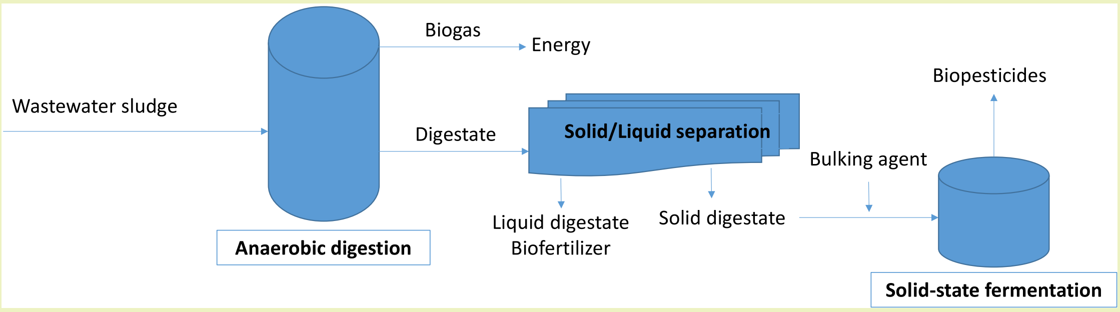
ACS Sustainable Resource Management
pubs.acs.org/acssrm
Perspective

A Perspective of Solid-State Fermentation As Emergent Technology for Organic Waste Management in the Framework of Circular Bioeconomy

Antoni Sánchez*

Cite This: *ACS Sustainable Resour. Manage.* 2024, 1, 1630−1638
Read Online



ABSTRACT: Among the different technologies to treat and valorize organic waste, solid-state fermentation (SSF) is gaining relevance in recent years as it permits the recovery of valuable biomaterials from waste, changing the paradigm: "from waste to raw material source". SSF is very similar to composting, as it implies the aerobic biodegradation of organic solid waste, but with the objective of obtaining bioproducts in some point of the process, although a compost-like end product may be also produced. Also, SSF can be coupled with anaerobic digestion, as solid digested materials can act as substrates for SSF, with a double benefit: renewable bioenergy and bioproducts. Among these bioproducts, SSF has moved from classical biotechnological compounds (enzymes or antibiotics) to more complex biomaterials, such as biopesticides, bioplastics, biosurfactants, or biostimulants, among others, which are now an emergent field of research and one of the main objectives of SSF. In summary, it is evident that SSF will have a predominant role in the framework of circular bioeconomy and in novel biorefineries for biowaste and wastewater sludge valorization, although some challenges still need further research (scale-up and down-stream).

KEYWORDS: *Bioproducts, Biorefinery, Down-stream, Circular Bioeconomy, Organic Waste, Scale-Up: Solid-State Fermentation*

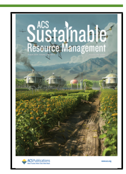
1. INTRODUCTION

One of the first studies to highlight the potential of solid-state fermentation (SSF) as an alternative way to manage organic waste in the framework of circular economy was published by Abu-Yazid et al. in 2017,[1] although few decades ago some previous works had presented the scientific fundamentals of this technology.[2,3]

In recent years, we have assisted in an important development of SSF, as a way to change the paradigm and to start considering organic waste as raw material to be transformed into valuable bioproducts. SSF beginnings were closely related to products that could only be produced by biological processes with specific strains, as it is the case of hydrolytic enzymes[4] and antibiotics.[5] In fact, enzymes are still the products more commonly published in SSF research.[6] In linear economy, the current scarcity of some raw materials and their high production costs coupled with high environmental burdens (specially their carbon and water footprints), has given SSF another turn of the screw. Now, SSF is perceived as an opportunity to obtain valuable materials, which are an alternative to their chemically-synthesized twins. This is the case for biosurfactants, bioplastics, antioxidants, or biopesticides, which are commercially available, and a wide range of other products, in different technology readiness levels.[7]

In fact, two main issues hamper the full implementation and commercialization of SSF in the value chain of organic waste: (i) bioreactor design and scale-up constraints: to avoid heat and mass transfer problems occurring in organic solid matrices and (ii) down-stream and purification: to obtain end products with similar quality than those from submerged fermentation at

Received: February 17, 2024
Revised: July 17, 2024
Accepted: July 17, 2024
Published: July 27, 2024



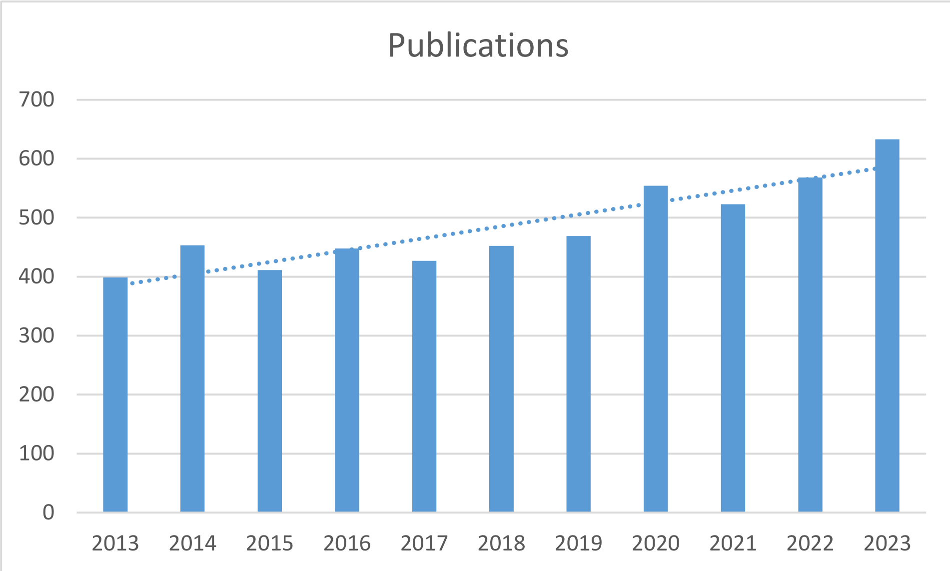


Figure 1. Papers published on "Solid-state fermentation" according to the Scopus© database in the last ten years.

competitive cost. In this sense, although in the case of scale-up there is an increasing effort to propose alternative bioreactor configurations,[8] down-stream processing is not often considered a critical point of SSF, when it can entail a considerable part of the total costs in terms of economics and environmental impact.[9]

Considering all these issues, it is also important to highlight the role of SSF in the development of the United Nation Sustainable Development Goals.[10] Although SSF can be indirectly linked with practically all of them, the most obviously related to this technology are SDG2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture; SDG9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation; SDG12: Ensure sustainable consumption and production patterns and SDG13: Take urgent action to combat climate change and its impacts.

The objective of this perspective paper is to present a general view of SSF as a powerful technology for organic waste management and valorization, beyond other classical well-settled biological treatments such as composting or anaerobic digestion, and its potential bioproducts, while highlighting its main current challenges.

2. SOLID-STATE FERMENTATION

2.1. Concept. Pandey[3] defined SSF in 2003 as "The fermentation involving solids in absence (or near absence) of free water; however, substrate must possess enough moisture to support growth and metabolism of microorganisms". This 20-year-old definition is presently absolutely valid; however SSF has evolved in several ways, which can complement the current concept of SSF from a broader point of view:

(a) Although the term "fermentation" is inherent to SSF, this is practically always developed under full aerobic conditions. In fact, a proper diffusion of oxygen inside the organic solid matrix to ensure the prevalence of an aerobic environment is necessary for most SSF processes. This also occurs in the composting processes of organic solid waste, where porosity is a controlling parameter[11] and oxygen uptake rate is often measured as overall biological activity.[12]

(b) "Free water" can coexist with SSF in some bioreactors as, for instance, biotrickling bioreactors, where the solid phase acts as support and is not only used in the nutrition of the microorganism but also creates a suitable porous environment, which is favorable for mass and heat transfer and where specifically selected strains can be used.[13]

In the context of circular bioeconomy, some specific points may complement the SSF definition from a practical point of view:

(a) "Solids" is a very general term. Currently, the majority of SSF processes uses organic solid waste as a substrate for the fermentation. In the terminology of circular bioeconomy, these solids are no longer wastes, but raw materials and feedstock. The number of waste types currently used for SSF is huge, and it moves from typical agricultural waste and crop residues[14] or municipal solid waste and its hydrolysates[15] to newly explored materials such as digestate from the exponential increase of anaerobic digestion in the world.[16]

(b) "Support growth and metabolism of microorganisms" needs more detailed explanations. On the one hand, SSF is typically performed with a sole strain, which is the producer of the compound of interest. This has evident implications in avoiding contamination and considering sterilization needs, contrary to other processes as composting.[17] On the other hand, some of the metabolites produced by SSF are secondary, which are not directly related to microorganisms' growth.[18]

Taking into account all these points, an updated condensed definition of SSF in the context of circular bioeconomy could be "the biological solid-state aerobic transformation of organic biodegradable waste into bioproducts that permits the substitution of raw sources of materials and energy."

2.2. Differences with Composting. According to the previous considerations regarding SSF, it is likely that composting seems to be similar to SSF regarding important technological aspects. Haug[19] precisely defined composting 30

https://doi.org/10.1021/acssusresmgt.4c00062
ACS Sustainable Resour. Manage. 2024, 1, 1630−1638

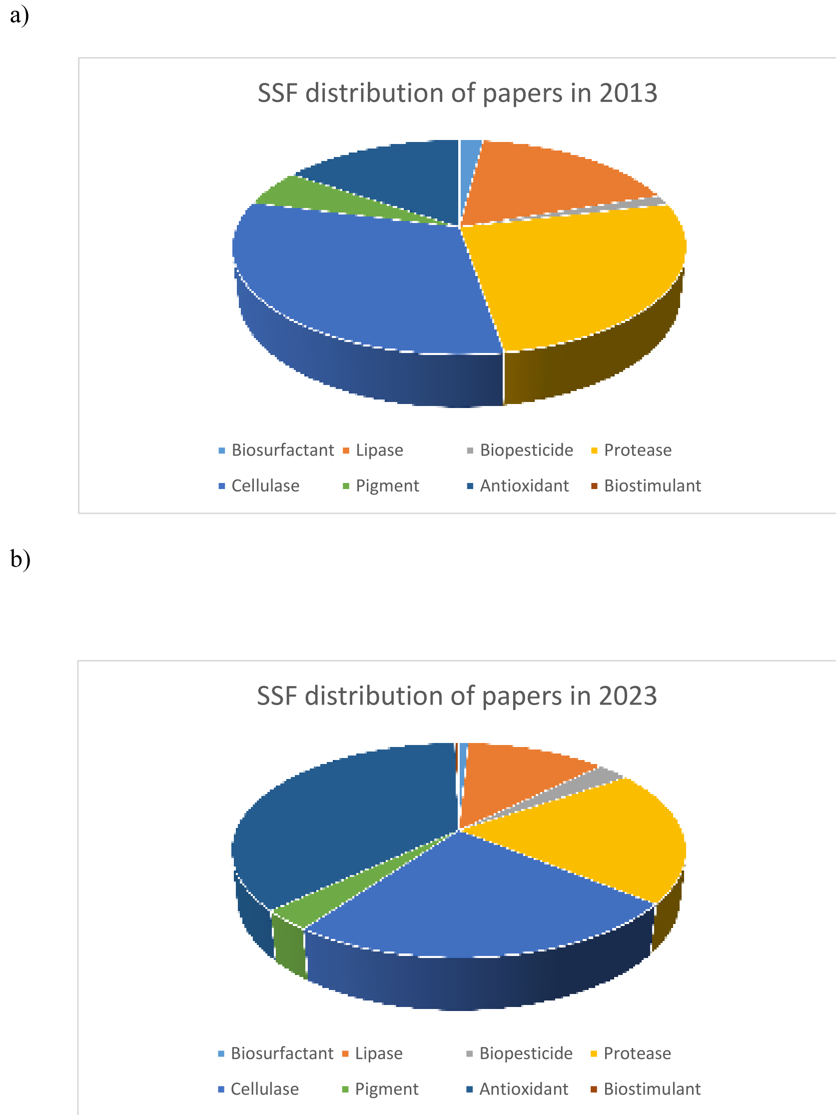


Figure 2. Topics of the papers published on "Solid-state fermentation according to the Scopus© database in (a) 2013 and (b) 2023.

years ago as "the biological decomposition and stabilization of organic substrates, under conditions that allow the development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, free of pathogens and plant seed and can be beneficially applied to land". Although this definition of composting is probably the most accepted one, it is evident that some common points with SSF are evident. Thus:

(a) Composting and SSF are technically similar: both are aerobic processes performed under solid-state conditions using organic substrates.
(b) They result in a more stabilized organic matter.

However:

(a) SSF is rarely thermophilic, although some exceptions can be found in recent literature,[20,21] in an attempt to overcome the problem of self-heating observed in organic matrices,[22] which often negatively affects the development of the desired mesophilic strain. On the contrary, composting is inherently thermophilic, as these temperatures are necessary for the sanitation of a product that is mainly applied to land as soil amendment.[23]
(b) Regarding the previous item, SSF has a different objective: to obtain a bioproduct with specific characteristics and performance. This is, by far, the fact that makes SSF more complicated than composting, as the prevalence of a specific strain is required,[24] contamination is undesirable (which can involve solid sterilization) and a down-stream process is often necessary, which can imply a high complexity when SSF is globally assessed.[25] This is the reason why composting is associated with waste management, whereas SSF is considered a biotechnology-related process. However, both technologies have many things in common, and they can serve to both purposes.[1,7]

3. EMERGING BIOPRODUCTS FROM SOLID-STATE FERMENTATION

A preliminary literature search of the term "solid-state fermentation" and its variations in Abstract, Title, or Keywords was carried out using the Scopus© database for papers published in the last ten years. The results are presented in Figure 1.

Although the increasing trend is obvious, probably the most interesting aspect is the comparison about the specific

https://doi.org/10.1021/acssusresmgt.4c00062
ACS Sustainable Resour. Manage. 2024, 1, 1630−1638

bioproducts that are studied in these papers in a ten-year interval (2013 versus 2023). The results are presented in Figure 2.

Although Figures 1 and 2 are not exact since some papers content more than one bioproduct, they show some relevant trends. For instance, hydrolytic enzymes are the most reported products in SSF research. In this case, the number of papers related to the use of cellulases to hydrolyse solid lignocellulosic waste to obtain fermentable sugars for bioethanol production has exponentially increased.[26] Another important trend is the diversification in the bioproducts that can be obtained by SSF. Specifically, the increase in the percentages of published papers related to antioxidants (from 62 papers in 2013 to 318 in 2023), biopesticides (from 6 papers in 2013 to 24 in 2023), and biostimulants (from 0 papers in 2013 to 5 in 2023) is remarkable (Figure 2). The case of antioxidants, however, needs a specific analysis, as this term is not referred to a compound or a chemically-similar group of compounds, but to a wide range of products with a common property, which can be of very different chemical composition.[27,28]

Finally, it is worthwhile to mention that the number of Review papers on SSF topics have significantly increased in the last years, from 29 published in 2013 to 76 published in 2023 (12 in January 2024), when restricting the search to the fact that the term "solid-state fermentation" appears explicitly in the title, according to the Scopus© database.

Although this perspective paper does not intend to conduct an exhaustive search on which bioproducts are currently being obtained by SSF, it is interesting to highlight some new materials that have been the objective of new research studies, beyond the already-settle ones, previously commented in Figure 2. They are presented in Table 1.

Table 1. Selection of Non-Conventional Products Obtained from Solid-State Fermentation

bioproduct	waste of origin	strain	reference
oleogels	wheat straw	*Streptomyces* sp.	29
ethyl carbamate	*Moutai*	*Lactobacillus* spp.	30
ferulic acid	cocoa shell brewer grain	*Aspergillus awamori*	31
lignin adhesive	barley straw	*Streptomyces* spp.	32
rubrosterone	*Asparagus filicinus*	*Fusarium oxysporum*	33
polyketides	brown rice malt extract	*Theissenia cinerea*	34
carotenoproteins	crawfish	*Lactobacillus paracasei*	35

As observed, several non-previously reported bioproducts can be obtained by SSF using organic waste as substrate. Again, this fact makes this technology an excellent approach to the field of circular bioeconomy, in an emerging moment of research development that is partially due to product diversification. In order to have a compilation of more typical SSF products, the reader can consult some excellent reviews published on this topic,[7,36−38] where a diversification of the bioproducts obtained by SSF along time can be easily inferred.

4. SOLID-STATE FERMENTATION CHALLENGES

4.1. Scale-Up. Contrarily to other processes with the same objective, especially submerged fermentation, where stirred forced-aerated reactors are very common, the impossibility of having an efficient mixture with solid substrates, makes SSF a challenge for reactor design. This has resulted in a large number of proposed configurations.[8] However, published papers with, at least, pilot scale experiments, are extremely scarce in scientific literature. This is a probably the main bottleneck SSF is currently facing and, in my opinion, it should be the focus of further research. It is somewhat useless to discover a new high-value bioproduct, if the experiment is performed in an Erlenmeyer flask under controlled sterilized conditions. In this sense, which are the reasons why this lab-scale experiment is not representative of a pilot one? The answer to this question is not simple, but two main issues can be highlighted, according to the principles of Transport Phenomena:

(a) *Heat transfer*: this is probably the main difference between SSF and composting. The fact that the thermal conductivity of organic matter is low,[19] hampers the release of the metabolic heat produced during fermentation, which is closely related to the waste biodegradability.[22] This is a negative point, as most of SSF strains are mesophilic. In fact, when using horticultural waste as substrates for fermentation with high lignocellulosic content, its high porosity prevents a proper heat transfer and results in the appearance of hot points, being this a critical issue in SSF bioproducts so important as bioethanol, biopesticides, or biostimulants.[7,39] In this sense, the search for thermophilic strains in SSF can be considered an attractive future line of research.[21]

(b) *Mass transfer*: oxygen is essential for SSF microorganisms. At large scale, the air provided into organic matrices tends to create preferential pathways, especially when enough porosity is not provided in the conditioning of the starting mixture and a compaction phenomenon occurs, which is also responsible for undesirable gaseous emissions.[40] This is still more complex when aeration strategies are not simple, and air supply must be adjusted during SSF to improve the process performance.[41] Anyway, it is evident that classical techniques from Chemical Engineering and Reactor Design, such as Residence Time Distributions, would be very useful.[42]

Considering these restrictions, which are often coupled with a lack of information, it is evident that modelling and related recent mathematical tools (digital twins, machine learning, or even artificial intelligence) could be of help in having robust and reproducible SSF experiments at large scale, making this technology a reliable market alternative. However, these tools have been scarcely explored, although some excellent papers have well-developed proposals,[43,44] and it should be also the focus of future research.

In a more practical strategy, I would like to highlight the use of two alternatives to classical reactors (packed-bed configurations provided with forced aeration, as shown in Figure 3) that have been applied to SSF with good results at pilot scale, overcoming some of the SSF mass and heat transfer limitations: plate reactors, with large area and low depth and well consolidated for fungi growth,[45] and the more recent approach consisting of Sequential Batch Reactors (SBR), which are also beneficial in terms of low inoculation needs and simulate a continuous processes.[46,47]

4.2. Down-Stream. This is the other main challenge of SSF. Here, we find an important difference between solid-state and submerged fermentation. In the latter case, being the product of interest in aqueous media, it is relatively easy to purify and separate it. This is not the case of SSF, where some bioproducts

https://doi.org/10.1021/acssusresmgt.4c00062
ACS Sustainable Resour. Manage. 2024, 1, 1630−1638

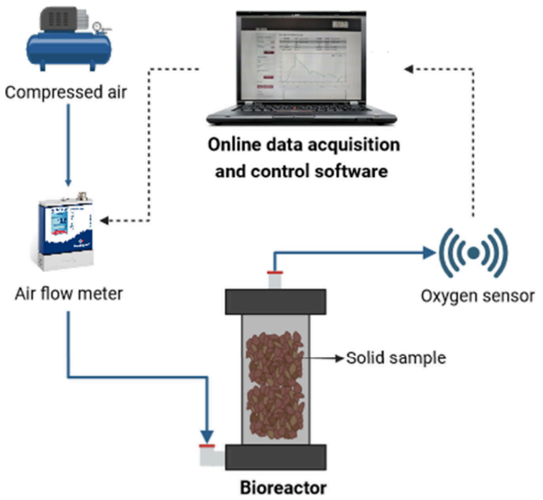


Figure 3. Simplified scheme of a packed-bed reactor typically used for solid-state fermentation. Compressed air is used to maintain aerobic conditions and exhaust gas oxygen is monitored to calculate oxygen consumption.

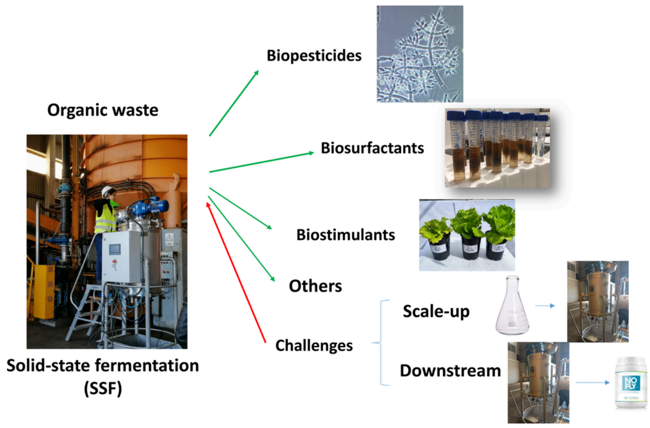


Figure 4. Main challenges of solid-state fermentation when it is used for the production of novel bioproducts from organic waste. Biopesticides, biostimulants, and biosurfactants are used as examples of bioproducts easily obtained from organic waste.

can show strong interactions with the solid phase, making very difficult and costly to have an acceptable purification if terms of recovery yield. This is especially relevant when these products are attractive on the basis of their interfacial properties and activation, as it is the case of lipases[48] and biosurfactants.[49] Nevertheless, one critical question related to down-stream and SSF must be clearly formulated: to what extent is down-stream necessary? To answer this question, two points must be rigorously analyzed:

(a) *Down-stream, purification, or characterization*? These three terms are often mentioned together, but is it evident that they mean different things. Down-stream is the sequence of operations needed to obtain an end product from fermentation, and must be assessed at a representative scale,[7] while purification and characterization are usually performed at a lower scale, with the objective of having a clear picture of what has been obtained from SSF.[20,21]

(b) *Type and use of bioproduct*? As commented above, it is evident that the complexity, cost, and feasibility of down-stream from exhaust SSF solids strongly depends on the bioproduct considered. Thus, it is completely different to extract a biosurfactant from a solid matrix[49] than a biopesticide[47] or a biostimulant[50] produced by fungi, which are better applied as soil amendments and where down-stream is not necessary at all. However, even in the case of a biosurfactant, its final application will condition its down-stream, for example, if the biosurfactant is not intended to be used as commercial detergent, but for bioremediation purposes or other environmental applications.[51]

Whatever the responses to these points are, it is evident that SSF research has prioritized obtaining attractive bioproducts with the discovery of alternative production routes (use of waste, low impact, circular bioeconomy, etc.) instead of how to reach the market, offering attractive bioproducts to the end user.[7] This has derived in a scarcity of publications on this topic, which must be urgently covered if SSF wants to be a real alternative (Figure 4).

5. ROLE OF SOLID-STATE FERMENTATION IN BIOREFINERIES

5.1. Integration of Solid-State Fermentation in Biorefineries. Considering that SSF is, from the practical point of view, a strategy to take profit from organic waste as raw material for the obtention of bioproducts of interest, it is quite evident that it is a suitable technology to be integrated in more complex facilities, especially those related to the treatment and valorization of largely-produced effluents such as organic solid waste and wastewater.[52] However, in this case, SSF is not only a complementary technology, but also another process step, which results in an increase of the complexity of existing plants[53,54] to be transformed into biorefineries.[55] Biorefineries can be defined as industrial facilities that convert biomass into energy, chemicals, and materials.[15] Having this definition in mind, SSF can be an excellent piece to complete the biorefinery puzzle, since its flexibility and variety of suitable feedstock is considerable, especially in the case where this feedstock comes from a previous treatment of organic waste or wastewater sludge, already active in the operation of current plants.[56,57]

Presently, there is a general consensus in the sense that biological treatments are the most suitable for organic waste valorization and for wastewater treatment. In the first case, several studies have pointed out that composting and anaerobic digestion are the most favorable technologies in terms of environmental impact to treat a wide variety of organic solid waste.[58,59] In the case of wastewater sludge, anaerobic digestion is being implemented in practically all the wastewater treatment plants, with the subsequent problem of digestate valorization.[16,60] In this context, SSF can have an active role to transform these facilities into multiproduct platforms (biorefineries), taking advantage of its flexibility.[7,61]

5.2. Examples. The integration of SSF in typical existing schemes of organic solid waste and wastewater (sludge line) treatment plants to convert them into biorefineries can be easily illustrated using two paradigmatic configurations:

Case 1: Mechanical-Biological Treatment Plant for Biowaste. The design, building, and operation of this kind of plants have exponentially increased in the last decades. Although the configuration of them can be somewhat different,[62] most of the operational steps are common. First, a mechanical selection is used to separate materials that can be easily recycled. Then, the organic matter is anaerobically digested to obtain biogas for

https://doi.org/10.1021/acssusresmgt.4c00062
ACS Sustainable Resour. Manage. 2024, 1, 1630−1638

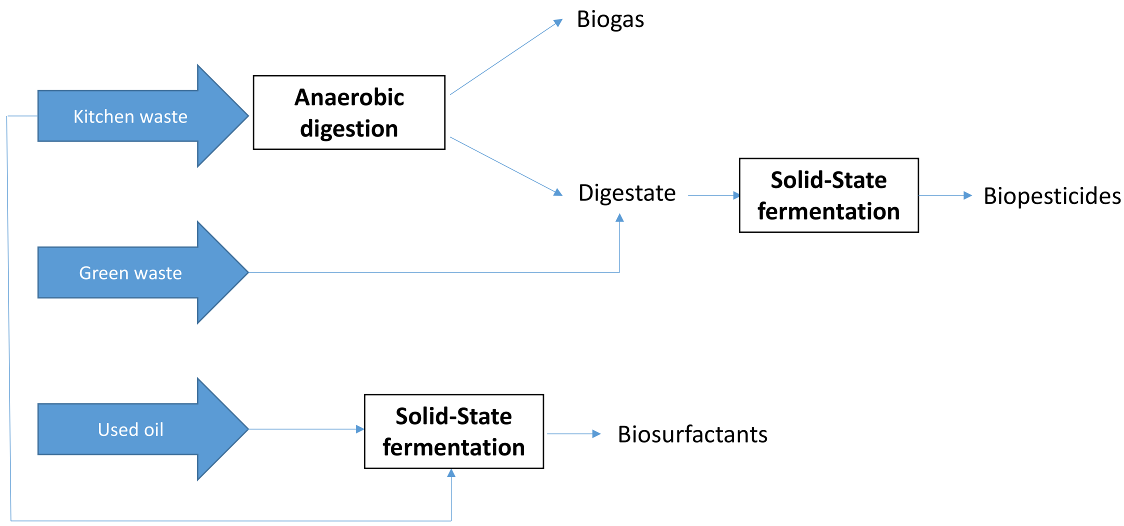


Figure 5. Alternative configuration of a biowaste treatment plant including solid-state fermentation in a biorefinery-like scheme. Kitchen waste is the main source of energy through anaerobic digestion, digestate is the source of carbon to produce biopesticides after amendment with green waste acting as bulking agent and used oil is used as hydrophobic carbon source for the production of biosurfactants (through solid-state fermentation).

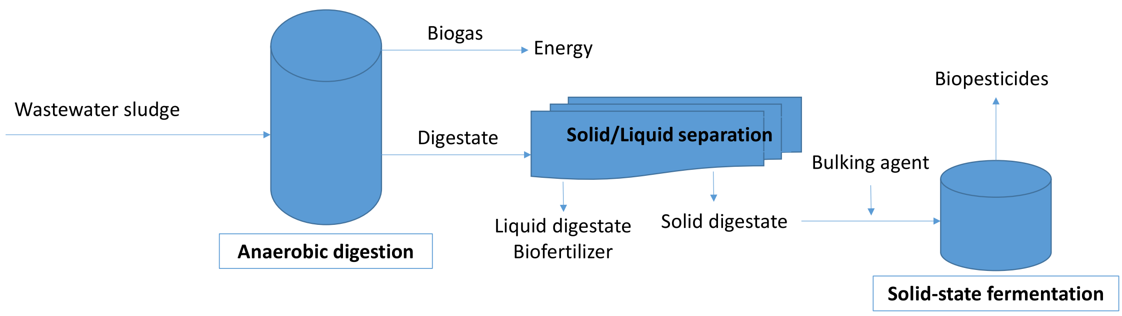


Figure 6. Alternative configuration of a wastewater treatment plant (sludge line) including solid-state fermentation in a biorefinery-like scheme. This configuration includes biopesticides production from digestate through solid-state fermentation.

energy purposes. Finally, digestate is separated in a liquid stream, which is treated as a wastewater, and a solid fraction, which normally undertakes a composting process to end up in a sanitized and stable compost.[63] If these plants are well managed, then they reach an acceptable level of organic matter stabilization[12,62] and a good performance regarding energy and materials recovery and economics.[64]

The question on how to convert these types of plants into biorefineries by including SSF has multiple answers. For instance, one possible approach is presented in Figure 5. Biorefineries are, by definition, multiple feedstock and multiple products plants. In this case, if source separation of organic matter (including kitchen waste from households, green waste from public gardening, and used oil) is well implemented, then an advanced biorefinery can include: (i) anaerobic digestion of kitchen waste, to provide energy to sustain the plant,[65] (ii) SSF with digestate and green waste as bulking agent to obtain a compost-like product enriched with biopesticide properties using well-known strains,[66,67] and (iii) a mixture of used oil with kitchen waste to provide a balanced substrate for yeast to produce biosurfactants[68,69] with a wide range of environmental applications.[51] Although this is only an example, it is illustrative of how SSF can be used to configure full-scale biorefineries in the framework of circular bioeconomy.

Case 2: Wastewater Treatment Plants (Sludge Line). In recent years, anaerobic digestion has undergone an unprecedented boost due to the search of renewable and locally-available sources of energy.[70,71] This increase has derived in the implementation of new anaerobic digesters, the search for additives to improve methane yield, such as biochar[72] or nanomaterials,[73] and a considerable number of recent publications on biogas upgrading research.[74] Unfortunately, this boost has not been accompanied by a similar increment either in implementation or in research to find alternative ways to valorize the other product of anaerobic digestion: digestate. This material is sometimes perceived as a problem because of their content in phytotoxic pollutants,[60,75] which hampers its typical application as soil organic amendment, where it presents great benefits.[76] In this case, SSF can be also of help, as the solid fraction of the digestate can be used as substrate for the growth of strains that are able to produce biopesticides, biostimulants, and enzymes, among others.[16,56,77,78] Figure 6 shows how a slight modification of the sludge line of a typical wastewater treatment plant can convert the plant into a most profitable facility following the biorefinery principles.

6. CONCLUSIONS AND FINAL REMARKS

SSF can be considered an emerging and very attractive biotechnology in the framework of the circular economy. Several important issues make SSF a flawless approach to be fully developed and implemented: the possibility of obtaining a wide range of different bioproducts, low or no need of water, no

https://doi.org/10.1021/acssusresmgt.4c00062
ACS Sustainable Resour. Manage. 2024, 1, 1630−1638

generation of wastewater, organic waste recovery, and valorization, with the resulting reduction of raw materials and low energy consumption carbon footprint, among others. These SSF important features are closely linked with the Sustainable Development Goals promoted by The United Nations at the worldwide level.

However, SSF needs additional research and engineering to face two important drawbacks that hamper its full development and implementation at commercial scale. The most important one is scale-up, especially for bioreactor design, in which we have new tools that could be an excellent topic for future SSF researchers, as is the case for machine learning and artificial intelligence. How the down-stream process will end up in a commercial bioproduct is the other important SSF challenge to be overcome in the near future. However, it is important to note that the complexity of this process largely depends on the bioproduct end use. Nevertheless, down-stream information is critical to have a complete SSF figure, including technological, environmental, and economic items. All these factors will inevitably condition the final extent of SSF in the future circular bioeconomy and in the configuration of a new generation of waste-based biorefineries.

■ AUTHOR INFORMATION

Corresponding Author

Antoni Sánchez − *GICOM Research Group, Department of Chemical, Biological and Environmental Engineering, School of Engineering, Edifici Q, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain;* orcid.org/0000-0003-4254-8528; Email: antoni.sanchez@uab.cat

Complete contact information is available at:
https://pubs.acs.org/10.1021/acssusresmgt.4c00062

Notes

The author declares no competing financial interest.

Biography

Dr. Antoni Sánchez is leading the Composting Research Group since year 2000. He works as Full Professor in the Department of Chemical, Biological, and Environmental Engineering of theUniversitat Autònoma de Barcelona. His research lines cover the main aspects involved in the treatment of organic solid waste, through several strategies. Composting, anaerobic digestion, and solid-state fermentation are the main topics. He has participated in and coordinated several Spanish and European projects on this topic, supervised PhD and Master Thesis, and is the author of more than 200 indexed papers as well as book chapters and patents.

■ ACKNOWLEDGMENTS

This work received financial support from the Spanish Ministerio de Ciencia e Innovación (Project PID2020-114087RB-I00, Surfing Waste).

■ REFERENCES

(1) Abu Yazid, N.; Barrena, R.; Komilis, D.; Sánchez, A. Solid-State Fermentation as a Novel Paradigm for Organic Waste Valorization: A Review. *Sustainability* **2017**, *9*, 224.

(2) Pandey, A. Solid-state fermentation. *Biochem. Eng. J.* **2003**, *13* (2-3), 81−84.

(3) Singhania, R.R.; Patel, A.K.; Soccol, C.R.; Pandey, A. Recent advances in solid-state fermentation. *Biochem. Eng. J.* **2009**, *44*, 13−18.

(4) Pandey, A.; Selvakumar, P.; Soccol, C.R.; Nigam, P. Solid state fermentation for the production of industrial enzymes. *Curr. Sci.* **1999**, *77* (1), 149−162.

(5) Yang, S.S. Antibiotics production of cellulosic waste with solid state fermentation by Streptomyces. *Renew. Energy* **1996**, *9* (1-4), 976−979.

(6) El-Bakry, M.; Abraham, J.; Cerda, A.; Barrena, R.; Ponsá, S.; Gea, T.; Sánchez, A. From Wastes to High Value Added Products: Novel Aspects of SSF in the Production of Enzymes. *Crit. Rev. Environ. Sci. Technol.* **2015**, *45* (18), 1999−2042.

(7) Oiza, N.; Moral-Vico, J.; Sánchez, A.; Oviedo, E.R.; Gea, T. Solid-State Fermentation from Organic Wastes: A New Generation of Bioproducts. *Processes* **2022**, *10*, 2675.

(8) Mitchell, D.A.; Ruiz, H.A.; Krieger, N.A. Critical Evaluation of Recent Studies on Packed-Bed Bioreactors for Solid-State Fermentation. *Processes* **2023**, *11*, 872.

(9) Catalán, E.; Komilis, D.; Sánchez, A. Environmental impact of cellulase production from coffee husks by solid-state fermentation: A life-cycle assessment. *J. Clean. Prod.* **2019**, *233*, 954−962.

(10) United Nations, 2016. Sustainable Development Goals. URL: https://sdgs.un.org/goals (accessed February 2024).

(11) Ruggieri, L.; Gea, T.; Artola, A.; Sánchez, A. Air filled porosity measurements by air pycnometry in the composting process: A review and a correlation analysis. *Bioresource Technol.* **2009**, *100* (10), 2655−2666.

(12) Sánchez, A. A perspective on the use of respiration indices beyond the measurement of the stability of compost. *Waste Manage. Bull.* **2023**, *1* (2), 1−5.

(13) Banat, I.M.; Carboué, Q.; Saucedo-Castañeda, G.; Cázares-Marinero, J. J. Biosurfactants: The green generation of speciality chemicals and potential production using Solid-State fermentation (SSF) technology. *Bioresour. Technol.* **2021**, *320* (A), 124222.

(14) Sala, A.; Vittone, S.; Barrena, R.; Sánchez, A.; Artola, A. Scanning agro-industrial wastes as substrates for fungal biopesticide production: Use of *Beauveria bassiana* and *Trichoderma harzianum* in solid-state fermentation. *J. Environ. Manage.* **2021**, *295*, 113113.

(15) Molina-Peñate, E.; Artola, A.; Sánchez, A. Organic municipal waste as feedstock for biorefineries: bioconversion technologies integration and challenges. *Rev. Environ. Sci. Biotechnol.* **2022**, *21*, 247−267.

(16) Cerda, A.; Mejias, L.; Rodríguez, P.; Rodríguez, A.; Artola, A.; Font, X.; Gea, T.; Sánchez, A. Valorisation of digestate from biowaste through solid-state fermentation to obtain value added bioproducts: A first approach. *Bioresource Technol.* **2019**, *271*, 409−416.

(17) Fang, J.; Liu, Y.; Huan, C.; Xu, L.; Ji, G.; Yan, Z. Comparison of poly-γ-glutamic acid production between sterilized and non-sterilized solid-state fermentation using agricultural waste as substrates. *J. Clean. Prod.* **2020**, *255*, 120248.

(18) Kumar, V.; Ahluwalia, V.; Saran, S.; Kumar, J.; Patel, A. K.; Singhania, R. R. Recent developments on solid-state fermentation for production of microbial secondary metabolites: Challenges and solutions. *Bioresour. Technol.* **2021**, *323*, 124566.

(19) Haug, R.T. *The Practical Handbook of Compost Engineering*; Lewis Publishers, Boca Raton, FL, 1993.

(20) El-Bakry; Gea, T.; Sánchez, A. Inoculation effect of thermophilic microorganisms on protease production through solid-state fermentation under non-sterile conditions at lab and bench scale (SSF). *Bioprocess Biosyst. Eng.* **2016**, *39*, 585−592.

(21) Argentin, M. N.; Martins, L. F.; Sousa, M. P.; Bossolan, N. R. S. Biosurfactant from a thermo-halophilic strain of *Bacillus alveayuensis* isolated from a Brazilian oil reservoir: Production, chemical characterization, antimicrobial activity, and efficiency in wettability reversal and oil removal from oil-soaked sand. *Geoenergy Sci. Eng.* **2023**, *231*, 212324.

(22) Barrena, R.; Canovas, C.; Sánchez, A. Prediction of temperature and thermal inertia effect in the maturation stage and stockpiling of a large composting mass. *Waste Manage.* **2006**, *26*, 953−959.

(23) Sayara, T.; Basheer-Salimia, R.; Hawamde, F.; Sánchez, A. Recycling of Organic Wastes through Composting: Process Perform-

ance and Compost Application in Agriculture. *Agronomy* **2020**, *10*, 1838.

(24) Martínez-Ávila, O.M.; Sánchez, A.; Font, X.; Barrena, R. 2-phenylethanol rose aroma production potential of an isolated *Pichia kudriavzevii* through solid-state fermentation. *Process Biochem.* **2020**, *93*, 94−103.

(25) Catalán, E.; Komilis, D.; Sánchez, A. A Life Cycle Assessment on the Dehairing of Rawhides: Chemical Treatment versus Enzymatic Recovery through Solid State Fermentation. *J. Ind. Ecol.* **2019**, *23*, 361−373.

(26) Wang, M.; Cui, H.; Gu, C.; Li, A.; Qiao, J.; Schwaneberg, U.; Zhang, L.; Wei, L.; Li, X.; Huang, H. Engineering All-Round Cellulase for Bioethanol Production. *ACS Synth. Biol.* **2023**, *12*, 2187−2197.

(27) Zhang, Y.; Zhou, J.; Zhang, N.; Zhao, L.; Wu, W.; Zhang, L.; Zhou, F. Process Optimization for Production of Ferulic Acid and Pentosans from Wheat Brans by Solid-State Fermentation and Evaluation of Their Antioxidant Activities. *ACS Food Sci. Technol.* **2022**, *2*, 1114−1122.

(28) Erskine, E.; Ozkan, G.; Lu, B.; Capanoglu, E. Effects of Fermentation Process on the Antioxidant Capacity of Fruit Byproducts. *ACS Omega* **2023**, *8*, 4543−4553.

(29) Borrero-López, A.M.; Blánquez, A.; Valencia, C.; Hernández, M.; Arias, M.E.; Eugenio, M.E.; Fillat, U.; Franco, J.M. Valorization of Soda Lignin from Wheat Straw Solid-State Fermentation: Production of Oleogels. *ACS Sustainable Chem. Eng.* **2018**, *6*, 5198−5205.

(30) Du, H.; Song, Z.; Xu, Y. Ethyl Carbamate Formation Regulated by Lactic Acid Bacteria and Nonconventional Yeasts in Solid-State Fermentation of Chinese *Moutai*-Flavor Liquor. *J. Agric. Food Chem.* **2018**, *66*, 387−392.

(31) dos Santos Costa, R.; de Almeida, S.S.; d'Avila Costa Cavalcanti, E.; Guimarães Freire, D.M.; Moura-Nunes, N.; Monteiro, M.; Perrone, D. Enzymes produced by solid state fermentation of agro-industrial by-products release ferulic acid in bioprocessed whole-wheat breads. *Food Res. Int.* **2021**, *140*, 109843.

(32) Blánquez, A.; Borrero-López, A.M.; Domínguez, G.; Valencia, C.; Molina-Guijarro, J.M.; Eugenio, M.E.; Ibarra, D.; Hernández, M. Solid-State Fermentation with *Streptomyces* as an Ecofriendly Route to Tune Lignin Properties and Its Use as a Binder in Adhesive Formulation. *ACS Sustainable Chem. Eng.* **2022**, *10*, 10403−10416.

(33) Li, Y.; Cai, L.; Dong, J.-W.; Xing, Y.; Duan, W.-H.; Zhou, H.; Ding, Z.-T. Innovative Approach to the Accumulation of Rubrosterone by Fermentation of *Asparagus filicinus* with *Fusarium oxysporum*. *J. Agric. Food Chem.* **2015**, *63*, 6596−6602.

(34) Hsieh, M.-H.; Hsiao, G.; Chang, C.-H.; Yang, Y.-L.; Ju, Y.-M.; Kuo, Y.-H.; Lee, T.H. Polyketides with Anti-neuroinflammatory Activity from *Theissenia cinerea*. *J. Nat. Prod.* **2021**, *84*, 1898−1903.

(35) Cremades, O.; Ponce, E.; Corpas, R.; Gutiérrez, J.F.; Jover, M.; Alvarez-Ossorio, M.C.; Parrado, J.; Bautista, J. Processing of Crawfish (*Procambarus clarkii*) for the Preparation of Carotenoproteins and Chitin. *J. Agric. Food Chem.* **2001**, *49*, 5468−5472.

(36) Lizardi-Jiménez, M.A.; Hernández-Martínez, R. Solid state fermentation (SSF): diversity of applications to valorize waste and biomass. *3 Biotech* **2017**, *7*, 44.

(37) Cerda, A.; Artola, A.; Barrena, R.; Font, X.; Gea, T.; Sánchez, A. Innovative Production of Bioproducts From Organic Waste Through Solid-State Fermentation. *Front. Sustain. Food Syst.* **2019**, *3*, 63.

(38) Mattedi, A.; Sabbi, E.; Farda, B.; Djebaili, R.; Mitra, D.; Ercole, C.; Cacchio, P.; Del Gallo, M.; Pellegrini, M. Solid-State Fermentation: Applications and Future Perspectives for Biostimulant and Biopesticides Production. *Microorganisms* **2023**, *11*, 1408.

(39) El Sheikha, A.F.; Ray, R.C. Bioprocessing of Horticultural Wastes by Solid-State Fermentation into Value-Added/Innovative Bioproducts: A Review. *Food Rev. Int.* **2023**, *39*, 3009−3065.

(40) Chang, F.; Fabian-Wheeler, E.; Richard, T.L.; Hile, M. Compaction effects on greenhouse gas and ammonia emissions from solid dairy manure. *J. Environ. Manage.* **2023**, *332*, 117399.

(41) Mejias, L.; Estrada, M.; Barrena, R.; Gea, T. A novel two-stage aeration strategy for *Bacillus thuringiensis* biopesticide production from biowaste digestate through solid-state fermentation. *Biochem. Eng. J.* **2020**, *161*, 107644.

(42) Puyuelo, B.; Gea, T.; Sánchez, A. A new control strategy for the composting process based on the oxygen uptake rate. *Chem. Eng. J.* **2010**, *165*, 161−169.

(43) Casciatori, F.P.; Bück, A.; Thoméo, J.C.; Tsotsas, E. Two-phase and two-dimensional model describing heat and water transfer during solid-state fermentation within a packed-bed bioreactor. *Chem. Eng. J.* **2016**, *287*, 103−116.

(44) Lopes Perez, C.; Casciatori, F.P.; Thoméo, J.C. Strategies for scaling-up packed-bed bioreactors for solid-state fermentation: The case of cellulolytic enzymes production by a thermophilic fungus. *Chem. Eng. J.* **2019**, *361*, 1142−1151.

(45) Aikat, K.; Bhattacharyya, B.C. Protease production in solid state fermentation with liquid medium recycling in a stacked plate reactor and in a packed bed reactor by a local strain of *Rhizopus oryzae*. *Process Biochem.* **2001**, *36*, 1059−1068.

(46) Cerda, A.; El-Bakry, M.; Gea, T.; Sánchez, A. Long term enhanced solid-state fermentation: Inoculation strategies for amylase production from soy and bread wastes by *Thermomyces* sp. in a sequential batch operation. *J. Environ. Chem. Eng.* **2016**, *4*, 2394−2401.

(47) Sala, A.; Barrena, R.; Sánchez, A.; Artola, A. Fungal biopesticide production: Process scale-up and sequential batch mode operation with *Trichoderma harzianum* using agro-industrial solid wastes of different biodegradability. *Chem. Eng. J.* **2021**, *425*, 131620.

(48) Santis-Navarro, A.; Gea, T.; Barrena, R.; Sánchez, A. Production of lipases by solid state fermentation using vegetable oil-refining wastes. *Bioresource Technol.* **2011**, *102*, 10080−10084.

(49) Varjani, S.J.; Upasani, V.N. Critical review on biosurfactant analysis, purification and characterization using rhamnolipid as a model biosurfactant. *Bioresource Technol.* **2017**, *232*, 389−397.

(50) Ghoreishi, G.; Barrena, R.; Font, X. Using green waste as substrate to produce biostimulant and biopesticide products through solid-state fermentation. *Waste Manage.* **2023**, *159*, 84−92.

(51) Eras-Muñoz, E.; Farré, A.; Sánchez, A.; Font, X.; Gea, T. Microbial biosurfactants: a review of recent environmental applications. *Bioengineered* **2022**, *13*, 12365−12391.

(52) Karolinczak, B.; Walczak, J.; Bogacka, M.; Zubrowska-Sudol, M. Life Cycle Assessment of sewage sludge mono-digestion and co-digestion with the organic fraction of municipal solid waste at a wastewater treatment plant. *Sci. Total. Environ.* **2024**, *907*, 167801.

(53) Pognani, M.; Barrena, R.; Font, X.; Sánchez, A. A complete mass balance of a complex combined anaerobic/aerobic municipal source-separated waste treatment plant. *Waste Manage.* **2012**, *32*, 799−805.

(54) González, D.; Colón, J.; Sánchez, A.; Gabriel, D. Multipoint characterization of the emission of odour, volatile organic compounds and greenhouse gases from a full-scale membrane-based municipal WWTP. *J. Environ. Manage.* **2022**, *313*, 115002.

(55) Molina-Peñate, E.; Artola, A.; Sánchez, A. Exploring biorefinery alternatives for biowaste valorization: a techno-economic assessment of enzymatic hydrolysis coupled with anaerobic digestion or solid-state fermentation for high-value bioproducts. *Bioengineered* **2024**, *15*, 1.

(56) Rodríguez, P.; Cerda, A.; Font, X.; Sánchez, A.; Artola, A. Valorisation of biowaste digestate through solid state fermentation to produce biopesticides from *Bacillus thuringiensis*. *Waste Manage.* **2019**, *93*, 63−71.

(57) Molina-Peñate, E.; Vargas-García, M.C.; Artola, A.; Sánchez, A. Filling in the gaps in biowaste biorefineries: The use of the solid residue after enzymatic hydrolysis for the production of biopesticides through solid-state fermentation. *Waste Manage.* **2023**, *161*, 92−103.

(58) Colón, C.; Cadena, E.; Pognani, M.; Barrena, R.; Sánchez, A.; Font, X.; Artola, A. Determination of the energy and environmental burdens associated with the biological treatment of source-separated Municipal Solid Wastes. *Energy Environ. Sci.* **2012**, *5*, 5731−5741.

(59) Pasqualino, J.C.; Meneses, M.; Abella, M.; Castells, F. LCA as a Decision Support Tool for the Environmental Improvement of the Operation of a Municipal Wastewater Treatment Plant. *Environ. Sci. Technol.* **2009**, *43*, 3300−3307.

(60) Gu, X.; Wong, J. W. C. Identification of Inhibitory Substances Affecting Bioleaching of Heavy Metals from Anaerobically Digested Sewage Sludge. *Environ. Sci. Technol.* **2004**, *38*, 2934−2939.

(61) Hu, Y.; Du, C.; Leu, S.-Y.; Jing, H.; Li, X.; Lin, C. S. K. Valorisation of textile waste by fungal solid state fermentation: An example of circular waste-based biorefinery. *Resour. Conserv. Recycl.* **2018**, *129*, 27−35.

(62) Colón, J.; Ponsá, S.; Álvarez, C.; Vinot, M.; Lafuente, F.J.; Gabriel, D.; Sánchez, A. Analysis of MSW full-scale facilities based on anaerobic digestion and/or composting using respiration indices as performance indicators. *Bioresource Technol.* **2017**, *236*, 87−96.

(63) Ponsá, S.; Gea, T.; Alerm, L.; Cerezo, J.; Sánchez, A. Comparison of aerobic and anaerobic stability indices through a MSW biological treatment process. *Waste Manage.* **2008**, *28*, 2735−2742.

(64) Abad, V.; Avila, R.; Vicent, T.; Font, X. Promoting circular economy in the surroundings of an organic fraction of municipal solid waste anaerobic digestion treatment plant: Biogas production impact and economic factors. *Bioresource Technol.* **2019**, *283*, 10−17.

(65) Komilis, D.; Barrena, R.; Lora Grando, R.; Vogiatzi, V.; Sánchez, A.; Font, X. A state of the art literature review on anaerobic digestion of food waste: influential operating parameters on methane yield. *Rev. Environ. Sci. Biotechnol.* **2017**, *16*, 347−360.

(66) Ballardo, C.; Vargas-García, M.C.; Sánchez, A.; Barrena, R.; Artola, A. Adding value to home compost: Biopesticide properties through *Bacillus thuringiensis* inoculation. *Waste Manage.* **2020**, *106*, 32−43.

(67) Ballardo, C.; Barrena, R.; Artola, A.; Sánchez, A. A novel strategy for producing compost with enhanced biopesticide properties through solid-state fermentation of biowaste and inoculation with *Bacillus thuringiensis*. *Waste Manage.* **2017**, *70*, 53−58.

(68) Jiménez-Peñalver, P.; Castillejos, M.; Koh, A.; Gross, R.; Sánchez, A.; Font, X.; Gea, T. Production and characterization of sophorolipids from stearic acid by solid-state fermentation, a cleaner alternative to chemical surfactants. *J. Clean. Prod.* **2018**, *172*, 2735−2747.

(69) Rodríguez, A.; Gea, T.; Font, X. Sophorolipids Production from Oil Cake by Solid-State Fermentation. Inventory for Economic and Environmental Assessment. *Front. Chem. Eng.* **2021**, *3*, 3.

(70) Satchwell, A.J.; Scown, C.D.; Smith, S.J.; Amirebrahimi, J.; Jin, L.; Kirchstetter, T.W.; Brown, N.J.; Preble, C.V. Accelerating the Deployment of Anaerobic Digestion to Meet Zero Waste Goals. *Environ. Sci. Technol.* **2018**, *52*, 13663−13669.

(71) Fonoll Almansa, X.; Starostka, R.; Raskin, L.; Zeeman, G.; De Los Reyes, F., III; Waechter, J.; Yeh, D.; Radu, T. Anaerobic Digestion as a Core Technology in Addressing the Global Sanitation Crisis: Challenges and Opportunities. *Environ. Sci. Technol.* **2023**, *57*, 19078−19087.

(72) Parra-Orobio, B.A.; Soto-Paz, J.; Oviedo-Ocaña, E.R.; Vali, S.A.; Sánchez, A. Advances, trends and challenges in the use of biochar as an improvement strategy in the anaerobic digestion of organic waste: a systematic analysis. *Bioengineered* **2023**, *14*, 1.

(73) Barrena, R.; Moral-Vico, J.; Font, X.; Sánchez, A. Enhancement of Anaerobic Digestion with Nanomaterials: A Mini Review. *Energies* **2022**, *15*, 5087.

(74) Zhao, J.; Li, Y.; Dong, R. Recent progress towards in-situ biogas upgrading technologies. *Sci. Total Environ.* **2021**, *800*, 149667.

(75) Caspersen, S.; Oskarsson, C.; Asp, H. Nutrient challenges with solid-phase anaerobic digestate as a peat substitute - Storage decreased ammonium toxicity but increased phosphorus availability. *Waste Manage.* **2023**, *165*, 128−139.

(76) Orner, K.D.; Smith, S.; Nordahl, S.; Chakrabarti, A.; Breunig, H.; Scown, C.D.; Leverenz, H.; Nelson, K.L.; Horvath, A. Environmental and Economic Impacts of Managing Nutrients in Digestate Derived from Sewage Sludge and High-Strength Organic Waste. *Environ. Sci. Technol.* **2022**, *56*, 17256−17265.

(77) Molina-Peñate, E.; Arenòs, N.; Sánchez, A.; Artola, A. *Bacillus thuringiensis* Production Through Solid-State Fermentation Using Organic Fraction of Municipal Solid Waste (OFMSW) Enzymatic Hydrolysate. *Waste Biomass Valor.* **2023**, *14*, 1433−1445.

(78) Bulgari, D.; Alias, C.; Peron, G.; Ribaudo, G.; Gianoncelli, A.; Savino, S.; Boureghda, H.; Bouznad, Z.; Monti, E.; Gobbi, E. Solid-State Fermentation of *Trichoderma* spp.: A New Way to Valorize the Agricultural Digestate and Produce Value-Added Bioproducts. *J. Agric. Food Chem.* **2023**, *71*, 3994−4004.