I. S., Amaral, P., Coelho, M. A. Z. (2025). The effect of agitation and the use of perfluorodecalin on lipase production by yarrowia lipolytica in a bioreactor. *Processes*, 13(3), 865. https://doi.org/10.3390/pr13030865
66. Cui, Y. Q., van der Lans, R. G. J. M., Luyben, K. C. A. M. (1997). Effect of agitation intensities on fungal morphology of submerged fermentation. *Biotechnology and Bioengineering*, 55(5), 715–726. https://doi.org/10.1002/(sici)1097-

0290(19970905)55:5%3C715::aid-bit2%3E3.0.co;2-e
67. Talukdar, S., Barzee, T. J. (2023). Fungal-assisted immobilization of microalgae for simultaneous harvesting and product customization: Effects of geometry, loading, and microalgae concentration. *Algal Research*, 103242. https://doi.org/10.1016/j.algal.2023.103242
68. Venkatachalam, M., Mares, G., Dufossé, L., Fouillaud, M. (2023). Scale-Up of pigment production by the marine-derived filamentous fungus, talaromyces albobiverticillius 30548, from shake flask to stirred bioreactor. *Fermentation*, 9(1), 77. https://doi.org/10.3390/fermentation9010077
69. Kövilein, A., Aschmann, V., Zadravec, L., Ochsenreither, K. (2022). Optimization of l-malic acid production from acetate with Aspergillus oryzae DSM 1863 using a pH-coupled feeding strategy. *Microbial Cell Factories*, 21(1). https://doi.org/10.1186/s12934-022-01961-8
70. Nazir, M., Iram, A., Cekmecelioglu, D., Demirci, A. (2024). Approaches for producing fungal cellulases through submerged fermentation. *Frontiers in Bioscience-Elite*, 16(1), 5. https://doi.org/10.31083/j.fbe1601005
71. Vidra, A., Németh, Á. (2024). Stress modulation strategies in Kluyveromyces marxianus: Unravelling the effects of shear force and aeration for enhanced specific ergosterol production. *Acta Alimentaria*. https://doi.org/10.1556/066.2024.00034
72. Zhu, H., Sun, J., Tian, B., Wang, H. (2014). A novel stirrer design and its application in submerged fermentation of the edible fungus Pleurotus ostreatus. *Bioprocess and Biosystems Engineering*, 38(3), 509–516. https://doi.org/10.1007/s00449-014-1290-6
73. de Oliveira, F., Lima, C. d. A., Lopes, A. M., Marques, D. d. A. V., Druzian, J. I., Pessoa Júnior, A., Santos-Ebinuma, V. C. (2020). Microbial colorants production in stirred-tank bioreactor and their incorporation in an alternative food packaging biomaterial. *Journal of Fungi*, 6(4), 264. https://doi.org/10.3390/jof6040264
74. Waldherr, P., Bliatsiou, C., Böhm, L., Kraume, M. (2023). Fragmentation of *Aspergillus niger* pellets in stirred tank bioreactors due to hydrodynamic stress. *Chemical Engineering Research and Design*. https://doi.org/10.1016/j.cherd.2023.05.038

ПЕРЕМІШУВАЛЬНІ ПРИСТРОЇ В КУЛЬТИВУВАННІ МІЦЕЛІАЛЬНИХ КУЛЬТУР: СУЧАСНИЙ СТАН І ПЕРСПЕКТИВИ

Поліщук В. Ю., Ружанський А. С.

Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського»

E-mail: anrux@protonmail.com

Мета. Систематизувати дані про вплив перемішувальних пристроїв на ріст, морфологію та продуктивність міцеліальних культур у біотехнологічних процесах з метою визначення сучасних розробок змішувальних пристроїв і їх конструкцій для подальшого розроблення власного сучасного та інноваційного імпеллера, який мінімізуватиме недоліки чинних систем (високе енергоспоживання та механічне пошкодження міцелію).

Методи. Проведено аналіз статей за 2004–2025 роки через *Scopus, ResearchGate, PubMed, Google Scholar*, зосереджуючись на типах перемішувальних систем.

Результати. Турбіни Rushton підвищують вихід метаболітів на 35–200% для аеробних культур, гідрофойлові та пневматичні системи знижують енергоспоживання на 10–15% і оптимальні для чутливих видів, збільшуючи біомасу до 15%. Надмірний зсув знижує продуктивність на 20%.

Висновки. Перемішувальні пристрої ключові для сталого виробництва антибіотиків, ензимів, біомаси. Перспективи — гібридні конструкції та автоматизація.

Ключові слова: культивування, ниткоподібні мікроорганізми, морфологія, ензими, перемішувальні пристрої, біотехнологія, масообмін, енергоефективність.