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ROYAL SOCIETY
OF CHEMISTRY

View Article Online
DOI: 10.1039/D4SU00582A

Sustainability Spotlight Statement

Sustainable treatment of biowastes or organic wastes like food wastes, municipal solid wastes, sewage sludge, plant's materials, animal biomasses, aquatic and terrestrial wastes, agricultural and forestry wastes, and many others are the need of time and different countries are working on the various related project in order to treat these biowastes and sustainably produce energy, biogases, methane, ethanol, carbohydrates, protein and several other useful chemicals. This type of sustainable literature review may helpful to better understand the goals of sustainable development. This critical review may be well aligned with various sustainable development goals of United Nations like 'affordable and clean energy' (UN's SDG 7), 'sustainable cities and communities' (UN's SDG 11) and 'responsible consumption and production' (UN's SDG 12).

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DOI: 10.1039/D4SU00582A

Fungal Pretreatment Methods for Organic Wastes: Advances and Challenges in Biomass Valorization

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ABSTRACT

View Article Online
DOI: 10.1039/D4SU00582A

Food wastes, municipal solid wastes, sewage sludge, plant's materials, animal biomasses, aquatic and terrestrial wastes, agricultural and forestry wastes, industrial and domestic wastes and many other lignocellulosic biomasses are considered under the category of organic wastes or bio-wastes. Various techniques, mainly mechanical pretreatment (high pressure homogenization and ultra-sonication), thermal (temperature based) pretreatment, microwave technology of pretreatment, chemical pretreatment, and biological pretreatment are found to be effective in the organic wastes valorization. Fungal pretreatment of organic wastes is a promising biological technology because of its excellent efficiency of the decomposition of various types of organic wastes like food wastes, ligno-cellulosic biomasses, hemicellulose, agricultural wastes, hardwoods, softwoods, switchgrass, spent coffee grounds, park wastes, cattle dung, and solid digestate which have been reviewed pointedly. Fungal pretreatment of the organic waste materials may give advantageous products like biogases, energy source, sugars' monomeric or oligomeric products, different type of acids, and many more. Major challenge associated with the fungal pretreatment technology is the requirement of higher time for greater degree of biomass valorization which raises the cost as well as vulnerability of contamination but the use of fungal pretreatment with other pretreatment techniques may reduce the time and enhance the functionality of the method with higher rate of biomass valorization. Heat generation in fungal pretreatment process and need of feedstock sterilization before fungal pretreatment are some other challenges to be properly tackled for its efficient application at industrial scale. In this review, use of different fungal pretreatment methods for the valorization of different types of biomasses and production of valuable products have been evaluated and discussed. Authors have provided an inclusive assessment of the fungal pre-treatment of various types of organic wastes along with the concise but effective discussions on the organic solid wastes and different pretreatment techniques involved in the bio-waste digestion processes. Techno-economic analysis, challenges and future perspectives have also been discussed.

Keywords: Fungal pretreatment, organic solid waste, bio-waste, ligno-cellulosic biomass, cellulose, biogas, methane gas.

1 INTRODUCTION

Solid wastes materials or organic wastes or bio-wastes materials are composed of large size organic molecules (macromolecules) like lignocellulose, lignin, hemicellulose, proteins, fats, and vitamins etc. and they are being produced due to the various reasons and their decomposition produces harmful gases and constituents which are needed to be resolved properly. Proper management of these bio-wastes may also produce several beneficial products like biogases, sugars, electricity (*via* biogases or other fuel sources derived from biowastes' valorization), short chain carboxylic acids, fertilizers and other several products. The growth of the generation of municipal solid wastes is expected to rise from 2.1 billion tonnes in year 2023 to 3.8 billion tonnes by the year 2050.[1] On other side, food loss and associated waste are global challenges and it is a prediction that 13% of the globally generated food is wasted per year from harvest up to, but not counting retail, with about four hundred billion US Dollars' economic value.[2] Additionally, households, restaurants and many other food services are responsible for about 19% of the food loss or food waste generation.[2] Disposed food wastes in 2017 were 38.1 million tons.[3] So, it is crucial to carefully manage the waste of food in order to avoid the health issues and contamination of environment.[4,5] The biggest waste produced in the course of the process of sewage treatment is sewage sludge which is very rich in the organic content and due to which it is thought as

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organic municipal solid waste.[6] The sewage sludge's generation has grown throughout the year. As for instance, sewage sludge's dry mass has heightened annually from ten million tons (in 2010) to 13.5 million tons (in 2020) in the twenty seven European Union countries.[7] The process of composting and anaerobic digestion is preferred because waste can be processed by these ways into the safe products like organic fertilizers and soil improvers.[8]

A series of management strategies are being promoted by the various countries and technologies for food waste treatment are being developed. In Germany, there were greater than nine thousand pertinent food waste anaerobic digestion projects in action by 2015, accounting for greater than eighty percent of the biogas based projects in Europe.[9] Additionally, food waste produces around fertilizer's 5 million tons every year.[10,11] By 2025, rate of recycling of food waste is intended to be increased by UK from current 10% to 70%.[12,13] Organic macromolecules like proteins, sugars and fats are found in the food waste materials. Food wastes also have trace elements like Fe (iron) and Co (cobalt), which facilitate the microorganisms' growth.[14]

Huge generations of bio-wastes are serious problems for the world, specifically for developing countries where managements are not as good as developed countries. But, they may also be converted into the useful form if proper managements of the bio-wastes' pretreatment are up to the mark because bio-pretreatment of such wastes may give huge amount of energy and useful products. There are some important pretreatment techniques known for the pretreatment of organic bio-wastes (**Fig. 1**) i.e. mechanical techniques of pretreatments including high pressure homogenization and ultrasonication, thermal technique of pretreatment, microwave assisted pretreatment, combined technology of pretreatment, chemical technology of pretreatment, biological method of pretreatment including bacterial pretreatment, enzymatic pretreatment, and fungal pretreatment techniques. Complexity of the lignocellulosic structures and problems linked with pretreatment's chemical as well as

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physical methods make the biological techniques very useful because they are environment friendly, economical, effective and does not require or release any toxic chemicals.[15] Aerobic method of pretreatment, temperature-phased anaerobic digestion, and enzyme-mediated pretreatment processes are promising biological pretreatment processes[16] which may be used as favorable alternatives of chemical, physical, or thermal processes. Aerobic process is depended on sludge's inherent enzymatic activity, which requires oxygen,[17] on the other hand temperature-phased anaerobic digestion is done through the configuration composed of two digesters in a series where thermophilic condition is applied for first digester while mesophilic ones for the second digester.[16] Enzyme-mediated process of pretreatment causes the improvement of the sludge bioconversion with the assistance of exogenous enzymes, contributing in the refractory compounds' degradation.[16] For the production of biogas from sludge, a critical review on various pretreatment methods has been presented by Mitraka et al.[18]

Fungi and their enzymatic systems are known for their huge biotechnological application due to their versatile capability and several enzymes producing ability.[19-22] Fungi have also the great roles in the environment restoration by eliminating or degrading the several toxic environmental pollutants like organic molecules or heavy metals.[23,24] Along with these applications, fungi also have strong potential in the biological pretreatment of organic wastes or bio-wastes. Out of several physical, chemical and biological pretreatment techniques,[18,25] fungal based biological methods may play an emerging role in this area. Fungal pretreatment method is an important conventional pretreatments' alternative that is mostly worked at 25–30 °C temperature range, in minimum use of water, at atmospheric pressure, and without the use of any chemicals.[26] Wood rot funguses like soft, white, or brown funguses have the most precious role in the fungal pretreatment technique because of their potential to change the lignocellulosic biomass' constituents.[27] After the fungal

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pretreatment, detoxification and/or washing are not generally necessary because the fungal treatment's mild conditions are unlikely to generate microbial inhibitory compounds. At higher feedstock's particle sizes, fungal technique of pretreatment is more effective than the most conventional methods of pretreatment.[26] Fungal pretreatment have also some disadvantages along with aforementioned advantages. Requirement of long time for reaction, smaller yields of sugars and the need of sterilization of feedstock are the potential shortcomings of the fungal pretreatment technique in comparison with traditional one.[28]

Utilization of solid state procedure with small energy and chemical involvements, fungal technique of pretreatment is considered as a low cost technique[27] but above described shortcomings, mainly, the longer time requirement in fungal pretreatment process may make it more costly which may be eliminated using the combined pretreatment technology. Sterility requirement, long time of residence, significant heat generation by fungal metabolic rate and need of the high rate of aeration for efficient delignification may have significant role in the techno-economic study of the fungi based pretreatment at the level of commercial scale, and it is still to be studied.[27] Even after a few shortcomings or challenges of the fungal pretreatment methods, several researches show that fungal pretreatment techniques may be a noteworthy biological pretreatment way for the treatment of varieties of biowastes or biomasses[29,30] because it provides a gentle, ecofriendly, and low cost future solution for the biomass conversion and it is widely utilized in the chemicals and biofuels production due to its role in the degradation of lignin, saccharification, lipid accumulation and fermentation.[29]

Observing the crucial involvement of fungi in the pretreatment of ligno-cellulosic biomasses, agricultural wastes, food wastes, saccharification process, biogas production, bioethanol production, and sugar production etc., authors have decided to prepare a comprehensive review on the fungal pretreatment of such biowastes materials. The principle objective of this review is to analyze the significance of the fungal pretreatment in the management of the problem of huge organic wastes or bio-waste materials and presents the techno-economic analysis, potential future challenges and its applicability. During the fungal pretreatment process, production of biogases, bioethanol, sugar molecules, and other biologically valuable components have great future to be used in the welfare of humanity. Several recent literatures have been discussed here in details in order to open and understand the promising possibilities of fungal pretreatment methods. Furthermore, brief but effective discussions have also been made here on topics of organic wastes and various pretreatment techniques.

2 ORGANIC WASTES OR BIO-WASTES OR SOURCES OF BIOMASS

Wide ranges of materials come under the topic of organic solid wastes or bio-wastes. Wastes of foods, sewage sludge, plants and animal biomasses, fungal and algal biomasses, several aquatic and terrestrial wastes, agricultural wastes, industrial wastes, and many other waste materials which are rich in organic components like polysaccharides, lignin, proteins, fats, and vitamins are considered as organic waste or organic solid wastes. **Fig. 2** presents the picture of huge plant biomasses from nature (dead plant materials as well as green plants). In a comprehensive critical review, Lizundia et al. have well-described the organic waste valorization.[31] Algae and crustaceans among the great diversity of aquatic organisms are considered as the good source of organic waste. The vast probabilities to get varied polysaccharides are offered by the marine algae’s high quantity reaching the coast and discarded marine. About 9.1 million tonnes are discarded by the fisheries annually[32] whereas seafood accounts for thirty one percent of the consumer- level food’s losses in United State of America (USA).[33] Wastes derived from forestry (softwood, grass, sawdust, and hardwood) offers biomasses with high ligno-cellulosic nature at small cost. As opposite to the waste

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from agriculture, intensive physico–chemical treatments are required by the forestry-lignocellulosic waste given the more complex structure of cell wall.[34] In order to extract the important and valuable materials, hydrolysis or thermo-chemical processes are applied. With a projected global production of egg of ninety million tons by 2030,[35] eggshells denote terrestrial animal wastes' classical example with portions still usable after discarding. It is a hydroxyapatite's resource after the calcination and following treatment with salts, for instance $Ca_3(PO_4)_2$.[36,37] Good access to hydroxyapatite is also offered by the porcine or bovine bones. After the removal of residual protein through alkaline process and calcination at large temperature, yields of ~65 wt% are attained.[38] Opposite to synthetic hydroxyapatite, bio-derived hydroxyapatite displays traces of Na^+, Mg^{2+}, K^+, Zn^{2+}, Al^{3+}, Sr^{2+}, F^-, Cl^-, SO_4^{2-}, and CO_3^{2-} which are valuable for stimulating the proliferation functions of cell.[39] Bovine bones may be utilized for the extraction of collagen fibres which are mineralized.[40]

There are a numbers of sources of bio-wastes with promising compositions from aquatic origin like fishes (hyaluronic acid, skin's collagen, gelatin after denaturation), red algae (carrageenans and agarose in the cell walls), brown algae (cell walls' based alginate), chitin (chitosan found upon chitin deacetylation), cephalopods endoskeleton (β-chitin, proteins, lipids), and cuticles from marine-arthropod (varied proteins enfolded alpha-chitin nanofibrils). Agricultural bio-wastes are cereals (rice, corn, wheat, rye, barley, oats etc), fruits (grape, orange, apple, coffee, mango, banana, apricot, pineapple etc), vegetables (carrots, tomato, olive husk, onions, potato, red beet), and legumes (lentils, cow pea, lupins, beans chickpea etc). Bio-wastes from the forestry origin are grass, softwood, hardwood, sawdust; cellulose, lignin, and hemicelluloses). Fungal bio-wastes have composition of glucans, chitin, glycoproteins, and melanin. Bio-wastes from the terrestrial animal origin are eggshell ($CaCO_3$, organic matter, $MgCO_3$, $Ca_3(PO_4)_2$), bones with natural hydroxyapatite and collagen fibres which are mineralized, feathers with beta-keratin, manure (carbon, oxygen, hydrogen,

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nitrogen, sulphur), wool with alpha-keratin, fat, impurities etc, structural proteins derived from animal (silk, collagen, and gelatin), and exoskeletons of terrestrial-arthropod (proteins enfolded chitin fibres).[31]

Parts of the plants like fruits, tubers, and seeds, from different crops like sunflower, rapeseed, palm, cotton, corn and soybean have been utilized in the generation of first-generation ethanol and biodiesel **(Fig. 3)**[41] while on the other hand, complete biomass of above-ground plant called as ligno-cellulosic feedstock (inedible leaves and stems) has been utilized for creation of the biofuels of second-generation.[41] Switchgrass, sorghum, miscanthus, and eucalyptus are some biofuel crops and a few of them have adaptability to deprived soils and marginal agronomic lands.[42] Olives, coconut and eastern black walnut's endocarps/shells are the feedstocks with great density and contain the maximum content of lignin of all recognized organs of plants and endocarp derived energy is equivalent to coal.[43] Worldwide, there is the availability of several million tons of the biomass of drupe endocarp (24-31 million tons),[44] that is greatly underutilized and countries could be benefited with energy scarcity by its proper management.[43] Agricultural and industrial wastes are also the important sources of lignocellulosic materials and may be used for the generation of biofuels. Lignin, cellulose, hemicellulose are the major components of plant cell wall while proteins, organic acids, tannins along with secondary metabolites are its minor components. Lignocellulosic material's composition varies with species, plant parts and ecological situations.[43,45]

3 PRETREATMENT METHODS FOR ORGANIC WASTES

Mainly two types of waste are generated by our daily garbage in which first type include non-biodegradable wastes (i.e. metals, plastics, glass etc.) while second one includes

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biodegradable wastes like leftover foods, dried leaves, fruits etc.[46] Several animal based products, plant linked products, garden wastes, food wastes, and degradable carbon are the examples of biodegradable organic wastes. Energy may be provided as biogas by using the organic waste's recycling methods of anaerobic digestion.[46] Efficiency of non-organic recycling is also improved by organic and non-organic wastes' separation.[47] Minimization of pollution in the water, air, and land by the recycling of organic wastes is its one of the promising advantages. For less effective techniques (disposal and incineration), amount of the garbage left over is also minimized by the recycling of the organic wastes. Organic waste's stabilization offers value by enhancing the content of nutrient and obtainability for utilization as fertilizer in the area of agriculture. Popular concepts like zero-waste strategies, cleaner production, sustainability, and bio-based circular economy are uplifted by the recycling of organic waste.[46,48,49] Different barriers in the management of the organic waste have also been assessed by the Kharola et al. (2022).[46]

The biogas generation from organic wastes may be a promising factor for a sustainable future. Organic wastes utilization for biogas generation applying the methods of mono-and co-digestion has been broadly reported.[25] In spite of the reactions of many-stages related with the production and hydrolysis is crucial as 1st step and helps in enhancing the complete yield. Hydrolysis step's optimization causes the complex organic matter's decomposition into the large quantities of monomeric/oligomeric components which can simply be used in anaerobic situation for biogas production. The aim of pretreatment approaches is making the existing nutrients reachable to the maximum species of microbes that accelerate the use of biomass for the duration of anaerobic digestion.[50] In a review, Mitraka et al. (2022) have comprehensively discussed the several pretreatment methods for the increased production of biogas from sewage sludge[18]. There are many methodologies of

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pretreatments of organic wastes for the biogas production[18,25] which have been concisely discussed here **(Table 1).**

3.1 Mechanical Pretreatment

This type of pretreatment method causes the reduction of the size of particles of organic wastes and does not generate any products.[25] It is a process which consumes energy and this is the main drawback of this method. Developments in milling approaches display that in compare with dry milling procedure, wet milling is better because of its greater pulverization properties with minimal consumption of energy.[51] de Oliveira *et al*. (2022) investigated 02 wet mechanical pre-treatments on bio-wastes from urban household that were air-compressed press and worm screw press.[52] In each experiment, they studied 02 liquid/solid ratios. Enhancement in the biodegradable organic matter's proportion extracted from bio-waste was allowed by enhancing the ratio of liquid to solid in pre-treatments up to 949 $gCOD.kgTS^{-1}$ from the household bio-waste. In constantly stirred-tank based reactor, a very good COD load conversion (81%) and methane's high production up to 345 $LCH_4.kgVS^{-1}$ was shown by the anaerobic digestion.[52] Cesaro et al. (2021) assessed the press-extrusion pretreatment's potential to upturn the concert of anaerobic degradation of organic part of solid municipal waste.[53] Among the methods of mechanical pretreatment, great interest was recently raised by the press-extrusion for its probable use to either increase the organic weight to digester or enhance the overall stability of process and methane's yields.[53] For the improvement in the production of bio-methane, Chevalier et al. (2023) successfully evaluated the influence of mechanical method of treatment *via* twin-screw extrusion using lignocellulosic biomasses of different types and they tested the 02 dissimilar shear stress screw profiles.[54] Specific rate were found to be enhanced by both extrusion

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mechanical treatments which was proved by the kinetic assessment of the production of methane.

3.1.1 High Pressure Homogenization Technique (HPH)

High potential of disintegration, minimal costs of operation, handling and operation's simplicity without chemical variations are a few of the benefits linked to the method.[25,55] Sun et al. (2022)[56] used HPH to treat the soybean protein isolate as potential method. Spatial structure of insoluble soybean protein isolate was destroyed by the pretreatment using HPH; particle size of the soybean protein isolate dispersion was significantly decreased.[56] Nabi et al. (2022)[57] explored the improvement of sludge's anaerobic breakdown by combining the HPH with FNA (free nitrous acid) pretreatment. In comparison with individual HPH treatment and FNA treatment, triggered sludge was solubilized by HPH-FNA pretreatment efficiently and thus, there was subsequent improvement in the anaerobic breakdown process.[57] Biogas's cumulative generation from combined HPH-FNA pretreated sewage sludge was 154, 108, and 284% higher than free nitrous acid, HPH, and raw sludge single pretreatment, respectively. Content of methane in biogas was 45%, 51%, 55% and 65% for the raw sludge, free nitrous acid, HPH, and HPH-free nitrous acid pretreated sludge, respectively.[57] HPH has also been utilized for the recovery of the agri-food remains.[58] Malik et al. (2023)[59] explores the potential of HPH technology in the functional foods development. In another study, HPH was optimized and used for the intensification of the bioactive components recovery from tomato byproducts.[60] Significant improvement in the biogas yield of sludge's anaerobic digestion was found using HPH methods.[61] Also, there are number of other studies on HPH utilization in biowaste management which have been omitted to be focused on the main subject.

3.1.2 Ultrasonication

Ultrasonication was described as the most effective method of pretreatment by Pilli *et al.* (2011)[62] and effectiveness of process is exclusively reliant on the biowaste/sludge's features. On the basis of literature availability, ultrasonication is extensively described for wastewater pretreatment, sludge pretreatment, and manure pretreatment in anaerobic digestion processes for generation of biogas.[25,63-65] There is a recent review on the ultrasonic processing of food waste by Wu et al. (2022)[66] who presents detailed insights on the use of ultrasound in the processing of food wastes. Karouach et al. (2020)[67] evaluated the influence of CMUP (combined mechanical and ultrasonic pretreatment) on household organic waste fraction's anaerobic digestion. They compared the results gained by the experiment with mechanical pretreatment and CMUP. Mechanical pretreatment was taken as control in this study. The 382 mL CH_4 g^{-1}VS (at 0 °C temperature, 1 atm pressure), 72%, and 493 mL CH_4 g^{-1}VS (at 0 °C temperature, 1 atm pressure), 86% were the yields of methane and control and combined mechanical & ultrasonic pretreatment (CMUP) biodegradability, respectively which displays the biodegradability enhancement and enhancement in the production of methane by CMUP. Result also suggests that hydrolysis stage and methanogenesis stage of procedure are upgraded by the combined way of pretreatment.[67] Ultrasonication was successfully utilized in order to improve the methane production from sewage sludge.[68] Ultrasound assisted technology has been reviewed for the valorization of bio-wastes purposes.[69] There are also several studies on the application of ultrasound.[70,71]

3.1.3 Utilities of Mechanical Pretreatment in Biological (Fungal) Pretreatment

There are several commonly used mechanical mechanisms for the size reduction of lignocellulosic organic wastes like cutting, shearing between flat surfaces, tearing,

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compression and breaking the materials.[72] Milling, grinding, ultrasonications, refining, and many others are also the widely utilized mechanical methods for particle reduction. Mechanical treatment of lignocellulosic materials or organic biowastes is a necessary step in the process of pretreatment in order to maximize the material's valorization potential.[72] Thus, it has great application in the biorefinery. Milling is a mechanical process which is generally applied to the materials before the start of any other treatment process. Thus, it may have great applicability in the fungal based biological pretreatment process to reduce the size of biowastes materials for the efficient use of these reduced materials in the bioreactor with fungal system (fungal mycelia and/or fungal enzymes). The use of mechanical treatment before the fungal or other treatment does not cause any chemical alteration in the materials to be treated and improves the effectiveness of other pretreatment processes which are applied after mechanical method.[72] Need of the lignocellulosic materials or biowastes in bulk amounts cause the difficulties in handling, transportation and processing for its fungal or other biological pretreatment process in bioreactors but the use of mechanical treatment before the fungal pretreatment process make the easy handling, transfer, and processing of these biowastes in large density. Optimization of the mechanical pretreatment process is needed because it is a process which consumes high energy. Various types of mills can be utilized but selection of equipment is based on the material's type and properties, final required size of the materials, and operational systems like continuous or batch system or bioreactor.[72] In literature, different types of equipment have been used for the continuous milling before the biological or other methods (as the final treatment process) like disc refiner,[73] screw extruder,[74] knife mill,[75] hammer mill,[76] and many others.[72]

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3.2 Thermal Pretreatment

Thermal method of pretreatment helps in hydrolyzing the organic wastes' complex organic components and has been detected to increase the anaerobic digestion.[25] El Gnaoui et al. (2022)[77] evaluated the thermal pretreatment's effect, including thermal pretreatment at 60 and 80 °C temperatures for sixty minutes, and thermal pretreatment at 100, 120, and 140 °C temperatures for thirty minutes, as well as pre-hydrolysis (biological) at temperatures 37, 55, 37 °C followed by temperatures 55 and 55 °C temperature followed by temperature 37 °C for forty hours on the performance of anaerobic breakdown of food waste in batch test. An enhancement in the soluble COD and efficiency of hydrolysis was caused by the pre-hydrolysis (biological) and thermal way of pretreatment. There was increase in the yield of methane from 371.17 mL CH_4/g VS for untreated food waste to 471.95 mL CH_4/ g VS. There was greatest methane yield for biological pre-hydrolysis at 37 °C temperature for twenty hours followed by 55 °C temperature for twenty hours. Rate of formation of biogas was increased and lag phase was decreased by the pretreatments.[77] There are also many other recent literatures on thermal pretreatment.[78-80]

3.3 Microwave Pretreatment

This is also a type of heat pretreatment method. Besides the generally utilized thermal method of pretreatment, microwave pretreatment are effective in the stabilization of the organic wastes and biogas formation.[25] There are a few benefits with this method which includes quick heating and penetration, simplicity of handling as well as control, pathogens elimination, effective dewaterability of sludge and sludge reduction[81] and due to which this method is more efficient in comparison with conventional thermal methods of pretreatment. Microwave pretreatment's effect on the model food waste's anaerobic fermentation to organic acids with small chains and ethanol was investigated.[82] Microwave pretreatment was studied at 120 °C, 150 °C, and 180 °C (three temperatures) and two, five and eight minutes residence times. The highest decrease in the volatile suspended solids (VSS) was 20%, representing organic matter solubilisation. There was greater (17.5% COD COD^{-1}) total product yield in the fermentation batch tests in comparison with for untreated substrate (11.1% COD COD^{-1}).[82] Influence of the microwave based pretreatment on sludge as well as food waste's anaerobic co-digestion was described by Liu et al. (2020).[83] Results displayed that microwave pretreatment was useful to the organic materials' dissolution, protein conversion to NH_4^+-N, cumulative production of CH_4, unit yield of bio-methane, and methane's formation reaction rate in sludge and food based waste's anaerobic system of co-digestion. In the co-digestion system, CH_4 maximum cumulative production reached 3446.3 ± 172.3 mL (thirty five days) that was 19.93% greater in compare with control. Moreover, microwave method of pretreatment considerably enhanced the volatile fatty acids accumulation and content of butyric acid in the anaerobic-digested effluent.[83] Hydrolysis of the cassava pulp was studied by Prasertsilp et al. (2023)[84] using microwave method for the effectual utilization of natural materials and four different factors like liquid-solid ratio, acids types, watt power and time were investigated. High glucose amount was provided by this study having 88.1% conversion. There are several other relevant studies on the microwave assisted pretreatment technology.[85,86]

3.4 Chemical Pretreatment Methods

In this method, oxidants, alkali, and/or acids are used to breakdown the organic components and it is found to be very effective for the purpose. Ozonation and peroxidation (oxidation) are found to be beneficial in the pretreatment causing in solubilisation of sludge.[25]

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Up to a certain limit, there are a dose-reliant association between concentration of oxidant and solubilization of sludge. Therefore, peroxidation and ozonation process tends to display greater rate of sludge degradation having compromised biogas's yield.[87,88] In a study, Alino et al. (2022)[89] assessed the effectiveness of a low-cost and greater sustainable method to enhance the sugarcane bagasse biodegradability and enhance methane's generation by its pre-collection with organic bio-wastes of acidic types (like cheese whey, wastes of fruit, and waste of vegetable). They got the best result with sugarcane bagasse plus waste of fruit and vegetable (5:95 ratio), being 520 ± 7 NL CH_4 kg VS^{-1} (27.6% greater in compare with control) with time of degradation (T90) decreased from thirteen days to seven days. Yield of methane was increased by 21.2% and 34.1% by the alkaline pretreatment with sodium hydroxide at 5% and 10% concentrations, respectively.[89] Jankovičová et al. (2022)[90] performed the work on material's hydrolysis in NaOH (0.5% and 5%) and H_2SO_4 (0.5% and 5%) at 90–100 °C for 2 hours. Influence of these techniques on the lignocellulosic constitution of rapeseed straw, maize based waste, and wheat straw and the yields of biogas were compared by them. The 0.5% NaOH pretreatment enhanced the production of biogas the most (for rapeseed straw by 159%, wheat straw by 240% and maize waste by 59%), furthermore, the solubilization degrees were greater.[90] Studies of Sreevathsan et al., (2023)[91] on ozonation effects on the biodegradability improvement and bio-methanation ability of the wastewater pretreatment and study of Qiao et al. (2023)[92] pretreatment of landfill leachate state the advantages of chemical pretreatment.

3.5 Combinations of Chemical Pretreatment Methods with Other Pretreatment

Chemical methods of pretreatment including the utilization of alkali and acid are typically used in amalgamation with additional method of treatments.[93-95] The combined techniques of pretreatment are beneficial in improving the solubilization of sludge, its sanitation, dewaterability and anaerobic way of digestion.[25] Influence of thermal and combined thermal-chemical pretreatments was investigated by Ahmed et al. (2022)[96] on solubilization of organics, yield of biogas, formation of recalcitrant, and efficiency of energy at changeable temperatures and alkali dosage. Municipal solid waste's organic fractions were applied to the thermal pretreatment (i.e. 100-200℃ temperature, 1.6–15.8 bar pressure, and 30–120 minutes reaction time) alone and in conjugation with dosage of alkali (1–7 g/L NaOH). Over control (331 mL/gVS$_{added}$), the maximum biogas production increase of 43% (474 mL/gVS$_{added}$) and 87% (618 mL/gVS$_{added}$) was noticed at temperature 125℃ and 125℃+3g/L sodium hydroxide (NaOH) dose, respectively.[96] Pham *et al.* (2021)[97] performed acid-catalyzed hydrolysis at temperatures 120, 150, and 180 °C utilizing H_2SO_4 (sulfuric acid) with 0–0.5 M concentrations within 90–180 minutes reaction time to yield bio-based chemicals from sludge of sewage. The maximum yield of xylose was 7.69 mol% while the maximum yield of glucose was 5.22 mol% at temperature 120 °C, 0.5 M H_2SO_4 in the course of 180 minutes of reaction time. Moreover, under acid-catalyzed hydrolysis at 180 °C temperature and 180 minutes, at 0.5 M H_2SO_4, levulinic acid production touched a highest level of 0.48 mol%, and at 0.1 M H_2SO_4, the maximum production of 5-hydroxymethylfurfural was 1.66 mol%.[97] Qiao et al., (2023)[92] describes the importance of combined physicochemical methods for the landfill leachate pretreatment process. Combination methods of pretreatment are more useful techniques in the pretreatment processes in compare with individual methods of pretreatment. In another study, plant wastes were studied by the combined pretreatment using physical, enzymatic and chemical techniques and this study also proved that the combined methods are more favorable.[98]

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3.6 Biological Pretreatment Methods

Biological pretreatments of organic wastes or bio-wastes are the promising ecofriendly methods which are based on the use of mainly fungi, bacteria, and enzymes. Use of them in the pretreatment of organic waste is very effective in decomposition of the large cellulosic or other organic materials into the monomeric or smaller units and generating valuable biogases. **Table 2**[78] shows the variation in the production of biogas from some lignocellulosic biomass after low temperature pretreatment process under biological condition.[99-106] In biological pretreatment and among various microorganisms, fungi are of utmost significance and filamentous fungi specifically *Basidiomycetes* have great potential in delignification and lignocellulosic bimass conversions with the role of effective involvement of their enzymatic machinery.[15] In bio-waste processing, microbial roles are promising in the improvement of production of biogas and the process can be enhanced by using various metagenomics approaches.[107] Literatures of Mitraka et al. (2022)[18] and Salihu and Alam (2016)[25] have also detailed discussions on biological pretreatment. Bacterial pretreatments have been very concisely discussed here with a few recent literatures because main purpose is to focus comprehensively on the fungal pretreatment techniques.

3.6.1 Bacterial Pretreatment of Organic Wastes

Bacteria have been found as effective candidates for the pretreatment of organic solid wastes. *Bacillus licheniformis* and *Bacillus oryzaecorticis* may be utilized in bio-waste managements as they have shown the promising role in the food waste degradation. Starch was degraded by the *Bacillus oryzaecorticis* and reducing sugars' big amount was found to be released, providing hydroxyl and COOH to fulvic acid molecules while positive result on the structure of humic acid was shown by *Bacillus licheniformis*, which had greater hydroxyl

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(OH), methyl (CH_3), and aliphatics.[108] Liu *et al.* (2022)[109] isolated nitrogen (N)-fixing and lignin-decomposing bacterial strain *R. ornithinolytica* RS-1, from an abandoned termite colony. In order to increase the enzymatic saccharification and degradation in corn stover, they utilized this strain for lignin depletion, combined with mild NaOH (2.5%) pretreatment for the further hemicellulose depletion. After only 7 days, this bacterial strain RS-1 degraded lignin with a 19% reduction whereas relative cellulose content was enhanced with 21%. Moreover, conversion of the cellulose of the corn stover was found up to 48.58% through a process of 2-stage using sodium hydroxide (2.5%) pretreatment. In the meantime, considerable removal of lignin and hemicellulose was observed. Furthermore, the highest activity of manganese peroxidase was found on day 3 (181.0256 U/L) while highest activity of lignin peroxidase was on day 5 (37.473 U/L), respectively.[109] Song *et al.* (2021)[110] presented an evaluation of paper waste's anaerobic and micro-aerobic pretreatment with various oxygen loadings through 5 microbial agents like composting inoculum, cow manure, straw-decomposing inoculum, digestate effluent, and sheep manure. Result showed that paper waste pretreated by digestate effluent with a 15 ml/gVS oxygen loading demonstrated the maximum cumulative yield of CH_4 of 343.2 ml/gVS, with a biodegradability of 79.3%. Besides digestate effluent, straw-decomposing inoculum and sheep manure were likewise observed as promising microbial agents due to the quickening of the production of methane at anaerobic digestion's early stage. It was demonstrated by the analysis of microbial community that after anaerobic way of pretreatment *via* straw-decaying inoculum, *Clostridium sensu stricto 10* and *Clostridium sensu stricto 1* possessed great relative abundance whereas after micro-aerobic pretreatment by sheep manure, *Macellibacteroides* and *Bacteroides* were enriched, which were all contributable to the degradation of cellulose. Besides, degradation of lignin was probably promoted by aerobic *Bacillus* in straw-decomposing inoculum and *Acinetobacter* in sheep manure and digestate effluent only in

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micro-aerobic conditions. In the course of anaerobic digestion *C. sensu stricto* 1, *VadinBC27*, *Caldicoprobacter,* and *Fastidiosipila* were the key bacteria that enabled the paper waste's bio-decomposition.[110] These works demonstrate the potential of bacteria in biological pretreatment of organic wastes and methane gas production.

3.6.2 Fungal Pretreatment

This is one of the important biological methods of pretreatment. Bio-wastes or organic wastes or lignocellulosic structures may be effectively treated with fungal system (fungi and/or associated enzymes).There are a number of significant studies on the fungal role in the pretreatment of such waste materials. As the key reason behind this review was to presents an insight view on the role of fungi in the pretreatment process of biomasses, this has been comprehensively and independently discussed in next section as main heading.

4 FUNGAL PRETREATMENT OF ORGANIC WASTES

Due to minimum energy condition and negligible toxicity, fungal pretreatment processes drew promising attention for their role in the biomass conversion. It prevents chemicals use, hinders the compounds production and has good selectivity towards lignin degradation.[111,112] Several choices are provided by the useful and copious species of fungi for the biomass conversion. Rice straw, wheat straw, corn straw, peanut shell, coconut shell, bagasse, spent coffee ground, food digestate, food wastes, hardwoods, softwoods and switchgrass etc are the recognized biowastes upon which fungal treatments techniques have been successfully applied. **Table 3** shows the major chemical compositions of various types of biowastes/organic waste.[113-121] After the degradation of ligno-cellulose structure, cellulose and hemicellulose efficiency in the biomass rises.[29] **Fig. 4** shows the complex structure of

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lignin[122] while **Fig. 5** shows the schematic presentation of cellulose degradation. Competence of subsequent fermentation and accumulation of lipid is promoted by the saccharification, and thus various downstream products can be formed from the biomass conversion.[123,124] However, its popularization has been hindered due to low efficacy of fungal pretreatment process, but applying the useful strategies may result in to the improvement of the efficiency of fungal technology.[29] This section has a comprehensive approach for the fungal pretreatment technology in the biomass conversion based on recent literature studies. Different methods based on fungi have been adopted and successfully performed the process of biomass/bio-waste valorization by several researches which have been reviewed and presented in this section with their results. Fungal pretreatments of organic wastes or biomasses has been discussed here as a main heading because the principle target of this review was to comprehensively evaluate the various studies already done on the fungal pretreatment technology in solving the problem of different organic waste or bio-wastes and production of many useful products like biogas, bioethanol, sugars, acids, and others.

4.1 Fungal Pretreatment of Lignocellulosic Biomass of Agricultural Wastes

Fungi play significant roles in the decomposition of the various cellulosic materials (like wheat straw, willow chips, rice straw, sugar bagasse, corn stover, and plants materials etc.) as well as agricultural wastes. Lignocellulosic biomass contains high amount of complex carbohydrates i.e. 55–75% in total solids (TS) and is renewable as well as widely available, that is why, it could be excellent feedstock for the purpose of the production of energy.[125] It is well established that WRF may be involved in the improvement of enzyme based hydrolysis and its subsequent sugar's yield.[126] Due to this reason, their involvement in pretreating the substrates, mainly for the generation of bioethanol[125,127] has been studied, though hardly for anaerobic digestion.[128] In case of submerged fermentation for pretreatment, Solid State Fermentation (SSF) process is found better which permits for greater loads of feedstock, prefers the fungal enzymes' attachments to substrate, along with diffusion of oxygen. SSF needs less aeration, mixing, water, and heating due to which there are lower cost than liquid culture.[129]

Pretreatment of lignocellulosic materials like wheat straw, woody willow chips, and corn stover was studied by Kovács et al. (2022)[130] with the help of four filamentous fungi, namely, *Penicillium aurantiogriseum*, *Gilbertella persicaria* (SZMC11086), *Trichoderma reesei* (DSM768), and *Rhizomucor miehei* (SZMC11005). Excellent production of hydrolytic enzyme and maximum yield of biogas from the partly decomposed substrates were shown by *P. aurantiogriseum*. Corn stover was the finest material for the breakdown of biomass and generation of the biogas. Highest effective strain for the pretreatment and biogas was *P. aurantiogriseum.* All the tested fungi preferred the corn stover substrate for the productivity of methane.[130] In 60 mL batch fermentation, within the first twenty days, a noteworthy portion of the generated methane (95%) was found to be evolved. Maximum yield of methane was for corn stover fed reactors. The maximum average production of methane (281 mL_N/g oTS) was yielded by the reactors pretreated with *P. aurantiogriseum.* During 300 mL batch fermentations, influence of the five-fold enhancement in volumetric scaling-up was also studied in the succeeding step. But, there was a point of attention that only 13.3% maximum difference (for the case of *P. aurantiogriseum* reactors) was observed between the outcomes of two reactor sizes which show the insensitiveness of the overall process to scaling up. *G. persicaria,_T. reesei,* and *R. miehei* based pretreatment of all substrates also showed same behavior.[130] Biogas production from corn silage was found to be enhanced by *Pleurotus ostreatus* and *Dichomitus squalens* while negative impact was shown by *Trametes versicolor* and *Irpex lacteus*.[131] Increase in the cumulative production of CH_4 was 1.55 fold with *P.*

ostreatus after ten days and at 28 °C while longer duration of pretreatment (30, 60 days) showed lower effect. With distinctive corn silage, CH_4 production was increased from 0.301 to 0.465 $m^3kg_{VS}^{-1}$ due to depolymerization of lignin.[131]

Pallín *et al*. (2024)[132] utilized *Irpex lacteus* for the lignocellulosic biomass's (wheat straw) pretreatment and assessed the feasibility at a demonstration scale. Like submerged cultures, scaling up SSFs is not forthright. Before choosing the best design for bioreactor, several issues like microbes' growth kinetics, need of agitation, solid substrate's physical properties, conditions of sterilization, and agitation generated mechanical stress should be tackled. During the process, agitation based design of SSF reactor was ruled out because of the agglomeration of *Irpex lacteus* into wheat straw. After considering the several points about SSFs reactor, an autoclavable vertical bioreactor of 22 L capacity was designed.[132] Digestibility of the wheat straw after 21 days of the pretreatment in the solid state fermentations bioreactor (60.6%) was alike to that found on a small scale i.e. 57.9%. In the 03 bioreactor experiments (B1, B2 and PB), sugars evolution was completely different after 21 days of treatment.[132] The 26.5% lignin's reduction was observed. There was greater lowering of lignin in experiment B2 i.e. 34.90 ± 0.87% in comparison with that of experiment B1 i.e. 26.7 ± 3.08%. A rise was noticed for all the compounds in the PB fermentation except lignin, which was lowered by 52.3 ± 0.69%. It was the biggest lessening of any biomass constituent obtained in 03 solid state fermentations reactor experiments. There was alike reduction of lignin i.e. 53.2 ± 0.60% in the flask-scale pretreatment.[132]

Two isolated species of fungi, namely, *Trichoderma harzanium* and *Aspergillus terreus* were used to investigate the degradation of the cellulose followed by bioethanol generation from acid-thermal pretreated rice straw and the experiment was conducted in two phases.[133] In first phase, *Aspergillus terreus* and *Trichoderma harzanium*, isolated cellulose degrading fungi were used for the pretreated rice straw's enzymatic hydrolysis which was parted into

HL (hydrolysate liquid) and RP (residual pulp) while in the second phase of the experiments, substrate (enzymatically hydrolyzed) was applied to the yeast fermentation for the generation of bioethanol. Results showed the 80% degradation of cellulose by these fungi. *Aspergillus terreus* performance upon cellulose lowering with hydrolysate liquid and residual pulp was 92% and 80%, respectively while for *Trichoderma harzanium* it was 93% and 82%, respectively. With the use of *A. terreus,* glucose formation from cellulose during enzyme hydrolysis was 12.15 g/L and 16 g/L while it was 10.8 g/L and 21.6 g/L using *T. harzanium.* Mechanism in this process involves the action on β-1, 4- glycosidic bonds by the cellulose degrading fungi through enzymatic activities only after the pretreatment process. Rice straw's RP treated with *T. harzanium* has led to in greater bioethanol of 5.4 g/L while for *Aspergillus terreus,* it was 4.7 g/L.[133] The pHs of the enzymatically pretreated reactors using *A. terreus* were 3.8 for control, 4.8 for hydrolysate liquid, and 4.5 for residual pulp while in the case of *T. harzanium* base reactors, pH values were 5.0, 4.9, and 4.8. Substrate and inoculum types are the major factors for the production of bioethanol between pH range of 3.5-6. In reactors based on hydrolysate liquid as substrate, *A. terreus* and *T. harzanium* performances in production of bioethanol was same as 4.5 g/L.[133]

A genuine challenge in the bioethanol production from rice straw is to remove lignin properly from biomass through pretreatment process because lignin removal is necessary to generate bioethanol from rice straw effectively by the saccharification and fermentation process.[134] This challenge may be tackled through the use of alkali assisted pretreatment and acid thermal pretreatment of rice straw. Devi and Munjam[133] have successfully used *A. terreus and T. harzanium* in the production of bioethanol from rice straw which was pretreated in acid-thermal way while study of Takano and Hoshino[134] shows the use of enzyme cocktail (optimized) and *Mucor circinelloides* (xylose fermenting fungus) in the ethanol production from alkali pretreated rice straw by concurrent saccharification and solid state fermentation. Abo-State et al.[135] subjected the rice straw to steam treatment (autoclaving) and various gamma irradiation doses like 50 and 70 Mrad. Now, different fungal isolates were used to enzymatically treat the steam treated rice straw throughout SSF process.[135] Therefore, any pretreatment processes which are effective in the removal of lignin from rice straw may be used and combined with the fungal treatment process for the production of bioethanol by saccharification and SSF process.

Furthermore, the effect of alkali sodium hydroxide (NaOH)/hydrogen peroxide (H_2O_2) based various pretreatment approaches on willow sawdust biomass was described by Atitallah *et al*. (2022)[136] utilizing the conventional yeast i.e. *Saccharomyces cerevisiae* and 03 non-conventional strains of yeasts like *Pachysolen tannophilus*, *Wickerhamomyces anomalus* X19, and *Pichia stipitis*. Result shows that greater delignification i.e. 38.3 ± 0.1% and efficiency of saccharification i.e. 31.7 ± 0.3% and greater concentration of ethanol and yield was led by the 2-stage pretreatment method i.e. 0.5% w/v NaOH for twenty four hours and 0.5% v/v H_2O_2 for twenty four hours. Yields of ethanol ranging from 11.67 ± 0.21 to 13.81 ± 0.20 g/100 g TS was observed by the *Saccharomyces cerevisiae* or *Wickerhamomyces anomalus* X19 monocultures and co-cultures with *Pichia stipitis*. *W. anomalus* was selected as non-conventional strain due to its high efficiency of bioethanol production whereas *S. cerevisiae* was utilized as the highest exploited strain of yeast for the production of bioethanol from sugar fermentation. There was reduction of hemicellulose to 1.3%, 18.9%, 25.1%, and 21.4% when willow sawdust was applied to different pretreatment approaches i.e. A (sodium hydroxide), C (sodium hydroxide and hydrogen peroxide mixture), D (initially sodium hydroxide followed by hydrogen peroxide) and E (initially hydrogen peroxide followed by sodium hydroxide), respectively (approach B i.e. H_2O_2 is omitted here). For the approach D, there was maximum removal of lignin (38.3%).[136] Co-cultures use for the bioethanol fermentation is generally considered beneficial over the monocultures because

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of the synergistic action of the involved microorganism's metabolic pathways.[137] In another study, filamentous fungi like *Rhizomucor miehei*, *Aspergillus nidulans*, *Gilbertella persicaria*, and *Trichoderma reesei* were tested for the pretreatment of dry CS (corn stover), WS (wheat straw) and WWC (willow wood chip).[138] *A. nidulans* based pretreatment doubled the yield of methane in compare with the untreated corn stover. Pretreatment with *G. persicaria* and *T. reesei* also gave noteworthy differences in the production of bio-methane in comparison with the samples having only untreated plant substrates, respectively. Outstanding great activity of endo-(1,4)-β-D-glucanase on willow wood chip and corn stover, and great activity of β-glucosidase on willow wood chip are shown by the *A. nidulans.* As the pretreatment's consequence, *A. nidulans* based pretreatment of samples generated highest biogas for all involved raw substances. This study recommended the use of short time pretreatment for cellulose-abundant substances, which in definite cases may double the yield of biogas.[138]

Phanerochaete chrysosporium, among the WRF, is recognized for its choosy lignin's breakdown and has ability to show numerous applications in biotechnology.[139] Pretreatment of richly found wheat straw (WS) can be done by applying WRF, which transforms the cellulose (complex plant biomass) in glucose.[140] This sugar can be used by the *Pichia fermentans* and IAA (indole-3-acetic acid) may be produced in tryptophan's presence. Besides effective WS pretreatment in the course of primary fermentation, *Phanerochaete chrysosporium* may also generate IAA in tryptophan's presence,[141] which may further participate in the enhancement of the creation of IAA in the course of secondary fermentation.[142] In a study, *P. chrysosporium* (150 µg/ml) based pretreatment of WS showed nine folds enhancement in IAA in comparison with untreated WS (16.44 µg/ml).[142] IAA was produced in 1.99–129.33 µg/ml range.[142] The WS was pretreated with *Phanerochaete chrysosporium* for releasing the sugar in medium that could be used by *Pichia fermentans* for the production of IAA. Considerable sugar amount was released by *P. chrysosporium* from 2nd day onwards and was highest on 9th day (0.89 mg/ml).[142] Production of IAA using yeasts has also been described earlier.[143] Lesser than 25 µg/ml was produced by the *Pichia guilliermondii* and *Hanseniaspora uvarum* when inoculated in the medium based on yeast extract-dextrose after incubation's seven days.[144] Furthermore, an endophytic yeast found in roots of maize, *Williopsis saturnus* was observed to be able of generating indole-3-acetic acid (22.51 µg/ml) *in vitro* in GPB medium (glucose-peptone broth).[145]

In the natural substrates' degradation, the consortium of effective microbes are found to be effective than a single organism.[146,147] Ramarajan and Manohar (2017)[148] found good lignocellulolytic activity for the fungal isolates, namely, GK1 (*Chaetomium globosum*), GK2 (*Chaetomium brasiliense*), G4 (*Engyodontium album*), G10 (*Metarhizium anisopliae*), G13 (*Engyodontium album*), M155 (*Acremonium persicinum*), M158 (*Acremonium minutisporum*), and M2E (*Inonotus tropicalis*). They evaluated the activity of these isolates and isolate 2a, *Cerrena unicolor*[149] in the liquid culture media and nice growth and ligninolytic activity were shown by the M2E and 2a while exceptional cellulolytic activity was shown by the isolates GK1 and GK2 on the lignocellulosic substrates i.e. RS (rice straw) and SCB (sugarcane bagasse). Upon treatment with individual isolates, highest sugar yield observed from SCB with GK2 was 1.35 g L^{-1} while it was less than 1 gL^{-1} sugar yield from RS and SCB after the treatment with individual isolates except GK2. Amongst the different consortia, the highest yield of sugar (4.39 gL^{-1}) was given by M2E+GK2 on sugarcane bagasse followed by the yield of 2.64 gL^{-1} on rice straw by 2a+GK2. This enhanced yield of sugar in case of consortia M2E+GK2 and 2a+GK2 could be due to the high manganese peroxidase activity on SCB by the consortium M2E+GK2 and enhanced activity of laccase by consortium 2a+GK2 on RS followed by noteworthy cellulolytic nature. Thus, developed lignolytic and cellulolytic marine-derived fungal consortium shows the potential for the application in the agricultural wastes.[148] Comparative study between biological and physical pretreatment were also performed by researchers. Yield of sugar was moderately increased from the substrates by physical and combination of physical and biological pretreatment but it was lesser than developed consortia-based biological pretreatment which demonstrates the potential of fungal isolates in the biological pretreatment.[148] Rouches, Zhou *et al*. (2016)[126] performed study on the pretreatment of wheat straw using different strains of fungi for studying the probability of increase in the production of methane. Anaerobic digestion was found to be improved up to 20% by *Polyporus brumalis* BRFM 985 even after the mass loss. Using this strain, they obtained up to 43% extra methane (CH_4)/gram of pretreated VS in comparison with control straw. Considering the dry weight loss studied in the pretreatment course in non-optimized conditions, there was up to 21% extra methane per gram of initial TS (total solids). For the fixed culture condition, there was lowering in the delignification upon increase in glucose addition between fifty and four hundred milligram/gram straw in a strain dependent way.[126]

4.2 Pretreatment of Hardwoods, Softwoods and Switchgrass

Lignin degradation ability was found to be increased by co-culturing of *Paracremonium* sp. LCB1 and *Clonostachys compactiuscula* LCN1 and pronounced drop of 76.37% in the weight of lignin was observed for the bamboo culms pretreatment using this co-culture at 30°C of temperature, 40 days of culture time and pH 5. There was high loss ratio of lignin/cellulose (>10).[150] It was also observed that co-culturing of two or three fungi gave higher degree of weight loss of lignin in comparison with single fungal strain culture. During the process of pretreatment, interacting fungi's co-cultivation over-expresses lignolytic enzymes and this may generate synergistic and combinatorial influence for effective delignification.[151] Resultantly, combination of LCB1+LCN1 gave the maximum loss of lignin weight.[150]

Trametes versicolor (a white rot fungus), and *Gloeophyllum trabeum* and *Rhodonia placenta* (two brown rot funguses) were used for the pre-treatment process of two softwood, namely, *Pinus yunnanensis* and *Cunninghamia lanceolata* and two hardwoods, namely, *Populus yunnanensis* and *Hevea brasiliensis* with different period of conversion.[152] Selective degradation in softwood was shown by *T. versicolor* where lignin and hemicellulose was converted preferentially while cellulose was selectively retained. On the other hand, in hardwood simultaneous conversion was achieved for cellulose, hemicellulose and lignin by *T. versicolor*. Carbohydrates were converted preferentially by the brown rot fungal species but cellulose conversion was selectively shown by the *R. placenta*. Wood cells accessibility was improved and porosity was enhanced by the fungal pre-treatment. It was concluded that cellulose content may be maximized by the use of *T. versicolor* pretreatment while pretreatment *via* using brown rot fungi (especially *R. placenta*) may be gainful for the biofuels, chemicals based on gasoline and other bio-chemicals.[152] Both brown rot fungi cause higher mass loss of softwoods in compare to *T. versicolor* as 28.59%, 36.19%, and 13.09%, decaying by *G. trabeum*, *R. placenta*, and *T. versicolor,* respectively in *P. yunnanensis* while in the wood of *Cunninghamia lanceolata*, there were 66.52%, 45.87%, and 35.57% decaying by *G. trabeum*, *R. placenta*, and *T. versicolor,* respectively. But, the case was reverse for hardwoods where hardwoods mass conversion by white rot fungi was higher than brown rot fungi. Nature of lignin and different pathways of bio-degradation between hard woods and softwoods may be the reasons behind this discrepancy in the degradation percentage by different group of fungi.[152]

On the other hand, a technoeconomic analysis was done by Olughu et al. (2023)[153] for the fungal pretreatment-dependent production of cellulosic ethanol where processing

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capacity of the plant was 2000 tonnes switchgrass/day. Ethanol yield of plant was projected to be 211.9 L/t of switchgrass and fungal pretreatment was the main contributor to the total capital investment. Switchgrass-based ethanol production's profitability was observed to be sensitive to the changes in the cost of feedstock, yield of glucose and yield of xylose. Growing yield of glucose from 60 to 80% resulted in a five-fold enhancement in the net present value. Additional, study on fermentation time's optimization in the course of fungi-based pretreatment and subsequent glucose yield optimization upon enzyme catalysed hydrolysis would be essential to improve the economic feasibility of this type of ethanol plant.[153]

4.3 Fungal Pretreatment of Spent Coffee Grounds (SCGs)

SCGs are biowastes materials produced after the coffee brewing which is generated in noteworthy volume each year globally. Exact volume of SCGs generated each year is not well known but probably its 6 million tons are globally produced each year on the wet basis.[154,155] Approximately, its 50% production comes from small-scale shops of coffee, cafeterias, individuals, or restaurants.[156] The discarded SCGs pose considerable challenges for the environment. Now, new technologies and policies are working on to develop SCGs as worthwhile feedstock for the bioproducts synthesis, platform for chemicals production, and value-added energy materials generation.[157,158] Furthermore, due to the rich source of polysaccharides, proteins, and lipids, SCGs are promising feedstock for bio-based and chemical processes to get great value products for cosmetics industries, pharmaceutical industries, and food industries.[159] Hemicellulose and lignin in SCG are found as 39.75%, and 23.1%, respectively while protein and caffeine are found as 10.82 and 1.83%, respectively.[160] Actually, coffee Valorization of SCGs can be done in many ways, including *via* the SCOAs

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(short-chain organic acids) production.[161] These organic acids with small chain are monocarboxylic acids (aliphatic) with 2 to 6 C-atoms (i.e. acetic, propionic, butyric, isobutyric, valeric, caproic, and lactic acids) having industrial applications either by the direct involvements or by uses as building block for further transformations.[162] Usually petrochemical processes are used for the production of these molecules but production *via* biological processes are being promoted due to the crude oil's growing cost and environmental impact, specially utilizing the organic wastes as substrate.[163]

There is a promising work on biological pretreatment of coffee waste's acidogenic fermentation[161] using two fungi i.e. *Paecilomyces variotii* NRRL-115 and *Trametes versicolor* CBS 109428. The production of SCOA (short chain organic acid) was positively influenced by the utilization of SCG_TvSmF (Spent coffee ground_submerged fermentation by *T. versicolor*) as pretreatment, getting a maximum of 2.44 gCOD/L that was high enhancement (87%) related to the control. There were the generation of acetic acids, propionic acids, and butyric acids in an average proportion (59.9/33.8/6.3%). Production of acetic acid throughout the assay was happened while appearance of butyric acids and propionic acids occurred after the 9th day and 18th day, respectively.[161] As observed before in another studies,[125] celluloses and hemicelluloses of spent coffee grounds were possibly broken down and consumed. Study shows that a pretreatment step's inclusion may assist to make spent coffee grounds an appropriate material for valorization and this work is nice contribution towards lessening the cost of enzymatic hydrolysis utilization as complex feedstock's pretreatment.[161] Afriliana *et al.* (2021)[160] studied the composting spent coffee ground using aerobic static batch composting with temperature control with help of *Aspergillus sp.*, and *Penicillium sp.* The basis for selecting these activator fungi in compositing was the hemicellulose and lignin's high contents. Study was performed *via* three samples analysis (control, C1, and C2) and greater degradation was observed for lignin in C2.

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DOI: 10.1039/D4SU00582A

In comparison with alike rates 35.56% in C1 and 31.1% in control, this led to improved global breakdown of lignin 40.28% in C2. Protein percentages decompositions i.e. 85.44% (sample C2), and 83.02% (sample C1) were greater than that of control (81.82%). Macromolecules decomposition rate were more than 40% in case of lignin while 70% in case of cellulose. With the help of this method, composting time can be speed up and results of the produced compost can be optimized.[160]

In a study, *Pleurotus ostreatus* capacity in the degradation of lignocellulosic nature of combined spent coffee grounds (SCG) and olive pruning residues (OLPR) was assessed by Fayssal *et al*. (2021).[164] They adopted the complete randomized design with 5 treatments i.e. S1:100% wheat straw (control), S2:33% wheat straw + 33% spent coffee grounds + 33% olive pruning residues, S3:66% wheat straw + 17% spent coffee grounds + 17% olive pruning residues, S4:17% wheat straw + 66% spent coffee grounds + 17% olive pruning residues, and S5: 17% wheat straw + 17% spent coffee grounds + 66% olive pruning residues, and ten replicates per treatment. Only S1, S2, and S3 were observed as productive. With the rise in the OLPR and SCG proportions, loss of organic matter reduced. Lignin loss percentage was greater in S1 in compare with S2 and S3 i.e. 53.51, 26.25, and 46.15%, respectively**.** Mushrooms' combined production yield harvested from 2 flushes of *Pleurotus ostreatus* cultured in grass and coffee pulp created a biological efficiency changing between 59.9 and 93%.[165] For accessing the holocellulose, the fungus requires firstly to break lignin[125] and a greater loss of lignin means for greater mycelial activity.[166] In all the studied substrates, degradation of hemicellulose was favorably occurred with respect to cellulose which was steady to the early results of Thompson *et al*. (2003)[167] found on the WS.[164]

Above discussions demonstrates the efficiency of fungal system in SCGs pretreatment as biological method. In recent years, a considerable attention has been received by the SCGs utilization as bio-resource for the many value added bio-products but there are certain noteworthy challenges which are required to be solved for effective industrial applications. SCGs' heterogeneity from their different sources and collection from coffee shops, consumers and other small-scale sources are the primary challenges. Inconsistency in SCG composition, factors like type of the coffee, method used for brewing and conditions required for the processing are some of the factors which generate difficulties to standardize the process of extraction and optimize the creation of value added bio-products. Furthermore, development of effective techniques is needed to sort and preprocess SCGs to make sure their reliable excellence and composition.[158] A big quantity of SCGs is achieved from the shops of coffee and domestic consumers and thus, logistical challenges are faced by the bioprocessing plants in concentrating the SCGs' huge volumes to the level of processing. Innovative approaches and more research are required to overcome these challenges.[158]

4.4 Fungal Digestion of Food Wastes

Various sources are responsible for the generation of the food wastes like canteens, households, hotels, function halls, gated communities, different industries of food processing, and many other.[168] Its decentralized treatment at source utilizing the best probable anaerobic digestion (AD) technique makes it remunerative[169] and food waste's diversion to landfills may be arrested to a high extent.[170] There are three configurations of AD process based on TS concentration in organic waste i.e. wet anaerobic digestion (total solids $\leq$ 10%), semi dry anaerobic digestion (total solids between 10%–15%), and dry anaerobic digestion (total solids > 15%).[171-173] Dry anaerobic digestion (solid-state digestion) is a positive technique, owed to various benefits in compare with wet anaerobic digestion (total solids < 10%) making it especially striking for food waste's treatment, municipal solid waste's organic fraction treatment, and treatment of agricultural wastes.[174]

Different pretreatment methods (namely, autoclaving, acid based, alkali based, aeration, and fungi based methods of pretreatment) were applied by the Bhurat et al. (2023)[175] for the pretreatment of food wastes. In comparison with control, the 3.8-fold improvement in the yield of hydrogen and 1.7-fold enhancement in the yield of methane were shown by the fungal treatment. In order to study the fungal succession and their ecological as well as engineering value, food wastes' AD bioreactors were performed by Yang *et al*. (2022).[176] It was observed that deterministic procedures slowly dominated fungal assembly succession (i.e. at the final stage up to 84.85%), signifying varying environmental status accountable for dynamics of the fungal community and specially, structure, diversity and biomass of the fungal community were controlled by the various environmental variables or the same variables with opposite influences.[176] A work on the fungal mash enzymatic pretreatment combined with pH adjusting approach was performed by Zhang *et al*. (2022)[177] using *Aspergillus awamori* (CICC 41363) to generate fungal mash enzymes *via* SSF. Complex amylase (CA) was the crude enzyme produced from this fungus that was added to the food waste fermentation's short-term anaerobic system. There was 116.9% enhancement in concentration of SCOD with CA addition relative to the control. After 24 hours, TOC and SCOD concentrations considerably increased with complex amylase (CA) addition under an extensive range of pH conditions. Here, total organic carbon and SCOD mean concentration were 12.5 g/L and 34.5 g/L, respectively that were 1.65 and 1.81 times greater than control (7.6 g/L and 19.1 g/L), respectively. The pH 8 was the optimal pH condition for the yield of VFAs that was reliable with the finding of Chen and co-workers.[178] This study may be an economical way to increase the yield of VFAs for the FW valorization in the course of anaerobic fermentation.[177]

Furthermore, fungal mash (in-situ produced) was also utilized by Yin *et al*. (2016)[179] showing the nice presence of hydrolytic enzymes to pretreat activated sludge, FW, and their combination before AD. Enzyme catalyzed pretreatment of activated sludge combined with FW caused in the generation of 3.72 g/L glucose and 51 mg/L free amino nitrogen, equivalent to SCOD (7.65 g/L) within twenty four hours, accompanied with 19.9% of the reduction of VS (volatile solids). The lowering of VS was found as 19.1% and 21.4% after the activated sludge and FW pretreatment, respectively through fungal mash. Moreover, yield of bio-methane of fungal mash pretreated mixed waste was 2.5 times greater than the activated sludge receiving no pretreatment, with as further decrease of volatile solids of 34.5%. These put forward a total reduction of volatile solids of 54.3% in suggested anaerobic system with fungal mash pretreatment. This study demonstrate that in the enhancement of the production of bio-methane as well as in the maximization of the mixed waste's volume reduction *via* anaerobic co-digestion, in-situ produced fungal mash based combined activated sludge and FW pretreatment would be a promising option.[179]

Effective role of fungi in the pretreatment of food biowastes and its conversion into the several useful bio-products has been well demonstrated. But, in order to reduce the harmful impacts of food wastes on environment and human health and conversion of food wastes into value added bio-products, certain challenges are needed to be resolved like bulk collection of food wastes from various sources, their proper separation from other types of inessential materials, their bulk storage and processing at biorefinery plants and elaborate the researches and studies at the level of industrial scale from the laboratory-scale experiments.

4.5 Saccharification of Grain Stillage

In terms of fiber's composition, grain stillage is mainly made of hemicellulose (15-25%) and cellulose (35-45%) which depends on the sources like rice, corn, sorghum, and wheat.[180] It is also considered as a feedstock for the bio-refinery because of its big content of

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carbohydrate [163].[181] Pretreatment of grain stillage using the microwave-assisted hydrothermal (MH) pretreatment, fungus based pretreatments, and their amalgamation was done by Ren et al. (2020)[181]. Superior reducing sugar yield (25.51 g/100 g) and efficiency of saccharification (66.28%) were achieved by microwave-assisted hydrothermal + *Phanerochaete chrysosporium* (microwave-assisted hydrothermal prior to the *Phanerochaete chrysosporium*) pretreatment. Considerable loss of mass i.e. 23.54 and 39.43% was caused by the joint pretreatments as *Phanerochaete chrysosporium* + microwave-assisted hydrothermal and microwave-assisted hydrothermal + *Phanerochaete chrysosporium*, respectively. The degrees of delignification were considerably enhanced to 32.80 (for *Phanerochaete chrysosporium* + microwave-assisted hydrothermal) and 43.34% (for microwave-assisted hydrothermal + *Phanerochaete chrysosporium*) after the combined pretreatment. Furthermore, the degree of delignification of the microwave-assisted hydrothermal + *Phanerochaete chrysosporium* was considerably greater than that of *Phanerochaete chrysosporium* + microwave-assisted hydrothermal pretreatment.[181] This may be because microwave-assisted hydrothermal pretreatment results the hydrogen bonds breakage and lignocellulose structure’s destruction through explosion and disruption, which stimulates the subsequent attack of *P. chrysosporium* for the delignification.[182,183] In order to enable the utilization of the cost effective grain stillage, use of joint microwave-assisted hydrothermal and *Phanerochaete chrysosporium* pretreatment may be an excellent method.[181]

4.6 Symbiotic Digestion of Lignocellulose

In world’s tropical and subtropical areas, fungus-growing termites have ability to consume 20-90% of dead plant’s materials.[184-186] Lignocellulosic materials can be completely degraded and digested by *Termitomyces* fungi with resulting ecological influences on the

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processes of the ecosystem, chiefly Carbon-cycling.[187] For investigating the digestion of lignocellulose in fungus-growing termite *O. formosanus* (Shiraki) symbiotic system and to equate the bacterial communities across various phases during degradation's process, Ahmad *et al*. (2022)[188] did many analytical works on the plant's biomass components' fate and performed 16S rRNA gene's amplicon sequencing. Young workers' digestive tract initiates the lignocellulose degradation but leaves maximum of the cellulose, lignin, and hemicellulose, which comes in the fresh fungus comb, where principally the decomposition happens. The consumed samples of lignocellulose (fresh, mature, and old comb) from three colonies were compared[188] with the original wood of mulberry through compositional analysis of lignocellulose with fiber detergent technique.[189] It was shown by the examination of the comb material that in all three colonies, there was considerable degradation of lignocellulosic constituents**.**[188] There was on average reduction of lignin, cellulose, and hemicellulose in fresh comb by 18.9%, 11.1%, and 15.0%, in the mature comb by 56.9%, 41.0%, and 32.5%, and in the old comb by 63.0%, 65.5%, and 53.4%, respectively.[188]

4.7 Fungal Pretreatment of Solid Digestate

Digestate fractions' fate generally involves agricultural aims like soil amendment and organic fertilizer.[190] Zanellati et al. (2020)[191] studied the fungal pretreatment on non-sterile solid digestate and inoculated the fungi *Coprinopsis cinerea* MUT 6385, *Cephalotrichum stemonitis* MUT 6326, and *Cyclocybe aegerita* MUT 5639 in the digestate's non-sterile solid fraction with aim to reuse it as feedstock for anaerobic digestion. In the *Cyclocybe aegerita*, *Cephalotrichum stemonitis*, and *Coprinopsis cinerea* pretreated samples, there were noteworthy reductions in the concentration of total solids (TS) i.e. 23.8%, 25.4%, and 28.5%, respectively. In the *C. cinerea* pretreated samples for ten days and

Cephalotrichum stemonitis pretreated samples for twenty days, NDF (neutral detergent fiber) losses percentage was ranged from 1.6% to 10.4%, respectively. Alike behavior was shown by the different strains towards the PCWP (Plant cell wall polymer), causing greater lessening in hemicellulose (18.5–59.3%) in compare with cellulose (0.2–8.2%) and lignin (1.0–9.6%). *C. stemonitis* based pretreatment for 20 days gave the maximum lowering in all the PCWP components and resulted in the reductions of hemicellulose, lignin, and cellulose as 59.3%, 9.6%, and 8.2%, respectively. The anaerobic digestion functioned superior with solid fraction of digestate treated by the fungal strain *Cephalotrichum stemonitis* for twenty days, that led to about 3-fold greater yields of biogas and CH_4 i.e. +182% and +214%, respectively in compare with untreated solid fraction of digestate. Cumulative methane formed with fungal strain *C. stemonitis* was considerably greater than that attained with fungal strains *Cyclocybe aegerita* and *Coprinopsis cinerea* for both ten and twenty days.[191] *M. isabellina* ATCC 42613 was applied by Zhong *et al.* (2016)[192] for accumulating the lipids on detoxified hydrolysate medium. Characteristics of digestates (solid and liquid) and AD effluent showed that soild digestate has 30.60% TS content and carbohydrate contents i.e. cellulose (26%), xylan (13%), and lignin (30%) to be utilized for fungal lipid accumulation as the lignocellulosic feedstock. After the pretreatment and hydrolysis processes, the mixture feed at the total solids of 10% produced a hydrolysate having glucose (13.85 g/L), xylose (8.95 g/L), and acetate (2.67 g/L). Study shows the substrate's consumption of *Mortierella isabellina* on hydrolysates.[192] Without detoxification, there was no consumption of sugars and acetate in the hydrolysate during culture period of 89 hours**.** In comparison with the culture of synthetic medium (consumption of all sugars and acetate in 66 hours), a delay (23 hours) of the consumption of substrate was noticed from the cultures on detoxified hydrolysates. There was complete consumption of glucose and acetate in 49–54 hours, respectively. At the batch culture's end (77 hours), xylose 1.79 g/L stayed in the broth, and biomass 8.98 g/L and lipid 1.50 g/L were accumulated. The corresponding yields of lipid and biomass were 0.07 g/g and 0.42 g/g, respectively.[192] Conclusively, fungi shows the promising presence in the pretreatment process of solid digestate with anaerobic digestion process.

4.8 Fungal Pretreatment of Park Wastes and Cattle Dung

For treating the cellulosic biomass to enhance its digestibility, Ali and Sun (2015)[193] studied the physic-chemical pretreatment's influence on the degradation of cellulose followed by treatment utilizing fungi *Trichoderma viride* and *Aspergillus terreus*. In their experimental set up, mixture of new leaves (125 g), dry leaves (125 g), and cattle dung (250 g) was present in each of the two digesters. Park wastes' fungal treatment was applied for seven days at 25 °C followed by both digesters' incubation for seventy days on incubator shaker (35° C temperature and 120 rpm) in order to help the mixing. Pre-treated and untreated substrate's biogas and CH_4 yields were measured. Three pre-treatment stages improved the production yields of daily biogas and CH_4 from the substrate. In comparison with untreated substrate, the pretreated substrate gave maximum yields of biogas and CH_4 of 2.6 and 1.9 L/KgVS, respectively in the 28th day. There was 102.6 L/KgVS biogas cumulative production for untreated substrate that was found to be improved to 125.9 L/KgVS for the pretreated substrate and in this way, there was 22.7% enhancement in comparison with the yield of biogas from untreated substrate. The pretreated and untreated substrate's cumulative production of CH_4 was 79.8 and 61.4 L/KgVS, respectively and in comparison with the yield of methane from untreated substrate, there was 30 % enhancement.[193] This study may be useful for the treatment of cattle dung and park waste and in the production of biogas with further improvement, optimization and/or with combined technology.

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4.9 Card Waste's Fungal Pretreatment

Card wastes are also a good source of hemicellulose, lignin, and cellulose. Suthar and Singh (2022) studied the waste cardboard's fungal pretreatment in the monoculture and mixed culture and then composted for 35 days after mingling with cow dung in various ratios.[194] They utilized fungi *Oligoporus placenta* and *Tremetes hirsuta* for fungal pretreatment. There was considerable lowering in contents of cellulose (28.3–35.8%), hemicellulose (61.4–68.4%), and lignin (67.5–69.3%) in waste card board. The pretreated waste cardboard displays better decrement' rates in TOC (26.02–47.92%), C-N ratio (19.4–23.5), and contents of lignocellulose, in addition to incensement in total N (40.48–63.31%), total K (51.92–73.91%), germination index (88.5–102.0%), and levels of elements i.e. copper, iron, zinc, chromium, and manganese. Thus, after the pretreatment with a white rot fungi consortium**,** waste cardboard could be utilized as an important substrate for the preparation of valuable-added compost.[194]

Therefore, now, it is very clear that fungi have a great future in the biological pretreatment technology for the management of various aforementioned organic wastes and the production of valuable energy, biogases and compounds. But there are also several associated challenges before such pretreatment technologies. There are some other literatures that may be significant for the readers in the field of bio-wastes degradation as well as opportunities and challenges.[195-208] **Table 4** summarizes the effective brief descriptions on the myco-pretreatment of different type's organic wastes. Along with an advantageous biological solution of the problems of bio-wastes management, fungal based bio-pretreatment processes may also generate various types of valuable products after the pretreatment processes from their macromolecules lignins, cellulose, hemicellulose, starch, pectins etc**.**

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5 TECHNO-ECONOMIC ANALYSIS AND SCALE-UP ISSUES FOR INDUSTRIAL IMPLEMENTATION OF FUNGAL PRETREATMENT METHODS

Fungal pretreatment process at industrial level requires big capital investments. From grasses to hardwoods, total capital investment ranges from 700 million (in dollars) to 1.2 billion (in dollars), respectively and this is approximately five to ten time greater than the previously estimated for the conventional treatment at parallel scale.[209] High cost are due to the expenses on large equipment's purchasing, installation, construction, engineering, many units' requirements for each of the main processes like autoclaving, fungal pretreatment and enzymatic hydrolysis expenses and other requirements. Packed-bed bioreactors utilized in the fungal pretreatment process are responsible for the majority of the cost value, mainly because of longer residence time. In the fungal pretreatment process, fermentable sugar's estimated price was 1.6-2.8 dollars/kg which were 4-5 times greater than the previously stated production cost of sugar utilizing the conventional pretreatment methods.[209,210] Due to the minimum requirement of energy and chemicals, fungal pretreatment process is believed to be a pretreatment method which requires low cost but analysis showed that it needs noticeably higher cost than conventional pretreatments and about one order of magnitude over that anticipated for a pretreatment to be feasible at commercial level.[210]

High cost of facility arrangement for the fungal pretreatment is primarily responsible for the need of high capital investment while feedstock cost is the second highest contributor to the cost of sugar production which contributed 18-22% of the complete cost of sugar production.[27] However, continuous advancements in the technologies may reduce the total cost of sugar production using fungal pretreatment techniques and it will make fungal pretreatment methods a commercially profitable environmentally safe and green technique. Longer time required for the fungal pretreatment, enhancement of the yield of sugar, and sterilization requirement of the feedstock before fungal pretreatment are in several bottleneck which are required to be overcome in order to expand and improve the fungal based pretreatment technique. Studies on the combination with different other pretreatments with low severity has achieved greater yield of sugar with significant reduced need of energy and chemicals.[211] Optimization of these processes are not only required at laboratory scale from technical perspective but also at commercial scale utilization from techno-economic perspective.[27] High temperature may affect the fungal based pretreatment processes because fungal enzymes are strongly involved in the enzymatic degradation process of lignocellulosic materials or other biowastes which are inactivated at higher temperatures so during the fungal based treatment plant set up, special attention should also be given on the control of temperature rise during the process.

6 CONCLUSION, CHALLENGES AND FUTURE PERSPECTIVES

Fungi are effective in the decomposition of lignocellulosic biomasses, food wastes, sewage sludge, polysaccharides, lignin, and hemicelluloses etc and found to be efficiently involved in saccharification, biogas productions, glucose production, ethanol production, and bio-fertilizer developments utilizing the organic wastes. They have significant contribution to the biomass valorization[29] *via* generation of alcohol,[202] biodiesel,[203] organic acids,[204] and gas fuels.[205] But, there are several challenges before the efficient use of pretreatment technologies in the digestion of organic wastes or bio-wastes and solid waste managements. Anaerobic decomposition of organic wastes occurs when dumped in landfills.[46] Harmful greenhouse gases like methane are produced by the decomposition of green waste in anaerobic condition, which are the main participant to the global warming.[206] Speedily depleting landfill space is another problem with the direct landfill. In proper management of organic wastes, there are various considerable barriers. Poor infrastructure, poor planning of strategy, capacity of staff,

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registration, programme engagement, information system, and unsystematic management of waste make it a difficult job.[46] Also, there is absence of participation in the initiatives of the separation of garbage and inadequate communication between the homeowners and municipality[207] which makes the management of organic waste very difficult. For allowing more effective value extraction and recycling process, separation of waste should be at source.[207] Separation of the types of wastes like dry wastes or wet wastes (biodegradable) make the pretreatment process more effective and significant. So, it is the main responsibility of producers of wastes along with the government's effective involvements. There are the needs of combined efforts of urban local bodies, governments, private sectors, and non-governmental bodies for the long term waste managements and visionary project developments are strongly needed in this regards. There is also strong need of well-defined roles and responsibility to work on waste management with continuous monitoring and assessment.[207] Kumar *et al*. (2017)[207] have nicely reviewed the challenges and opportunities related to the management of the waste materials in Indian scenario. Thus, in order to implement perfectly the fungal pretreatment technology either individually or in combination with other technology for the green and sustainable environment, the above barriers need to be tackled because in poor countries organic waste disposal is a very difficult task. Consistent and properly managed involvements of the system (government, industries and public) in organic waste management with appropriate methodologies are very essential to pretreat the organic or bio-wastes biologically. Higher pretreatment time is generally required by the fungal technology to gain the high removal rates of lignin and saccharification of cellulose which generate problems regarding cost rise and contamination by bacteria.[125] Except longer pretreatment time; requirement of feedstock's sterilization before the pretreatment process, heat generation during the fungal pretreatment process, and lower yield of sugar are some other challenges and shortcomings of fungal pretreatment which are needed to be properly tackled in future to make the fungal pretreatment technology more efficient and cost-effective. Biomass' big solids content is the principal reason restraining its solid fermentation, which generates ethanol. Similar to glucose fermentation, yield of ethanol and titer can be achieved through the amalgamation of cosolvent-improved lignocellulose fractionation and the following saccharification and fermentation.[208] Fungal pretreatment in combination with other methods of pretreatment may increase the enzymatic digestibility and lessen the time of fungal pretreatment.[29] Fungal technology has great advantages in the field of biomass conversion because several derived products from biomass's hydrolyzed sugar are important from the point of energy generation. 5-hydroxymethylfurfural, levulinic acid, and furfural have the ability as great-worth chemicals *via* the fungal technology.[29] Future development will require the more upgraded fungal technology with lesser pretreatment time, lesser or no sterilization requirements, enhanced enzymatic digestibility, reduced chances of contamination, and more yields of the products and such upgraded fungal pretreatment technologies should break more efficiently the biomass's complex structures enhancing the production of various valuable products.[29] Biogases (like methane) and other useful organic components (bioethanol, monomeric sugars etc.) produced during the process of fungal pretreatment technology may be utilized in human welfare with opting the consistent management techniques.

ACKNOWLEDGEMENT

Dr. Pankaj Kumar Chaurasia is grateful to the P.G. Department of Chemistry, L.S. College, Muzaffarpur and Dr. Shashi Lata Bharati is grateful to the Department of Chemistry, NERIST, Nirjuli (Arunachal Pradesh) for any support during the work. Other authors are also thankful to their respective departments for providing any facility during the work.

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DOI: 10.1039/D4SU00582A

DATA AVAILABILITY STATEMENT

Not applicable

Authors Contributions

Dr. Pankaj Kumar Chaurasia and Dr. Shashi Lata Bharati prepared the original manuscript's draft, wrote major sections, supervised, and edited the manuscript; Dr. Sunita Singh wrote specific sections and performed formal analysis and editing; Dr. Azhagu Madhavan Sivalingam, and Dr. Shiv Shankar performed formal analysis and editing. Dr. Ashutosh Mani was involved in supervision, editing and formal analysis. All authors also reviewed the manuscript.

Funding

Not applicable

Competing Interests

No any competing interests

View Article Online
DOI: 10.1039/D4SU00582A

REFERENCES

1 United Nations Environment Programme (UNEP), 2024, Global Waste Management Outlook 2024–Beyond an Age of Waste, Turning Rubbish into a Resource- International solid waste association ISWA. https://www.unep.org/resources/global-waste-management-outlook-2024

2 Food and Agricultural Organization of the United Nations (FAO 2024), 2024 Food loss and waste masterclass: the basics. https://www.fao.org/platform-food-loss-waste/flw-events/events/events-detail/2024-food-loss-and-waste-masterclass--the-basics/en

3 Environmental Protection Agency (EPA), “Composting at home,” 2020, https://www.epa.gov/recycle/composting-home/.

4 H. C. Moon, and I. S. Song, Enzymatic hydrolysis of Food Waste and methane production using UASB bioreactor. *Int. J. Green Energy*, 2011, **8**(3), 361–371. https://doi.org/10.1080/15435075.2011.557845

5 M. Rajin, A. Z. Yaser, S. Saalah, Y. Jagadeson, M. Ag Duraim. The effect of enzyme addition on the anaerobic digestion of food waste, Green Engineering for Campus Sustainability, Springer, Berlin, Germany, 2020.

6 A. Z. Yaser, J. Lamaming, E. Suali, M. Rajin, S. Saalah, Z. Kamin, N. N. Safie, N. A. S. Aji, and N. Wid. Composting and Anaerobic Digestion of Food Waste and Sewage Sludge for Campus Sustainability: A Review, *Int. J. Chem. Eng.,* 2022, vol. 2022, Article ID 6455889, 14 pages. https://doi.org/10.1155/2022/6455889

7 J. Havukainen, A. Saud, T. F. Astrup, P. Peltola, and M. Horttanainen. Environmental performance of dewatered sewage sludge digestate utilization based on life cycle assessment, *Waste Manag.* 2022, 137, 210–221. https://doi.org/10.1016/j.wasman.2021.11.005

View Article Online
DOI: 10.1039/D4SU00582A

8 A. Kwarciak-Kozłowska. Industrial and Municipal Sludge, Butterworth-Heinemann, Oxford, UK, 2019, pp. 337-360. https://doi.org/10.1016/B978-0-12-815907-1.00015-5

9 S. Wang, C. Xu, L. Song, and J. Zhang. Anaerobic Digestion of Food Waste and Its Microbial Consortia: A Historical Review and Future Perspectives, *Int. J. Environ. Res. Public Health,* 2022, 19(15)*,* 9519. https://doi.org/10.3390/ijerph19159519

10 F. Appel, A. Ostermeyer-Wiethaup and A. Balmann. Effects of the German Renewable Energy Act on structural change in agriculture–The case of biogas, *Utilities Policy* 2016, 41, 172–182. https://doi.org/10.1016/j.jup.2016.02.013

11 A. Pazera, R. Slezak, L. Krzystek, S. Ledakowicz, G. Bochmann, W. Gabauer, S. Helm, S. Reitmeier, L. Marley, and F. Gorga, Biogas in Europe: Food and beverage (FAB) waste potential for biogas production, *Energy Fuels,* 2015, 29, 4011–4021. https://doi.org/10.1021/ef502812s

12 A. Whiting and A. Azapagic, Life cycle environmental impacts of generating electricity and heat from biogas produced by anaerobic digestion, *Energy* 2014, 70, 181–193. https://doi.org/10.1016/j.energy.2014.03.103

13 A. D. Bees, I. D. Williams, Explaining the differences in household food waste collection and treatment provisions between local authorities in England and Wales, *Waste Manag.,* 2017, 70, 222–235. https://doi.org/10.1016/j.wasman.2017.09.004

14 L. Zhang, and D. Jahng, Long-term anaerobic digestion of food waste stabilized by trace elements, *Waste Manag.,* 2012, 32, 1509–1515. https://doi.org/10.1016/j.wasman.2012.03.015

15 Anu, Alokika, R. C. Kuhad, A. Rapoport, V. Kumar, D. Singh, V. Kumar, S. K. Tiwari, S. Ahlawat and B. Singh, Biological pretreatment of lignocellulosic biomass: An environment-benign and sustainable approach for conversion of solid waste into value-

View Article Online
DOI: 10.1039/D4SU00582A

added products, *Crit. Rev. Environ. Sci. Technol.*, 2024, 54(10), 771-796. https://doi.org/10.1080/10643389.2023.2277670.

16 U. Brémond, R. de Buyer, J.-P. Steyer, N. Bernet and H. Carrere, Biological pretreatments of biomass for improving biogas production: An overview from lab scale to full-scale, Energy Rev., 2018, 90, 583–604. https://doi.org/10.1016/j.rser.2018.03.103

17 F. Girotto, W. Peng, R. Rafieenia and R. Cossu, Effect of Aeration Applied During Different Phases of Anaerobic Digestion. *Waste Biomass Valor.,* 2018, 9, 161–174. https://doi.org/10.1007/s12649-016-9785-9

18 G.-C. Mitraka, K. N. Kontogiannopoulos, M. Batsioula, G. F. Banias, A. I. Zouboulis and P. G. Kougias, A Comprehensive Review on Pretreatment Methods for Enhanced Biogas Production from Sewage Sludge, *Energies* 2022, 15, 6536. https://doi.org/10.3390/en15186536

19 P. K. Chaurasia, S. L. Bharati and S. Yadava, Nano-reduction of gold and silver ions: A perspective on the fate of microbial laccases as potential biocatalysts in the synthesis of metals (gold and silver) nano-particles, *Curr. Res. Microb. Sci.,* 2022, 3, 100098. https://doi.org/10.1016/j.crmicr.2021.100098.

20 P. K. Chaurasia and S. L. Bharati, Research Advances in the Fungal World: Culture, Isolation, Identification, Classification, Characterization, Properties and Kinetics, Publisher: Nova Science Publishers, Inc., USA. 2020, Pages: 1-419, ISBN: 978-1-53617-197-6.

21 P. K. Chaurasia and S. Yadava, S. L. Bharati and S. K. Singh, *Russ. J. Bioorg. Chem.***,** 2014, 40(4), 455–460. https://doi.org/10.1134/S1068162014040025

22 P. K. Chaurasia, S. L. Bharati and S. K. Singh, *Russ. J. Bioorg. Chem.*, 2014, 40(3), 288–292**.** https://doi.org/10.1134/S1068162014020034.

23 P. K. Chaurasia, Nagraj, N. Sharma, S. Kumari, M. Yadav, S. Singh, A. Mani, S. Yadava and S. L. Bharati, Fungal assisted bio-treatment of environmental pollutants with comprehensive emphasis on noxious heavy metals: Recent updates, *Biotechnol. Bioeng.,* 2023, 120(1), 57-81 . https://doi.org/10.1002/bit.28268

24 P. K. Chaurasia, N. Sharma, Nagraj, D. M. Rudakiya, S. Singh and S. L. Bharati, Fungal-Assisted Bioremediation of Agricultural Organic Pollutants (Pesticides and Herbicides), *Curr. Green Chem.,* 2022, 9(1), 14-25. https://dx.doi.org/10.2174/2213346109666220927121948

25 A. Salihu and M. Z. Alam, Pretreatment methods of organic wastes for biogas production, *J. Appl. Sci.,* 2016, 16, 124-137. https://dx.doi.org/10.3923/jas.2016.124.137

26 C. Wan and Y. Li, Fungal pretreatment of lignocellulosic biomass, *Biotechnol. Adv.* 2012, 30, 1447–1457. https://doi.org/10.1016/j.biotechadv.2012.03.003

27 J. Vasco-Correa and A. Shah, Techno-Economic Bottlenecks of the Fungal Pretreatment of Lignocellulosic Biomass, *Fermentation* 2019, *5*, 30. https://doi.org/10.3390/fermentation5020030

28 J. Vasco-Correa, X. Ge and Y. Li, Biological pretreatment of lignocellulosic biomass. In Biomass Fractionation Technologies for a Lignocellulosic Feedstock Based Biorefinery; Mussatto, S.I., Ed.; Elsevier: Amsterdam, The Netherlands, 2016; pp. 561–586. ISBN 9780128023235.

29 Y. Chai, M. Bai, A. Chen, L. Peng, J. Shao, S. Luo, Y. Deng, B. Yan and C. Peng, Valorization of waste biomass through fungal technology: Advances, challenges, and prospects *Ind. Crops Prod.,* 2022, 188, Part A, 115608, https://doi.org/10.1016/j.indcrop.2022.115608.

30 N. Nadir, N. L. Ismail and A. S. Hussain, Fungal Pretreatment of Lignocellulosic Materials. In (Ed.), Biomass for Bioenergy - Recent Trends and Future Challenges. IntechOpen. 2019. https://doi.org/10.5772/intechopen.84239

31 E. Lizundia, F. Luzi, and D. Puglia, Organic waste valorisation towards circular and sustainable biocomposites, *Green Chem.,* 2022, 24, 5429-5459. https://doi.org/10.1039/D2GC01668K

32 E. Gilman, A. Perez Roda, T. Huntington, S. J. Kennelly, P. Suuronen, M. Chaloupka, P. A. H. Medley, Benchmarking global fisheries discards**,** *Sci. Rep.,* 2020, 10, 14017. **https://doi.org/10.1038/s41598-020-71021-x**

33 D. Gunders and J. Bloom, Wasted: How America is losing up to 40 percent of its food from farm to fork to landfill*,* Natural Resources Defense Council, 2017.

34 K. C. Badgujar and B. M. Bhanage, Dedicated and waste feedstocks for biorefinery: an approach to develop a sustainable society*,* In: T. Bhaskar, A. Pandey, S. V. Mohan, D.-J. Lee and S. K. B. T.-W. B. Khanal (eds), Waste Biorefinery: Potential and Perspectives, Elsevier, 2018, 3–38. https://doi.org/10.1016/B978-0-444-63992-9.00001-X

35 Food and Agriculture Organization of the United Nations Statistics Division (FAOSTAT) Production: Livestock Primary: Eggs Primary*,* 2019.

36 S.-C. Wu, H.-C. Hsu, S.-K. Hsu, Y.-C. Chang and W.-F. Ho, Synthesis of hydroxyapatite from eggshell powders through ball milling and heat treatment**,** *J. Asian Ceram. Soc.,* 2016, 4, 85-90. https://doi.org/10.1016/j.jascer.2015.12.002

37 S. Mignardi, L. Archilletti, L. Medeghini, C. De Vito, Valorization of Eggshell Biowaste for Sustainable Environmental Remediation. *Sci. Rep.***,** 2020, 10, 2436. https://doi.org/10.1038/s41598-020-59324-5

38 N. A. M. Barakat, M. S. Khil, A. M. Omran, F. A. Sheikh, H. Y. Kim, Extraction of pure natural hydroxyapatite from the bovine bones bio waste by three different methods, *J. Mater. Process. Technol.,* 2009, 209, 3408-3415. **https://doi.org/10.1016/j.jmatprotec.2008.07.040**

39 P. Shi, M. Liu, F. Fan, C. Yu, W. Lu and M. Du, Characterization of natural hydroxyapatite originated from fish bone and its biocompatibility with osteoblasts, *Mater. Sci. Eng.: C,* 2018, 90, 706-712. **https://doi.org/10.1016/j.msec.2018.04.026**.

40 F. A. Sheikh, M. A. Kanjwal, J. Macossay, M. A. Muhammad, T. Cantu, I. S. Chronakis, N. A. M. Barakat, H. Y. Kim, Fabrication of Mineralized Collagen from Bovine Waste Materials by Hydrothermal Method as Promised Biomaterials. *J Biomater. Tissue Eng.,* 2011, 1, 194-197. https://doi.org/10.1166/jbt.2011.1017

41 C. M. Welker, V. K. Balasubramanian, C. Petti, K. M. Rai, S. DeBolt and V. Mendu, Engineering Plant Biomass Lignin Content and Composition for Biofuels and Bioproducts. *Energies*., 2015, 8(8), 7654-7676. https://doi.org/10.3390/en8087654

42 Z. Qin, Q. Zhuang, X. Zhu, X. Cai and X. Zhang, Carbon Consequences and Agricultural Implications of Growing Biofuel Crops on Marginal Agricultural Lands in China. *Environ. Sci. Technol*., 2011, 45, 10765–10772. https://doi.org/10.1021/es2024934

43 V. Mendu, A. E. Harman-Ware, M. Crocker, *et al.* Identification and thermochemical analysis of high-lignin feedstocks for biofuel and biochemical production. *Biotechnol. Biofuels,* 4, 43 (2011). https://doi.org/10.1186/1754-6834-4-43

44 V. Mendu, T. Shearin, J. E. Campbell, J. Stork, J. Jae, M. Crocker, G. Huber and S. DeBolt, Global bioenergy potential from high-lignin agricultural residue. *Proc. Natl. Acad. Sci*., 2012, 109, 4014–4019. https://doi.org/10.1073/pnas.1112757109

45 V. K. Thakur and M. K. Thakur, Recent advances in green hydrogels from lignin: a review. *Int. J. Biol. Macromol.*, 2015, 72, 834–847. https://doi.org/10.1016/j.ijbiomac.2014.09.044

46 S. Kharola, M. Ram, N. Goyal, S. K. Mangla, O. P. Nautiyal, A. Rawat, Y. Kazancoglu and D. Pant, Barriers to organic waste management in a circular economy. *J. Clean. Prod.,* 2022, 362, 132282. https://doi.org/10.1016/j.jclepro.2022.132282.

47 M. S. Aini, A. Fakhru'l-Razi, S. M. Lad and A. H. Hashim, Practices, attitudes and motives for domestic waste recycling. *Int. J. Sustain. Dev. World Ecol.*, 2002, 9(3), 232–238. https://doi.org/10.1080/13504500209470119

48 B. Sharma, B. Vaish, U. K. Singh, P. Singh and R. P. Singh, Recycling of organic wastes in agriculture: an environmental perspective. *Int. J. Environ. Res.,* 2019, 13(2), 409–429. https://doi.org/10.1007/s41742-019-00175-y

49 A. Kumar, S. K. Mangla and P. Kumar, An Integrated Literature Review on Sustainable Food Supply Chains: Exploring Research Themes and Future Directions. *Sci. Total Environ.,* 2022, 821, 153411. https://doi.org/10.1016/j.scitotenv.2022.153411

50 P. N. Patil, P. R. Gogate, L. Csoka, A. Dregelyi-Kiss and M. Horvath, Intensification of biogas production using pretreatment based on hydrodynamic cavitation. *Ultrason. Sonochem.*, 2016, 30, 79-86. https://doi.org/10.1016/j.ultsonch.2015.11.009

51 D. W. Fuerstenau and A. Z. M. Abouzeid, The energy efficiency of ball milling in comminution. *Int. J. Miner. Process.,* 2002, 67, 161-185. https://doi.org/10.1016/S0301-7516(02)00039-X

52 M. M. de Oliveira, P. Moretti, C. Malinowsky, R. Bayard, P. Buffière, A. B. de Castilhos Júnior, J. de Araujo Morais Júnior, G. B. A. Júnior and R. Gourdon, Mechanical pre-treatment of source-collected municipal biowaste prior to energy recovery by anaerobic

View Article Online
DOI: 10.1039/D4SU00582A

digestion. *Chemosphere,* 2022, 292, 133376, https://doi.org/10.1016/j.chemosphere.2021.133376.

53 A. Cesaro, V. Cieri and V. Belgiorno, Press-extrusion pretreatment of the organic fraction of municipal solid waste for enhanced methane production. *J. Mater. Cycles Waste Manag.,* 2021, **23**, 130–138.. https://doi.org/10.1007/s10163-020-01105-3

54 A. Chevalier, P. Evon, F. Monlau, V. Vandenbossche and C. Sambusiti, Twin-Screw Extrusion Mechanical Pretreatment for Enhancing Biomethane Production from Agro-Industrial, Agricultural and Catch Crop Biomasses. *Waste* **2023**, *1*, 497-514. https://doi.org/10.3390/waste1020030

55 C. L. Rai and P. G. Rao, Influence of sludge disintegration by high pressure homogenizer on microbial growth in sewage sludge: An approach for excess sludge reduction. *Clean Technol. Environ. Policy,* 2009, **11**, 437-446. https://doi.org/10.1007/s10098-009-0202-y

56 D. Sun, M. Wu, C. Bi, F. Gao, W. Wei and Y. Wang, Using high-pressure homogenization as a potential method to pretreat soybean protein isolate: Effect on conformation changes and rheological properties of its acid-induced gel. *Innov. Food Sci. Emerg. Technol.,* 2022, 82, 103195. https://doi.org/10.1016/j.ifset.2022.103195.

57 M. Nabi, D. Gao, J. Liang, Y. Cai and P. Zhang, Combining high pressure homogenization with free nitrous acid pretreatment to improve anaerobic digestion of sewage sludge. *J. Environ. Manag.,* 2022, **318**, 115635. https://doi.org/10.1016/j.jenvman.2022.115635

58 A. Pirozzi and F. Donsì, Impact of High-Pressure Homogenization on Enhancing the Extractability of Phytochemicals from Agri-Food Residues. *Molecules* **2023**, *28*, 5657. https://doi.org/10.3390/molecules28155657

59 T. Malik, R. Sharma, K. Ameer, O. Bashir, T. Amin, S. Manzoor and I. A. M. Ahmed, Potential of high-pressure homogenization (HPH) in the development of functional foods. *Int. J. Food Properties*, 2023, 26(1), 2509-2531. https://doi.org/10.1080/10942912.2023.2249262

60 S. Carpentieri, G. Ferrari and F. Donsì High-Pressure Homogenization for Enhanced Bioactive Recovery from Tomato Processing By-Products and Improved Lycopene Bioaccessibility during In Vitro Digestion. Antioxidants (Basel), 2023, 12(10), 1855. https://doi.org/10.3390%2Fantiox12101855

61 H. Xiao, J. Liang, Y. Zhang, J. Chang, R. Zhang and P. Zhang, Conversion of Materials and Energy in Anaerobic Digestion of Sewage Sludge with High-Pressure Homogenization Pretreatment. *Processes* **2023**, *11*, 2467. https://doi.org/10.3390/pr11082467

62 S. Pilli, P. Bhunia, S. Yan, R. J. LeBlanc, R. D. Tyagi, R. Y. Surampalli, Ultrasonic pretreatment of sludge: A review. *Ultrason. Sonochem.,* 2011, **18**, 1-18. https://doi.org/10.1016/j.ultsonch.2010.02.014

63 E. Elbeshbishy, S. Aldin, H. Hafez, G. Nakhla and M. Ray, Impact of ultrasonication of hog manure on anaerobic digestability. *Ultrason. Sonochem.,* 2011, **18**, 164-171. https://doi.org/10.1016/j.ultsonch.2010.04.011

64 Apul, O.G., Sanin, F.D. (2010). Ultrasonic pretreatment and subsequent anaerobic digestion under different operational conditions. *Bioresource Technology* **101**, 8984-8992. https://doi.org/10.1016/j.biortech.2010.06.128

65 N. A. Oz, C. C. Yarimtepe, Ultrasound assisted biogas production from landfill leachate. *Waste Manag.,* 2014, **34**, 1165-1170. https://doi.org/10.1016/j.wasman.2014.03.003

66 Y. Wu, S. Yao, B. A. Narale, A. Shanmugam, S. Mettu and M. Ashokkumar, Ultrasonic Processing of Food Waste to Generate Value-Added Products. *Foods,* 2022, **11**, 2035. https://doi.org/10.3390/foods11142035

67 F. Karouach, M. Bakraoui, Y. El Gnaoui, N. Lahboubi and H. El Bari, Effect of combined mechanical–ultrasonic pretreatment on mesophilic anaerobic digestion of household organic waste fraction in Morocco. *Energy Reports*, 2020, **6** (Supplement 2), 310-314. https://doi.org/10.1016/j.egyr.2019.11.081.

68 K. Zhao, G. Song, C. Lu, J. Wang, R. Liu and C. Hu, Ultrasonication as anaerobic digestion pretreatment to improve sewage sludge methane production: Performance and microbial characterization, *J. Environ. Sci.*, 2023. https://doi.org/10.1016/j.jes.2023.04.022

69 M. Buvaneshwaran, M. Radhakrishnan and V. Natarajan, Influence of ultrasound-assisted extraction techniques on the valorization of agro-based industrial organic waste – A review, *J. Food Process Eng.,* 2023, 46(6), e14012. https://doi.org/10.1111/jfpe.14012

70 N. Wang, L. Li, K. Wang, X. Huang, Y. Han, X. Ma, M. Wang, X. Lv and X. Bai, Study and Application Status of Ultrasound in Organic Wastewater Treatment. ***Sustainability*** 2023, ***15***, 15524. https://doi.org/10.3390/su152115524

71 O. Sarkar, L. Matsakas, U. Rova and P. Christakopoulos, Ultrasound-controlled acidogenic valorization of wastewater for biohydrogen and volatile fatty acids production: Microbial community profiling, iScience, 26(4), 2023, 106519. https://doi.org/10.1016/j.isci.2023.106519.

72 C. Arce and L. Kratky, Mechanical pretreatment of lignocellulosic biomass toward enzymatic/fermentative valorization, iScience, 2022, 25(7), 104610. https://doi.org/10.1016/j.isci.2022.104610.

73 J. Chen, K. Adjallé, T. T. Lai, S. Barnabé, M. Perrier, J. Paris. Effect of mechanical pretreatment for enzymatic hydrolysis of woody residues, corn stover and alfalfa. *Waste Biomass Valorization*, 11 (2020), pp. 5847-5856. https://doi.org/10.1007/s12649-019-00856-x

74 Q. Liu, H. Fan, H. Mou, J. Liu, J. Huang, X. Dong, H. Song. Preparation and characterization of xylan by an efficient approach with mechanical pretreatments. *Ind. Crop. Prod.*, 165 (2021), p. 113420. https://doi.org/10.1016/j.indcrop.2021.113420

75 M. Garuti, E. Sinisgalli, M. Soldano, F.G. Fermoso, A.J. Rodriguez, M. Carnevale, F. Gallucci, Mechanical pretreatments of different agri-based feedstock in full-scale biogas plants under real operational conditions. Biomass Bioenergy, 158 (2022), p. 106352. https://doi.org/10.1016/j.biombioe.2022.106352

76 L. Luo, Y. Qu, W. Gong, L. Qin, W. Li, Y. Sun, Effect of particle size on the aerobic and anaerobic digestion characteristics of whole rice straw. Energies, 14 (2021), p. 3960. https://doi.org/10.3390/en14133960

77 Y. El Gnaoui, A. Frimane, N. Lahboubi, C. Herrmann, M. Barz and H. EL Bari, Biological pre-hydrolysis and thermal pretreatment applied for anaerobic digestion improvement: Kinetic study and statistical variable selection. *Cleaner Waste Systems,* 2022, **2**, 100005. https://doi.org/10.1016/j.clwas.2022.100005.

78 M. Wang, J. Wang, Y. Li, Q. Li, P. Li, L. Luo, F. Zhen, G. Zheng and Y. Sun, Low-Temperature Pretreatment of Biomass for Enhancing Biogas Production: A Review. *Fermentation,* 2022, **8**, 562. https://doi.org/10.3390/fermentation8100562

79 J. Rühl, S. Agrawal and M. Engelhart, Efficacy of thermal hydrolysis for boosting specific methane yield depending on temperature-normalized solids retention time in an activated sludge process. *Environ. Sci.: Water Res. Technol.*, 2022, 8, 2971-2980**.** https://doi.org/10.1039/D2EW00206J

80 X. Liu, Q. Wang, Y. Tang and S. G. Pavlostathis, A comparative study on biogas production, energy balance, and nutrients conversion with inter-stage hydrothermal treatment of sewage sludge, *Applied Energy*, 2021, **288**, 116669. https://doi.org/10.1016/j.apenergy.2021.116669

81 D. A. Jones, T. P. Lelyveld, S. D. Mavrofidis, S. W. Kingman and N. J. Miles, Microwave heating applications in environmental engineering-a review. *Resources, Conservation and Recycling,* 2002, **34**, 75-90. https://doi.org/10.1016/S0921-3449(01)00088-X

82 S. Simonetti, C. F. Martín and D. Dionisi, Microwave Pre-Treatment of Model Food Waste to Produce Short Chain Organic Acids and Ethanol via Anaerobic Fermentation. *Processes,* 2022, **10**(6), 1176. https://doi.org/10.3390/pr10061176

83 J. Liu, M. Zhao, C. Lv and P. Yue, The effect of microwave pretreatment on anaerobic co-digestion of sludge and food waste: Performance, kinetics and energy recovery, *Environmental Research,* 2020, **189**, 109856. https://doi.org/10.1016/j.envres.2020.109856

84 P. Prasertsilp, K. Pattaragulwanit, B. S. Kim and S. C. Napathorn, Microwave-assisted cassava pulp hydrolysis as food waste biorefinery for biodegradable polyhydroxybutyrate production. *Front. Bioeng. Biotechnol.,* 2023, 11, 1131053. https://doi.org/10.3389/fbioe.2023.1131053

85 Z. Jie, C. Liu, D. Xia, *et al.* An atmospheric microwave plasma-based distributed system for medical waste treatment. *Environ. Sci. Pollut. Res.,* 2023, **30**, 51314–51326. https://doi.org/10.1007/s11356-023-25793-0

86 Z. Jie, C. Liu, D. Xia, *et al.* Microwave plasma torches for solid waste treatment and vitrification. *Environ. Sci. Pollut. Res.,* 2023, **30**, 32827–32838. https://doi.org/10.1007/s11356-022-24523-2

View Article Online
DOI: 10.1039/D4SU00582A

87 H. Carrère, C. Dumas, A. Battimelli, D. J. Batstone, J. P. Delgenès, J. P. Steyer and I. Ferrer, Pretreatment methods to improve sludge anaerobic degradability: A review, *J. Hazard. Mater.,* 2010, **183**, 1-15. https://doi.org/10.1016/j.jhazmat.2010.06.129

88 I. T. Yeom, K. R. Lee, K. H. Ahn and S. H. Lee, Effects of ozone treatment on the biodegradability of sludge from municipal wastewater treatment plants, *Water Sci. Technol.,* 2002, **46**, 421-425. https://doi.org/10.2166/wst.2002.0641

89 J. H. L. Alino, J. A. Bastos, P. V. Remor, L. M. Frare, F. Orssatto, F. M. Damaceno and T. Edwiges, Alkaline Pretreatment and Pre-Hydrolysis Using Acidic Biowastes to Increase Methane Production from Sugarcane Bagasse, *Methane,* 2022, **1**, 189–200. https://doi.org/10.3390/methane1030015

90 B. Jankovičová, M. Hutňan, M. N. Czölderová, K. Hencelová and, Z. Imreová, Comparison of acid and alkaline pre-treatment of lignocellulosic materials for biogas production, *Plant, Soil Environ.,* 2022, 68(4), 195–204. https://doi.org/10.17221/421/2021-PSE

91 S. Sreevathsan, I. Crasta, B. K. Bhavana, S. N. Mudliar, Effect of ozonation on biodegradability enhancement and biomethanation potential of pretreatment process wastewaters from 2G ethanol production, *J. Chem. Technol. Biotechnol.*, 98(6), 1425-1434. https://doi.org/10.1002/jctb.7361

92 Y. Qiao, R. Jin, J. Gao, K. Wang, Y. Jiang, J. Xiong, M. Jia, Z. He and J. Liu, Process of landfill leachate pretreatment using coagulation and hydrodynamic cavitation oxidation. *RSC Adv.*, 2023, 13, 32175-32184. https://doi.org/10.1039/D3RA04259F

93 M. S. Shehu, Z. A. Manan and S. R. W. Alwi, Optimization of thermo-alkaline disintegration of sewage sludge for enhanced biogas yield. *Bioresour. Technol.,* 2012, **114**, 69-74. https://doi.org/10.1016/j.biortech.2012.02.135

94 J. Xu, H. Yuan, J. Lin and W. Yuan, Evaluation of thermal, thermal-alkaline, alkaline and electrochemical pretreatments on sludge to enhance anaerobic biogas production, *J. Taiwan Inst. Chem. Eng.,* 2014, **45**, 2531-2536. https://doi.org/10.1016/j.jtice.2014.05.029

95 G. Zhen, X. Lu, Y. Y. Li and Y. Zhao, Combined electrical-alkali pretreatment to increase the anaerobic hydrolysis rate of waste activated sludge during anaerobic digestion. *Applied Energy,* 2014, **128**, 93-102. https://doi.org/10.1016/j.apenergy.2014.04.062

96 B. Ahmed, V. K. Tyagi, A. A. Kazmi and A. Khursheed, New insights into thermal-chemical pretreatment of organic fraction of municipal solid waste: Solubilization effects, recalcitrant formation, biogas yield and energy efficiency. *Fuel,* 2022, **319**, 123725. https://doi.org/10.1016/j.fuel.2022.123725.

97 V. T. Pham, C. Y. Guan and P. C. Han, B. M. Matsagar, K. C. W. Wu, T. Ahamad, C. Y. Chang, C. P. Yu, Acid-catalyzed hydrothermal treatment of sewage sludge: effects of reaction temperature and acid concentration on the production of hydrolysis by-products. *Biomass Conv. Bioref.,* 2023, **13**, 7533–7546. https://doi.org/10.1007/s13399-021-01495-w

98 A. Bendaoud, A. Belkhiri, M. Maai, T. Moubchir, A. Hmamou, S. Tlemcani, N. Eloutassi, A. Lahkimi, Simple and Combined Pretreatment of a Mixture of Forestry and Aromatic-Medicinal Plant Waste by Chemical, Physical and Enzymatic Methods, *J. Ecol. Eng.*, 2023; 24(4):376-383. https://doi.org/10.12911/22998993/160094

99 A. A. Rajput, Zeshan and M. Hassan, Enhancing Biogas Production through Co-Digestion and Thermal Pretreatment of Wheat Straw and Sunflower Meal, *Renew. Energy* **2021**, 168, 1–10. https://doi.org/10.1016/j.renene.2020.11.149

100 J. J. Montoya-Rosales, M. Peces, L. M. González-Rodríguez, F. Alatriste-Mondragón and D. K. Villa-Gómez, A Broad Overview Comparing a Fungal, Thermal and Acid Pre-Treatment of Bean Straw in Terms of Substrate and Anaerobic Digestion Effect. *Biomass Bioenergy,* **2020**, 142, 105775. https://doi.org/10.1016/j.biombioe.2020.105775

101 J. Du, Y. Qian, Y. Xi and X. Lü, Hydrothermal and Alkaline Thermal Pretreatment at Mild Temperature in Solid State for Physicochemical Properties and Biogas Production from Anaerobic Digestion of Rice Straw. Renew. Energy, **2019**, 139, 261–267. https://doi.org/10.1016/j.renene.2019.01.097

102 T. Luo, H. Huang, Z. Mei, F. Shen, Y. Ge, G. Hu and X. Meng, Hydrothermal Pretreatment of Rice Straw at Relatively Lower Temperature to Improve Biogas Production via Anaerobic Digestion, *Chin. Chem. Lett.*, **2019**, 30, 1219–1223. https://doi.org/10.1016/j.cclet.2019.03.018

103 D. Wang, F. Shen, G. Yang, Y. Zhang, S. Deng, J. Zhang, Y. Zeng, T. Luo, Z. Mei, Can Hydrothermal Pretreatment Improve Anaerobic Digestion for Biogas from Lignocellulosic Biomass? *Bioresour. Technol.*, **2018**, 249, 117–124. https://doi.org/10.1016/j.biortech.2017.09.197

104 A. A. Rajput, Zeshan, C. Visvanathan, Effect of Thermal Pretreatment on Chemical Composition, Physical Structure and Biogas Production Kinetics of Wheat Straw, *J. Environ. Manag.,* **2018**, 221, 45–52. https://doi.org/10.1016/j.jenvman.2018.05.011

105 S. Bolado-Rodríguez, C. Toquero, J. Martín-Juárez, R. Travaini and P. A. García-Encina, Effect of Thermal, Acid, Alkaline and Alkaline-Peroxide Pretreatments on the Biochemical Methane Potential and Kinetics of the Anaerobic Digestion of Wheat Straw and Sugarcane Bagasse, *Bioresour. Technol.*, **2016**, 201, 182–190. https://doi.org/10.1016/j.biortech.2015.11.047

106 G. Jin, T. Bierma and P. M. Walker, Low-Heat, Mild Alkaline Pretreatment of Switchgrass for Anaerobic Digestion, *J. Environ. Sci. Health Part A,* **2014**, 49, 565–574. https://doi.org/10.1080/10934529.2014.859453

107 A. Das, S. Das, N. Das, P. Pandey, B. Ingti, V. Panchenko, V. Bolshev, A. Kovalev and P. Pandey, Advancements and Innovations in Harnessing Microbial Processes for Enhanced Biogas Production from Waste Materials, *Agriculture,* **2023**, *13(9)*, 1689. https://doi.org/10.3390/agriculture13091689

108 D. Mu, K. Ma, L. He and Z. Wei, Effect of microbial pretreatment on degradation of food waste and humus structure, *Bioresour Technol.*, 2023; 385:129442. https://doi.org/10.1016/j.biortech.2023.129442

109 G. Liu, D. Han and S. Yang, Combinations of mild chemical and bacterial pretreatment for improving enzymatic saccharification of corn stover. *Biotechnol. Biotechnol.l Equip.,* 2022, **36**(1), 598-608. https://doi.org/10.1080/13102818.2022.2112910

110 C. Song, W. Li, F. Cai, G. Liu and C. Chen, Anaerobic and Microaerobic Pretreatment for Improving Methane Production From Paper Waste in Anaerobic Digestion, *Front. Microbiol.,* 2021, **12**, 688290. https://doi.org/10.3389/fmicb.2021.688290

111 A. Chen, W. Li, X. Zhang, C. Shang, S. Luo, R. Cao and D. Jin, Biodegradation and detoxification of neonicotinoid insecticide thiamethoxam by white-rot fungus Phanerochaete chrysosporium, *J. Hazard. Mater.*, 2021, 417, 126017 https://doi.org/10.1016/j.jhazmat.2021.126017.

112 X. Zhang, J. Shao, A. Chen, C. Shang, X. Hu, S. Luo, M. Lei, L. Peng and Q. Zeng, Effects of cadmium on calcium homeostasis in the white-rot fungus Phanerochaete chrysosporium, *Ecotoxicol. Environ. Saf.*, 2018, 157, 95–101. https://doi.org/10.1016/j.ecoenv.2018.03.071

View Article Online
DOI: 10.1039/D4SU00582A

113 H. Z. Chen and Z. H. Liu, Multilevel composition fractionation process for high-value utilization of wheat straw cellulose, *Biotechnol. Biofuels,* 2014, **7**, 137. https://doi.org/10.1186/s13068-014-0137-3

114 B. Singh, Rice husk ash. In: Waste and Supplementary Cementitious Materials in Concrete, 2018, *417–460.* https://doi.org/10.1016/B978-0-08-102156-9.00013-4

115 B. Niu and B. H. Kim, Method for Manufacturing Corn Straw Cement-Based Composite and Its Physical Properties, *Materials,* **2022**, *15*, 3199. https://doi.org/10.3390/ma15093199

116 P. Pączkowski, A. Puszka and B. Gawdzik, Effect of Eco-Friendly Peanut Shell Powder on the Chemical Resistance, Physical, Thermal, and Thermomechanical Properties of Unsaturated Polyester Resin Composites, *Polymers,* **2021**, *13*, 3690. https://doi.org/10.3390/polym13213690

117 C. A. Rezende, M. A. de Lima, P. Maziero, *et al.* Chemical and morphological characterization of sugarcane bagasse submitted to a delignification process for enhanced enzymatic digestibility. *Biotechnol. Biofuels,* 2011, **4**, 54. https://doi.org/10.1186/1754-6834-4-54

118 W. A. Rizal, K. Nisa, R. Maryana, D. J. Prasetyo, D. Pratiwi, T. H. Jatmiko, D. Ariani and A. Suwanto, Chemical composition of liquid smoke from coconut shell waste produced by SME in Rongkop Gunungkidul, *IOP Conf. Series: Earth and Environ. Sci.,* 2020, 462, 012057. doi:10.1088/1755-1315/462/1/012057

119 C. S. G. P. Queirós, S. Cardoso, A. Lourenço, *et al.* Characterization of walnut, almond, and pine nut shells regarding chemical composition and extract composition, *Biomass Conv. Bioref.,* **10**, 175–188 (2020). https://doi.org/10.1007/s13399-019-00424-2

120 D. Wojcieszak, J. Przybył, I. Ratajczak, P. Goliński, D. Janczak, A. Waśkiewicz, K. Szentner and M. Woźniak, Chemical composition of maize stover fraction versus

View Article Online
DOI: 10.1039/D4SU00582A

methane yield and energy value in fermentation process, *Energy*, 2020, 198, 117258. https://doi.org/10.1016/j.energy.2020.117258

121 K. Slopiecka, F. Liberti, S. Massoli, P. Bartocci and F. Fantozzi, Chemical and physical characterization of food waste to improve its use in anaerobic digestion plants, *Energy Nexus*, 2022, 5, 100049. https://doi.org/10.1016/j.nexus.2022.100049

122 Y. Lu, Y-C. Lu, H-Q. Hu, F-J. Xie, X-Y. Wei and X. Fan, Structural Characterization of Lignin and Its Degradation Products with Spectroscopic Methods, *J. Spectrosc.*, 2017, vol. 2017, Article ID 8951658, 15 pages. https://doi.org/10.1155/2017/8951658

123 D. Deswal, R. Gupta, P. Nandal and R. C. Kuhad, Fungal pretreatment improves amenability of lignocellulosic material for its saccharification to sugars, *Carbohydr. Polym.*, 2014, 99, 264–269. https://doi.org/10.1016/j.carbpol.2013.08.045.

124 G. Valdés, R. T. Mendonça and G. Aggelis, lignocellulosic biomass as a substrate for oleaginous microorganisms: a review, *Appl. Sci.*, 2020, 10 (21), 7698. https://doi.org/10.3390/app10217698.

125 C. Wan and Y. Li, Fungal pretreatment of lignocellulosic biomass, *Biotechnol. Adv.,* 2012, 30, 1447–1457, http://dx.doi.org/10.1016/j.biotechadv.2012.03.003

126 E. Rouches, S. Zhou, J. P. Steyer and H. Carrere, White-Rot Fungi pretreatment of lignocellulosic biomass for anaerobic digestion: Impact of glucose supplementation. *Process Biochem.,* 2016 51(11), 1784-1792. http://dx.doi.org/10.1016/j.procbio.2016.02.003

127 A. Vaidya and T. Singh, Pre-treatment of Pinus radiata substrates by basidiomycetes fungi to enhance enzymatic hydrolysis, *Biotechnol. Lett.,* 2012, 34, 1263–1267, http://dx.doi.org/10.1007/s10529-012-0894-7.

128 E. Rouches, I. Herpoël-Gimbert, J. P. Steyer, H. Carrere, Improvement of anaerobic degradation by white-rot fungi pretreatment of lignocellulosic biomass: a review.

View Article Online
DOI: 10.1039/D4SU00582A

Renew. Sustain. Energy Rev., 2016, 59, 179–198. https://doi.org/10.1016/j.rser.2015.12.317

129 X.-F. Tian, Z. Fang and F. Guo, Impact and prospective of fungal pre-treatment of lignocellulosic biomass for enzymatic hydrolysis, *Biofuels Bioprod. Bioref.,* 2012, 6, 335–350. https://doi.org/10.1002/bbb.346

130 E. Kovács, C. Szűcs, A. Farkas, M. Szuhaj, G. Maróti, Z. Bagi, G. Rákhely and K. L. Kovács, Pretreatment of lignocellulosic biogas substrates by filamentous fungi, *J. Biotechnol.,* 2022, **360**, 160-170. https://doi.org/10.1016/j.jbiotec.2022.10.013

131 P. Basinas, J. Rusín, K. Chamrádová, K. Malachová, Z. Rybková and C. Novotný, Fungal pretreatment parameters for improving methane generation from anaerobic digestion of corn silage, *Bioresour. Technol.*, 2022, 345, 126526. https://doi.org/10.1016/j.biortech.2021.126526.

132 M. Á. Pallín, S. González-Rodríguez, G. Eibes, M. López-Abelairas, M. T. Moreira, J. M. Lema and T. A. Lú-Chau, Towards industrial application of fungal pretreatment in 2G biorefinery: scale-up of solid-state fermentation of wheat straw. *Biomass Convers. Bioref.*, 2024, **14**, 593–605. https://doi.org/10.1007/s13399-022-02319-1

133 M. H. Devi and S. Munjam, Bioethanol Production from Rice Straw and Cellulose Degradation using *Aspergillus terreus* and *Trichoderma harzanium, Biosci. Biotechnol. Res. Asia,* 2022, **19**(3), 699-711. http://dx.doi.org/10.13005/bbra/3022

134 M. Takano and K. Hoshino, Bioethanol production from rice straw by simultaneous saccharification and fermentation with statistical optimized cellulase cocktail and fermenting fungus, *Bioresour. Bioprocess.* **5**, 16 (2018). https://doi.org/10.1186/s40643-018-0203-y

135 M. Abo-State, A. Ragab, N. EL-Gendy, L. Farahat and H. Madian, Bioethanol Production from Rice Straw Enzymatically Saccharified by Fungal Isolates,

View Article Online
DOI: 10.1039/D4SU00582A

Trichoderma viride F94 and Aspergillus terreus F98. *Soft*, 2014, **3**, 19-29. http://dx.doi.org/10.4236/soft.2014.32003

136 I. B. Atitallah, G. Antonopoulou, I. Ntaikou, A. S. Beobide, V. Dracopoulos, T. Mechichi, G. Lyberatos, A Comparative Study of Various Pretreatment Approaches for Bio-Ethanol Production from Willow Sawdust, Using Co-Cultures and Mono-Cultures of Different Yeast Strains, *Molecules,* 2022, **27**, 1344. https://doi.org/10.3390/molecules27041344

137 I. Ntaikou, N. Menis, M. Alexandropoulou, G. Antonopoulou and G. Lyberatos, Valorization of kitchen biowaste for ethanol production via simultaneous saccharification and fermentation using co-cultures of the yeasts *Saccharomyces cerevisiae* and *Pichia stipites*, *Bioresour. Technol.,* 2018, **263**, 75–83. https://doi.org/10.1016/j.biortech.2018.04.109

138 C. Szűcs, E. Kovács, Z. Bagi, G. Rákhely and K. L. Kovács, Enhancing biogas production from agroindustrial waste pre-treated with filamentous fungi, *Biologia Futura,* 2021, **72**(3), 341-346. https://doi.org/10.1007/s42977-021-00083-3

139 R. K. Sharma, P. Chandra and D. S. Arora, Antioxidant properties and nutritional value of wheat straw bioprocessed by *Phanerochaete chrysosporium* and *Daedalea flavida*. *J. Gen. Appl. Microbiol.,* 2011, **56**, 519–523. https://doi.org/10.2323/jgam.56.519

140 P. K. Sadh, S. Duhan and J. S. Duhan,Agro-industrial wastes and their utilization using solid state fermentation: a review, *Bioresour. Bioprocess.,* 2018, **5**, 1. https://doi.org/10.1186/s40643-017-0187-z

141 P. Chandra, D. S. Arora, M. Pal, R. K. Sharma, Antioxidant potential and extracellular auxin production by white rot fungi, *Appl. Biochem. Biotechnol.,* 2019, **187**, 531–539. https://doi.org/10.1007/s12010-018-2842-z

View Article Online
DOI: 10.1039/D4SU00582A

142 R. Giri and R. K. Sharma, Fungal pretreatment of lignocellulosic biomass for the production of plant hormone by *Pichia fermentans* under submerged conditions, *Bioresour. Bioprocess.,* 2020, **7**, 30. https://doi.org/10.1186/s40643-020-00319-5

143 R. Pandi, G. Velu, P. Devi and B. Dananjeyan, Isolation and screening of soil yeasts for plant growth promoting traits, *Madras Agric. J.,* 2019, **106**, 439-443. https://doi.org/10.29321/maj.2019.000289

144 H. Basha and B. Ramanujam, Growth promotion effect of *Pichia guilliermondii* in chilli and biocontrol potential of *Hanseniaspora uvarum* against *Colletotrichum capsici* causing fruit rot, *Biocontrol Sci. Technol.,* 2015, **25**, 185–206. https://doi.org/10.1080/09583157.2014.968092

145 A. H. Nassar, K. A. El-Tarabily and K. Sivasithamparam, Promotion of plant growth by an auxin-producing isolate of the yeast *Williopsis saturnus* endophytic in maize (*Zea mays* L.) roots, *Biol. Fertil. Soils,* 2005, **42**, 97–108. https://doi.org/10.1007/s00374-005-0008-y

146 L. Cortes-Tolalpa, D. J. Jiménez, M. J. L. Brossi, J. Falcao-Salles, J. D. van Elsas, Different inocula produce distinctive microbial consortia with similar lignocellulose degradation capacity, *Appl. Microbiol. Biotechnol.,* 2016, **100**(17), 7713 – 7725. https://doi.org/10.1007/s00253-016-7516-6

147 H. Kausar, M. R. Ismail, H. M. Saud, R. Othman and S. Habib, Use of lignocellulolytic microbial consortium and pH amendment on composting efficacy of rice straw. *Compost Sci. Util.,* 2013, **21**, 121–133. https://doi.org/10.1080/1065657X.2013.842131

148 R. Ramarajan and C. S. Manohar, Biological pretreatment and bioconversion of agricultural wastes, using ligninolytic and cellulolytic fungal consortia, *Bioremed. J.,* 2017, **21**(2), 89-99. https://doi.org/10.1080/10889868.2017.1282937

149 D. D'Souza-Ticlo, D. Sharma and C. Raghukumar, A thermostable metal-tolerant laccase with bioremediation potential from a marine-derived fungus, *Marine Biotechnol.,* 2009, 11(6), 725-737. https://doi.org/10.1007/s10126-009-9187-0

150 B. Zhao, R. Liu, Q. Guo, G. Xu, L. Zhang, P. Sun, Y. Cao and S. Hu, The use of newly isolated fungal cultures for the selective delignification of bamboo culms, *Front. Bioeng. Biotechnol.,* 2023, 11:1265420. https://doi.org/10.3389/fbioe.2023.1265420

151 H. Meehnian, A. K. Jana and M. M. Jana, Pretreatment of cotton stalks by synergistic interaction of *Daedalea flavida* and *Phlebia radiata* in co-culture for improvement in delignification and saccharification. *Int. Biodeterior. Biodegrad.,* 2017, 117, 68–77. https://doi.org/10.1016/j.ibiod.2016.11.022

152 J. Qi, F. Li, L. Jia, X. Zhang, S. Deng, B. Luo, Y. Zhou, M. Fan and Y. Xia, Fungal Selectivity and Biodegradation Effects by White and Brown Rot Fungi for Wood Biomass Pretreatment. *Polymers,* **2023**, *15*, 1957. https://doi.org/10.3390/polym15081957

153 O. O. Olughu, L. G. Tabil, T. Dumonceaux, E. Mupondwa, D. Cree and X. Li, Technoeconomic analysis of a fungal pretreatment-based cellulosic ethanol production, *Results Eng*., 2023, 19, 101259. https://doi.org/10.1016/j.rineng.2023.101259.

154 K. Johnson, Y. Liu and M. Lu, A Review of Recent Advances in Spent Coffee Grounds Upcycle Technologies and Practices. *Front. Chem. Eng*., **2022**, 4, 2. https://doi.org/10.3389/fceng.2022.838605

155 S. I. Mussatto, E. M. S. Machado, S. Martins and J. A. Teixeira, Production, Composition, and Application of Coffee and Its Industrial Residues. *Food Bioprocess Technol.,* **2011**, 4, 661–672. https://doi.org/10.1007/s11947-011-0565-z

156 M. Taifouris, M. L. Corazza and M. Martín, Integrated Design of Biorefineries Based on Spent Coffee Grounds, *Ind. Eng. Chem. Res.*, **2021**, 60, 494–506. https://doi.org/10.1021/acs.iecr.0c05246

157 S. K. Karmee, A Spent Coffee Grounds Based Biorefinery for the Production of Biofuels, Biopolymers, Antioxidants and Biocomposites, *Waste Manag.*, **2018**, 72, 240–254. https://doi.org/10.1016/j.wasman.2017.10.042

158 H. Ahmed, R. S. Abolore, S. Jaiswal and A. K. Jaiswal, Toward Circular Economy: Potentials of Spent Coffee Grounds in Bioproducts and Chemical Production, *Biomass,* **2024**, *4*, 286-312. https://doi.org/10.3390/biomass4020014

159 J. McNutt and Q. He, Spent coffee grounds: A review on current utilization, *J. Ind. Eng. Chem.,* 2019, **71**, 78–88. https://doi.org/10.1016/j.jiec.2018.11.054

160 A. Afriliana, E. Hidayat, Y. Mitoma, T. Masuda and H. Harada, Studies on Composting Spent Coffee Grounds by *Aspergillus* sp and *Penicillium* sp in Aerobic Static Batch Temperature Control, *J. Agric. Chem. Environ.,* 2021, **10**, 91-112. https://doi.org/10.4236/jacen.2021.101007

161 J. Pereira, A. Cachinho, M. M. R. de Melo, C. M. Silva, P. C. Lemos, A. M. R. B. Xavier and L. S. Serafim, Enzymatic Potential of Filamentous Fungi as a Biological Pretreatment for Acidogenic Fermentation of Coffee Waste. *Biomolecules,* 2022, **12**(9), 1284. https://doi.org/10.3390/biom12091284

162 W. S. Lee, A. S. M. Chua, H. K. Yeoh, G. C. Ngoh, A review of the production and applications of waste-derived volatile fatty acids, *Chem. Eng. J.,* 2014, **235**, 83–99. https://doi.org/10.1016/j.cej.2013.09.002

163 L. Sun, M. Gong, X. Lv, Z. Huang, Y. Gu, J. Li, G. Du and L. Liu, Current advance in biological production of short-chain organic acid. *Appl. Microbiol. Biotechnol.,* 2020, **104**, 9109–9124. https://doi.org/10.1007/s00253-020-10917-0

View Article Online
DOI: 10.1039/D4SU00582A

164 S. A. Fayssal, Z. El Sebaaly, M. A. Alsanad, R. Najjar, M. Böhme, M. H. Yordanova, Y. N. Sassine, Combined effect of olive pruning residues and spent coffee grounds on *Pleurotus ostreatus* production, composition, and nutritional value, *PLoS ONE,* 2021, **16**(9), e0255794. https://doi.org/10.1371/journal.pone.0255794

165 D. Hernández, J. Sánchez and K. Yamasaki, A simple procedure for preparing substrate for *Pleurotus ostreatus* cultivation, *Bioresour. Technol.,* 2003, **90**, 145–150. https://doi.org/10.1016/S0960-8524(03)00118-4

166 F. Zadrazil, D. N. Kamarad, O. S. Isikhuemhen, F. Shucharfdt and G. Flachwosky, Bioconversion of lignocellulose into ruminant feed with white rot fungi—review of work done at FAL, Braunschweig. *J. Appl. Animal Res.,* 1996, **10**, 105–124. https://doi.org/10.1080/09712119.1996.9706139

167 D. N. Thompson, T. N. Houghton, J. A. Lacey, G. Peter, P. G. Shaw and R. Hess, Preliminary investigation of fungal bioprocessing of wheat straw for production of straw-thermoplastic composites. *Appl. Biochem. Biotechnol.,* 2003, 106, 423–436. https://doi.org/10.1385/ABAB:106:1-3:423

168 K. Paritosh, S. K. Kushwaha, M. Yadav, N. Pareek, A. Chawade and V. Vivekanand, Food Waste to Energy: An Overview of Sustainable Approaches for Food Waste Management and Nutrient Recycling, *BioMed Res. Int.,* 2017, vol. 2017, Article ID 2370927, 19 pages. https://doi.org/10.1155/2017/2370927

169 K. Kuruti, S. Begum, S. Ahuja, G. Anupoju, S. Juntupally, B. Gandu, D. Ahuja, Exploitation of rapid acidification phenomena of food waste in reducing the hydraulic retention time (HRT) of high rate anaerobic digester without conceding on biogas yield, *Bioresour. Technol.,* 2017, **226**, 65–72. https://doi.org/10.1016/j.biortech.2016.12.005

170 S. Jain, Global Food Waste Management: An Implementation Guide for Cities|Urban Food Actions Platform|Food and Agriculture Organization of the United Nations, 2018.

Available online: http://www.fao.org/urban-food-actions/knowledge-products/resources-detail/en/c/1136010/

171 V. Arelli, S. Begum, G. Anupoju, K. Kuruti and S. Shailaja, Dry anaerobic co-Digestion of food waste and cattle manure: Impact of total solids, substrate ratio and thermal pre treatment on methane yield and quality of biomanure. *Bioresour. Technol.,* 2018, **253**, 273–280. https://doi.org/10.1016/j.biortech.2018.01.050

172 A. Abbassi-Guendouz, D. Brockmann, E. Trably, C. Dumas, J. Delgenes, J. Steyer and R. Escudie, Total solids content drives high solid anaerobic digestion via mass transfer limitation, *Bioresour. Technol.,* 2012, **111**, 55–61. https://doi.org/10.1016/j.biortech.2012.01.174

173 M. Madsen, J. B. Holm-Nielsen, K. M. Esbensen, Monitoring of anaerobic digestion processes: A review perspective, *Renew. Sustain. Energy Rev.,* 2011, **15**, 3141–3155. https://doi.org/10.1016/j.rser.2011.04.026

174 V. Arelli, S. Juntupally, S. Begum, G. R. Anupoju, Significance of Pretreatment in Enhancing the Performance of Dry Anaerobic Digestion of Food Waste: An Insight on Full Scale Implementation Strategy with Theoretical Analogy, *Processes,* 2020, *8*, 1018. https://doi.org/10.3390/pr8091018

175 K. S. Bhurat, T. Banerjee, P. V. Bobde and S. S. Bhurat, Effect of chemical, physical, and biological pre-treatment of food wastes on bio-hydrogen production by dark anaerobic fermentation under mesophilic conditions, *Energy Sources, Part A: Recovery, Util. Environ. Eff.,* 2023, 45:1, 1017-1029. https://doi.org/10.1080/15567036.2023.2174615

176 X. Yang, Z. Zhang, S. Li, Q. He, X. Peng, X. Du, K. Feng, S. Wang and Y. Deng, Fungal dynamics and potential functions during anaerobic digestion of food waste. *Environ. Res*., 2022, 212, Part B, 113298. https://doi.org/10.1016/j.envres.2022.113298

177 M. Zhang, D. Zhang, Y. Wei, B. Zhou, C. Yan, D. Wang, J. Liang and L. Zhou, Fungal mash enzymatic pretreatment combined with pH adjusting approach facilitates volatile fatty acids yield via a short-term anaerobic fermentation of food waste. *Waste Manag.,* 2022, 151, 1–9. https://doi.org/10.1016/j.wasman.2022.07.028

178 Y. Chen, J. Luo, Y. Yan and L. Feng, Enhanced production of short-chain fatty acid by co-fermentation of waste activated sludge and kitchen waste under alkaline conditions and its application to microbial fuel cells. *Applied Energy,* 2013, 102, 1197–1204. https://doi.org/10.1016/j.apenergy.2012.06.056

179 Y. Yin, Y.-J. Liu, S.-J. Meng, E. U. Kiran and Y. Liu, Enzymatic pretreatment of activated sludge, food waste and their mixture for enhanced bioenergy recovery and waste volume reduction via anaerobic digestion. *Applied Energy,* 2016 179, 1131-1137. https://doi.org/10.1016/j.apenergy.2016.07.083

180 H. Ren, T. Zhao, J. Xing, Y. Zhang, Z. Li, Y. Wang and W. Ma, Isolation and Characterization of Microcrystalline Cellulose from Distillers Grains, *J. Biobased Mater. Bioenergy,* 2015, **9**, 515−522. https://doi.org/10.1166/jbmb.2015.1550

181 H. Ren, W. Sun, Z. Wang, S. Fu, Y. Zheng, B. Song, Z. Li and Z. Peng, Enhancing the Enzymatic Saccharification of Grain Stillage by Combining Microwave-Assisted Hydrothermal Irradiation and Fungal Pretreatment, *ACS Omega,* 2020, **5**, 12603-12614. https://dx.doi.org/10.1021/acsomega.9b03681.

182 M. Selig, N. Weiss and Y. Ji, Enzymatic saccharification of lignocellulosic biomass. National Renewable Energy Laboratory NREL/TP-510-42629; Golden: Colo, USA, 2008.

183 X. Kan, J. Zhang, Y. W. Tong and C. H. Wang, Overall evaluation of microwave-assisted alkali pretreatment for enhancement of bio-methane production from brewers'

View Article Online
DOI: 10.1039/D4SU00582A

spent grain. *Energy Conv. Manag.,* 2018 **158**, 315–326. https://doi.org/10.1016/j.enconman.2017.12.088

184 G. Bastien, G. Arnal, S. Bozonnet, S. Laguerre, F. Ferreira, R. Fauré, B. Henrissat, F. Lefèvre. P. Robe, O. Bouchez, C. Noirot, C. Dumon and M. O'Donohue, Mining for hemicellulases in the fungus-growing termite *Pseudacanthotermes militaris* using functional metagenomics, *Biotechnol. Biofuels,* 2013, **6**, 78. https://doi.org/10.1186/1754-6834-6-78

185 R. D. Buxton, Termites and the turnover of dead wood in an arid tropical environment, *Oecologia,* 1981, 51, 379–384. https://doi.org/10.1007/bf00540909

186 M. Ohkuma, Termite symbiotic systems: efficient bio-recycling of lignocellulose. *Appl. Microbiol. Biotechnol.,* 2003, **61**, 1-9. https://doi.org/10.1007/s00253-002-1189-z

187 J. A. Bonachela, R. M. Pringle, E. Sheffer, T. C. Coverdale, J. A. Guyton, K. K. Caylor and S. A. Levin, C. E. Tarnita, Termite mounds can increase the robustness of dryland ecosystems to climatic change. *Science,* 2015, **347**, 651–655. https://doi.org/10.1126/science.1261487

188 F. Ahmad, G. Yang, Y. Zhu, M. Poulsen, W. Li, T. Yu, J. Mo, Tripartite Symbiotic Digestion of Lignocellulose in the Digestive System of a Fungus-Growing Termite, *Microbiol. Spectr.,* 2022, **10**(6), e01234-22. https://doi.org/10.1128/spectrum.01234-22

189 P. J. V. Soest, Use of detergents in the analysis of fibrous feeds. II. A rapid method for the determination of fiber and lignin, *J. Assoc. Off. Agric. Chem.,* 1963, **46**, 829–835. https://doi.org/10.1093/jaoac/46.5.829

190 R. Nkoa, Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: A review, *Agron. Sustain. Dev.,* 2014, **34**, 473–492. https://doi.org/10.1007/s13593-013-0196-z

191 A. Zanellati, F. Spina, L. Rollé, G. C. Varese and E. Dinuccio, Fungal Pretreatments on Non-Sterile Solid Digestate to Enhance Methane Yield and the Sustainability of Anaerobic Digestion, *Sustainability,* 2020, *12(20)*, 8549. https://doi.org/10.3390/su12208549

192 Y. Zhong, Z. Liu, C. Isaguirre, Y. Liu, W. Liao, Fungal fermentation on anaerobic digestate for lipid-based biofuel production. *Biotechnol. Biofuels,* 2016, **9**, 253. https://doi.org/10.1186/s13068-016-0654-3

193 S. S. Ali and J. Sun, Physico-chemical pretreatment and fungal biotreatment for park wastes and cattle dung for biogas production. *SpringerPlus*, 2015, **4**, 712. https://doi.org/10.1186/s40064-015-1466-9

194 S. Suthar, N. K. Singh, Fungal pretreatment facilitates the rapid and valuable composting of waste cardboard. Bioresour. Technol., 2022, 344, Part A, 126178. https://doi.org/10.1016/j.biortech.2021.126178

195 M. Andlar, T. **Rezić**, N. **Marđetko**, D. **Kracher**, R. **Ludwig and** B. **Šantek**, Lignocellulose degradation: An overview of fungi and fungal enzymes involved in lignocellulose degradation, *Eng. Life Sci.*, 2018, **18**(11), 768–778. https://doi.org/10.1002%2Felsc.201800039

196 E. A. Moreira, G. F. Persinoti, L. R. Menezes, D. A. A. Paixão, T. M. Alvarez, J. P. L. F. Cairo, F. M. Squina, A. M. Costa-Leonardo, A. Rodrigues, D. Sillam-Dussès and A. Arab, Complementary Contribution of Fungi and Bacteria to Lignocellulose Digestion in the Food Stored by a Neotropical Higher Termite. *Front. Ecol. Evol.,* 2021, **9**, 632590. https://doi.org/10.3389/fevo.2021.632590

197 A. Khalid, M. Arshad, M. Anjum, T. Mahmood and L. Dawson, The anaerobic digestion of solid organic waste. *Waste Manag.,* 2011, **31**(8) 1737-1744. https://doi.org/10.1016/j.wasman.2011.03.021

198 L. M.Rodríguez-Jiménez, A. Pérez-Vidal and P. Torres-Lozada, Research trends and strategies for the improvement of anaerobic digestion of food waste in psychrophilic temperatures conditions, *Heliyon,* 2022, **8**(10), e11174. https://doi.org/10.1016/j.heliyon.2022.e11174

199 M. Kilucha, S. Cheng, S. Minza, S. M. Nasiruddin, K. Velempini, X. Li, X. Wang, K. M. Doroth and Z. Li,. Insights into the anaerobic digestion of fecal sludge and food waste in Tanzania, *Front. Environ. Sci.,* 2022, **10**, 911348. https://doi.org/10.3389/fenvs.2022.911348

200 M. Dashtban, H. Schraft and W. Qin, Fungal Bioconversion of Lignocellulosic Residues; Opportunities & Perspectives, *Int. J. Biol. Sci.,* 2009, **5**(6), 578-595. https://doi.org/10.7150/ijbs.5.578.

201 P. K. Singh, P. Mohanty, S. Mishra and T. K. Adhya, Food Waste Valorisation for Biogas-Based Bioenergy Production in Circular Bioeconomy: Opportunities, Challenges, and Future Developments, *Front. Energy Res.,* 2022, **10**, 903775. https://doi.org/10.3389/fenrg.2022.903775

202 Sulfahri, S. Mushlihah, D. R. Husain, A. Langford, A. C. M. A. R. Tassakka, Fungal pretreatment as a sustainable and low cost option for bioethanol production from marine algae, *J. Clean. Prod.*, 2020, 265, 121763 https://doi.org/10.1016/j.jclepro.2020.121763

203 X. Yu, Y. Zheng, K. M. Dorgan and S. Chen, Oil production by oleaginous yeasts using the hydrolysate from pretreatment of wheat straw with dilute sulfuric acid, *Bioresour. Technol.*, 2011, 102 (10), 6134–6140. https://doi.org/10.1016/j. biortech.2011.02.081

204 A. Jimenez-Quero, E. Pollet, M. Zhao, E. Marchioni, L. Averous and V. Phalip, Fungal fermentation of lignocellulosic biomass for itaconic and fumaric acid production, *J. Microbiol. Biotechnol.*, 2017, 27, 1–8. https://doi.org/10.4014/ jmb.1607.07057

205 W. Suksong, N. Wongfaed, B. Sangsri, P. Kongjan, P. Prasertsan, S. M. Podmirseg, H. Insam and S. O-Thong, Enhanced solid-state biomethanisation of oil palm empty fruit bunches following fungal pretreatment, *Ind. Crops Prod.*, 2020, 145, 112099 https://doi.org/10.1016/j.indcrop.2020.112099

206 M. El-Fadel and M. Massoud, Emissions from landfills: a methodology comparative assessment, *Environ. Technol.,* 2000, 21(9), 965–978. https://doi.org/10.1080/09593332108618041

207 S. Kumar, S. R. Smith, G. Fowler, C. Velis, S. J. Kumar, S. Arya, Rena, R. Kumar and C. Cheeseman, Challenges and opportunities associated with waste management in India. *Royal Society Open Science,* 2017, 4(3), 160764. https://doi.org/10.1098/rsos.160764

208 T. Y. Nguyen, C. M. Cai, R. Kumar, C. E. Wyman, Overcoming factors limiting high-solids fermentation of lignocellulosic biomass to ethanol, *Proc. Natl. Acad. Sci. USA,* 2017, 114 (44), 11673–11678. https://doi.org/10.1073/pnas.1704652114

209 N. R. Baral and A. Shah, Comparative techno-economic analysis of steam explosion, dilute sulfuric acid, ammonia fiber explosion and biological pretreatments of corn stover. *Bioresour. Technol.*, **2017**, 232, 331–343. https://doi.org/10.1016/j.biortech.2017.02.068

210 D. Humbird, R. Davis, L. Tao, C. Kinchin, D. Hsu, A. Aden, P. Schoen, J. Lukas, B. Olthof, M. Worley, et al. Process. Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol; National Renewable Energy Laboratory: Golden, CO, USA, May 2011.

211 E. Shirkavand, S. Baroutian, D. J. Gapes and B. R. Young, Combination of fungal and physicochemical processes for lignocellulosic biomass pretreatment—a review, *Renew. Sustain. Energy Rev.*, **2016**, 54, 217–234. https://doi.org/10.1016/j.rser.2015.10.003

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Figures Legends

Fig. 1: Different pretreatment techniques involved in the pretreatment process of organic or bio-wastes.

Fig. 2: Plants (dead and/or green) as the huge source of ligno-cellulose, lignin, cellulose, hemicellulose, small carbohydrates along with proteins, vitamins and several biologically organic compounds (1-8: Dead or dry woody or non-woody plants/leaves as bio-wastes; 9-15: Green woody and non-woody plants; 16-21: Varieties of flowers/herbs (green) become bio-wastes).

Fig. 3: Different type of biomasses and their application in biofuels, bioenergy and bio-products generation.[41]

Fig. 4: A model structure of lignin.[122]

Fig. 5: Schematic presentation of the cellulose degradation and its possible products.

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Tables Legends

Table 1: Simplified and comparative presentation of some pretreatment techniques, their potential features, drawbacks and types.

Table 2: Variation in the production of biogas/methane from lignocellulosic biomass after low temperature pretreatment process.[78]

Table 3: Major components in some agricultural wastes and food wastes.

Table 4: A comparative table of different recent studies on the fungal pretreatment of various organic wastes and their outcomes

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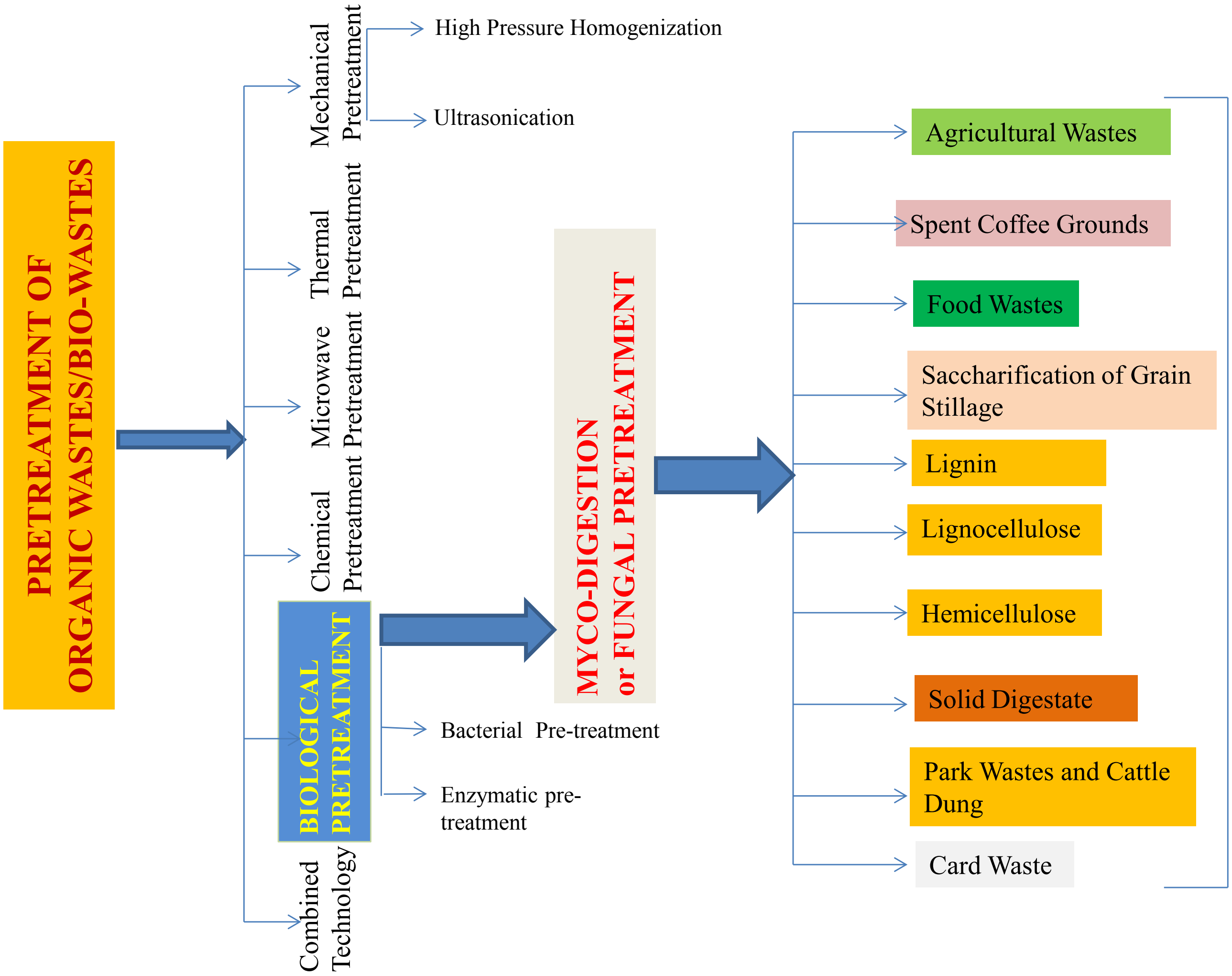

Fig. 1

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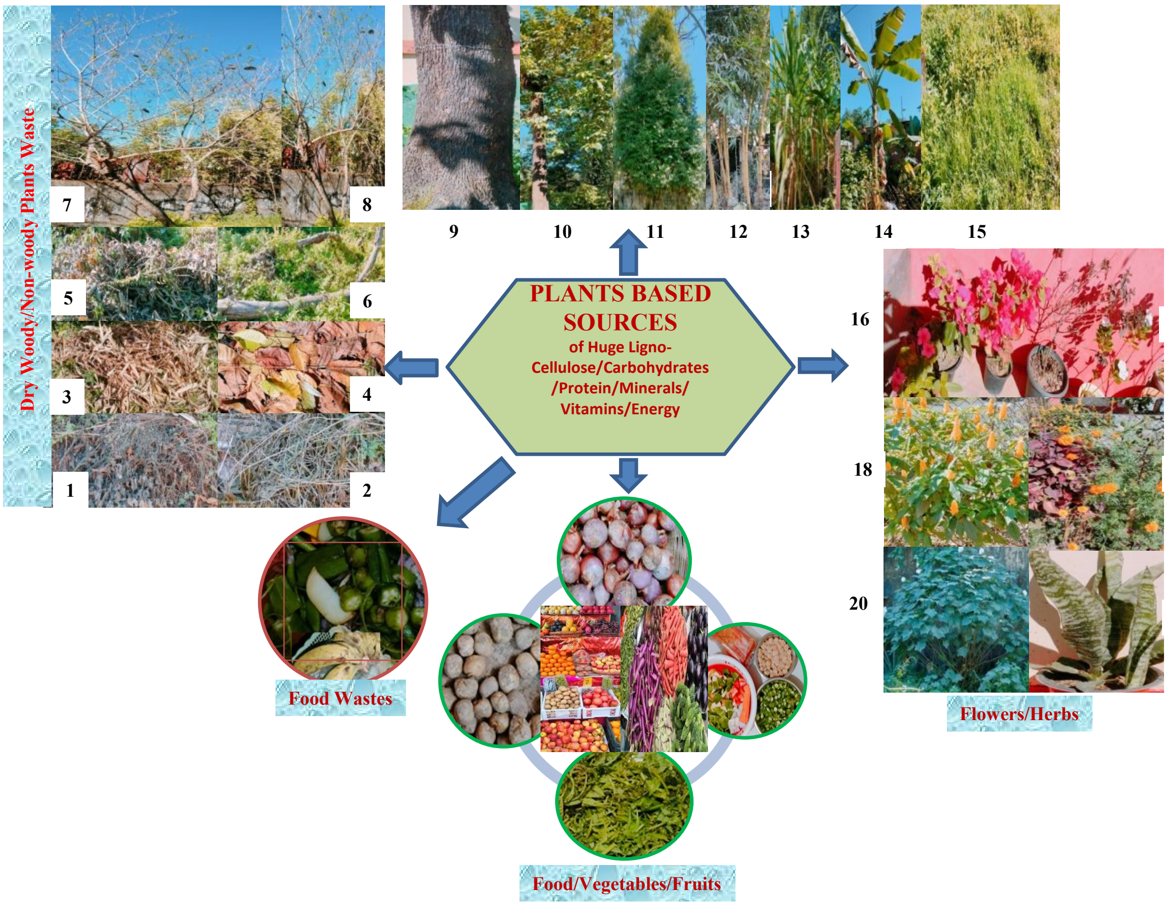

Fig. 2

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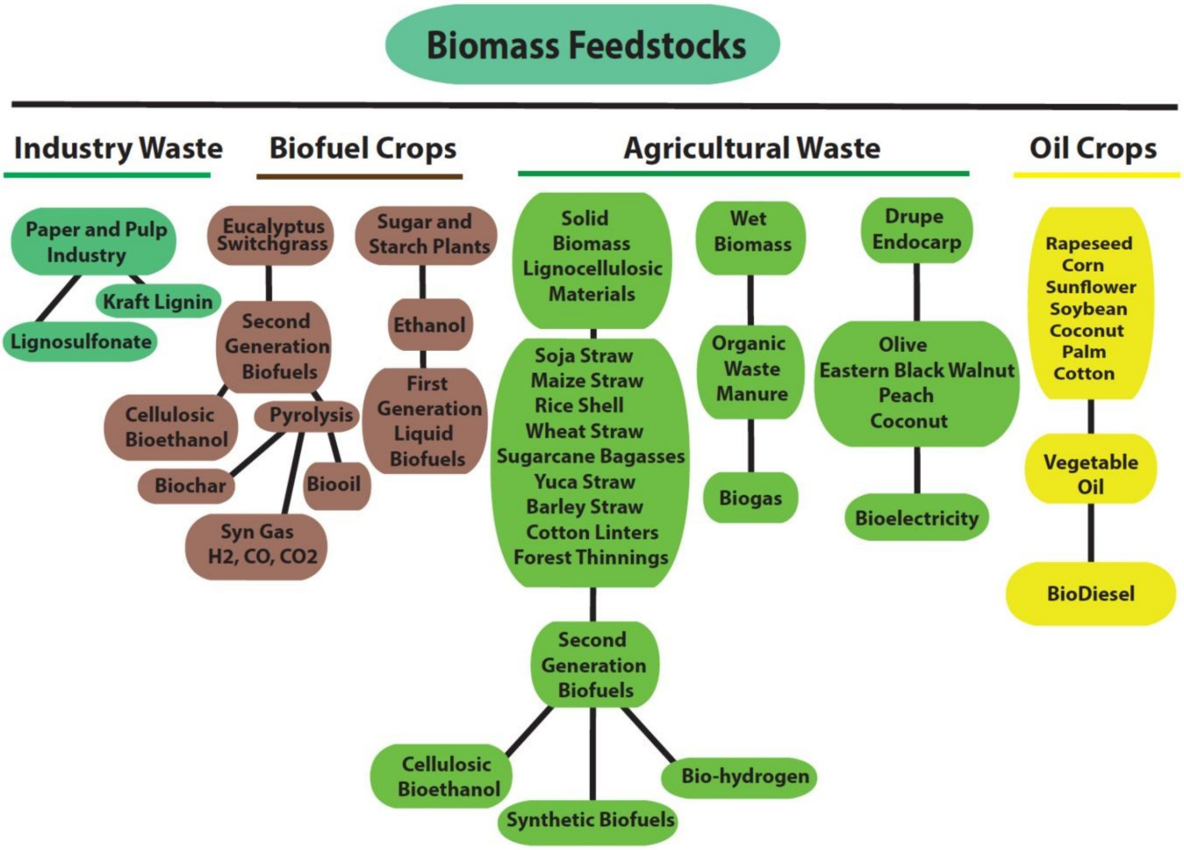

Fig. 3

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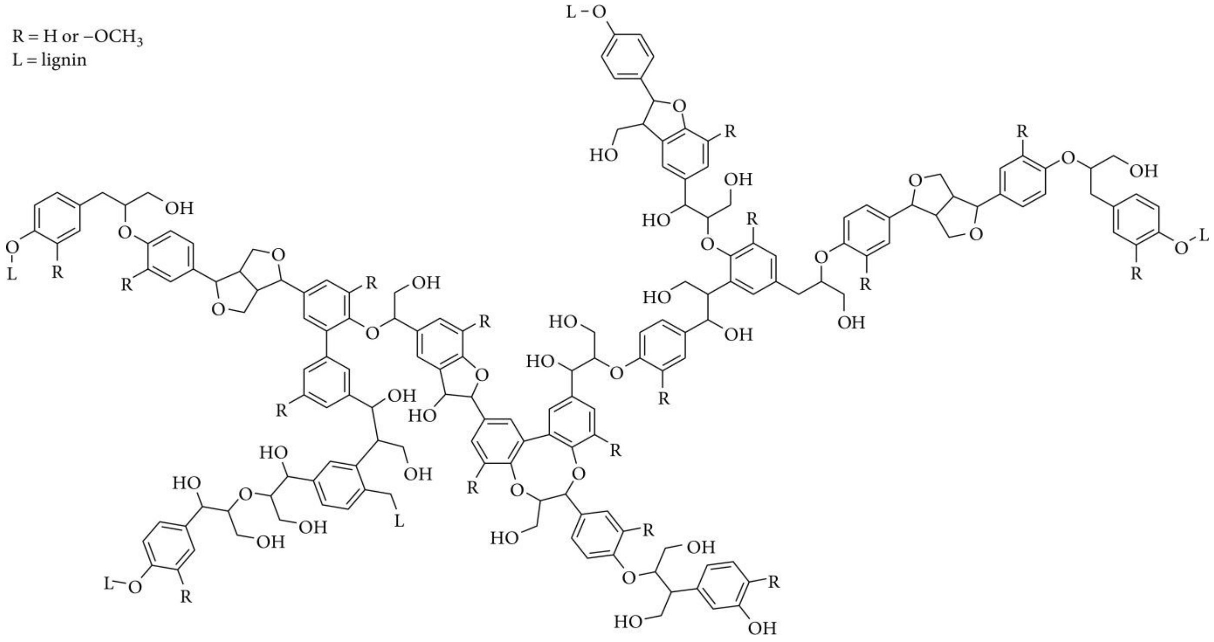

Fig. 4

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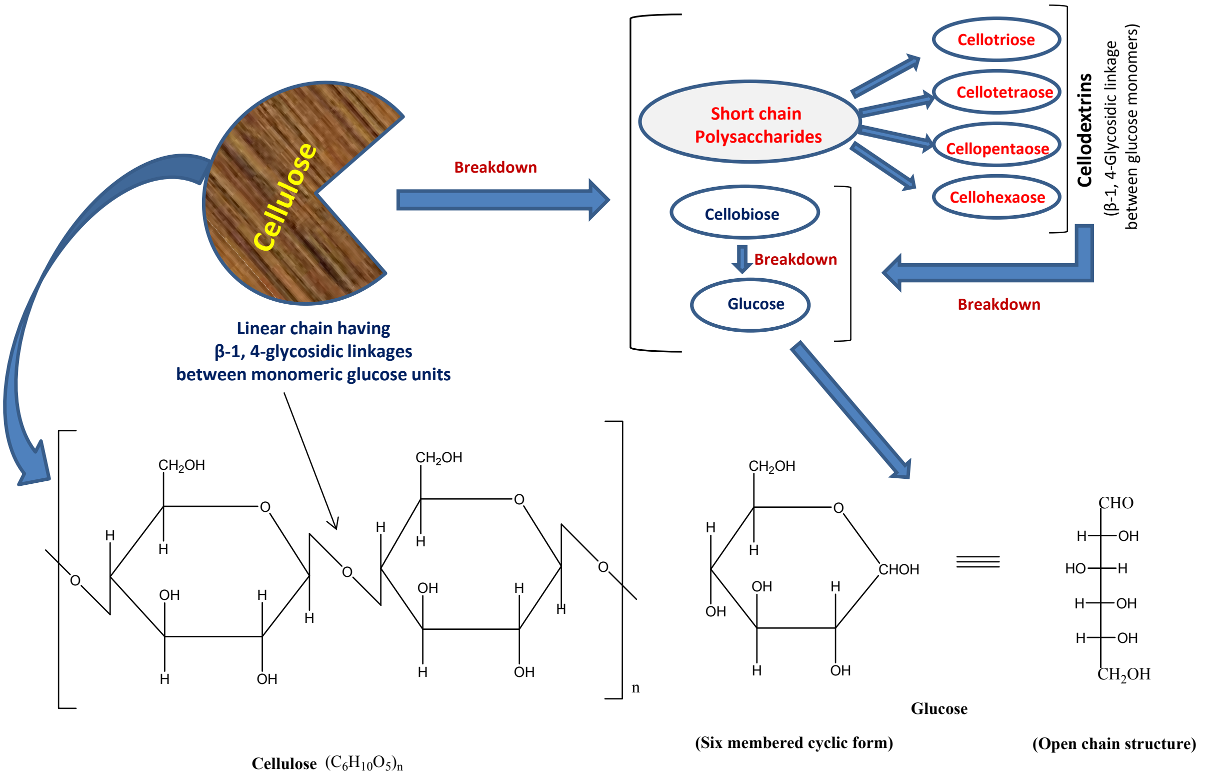

Fig. 5

Table 1

S.N.	Pretreatment techniques	Potential Features	Potential Drawbacks	Potential Types
1	Mechanical treatment	(i) Size reduction without producing any products and chemical alteration. (ii) No chemical needed. (iii) It's use before biological or other pretreatment methods is needed and makes the easy handling, transport and processing of even a big density of lignocellulosic materials.	High energy consumption	High pressure homogenization technique, Ultrasonication etc
2	Thermal pretreatment	(i) Helps in complex structures' hydrolysis. (ii) Helps in enhancing the anaerobic digestion.	Mostly high temperature requirement.	Low temperature based treatment, High temperature based pretreatment
3	Microwave assisted pretreatment	A type of heat pretreatment and helpful in the stabilization of wastes.	Electromagnetic radiation required.	-
4	Chemical based pretreatments	(i) Chemical constituents of bio-wastes are broken down using oxidants, alkali, and acids. (ii) Helping in the solubilisation of sludge	Harmful/toxic chemicals or reagents required. Used chemicals may be harmful for environment and human health.	Pretreatment using alkali, Pretreatment using acids, Ozonation, Peroxidation etc
5	Biological methods of pretreatment	(i) Microbial utilization for the degradation of organic wastes. (ii) No adverse conditions are required. (iii) Efficient in biodegradation, valuable products formation, bioconversion and biogas production. (iv) Bacterial, fungal and enzymatic methods are very effective techniques.	Comparatively time consuming process, contamination possibility, need of sterilization, works in optimized conditions like pH, temperature, concentrations etc.	Bacterial method of pretreatment, Fungal method of pretreatment, Enzymatic ways Combined methods

6	Combination of methods	(i) Utilization of two or more different methods for the pretreatment of organic wastes. (ii) More effective and efficient.	Depends on methods combined together for pretreatment.	Thermal-chemical methods, Chemical-biological techniques, Physical-chemical-biological methods, Other possible methods

Table 2

S.N.	Lignocellulosic sources	AD condition/Mode	Temperature /Time	Yield of Biogas/methane	Rise	References
1	67% Wheat straw and 33% sunflower meal	Mesophilic/Batch mode (45 days)	120 °C/ 1 hour	-/ 370 mL·g^{-1} VS	8.8%	99
			140 °C/ 1 hour	-/ 390 mL·g^{-1} VS	14.7%	
2	Bean straw	Mesophilic/Continuous mode (Hydraulic retention time 4.5 d)	121 °C/ 1 hour	145 mL·g^{-1} COD /-	-	100
3	Rice straw	Mesophilic /Batch mode (30 days)	80 °C/ 6 hours	372.5 mL·g^{-1} VS /-	12.4%	101
4	Rice straw	Mesophilic/Batch mode (35 days)	100 °C/ 150 minutes	128 L·kg^{-1} TS /-	22.8%	102
			130 °C/ 150 minutes	125 L·kg^{-1} TS /-	19.8%	
5	Rice straw	Mesophilic/Batch mode (50 days)	90 °C/ 15 minutes	307 mL·g^{-1} TS /-	3.0%	103
6	Wheat straw	Mesophilic/Batch mode (45 days)	120 °C/ 60 minutes	496 mL·g^{-1} VS /-	22.8%	104
7	Wheat straw	Mesophilic/Batch mode (30 days)	121 °C/ 60 minutes	-	29%	105
8	Sugarcane bagasse	Mesophilic/Batch mode (30 days)	121 °C/ 60 minutes	-	11%	105
9	Switchgrass	Mesophilic/Batch mode (1100 hours)	100 °C/ 6 hours	-	25.9%	106

Table 3

S.N.	**Common bio-wastes**	**Composition**		**References**
1	Wheat straw	Cellulose: 44.2%, Hemicellulose: 26.5%, Lignin: 22.4%, Ash: 2.8%		113
2	Rice straw	Cellulose: 36.1%, Hemicellulose: 27.2%, Lignin: 19.7%, Ash: 12.1%		113
3	Rice husk	Cellulose: 50%, Lignin: 25%-30%, Moisture: 10%-15% and Silica: 15%-20%		114
4	Poplar	Cellulose: 39.2%, Hemicellulose: 18.8%, Lignin: 29.6%, Ash: 1.5%		113
5	Corn straw	Cellulose: 33%, Lignin: 19.47%, Cellulose sugar: 23.58%, Ash: 5.12%		115
6	Peanut shell	Cellulose: 44.8%, Lignin: 36.1% and Hemicellulose: 5.6%		116
7	Bagasse	Cellulose: 35.2%, Hemicellulose: 24.5%, Lignin: 22.2 %, Ash: 20.9%		117
8	Coconut shell	Cellulose: 36.13%, Lignin: 32.33%, Hemicellulose: 20.36 %, Content soluble in water: 11.17%		118
9	Walnut shells	Polysaccharides: 49.7%, Lignin: 30.1%, Extractives: 10.6%		119
10	Almond shells	Polysaccharides: 56.1%, Lignin: 28.9%, Extractives: 5.7%		119
11	Pine nut shells	Polysaccharides: 48.7%, Lignin: 40.5%, Extractives: 4.5%		119
12	Corn stover fractions	Cobs	Cellulose: 37.8%, Lignin: 13.5%	120
		Husk	Cellulose: 38.1%, Lignin: 12.6%	
		Leaves	Cellulose: 39.3%, Lignin: 17.6%	
		Stalks	Cellulose: 44.9%, Lignin: 19.9%	
13	Food wastes	Fruits and vegetables wastes	Protein: 5.20%, Fat: 1.36%, Carbohydrates: 39.01%	121
		Waste of mixed vegetables	Protein: 15.3%, Fat: 0.87%, Carbohydrates: 83.83%	
		Dairy related products	Protein: 14.05%, Fat: 28.43%, Carbohydrates: 57.51%	

		Waste of cereal products	Protein: 11.71%, Fat: 3.83%, Carbohydrates: 84.98%	
		Bakery wares related wastes	Protein: 12.92%, Fat: 6.03%, Carbohydrates: 81.05%	
		Wastes of meat related products	Protein: 25.17%, Fat: 57.74%, Carbohydrates: 17.10%	
		Wastes of fish related products	Protein: 27.48%, Fat: 65.53%, Carbohydrates: 6.98%	
		Wastes from egg related products	Protein: 19%, Fat: 73.06%, Carbohydrates: 7.94%	
		Wastes from restaurants	Protein: 15.59%, Fat: 19.05%, Carbohydrates: 65.36%	
14	Rice wastes	Carbohydrates: 91%, Protein: 8%		121
15	Spent coffee grounds	Protein: 39.88%, Fat: 60.12%		121
16	Tea wastes	Carbohydrates: 76.59%, Protein: 23.04%		121

Table 4

S.N.	Fungi	Enzyme activity	Substrates	Some Outputs	References
1	*Trametes versicolor* (WRF), *Gloeophyllum trabeum* and *Rhodonia placenta* (Brown rot fungi)	-	Softwoods and hardwoods	• Softwoods mass conversion by two brown fungal species was greater than white rot fungi. • Hardwoods mass conversion by WRF exceeded that by BRF.	152
2	Fungal source	-	Switchgrass	• Yield of ethanol was projected to be 211.9 L/t of switchgrass and fungal pretreatment was the main contributor to the total capital investment. • Growing yield of glucose from 60 to 80% resulted in a five-fold enhancement in the net present value.	153
3	*Paracremonium* sp. LCB1 and *Clonostachys compactiuscula* LCN1	Hemicellulase and ligninolytic enzyme	Bamboo culms	• Significant lowering in the lignin weight (76.37%). • Lignin/cellulose ratio showed high loss (>10).	150
4	*Penicillium aurantiogriseum*, *Gilbertella persicaria* (SZMC11086), *Rhizomucor miehei* (SZMC11005), and *Trichoderma reesei* (DSM768)	Endoglucanase, β-glucosidase, and cellobiohydrolase	Wheat straw, woody willow chips, and corn stover	• Excellent production of hydrolytic enzyme and maximum yield of biogas from the partly decomposed substrates were shown by *P. aurantiogriseum* • Maximum yield of methane was for corn stover fed reactors • All the tested fungi preferred the corn stover substrate for the productivity of methane	130
5	*Pleurotus ostreatus* and *Dichomitus squalens*	-	Corn silage	• Biogas production was enhanced. • Methane gas was found to be increased by 1.55 fold. • Lignin de-polymerization increased the production of methane 0.301 to 0.465 $m^3kg_{VS}^{-1}$.	131
6	*Irpex lacteus*	-	wheat straw	• Wheat straw digestibility found after 21 days of the pretreatment in the solid	132

				state fermentations bioreactor (60.6%) was alike to that found on a small scale i.e. 57.9%. • In the 03 bioreactor experiments, sugars evolution was completely different after 21 days of treatment. • Greater lowering of lignin in experiment B2 i.e. 34.90 ± 0.87% in comparison with that of experiment B1 i.e. 26.7 ± 3.08%. • Alike reduction of lignin i.e. 53.2 ± 0.60% in the flask-scale pretreatment	
7	*Aspergillus terreus* and *Trichoderma harzanium*	-	Rice straw	• Degradation of cellulose • Production of bioethanol • The 80% degradation of cellulose by the isolated fungi *A. terreus* and *T. harzanium*. • *A. terreus performance on the decrease of cellulose with* HL and RP as substrate was 92% and 80%, respectively. • *T. harzanium performance on the decrease of cellulose with* HL and RP as substrate was 93% and 82%, respectively. • Rice straw's RP treated with *T. harzanium* has resulted in greater bioethanol of 5.4 g/L	133
8	*Saccharomyces cerevisiae, Pichia stipitis*, *Pachysolen tannophilus*, and *Wickerhamomyces anomalus* X19	-	Willow sawdust	• Bioethanol production • Yields of ethanol ranging from 11.67 ± 0.21 to 13.81 ± 0.20 g/100 g TS was shown by the *S. cerevisiae* or *W. anomalus* X19 monocultures and co-cultures with *P. stipitis*. • For the approach D, there was maximum removal of lignin (38.3%). • Co-cultures was useful	136
9	*Rhizomucor miehei*, *Aspergillus nidulans*, *Gilbertella persicaria*,	β-Glucosidase and endoglucanase	Dry CS (corn stover), WS	• β-Glucosidase and endo-(1,4)-β-D-glucanase activity • Yield of methane	138

	and *Trichoderma reesei*		and WWC		
10	*Pichia fermentans, Phanerochaete chrysosporium*	-	Wheat straw	• Auxin production by *P. fermentans* • Indole-3-acetic acid (IAA) production • The wheat straw was pretreated by *P. chrysosporium* for releasing the sugar in the medium which may be used by *P. fermentans* for the production of IAA • Sugar amount was released by *P. chrysosporium* from 2nd day onwards and was highest on 9th day	142
11	GK1 (*Chaetomium globosum*), GK2 (*Chaetomium brasiliense*), G4 (*Engyodontium album*), G10 (*Metarhizium anisopliae*), G13 (*Engyodontium album*), M155 (*Acremonium persicinum*), M158 (*Acremonium minutisporum*), and M2E (*Inonotus tropicalis*).	LiP (lignin peroxidase), laccase, CMCase, MnP (manganese peroxidase), and xylanase	Rice straw and sugarcane bagasse	• LiP (lignin peroxidase), laccase, CMCase, MnP (manganese peroxidase), and xylanase activity • Amongst the different consortia, the highest yield of sugar (4.39 gL^{-1}) was given by M2E+GK2 • ligninolytic and cellulolytic marine-derived fungal consortium were effective for agricultural wastes	148
12	*Polyporus brumalis* BRFM 985	-	Wheat straw	• Enhancement in the production of methane • They obtained up to 43% extra methane (CH_4) per gram of pretreated VS in comparison with control straw	126
13	*Paecilomyces variotii* NRRL-115 and *Trametes versicolor* CBS 109428	Enzymatic extracts	Spent coffee grounds	• Biological pretreatment for coffee waste's acidogenic fermentation • Generation of acetic acids, propionic acids, and butyric acids in an average proportion (59.9/33.8/6.3%) • Production of SCOA in the course of Acidogenic fermentation	161
14	*Aspergillus sp.*, and *Penicillium sp*	-	Spent coffee	• Chemical composition of SCG (%) as hemicellulose (39.75 ± 0.007), lignin	160

			grounds	(23.1 ± 0.007), caffeine (1.83 ± 0.007), and protein (10.82 ± 0.007). • Study *via* three samples analysis (control, C1, and C2) • Greater degradation of lignin in C2 • Composting time can be speed up and results of the produced compost can be optimized by this composting method	
15	*Pleurotus ostreatus*	-	Spent coffee grounds and olive pruning residues	• *Adopted the complete randomized design with 5 treatments* • They observed only S1, S2, and S3 as productive • Lignin loss percentage was greater in S1 in compare with S2 and S3 i.e. 53.51, 26.25, and 46.15%, respectively • Degradation of hemicellulose was preferentially occurred with respect to cellulose	164
16	*Aspergillus awamori* (CICC 41363)	Complex amylase (CA)	Food wastes	• Solubility and degradability of the organics in food waste were considerably enhanced by CA addition • The 116.9% increase in concentration of SCOD with the CA addition relative to the control • TOC and SCOD mean concentration were 12.5 g/L and 34.5 g/L, respectively • Under weakly basic and neutral conditions, a greater VFAs concentration was found • In enhancing FW hydrolysis, the pretreatment method of adding CA could be an effective method	177
17	Fungal mash	Hydrolytic enzymes	Food wastes	• Enzymatic pretreatment of activated sludge mixed with FW caused in the production of glucose (3.72 g/L) • The reduction of VS was found as 19.1% and 21.4% after the activated sludge and FW pretreatment, respectively by the fungal mash	179

				• Yield of bio-methane of fungal mash pretreated mixed waste was 2.5 times greater than the activated sludge receiving no pretreatment, with as further reduction of VS of 34.5%.	
18	*Phanerochaete chrysosporium*	Ligninolytic enzyme activity	Grain stillage	• Pretreatment of grain stillage • The maximum activities of ligninolytic enzyme was achieved by the fungal pretreatment with *Phanerochaete chrysosporium* digestion (PC) in six days with 10% inoculum size at which yield of reducing sugar and efficiency of saccharification reached 19.74 g/100 g and 36.29%, respectively. • The degrees of delignification were considerably enhanced to 32.80 (for PC + MH) and 43.34% (for MH + PC) after the combined pretreatment. • Use of combined MH and PC pretreatment could be an excellent method	181
19	*Coprinopsis cinerea* MUT 6385, *Cephalotrichum stemonitis* MUT 6326, and *Cyclocybe aegerita* MUT 5639	-	Solid digestate	• In the *C. aegerita*, *C. stemonitis*, and *C. cinerea* pretreated samples, there was significant decrease in the concentration of total solids (TS) i.e. 23.8%, 25.4%, and 28.5%, respectively • The anaerobic digestion functioned superior with SFD treated by the fungal strain *C. stemonitis* for twenty days • Cumulative yields of biogas and methane also studied	191
20	*Mortierella isabellina*	-	Anaerobic digestate	• Production of lignocellulosic biodiesel • Accumulation of lipid • After the process of pretreatment and hydrolysis, the mixture feed at the total solids of 10% produced a hydrolysate having glucose (13.85 g/L), xylose (8.95 g/L), and acetate (2.67 g/L). • Complete consumption of glucose and acetate in 49–54 hours, respectively	192

21	*Aspergillus terreus* and *Trichoderma viride*	-	Park wastes	• Physico-chemical pretreatment's influence on the degradation of cellulose followed by fungal treatment • TS, VS, TOC etc were studied • Study on biogas and CH_4 yields	193
22	Oligoporus placenta and *Tremetes hirsuta*	-	Card wastes	• Fungal pretreatment of waste cardboard • *Considerable lowering in cellulose* (28.3–35.8%), hemicellulose (61.4–68.4%), and lignin (67.5–69.3%) content in waste card board	194

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Data availability statements

This is a review article and during the preparation of this article, no new data were generated or analysed as part of this review.