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Trends in mitigation of industrial waste: Global health hazards, environmental implications and waste derived economy for environmental sustainability

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Abstract

Majority of industries, in order to meet the technological development and consumer demands, generate organic waste. The untreated waste spreads out toxic and harmful substances in the environment which serves as a breeding ground for pathogenic microorganisms thus causing severe health hazards. The three industrial sectors namely food, agriculture, and oil industry are among the primary organic waste producers that affect urban health and economic growth. Conventional treatment generates a significant amount of greenhouse gases which further contributes to global warming. Thus, the use of microbes for utilization of this waste, liberating CO_2 offers an indispensable tool. The simultaneous production of value-added products such as bioplastics, biofuels, and biosurfactants increases the economics of the process and contributes to environmental sustainability. This review for the first time comprehensively summarized the composition of organic waste generated from the food, agriculture, and oil industry. The linkages between global health hazards of industrial waste and environmental implications have been uncovered. Stare-of-the-art information on their subsequent utilization as a substrate to produce value-added products through bio-routes has been elaborated. The research gaps, economical perspective, and future research directions have been identified and discussed to strengthen environmental sustainability.

Keywords: Environmental sustainability; Waste derived economy; Bioplastic; Biosurfactants; Organic waste

1. Introduction

The leapfrog increase in population urged the manufacturing industries to meet technological development and consumer demand. Thus, along with the development of a new product, a different category of waste is generated substantially which causes social and environmental challenges due to its disposal and mismanagement (Gaur et al., 2020a; Sindhu et al., 2019; Varjani et al., 2015). An articulate and determined action is needed to manage the waste that can later be recycled and reused as a valuable resource (Alonso et al., 2015; Kundariya et al., 2021). Industrialization in the food, agriculture, and oil sector contributes a significant amount to waste generation. It has been evaluated that the agricultural sector furnishes 24 million tons of food around the world generating tons of solid waste with an increase of approximately 7.5% per year (Adejumo and Adebiyi, 2020). According to the Food and Agriculture Organization (FAO), United Nations, 1.3 billion tons of waste was generated from the food industry globally. Agro-industries during crop processing generates 250 million tons of waste globally from non-edible plants per year (Sharma et al., 2020). Another noteworthy contribution to organic waste was from the oil industry. Vegetable or petroleum oil industries generate a significant amount of waste during processing (Gaur et al., 2021a). The global vegetable oil market is estimated to increase at a 5.1% compound annual growth rate from 2015 to 2024 and reach US$ 130.3 billion by 2024 (Ahmad et al., 2020). During the production and processing of oil, a significant amount of waste is generated which includes organic soil waste (containing husks and seeds), inorganic residues, and wastewater (Ngoie et al., 2020). Most interestingly is the fact that a major fraction of theses waste is organic and thus if left untreated can cause severe environmental and human health hazards (Espinosa-Ortiz et al., 2021; Gaur et al., 2020a).

The traditional approaches of incineration, land-filling, composting also add up to environmental hazards by giving rise to greenhouse gases and by becoming a breeding ground to pathogenic microorganisms (Rajendran et al., 2021; Sharma et al., 2020; Tsang et al., 2019). These techniques have various inherent flaws like low accuracy and efficiency, exorbitant cost, and budding environmental risks. To address the pertaining issues intervention of machine learning, artificial neural network and Artificial intelligence like sophisticated technique are warranted for mitigation of non-linear organic waste generation and accumulation (Guo et al., 2021). To improve the environmental balance, search for an innovative concept like waste valorization will be able to reduce and manage industrial waste (Sharma et al., 2021). Thus alternatively, this unprocessed and incompetently treated waste can serve as raw material for the production of valuable products thus significantly assisting in waste management (Adebayo and Obiekezie, 2018; Rene et al., 2020). Waste valorization is a process of transforming waste matter into valuable products like bioactive molecules, fuels, and chemicals (Leong et al., 2021).

Recycling industrial wastes into valuable and alternative products has noteworthy benefits for the environment, community, and industries (Mohanty et al., 2021). Waste derived from industries has plenty of lipids, proteins, lignocelluloses, carbohydrates, and other organic compounds which can be turned into value-added products with the help of microbial action (Rajmohan et al., 2021; Gaur et al., 2020a; Sirohi et al., 2021). Several bacterial species such as *Pseudomonas aeruginosa*, *Brevibacillus borstelensis, Bacillus licheniformis, Bacillus subtilis*, *Enterococcus hirae, Staphylococcus aureus,* and *Lactobacillus delbrueckii* (Al-Wasify et al., 2017; Awasthi et al., 2018; Khanal et al., 2020; Msarah et al., 2020) and fungal species such as *Alternaria* sp., *Trichoderma harzianum, Fusarium* sp., *Phanerochaete chrysosporium,* and *Aspergillus* (Chen et al., 2019) has been reported with the potential to bio-transform wastes to produce value-added products. Products like biofuels, fire resistance material, biogas, bio-hydrogen, eicosapentaenoic acid, secondary metabolites, hydrochar, poly-hydroxyalkanotes, enzymes, dispersants, and synthetic fertilizer are well synthesized from microbes using industrial waste as a sole source of carbon (Chong et al., 2021b; Pandey et al., 2021; Sharma et al., 2020; Sirohi et al., 2021).

This review essentially highlights the food, agri-, and oil industry sources of organic waste and their effect on the environment. The composition of different wastes has been discussed. This study for the first time comprehensively summarizes the valorization strategy for the waste generated from these three industries and the microorganisms involved in the valorization and degradation of these wastes. The global health hazards of industrial waste, its environmental implications, and policies for waste management have been discussed. The impact on environmental sustainability and the future direction is proposed to attain a circular bioeconomy from this waste.

2. Organic waste and its Industrial sources

2.1 Oil industry

Waste streams from household kitchens, commercial kitchens, oil mills, are the major contributors in oil-rich waste production. Lipids are the main constituent of these streams which was reported to be contaminating approximately 1 million litres of natural water/ litre of lipid waste (Okino-Delgado et al., 2017), whereas petroleum industries and refineries contribute towards hydrocarbon waste (Varjani, 2017). It was observed that a huge volume of waste was produced by edible oil refining industries during various steps of processing (Welz, 2019). These industries utilize high amount of water and steam during different processes such as degumming, bleaching, neutralization, and deodorization process. This water was retrieved as effluent wastewater laden with impurities like fatty acids, carbohydrates, protein, aldehydes, ketones, waxes, and oil content (Sharma et al., 2020; Welz, 2019).

According to statistics of the United States Department of Agriculture (USDA) Foreign Agricultural Service, in 2019 around 208 million metric tons of edible vegetable oil was produced globally (Welz, 2019). Approximately 350.9 million tonnes of de-oiled cake and oil meal was discharged through these industries as an oil processing waste every year. As per the United States Environmental Protection Agency (USEPA) 2014, about 70,000–80,000 tons of waste cooking oil was produced by households, street vendors, and food plants in Taiwan. In tropical regions, oil meal was obtained as a by-product of processing of oil seeds like soybean, peanut, sesame in the vegetable oil processing industry (Chang et al., 2018). The edible de-oiled cakes are highly rich in protein content so they can be further utilized in different industries for value added products development like cattle feed and fertilizer (Barik and Murugan, 2015; Chang et al., 2018). Non-edible oil cakes are toxic therefore they cannot be used for fertilizer production or direct usage in farming. Microbial decomposition of these non-edible oil cakes in open land produces various anthropogenic gases, such as CO_2, CH_4, H_2S, N_2O, NH_3, and organic volatile compounds which may show potential contribution in global warming (Barik and Murugan, 2015). Disposal of oil industries wastewater into natural water resources produces film onto the surface of water bodies and poses a severe threat to the embedded aquatic life.

Petroleum oil industries and refineries are disposing different organic and inorganic pollutants into soil and natural water bodies like hydrocarbons (aliphatic, aromatic, asphaltenes, O, N, and S containing compounds), phenol, BTEX, sulfides, and heavy metals (Gaur et al., 2021b; Varjani et al., 2017; Varjani and Gnansounou, 2017). The process of oil production, refining, transportation, storage, and distribution produces large quantities of toxic substances which are harmful to both environment and human health (Varjani et al., 2020a). The pH of oil sludge obtained from oil industry usually ranges from 6.5 to 7.5 depending upon the sources of crude oil, processing method, and reagents used, etc. (Jasmine and Mukherji, 2019). Petroleum industry wastewater possesses higher levels of BOD, COD, total solids, hydrocarbons, and other waste. Petroleum waste is highly rich in oil sludge, grease content, heavy metals, waste catalyst, volatile organic compounds, total dissolved salts, nitrates, ammonia, sulfides, etc. (Jasmine and Mukherji, 2019; Varjani and Upasani, 2017). The pollutants present in wastewater may cause a uniform attack, pitting, erosion, and galvanic type of corrosion in metallic bodies. This was attributed due to their toxic nature, which may further compromise the health of human beings (Khadom et al., 2015).

2.2. Food Processing Industries

The demand for processed food is exponentially rising in the modern era of technological development. This emphasizes excessive stress on natural resources to match the requirement and imposes pressure to deal with processing wastes and by-products (Nikmaram and Rosentrater, 2019). There are two types of discharges produced by food processing industries: i) primary waste, ii) secondary waste. The primary wastes discharged from processing industries are organic substances, chiefly comprising of carbohydrate, protein, lipids, etc., in the form of trims, culls, peels, seeds, and pomace from fruits and vegetables processing industries. Furthermore blood, bones, feathers, intestines, tripe and various animal organs were released from slaughterhouses and meat processing industries (Osorio et al., 2021; Vendruscolo et al., 2008). The secondary wastes were problematic discharges of food processing industries that include wastewater, greenhouse gases, packaging material, etc. (Nikmaram and Rosentrater, 2019).

As per an estimate of FAO, globally, one-third of the total food produced was lost before reaching to human mouth which is equivalent to the total production received from

28% of the total agriculture area i.e. 1.4 billion hectares of global fertile land (Sharma et al., 2020). These losses can be checked to a certain limit by using proper industrial processing of food products. Processing furnishes longevity and esteem to food products, influencing the nutritional and structural composition in terms of its digestibility, bioactive compounds bioavailability, and shelf life extension (Sharma et al., 2020). In 2016, the slaughtering of 70 million tonnes of livestock in animal processing industries had produced 14 million tonnes of by-products in the European Union. In Turkey, approximately 41,121,380 kg of bone waste and 17,990,604 kg of blood waste were produced in the year 2020 (Ranaei et al., 2021). Food processing waste is a challenge incurred during the whole food supply chain which raises serious concerns about food security, profitability, sustainability, and economic problems (Ghosh et al., 2016). Globally, food waste accounts for a total loss of around US$ 936 billion every year along with a burden on the environment. In the USA food costing around US$ 90–100 billion was wasted every year. In the UK 7 million tonnes of food waste was produced every year incurring a total capital loss of £10.2 billion including the cost of production, harvesting, processing, and waste management (Sharma et al., 2021).

Food processing industries are of various types as per the processing raw material such as cereal and pulses industry, fruits and vegetable industry, edible oil industry, meat and poultry industry, seafood industry, and dairy industry (Gaur et al., 2020a). Caldeira et al. (2020) found that cereals, fruits, and vegetable processing industries are responsible for the generation of the highest share of food waste as compared to other food processing industries (Caldeira et al., 2020). Globally, fruits and vegetable juice processing, canning & frozen food, wine manufacturing industries annually liberate 5.5 MMT, 6 MMT, and 9 MMT of peels, leaves, stalk, stems, seeds, and pomace waste respectively into the environment. Grapes juice processing solely discharges around 5MMT of waste annually (Gaur et al., 2020a).

In the USA animal processing industry produces waste of value around US$ 83,127 million and US$ 69,100 million in the form of meat product waste and poultry waste respectively. In Australia meat and fishes costing around AUS$ 872.5 million (US$ 637.5 million) are wasted every year (Ghosh et al., 2016). On an average solid waste production from bovine slaughterhouses was around 275 kg/tonne of live animal weight, pig slaughterhouse produces 2.3 kg of waste per animal slaughtered which represents around 4% of total animal weight (Jayathilakan et al., 2012). In Mexico, milk processing industries generate around 3.74 and 11.22 million m^3 of waste products each year which nearly equals to one to three times the volume of milk produced annually. While in Denmark, 71,000 tonnes of milk and dairy products waste was discharged annually (Ghosh et al., 2016).

2.3. Agri industrial waste

The agriculture industry is primarily dedicated to agriculture, livestock, fishing, forestry, and agri-business operations, where the transformation of raw materials into semi-finished edible products takes place. The agriculture industry produces raw materials for various subcategories of food industries such as the dairy industry, fruit and vegetable industry, oil and fat industry, milling industry, meat industry, fish and seafood industry, etc. (Osorio et al., 2021; Scoma et al., 2016). A considerable amount of agricultural productivity loss during pre-processing provokes worldwide concern of policymakers and other stakeholders including governments. It immensely contributes to economic, environmental, and social problems (Osorio et al., 2021; Panda et al., 2018). Agro-industrial waste is the waste accumulated from agricultural activities and during the processing of agriculture and animal products. The crop harvesting process leads to the production of agriculture residues which is majorly composed of stalks, stems, leaves, roots, straw, seeds, pods, hull, husk, etc. which declines the objective of the successive food supply chain (Kumla et al., 2020; Osorio et al., 2021).

Asia ranks first in agricultural residues production with a share of 47%, followed by the US, Europe, Brazil, India, and Oceania (Bakker, 2013; Kumla et al., 2020). In India, around 600 metric tons of agro-industrial waste was produced annually which is supposed to be elevated considerably throughout the world from 2020 through 2021 due to COVID-19 pandemic crisis when proper harvesting and processing means were not available in time. (Maraveas, 2020; Osorio et al., 2021). In developed countries around 198.9 kg/year per capita of agriculture waste and food loss is generated. In the United States, 40% of the whole productivity is lost annually. In North Africa, West and Central Asia 32% of the global production is wasted while the European continent stood third in the list with a 20% loss of the total productivity worldwide (Osorio et al., 2021).

Among all commodities, fruits, vegetables, roots, and tubers are the highest waste generating commodities causing 44% (520–650 million tonnes) and 20% of the global quantitative food losses respectively followed by a 19% contribution of cereals (Ravindran et al., 2018; Tassoni et al., 2020). In Mexico, losses of fruits, vegetables, cereals as husk, bark, seeds, pomace account for an annual loss of 76 million tons (Leyva-López et al., 2020). In European Union, 89 million tons of food waste is produced every year as agricultural residues costing around 367 million tons per year (Ravindran et al., 2018). These wastes are organic substances that emerged as opportunistic, low-cost substrates for the production of high-value products including enzymes, bioactive components, building materials, filler materials, etc. Agriculture waste such as rice husk ash, sugarcane bagasse ash, and bamboo leaves ash are used in the sustainable development of construction material. Agri-crop wastes such as rice husks, rice straw, peanut shells, and coconut shells, are successfully incorporated into cement blocks as partial replacement of sand and meet ASTM standards in strength and durability features (Maraveas, 2020).

3. Linkages between global health hazards of industrial waste, environmental implications, and global regulations

Industrialization is being a major element for evaluating the economic ranking of a nation. Although the expansion of industries does not stand up without a cost, it induces serious threats to the environment including deterioration and environmental pollution (Ofoezie and Sonibare, 2004). The nature, quantity, and composition of industrially derived waste affect their impact on the environment (Mishra et al., 2020). Waste generation may differ substantially according to the operations and processing of the industries (Tyler, 2002; Shah et al., 2021). However, industries like food, agriculture, and oil processing are the prominent ones for the utility of raw materials, processing of intermediate products, packaging, and washing. Among them, agro-industries are the global leaders by offering food across the world (Gaur et al., 2020a), but the waste generated by agro-industries was also evident. Dust, mist, gypsum, and acids are the eminent category of waste from the agro-industry, which directly emerge from the processing unit. Pollutants like heavy metals and trichloroethylene were reported to release from agricultural industries which give rise to several diseases in mankind (Gaur et al., 2020a). Synthetic manure used in the agricultural field tends to cause problems associated with ammonia toxicity and infestation of pathogenic microbes (Dominguez and Edwards, 2011). Solid agricultural waste (peel of fruits and vegetables) requires high salt concentration for processing and was known to cause a detrimental effect on the terrestrial ecosystem by changing permeability and porosity of soil thus decreasing the merit of irrigation (Cheng et al., 2020; Loehr, 1978). Potential leaching of nutrients like phosphorus leads to eutrophication in the river ecosystem alters taste and odour of drinking water and accelerated deoxygenation of water followed by the killing of aquatic organisms.

Wastewater and effluent from the meat processing industry carry a considerable amount of organic load which if discharged affects the aquatic ecosystem by depleting oxygen and producing odour and scum (Alneyadi et al., 2018; Irshad et al., 2016; Mishra et al., 2019; Devda et al., 2021). The United Nations has evaluated that 18% of the total greenhouse gas emission was contributed by highly malodorous waste from the food and meat processing industry. Waste originated from food processing and production units are rich in total suspended solids and contribute to an excessive amount of nitrogen, phosphorus, and infectious microorganisms (Khedkar and Singh, 2018). Fruit and vegetable processing industries release immoderate amount of effluent which contains pesticide residues that adds up during washing from the raw feedstock. Pesticide from industries reaches to soil and water ecosystem and was reported to cause acute as well as chronic disorders in human beings (Irshad et al., 2016). Some sulfur compounds such as sodium dioxide/sodium bisulfide used in the treatment of fruits and vegetables found their way in wastewater effluent and led to terrifying effects on the brain hypothalamus and nervous system of aquatic animals (Last, 1982). Adherence to pathogenic microorganisms on the surface of fruits and vegetables was the major concern as they flush out with effluent during washing.

A large amount of food industry waste after composting produces a significant amount of methane gas which absorbs infrared radiation and makes the earth's temperature hot thus causes climate change. Among all industries, the petroleum industry also contributes to the proliferation of carbonaceous compounds into the earth's biosphere. Oil processing industries and oil refineries release several undesired components like traces of heavy metals, salts, and hydrocarbons to the environment that can significantly pollute the environment (Varjani et al., 2020c, 2020b; Varjani and Upasani, 2016). The effect of high concentration of heavy metals in the environment was evident by their interaction with proteins/enzymes, which further inhibits biochemical processes in animal cells. The inhibition of metabolic processes adversely affects the kidney, liver, and nervous system. During drilling of oil, a high concentration of salts was disposed to the soil ecosystem which alters the porosity of soil and limits the access of air into soil particles and plant roots (Cormack, 1983). Volatile organic compounds released from vegetable oil industries react with the sunlight and form ground level ozone, which triggers asthma in humans. Over the past years, the inappropriate release of waste from different industries is wreaking havoc on earth. The consequences of these irregular practices had led to a large degree of environmental hazard leading to serious threat for human and environmental health (Nguyen et al., 2021). However, the amount of waste generated by industries may be small, but the menace it causes to the environment is extensively large and thus cannot be avoided. Thus the utilization of waste as a resource significantly contributes to the concept of circular bioeconomy (Fig. 1).

For management and utilization of food waste from different streams, the intervention of government policies is mandatory to regulate the food supply, monitoring production, capacity, demand, and waste management-cum-valorization (Joshi and Visvanathan, 2019). Policies for sustainable food waste management are emphasizing upon waste reduction, and its effective management through awareness campaigns among consumers, retailers, farmers, authorities, charities, and marketers, etc. to reach the international and national goal of sustainable development (Thyberg and Tonjes, 2016). Policy makers should also consider market-based tools for financial assistance and tax relaxation in order to reduce economic loss in terms of food waste (Fattibene et al., 2020). It is the responsibility of each one of stakeholder to stick to the regulations for the conservation of resources and to generate maximum revenue or benefit out of bioresource. In 2018 European Union has adopted and revised waste framework directives as a “Circular economy package” to reduce, prevent, recycle, and valorization of food waste. The “4 Rs” of waste management i.e. reduce, reuse, recycle and recovery discussed in the “7th Environment Action Programme of EU to 2020” has substantially reduced accumulation and release of food waste from processing industries especially in Japan (17%) during 2008-2012 (Gaur et al., 2020a).

4. Bio-routes for valorization of different industrial feedstocks

The increase in waste production and improper disposal in the environment can be managed by employing different techniques like incineration, landfills, and 3R’s (i.e., reduce, reuse, and recycle). In recent years, the use of microorganisms for waste mitigation/management had significantly increased (Table 1). Microorganisms like, bacteria and fungi have the ability to metabolize nearly all types of organic compounds present in waste materials (Adebayo and Obiekezie, 2018).

Microbial biotechnology techniques like bio-composting, biodegradation, bioremediation, and biotransformation can be employed to degrade, mitigate or valorize waste (Mondal and Palit, 2019). During the process of composting, organic waste can be converted and mitigated into less harmful or more stabilized form with the help of microbes. This process was facilitated by a wide diversity of bacteria and fungi under aerobic or anaerobic environments (Chong et al., 2021a). In aerobic composting, food and agricultural wastes are decomposed into simpler organic compounds such as ammonia, carbon dioxide, heat, and water whereas anaerobic decomposition produces organic acid, methane, and hydrogen sulfide (SI, 2016). The optimum conditions required for composting were: i) Temperature should range between 50-60°C as above this temperature a reduction in microbial activity was reported. ii) Optimum pH range should be within 6.0-7.5 for bacterial growth and 5.5-8.0 for fungi. iii) The suitable moisture content for composting ranges between 60-70%. Moisture content below 40% and above 70% gradually reduces microbial activities. iv) The carbon to nitrogen (C/N) ratio should be ranging between 25 and 35. The C/N ratio is an important factor as carbon source provides energy and nitrogen is essential for the growth of microorganisms (DeRouchey, 2014; Mondal and Palit, 2019). The C/N ratio less than 20 was considered mature compost and can be used as fertilizer (Chen et al., 2019).

Another strategy namely biodegradation is a naturally occurring process that converts complex organic compounds into simpler ones with the help of microorganisms mainly bacteria, fungi, and yeast. It is one of the major techniques for waste management and environmental sustainability. During this process, aerobic biodegradation leads to the formation of carbon dioxide and water whereas the end products of anaerobic degradation are carbon dioxide, water, and methane (Pérez et al., 2002). A combination of amylolytic properties bearing bacteria namely *Bacillus subtilis* and *Bacillus licheniformis* enhanced the degradation of domestic food waste comprising of vegetables, fruits, grains, chicken, etc. They observed that both strains together degrade 43% food waste at 45 °C in 12 d. The experiment showed a faster degradation rate than α-amylase alone (Msarah et al., 2020).

Ivanov et al. (2004) monitored biodegradation of a mixture of food waste and sewage sludge using aerobic thermophile, *Bacillus thermoamylovorans* SW25. The degradation rate was measured by the amount of carbon dioxide released. A decrease in organic matter from 3.8 to 1.3 mg CO_2 per g of organic matter per day was observed (Ivanov et al., 2004). The biodegradation of food waste with the help of amylolytic strains such as *Bacillus licheniformis* and *Brevibacillus borstelensis* and cellulolytic strains like *Bacillus thuringiensis* was studied. The pre- and post-consumed food wastes in the ratio 1:1 showed a reduction of 64.38% organic matter after 15 d (Awasthi et al., 2018). Al-Wasify et al. (2017) investigated the biodegradation of dairy wastewater. Five member bacterial consortia, including *Pseudomonas aeruginosa*, *Lactobacillus delbrueckii*, *Bacillus subtilis*, *Enterococcus hirae,* and *Staphylococcus aureus,* and three fungal strains namely *Alternaria* sp., *Fusarium* sp., and *Aspergillus* sp. were inoculated in different reactors. The bacterial consortium showed better degradative capability with biological oxygen demand (BOD) removal of 78.7% whereas fungal consortium obtained 74.7% BOD removal (Al-Wasify et al., 2017). Microalgae bear extraordinary potential to breed in wastewater due to its tolerance for a broad spectrum of water salinity, pH and temperature, SO_2, N_2O, and CO_2 (Vinayak et al., 2021). Therefore, microalgae are promising organism for natural remediation of nutrients rich wastewater (Aron et al., 2021). In symbiotic relationship of microalgae and bacterial consortium algae utilizes CO2 for organic compounds production, which is consumed by heterotrophic bacteria for production of secondary metabolites of human interest. In the coming days, microalgal-bacterial consortia would also be adopted for sustainable wastewater treatment, CO2 fixation, bioenergy production and further advancement of life sciences sectors (Khoo et al., 2021).

Furthermore, the emerging technology of bioremediation includes biological degradation or removal of organic wastes under controlled environmental conditions (Fig. 2). The mechanism of bioremediation involves the reduction, degradation, detoxification, mineralization, and transformation of toxic pollutants (Sharma, 2020). In-situ bioremediation treatment is performed on-site and the process is less expensive covering a large surface area at the same time whereas, in ex-situ bioremediation, the soil was excavated and placed in a different treatment area for further degradation processes (Butnariu and Butu, 2020; Mondal and Palit, 2019). The factors affecting bioremediation are energy sources, temperature, pH, oxygen concentration, and moisture content (Abatenh et al., 2017).

Microorganisms like bacteria, fungi, algae, and yeast are involved in the bioremediation of contaminants. Many aerobic and anaerobic bacteria exhibit the ability to remediate or degrade pesticides, polyaromatic hydrocarbons, polychlorinated biphenyls, etc. (Sharma, 2020). The potential of indigenous bacteria in diesel bioremediation was studied by Safdari et al. (2017). *Pseudomonas aeruginosa* and *Bacillus subtilis* from petroleum hydrocarbon contaminated soil were isolated and each was inoculated separately in a 2% (v/v) diesel solution. *P. aeruginosa* showed higher degradation efficiency of hydrocarbons about 87% whereas *B. subtilis* degraded 75% of total hydrocarbons after 20 d (Safdari et al., 2017). Electro-kinetic remediation was coupled with bioremediation to enhance crude oil remediation. Biosurfactant producing microbes namely *Bacillus subtilis*, *Bacillus velezensis,* and *Bacillus licheniformis* were selected. Biosurfactant enhances electro-kinetic remediation by increasing solubilization of hydrocarbon which leads to its speedy electro-migration. The biodegradation efficiency of *B. subtilis*, *B. licheniformis,* and *B. velezensis* was found to be 88%, 92%, and 97% respectively (Prakash et al., 2021). Four fungal species namely *Aspergillus niger*, *Saccharomyces cerevisiae*, *Candida glabrata,* and *Candida krusei* were isolated from petroleum contaminated soil and were studied for their potential to utilize crude oil. For the degradation study, 4% (v/v) of each strain was inoculated in 1% crude oil and after 7 d of incubation, *A. niger* showed maximum biodegradation of 94% (Burghal et al., 2016).

5. Value added products from organic wastes

These industrial sectors primarily produce organic waste at every stage of its processing throughout the end life of its product which can be efficiently converted to a number of value-added products upon microbial action (Fig 3). This section detailed the utilization of this waste for the production of biofuel (an alternate to reduce the use of non-renewable energy resources), bioplastics (biodegradable plastic to reduce conventional ones), biosurfactant (21st century biomolecules exhibiting multifarious applications).

5.1. Bioplastic(s)

Plastic is an indispensable commodity owing to its diverse applications. Globally, approximately 300 Mt of plastic was produced annually causing serious disposal concerns polluting land and waterways. It was reported that 10–20 Mt of plastics accumulates in the oceans annually (Pratt et al., 2019). This has led to the search and use of biodegradable bio-origin plastic also termed bio-plastics which is meant to replace the use of plastics from shopping bags to everything including automobiles (Kaeb et al., 2016). Bio-plastic was reported to contain the formulation ingredients obtained from renewable substrates. The huge production of plastic also corresponds to the depletion of fossil fuels, thus it became imperative to look for alternate sources for the generation of bio-plastics (Kumar et al., 2021b). Some of the major bio-plastics include starch blends, polyhydroxyalkanoate (PHA), polybutylene succinate (PBS), hydroxybutyrate (PHB), polylactic acid (PLA), and polyvinyl alcohol (PVA) (Sharma et al., 2020; Tsang et al., 2019). An array of microorganisms from *Bacillus, Ralstonia, Pseudomonas, Allochromatium, Burkholderia,* and *Methylobacterium* genera were found to synthesize PHA by utilizing carbon waste following three main pathways in microbial system viz. pathway I (acetyl-CoA → 3-hydroxybutyryl-CoA), pathway II (β oxidation of fatty acids), pathway III (fatty acid biosynthesis) (Saratale et al., 2021).

Among the bioplastics, polyhydroxyalkanoates (PHAs) is one of the important class that emerged because of their mechanical, biodegradable, and thermoplastic properties. PHAs are synthesized by microbial strain under non-favourable conditions viz., excess carbon, and limiting oxygen, phosphorus, or nitrogen (Colombo et al., 2016). PHAs are intracellularly produced as energy and carbon storage molecules. The properties of PHAs can be controlled by changing the producing microbial strain, fermentation conditions, and substrate utilized (Yadav et al., 2020). The major limitation of PHAs is their high production cost as the conventional polymer cost around US$ 1000 to 1500 per Mt, whereas PHB cost from US$ 4000 to 15000 per Mt (Kosseva and Rusbandi, 2018). It was reported that the compound annual growth rate (CAGR) of the PHA market is 6.27% from 2016 to 2021 and reach

23734.65 Mt by 2021 (Perez-Rivero et al., 2019). To overcome the cost barrier, several wastes generated from different sources were used for the production of PHAs as it was noted that feedstock accounts for approximately 30-50% cost of PHA production.

The utilization of waste also reduced waste disposal cost and aids in waste management (Yadav et al., 2020). Bioplastic was considered essential in increasing the sustainability that can be defined by socio-economic and environmental balance which follows the concept of ‘4e’ i.e. ethical, economic, engineering, and environmental aspects (Koller et al., 2017). Wastes such as molasses, palm oil, and olive oil mill effluents, paper-mill wastewater, coffee waste, biodiesel industry waste, lingo-cellulosic biomass, cheese whey, and sludge were used as substrates for PHA production (Yadav et al., 2020). Waste oil was considered a good carbon source as it does not require a pretreatment step, irrespective of its origin. *Pseudomonas* sp. and *Cupriavidus necator* were reported to produce PHAs in the range of 35 to 68% of cell dry weight by utilizing waste frying sunflower, corn, and palm oil (Khatami et al., 2020). Propanol is a precursor of 3-hydroxyvalerate was added to the culture of *Cupriavidus necator* to obtain a high yield of PHA. It was recorded that waste rapeseed oil as a substrate in the presence of propanol yielded 80% dry cell weight of PHAs (Obruca et al., 2010). *Bacillus thermoamylovorans* produced 87% cell dry weight PHA by utilizing waste cooking oil (Sangkharak et al., 2020). The produced PHA was found to act as a feedstock for the production of 3-hydroxyalkanoate methyl ester as a blending agent that was used to reduce the cetane number for diesel engines. The yield of PHA was doubled by disabling the *tctA* gene in *P. putida* strain KT2440. This recombinant *P. putida* produced 1.91 g/L of medium-chain length-PHA in 72 h by utilizing waste vegetable oil as a substrate (Borrero-de Acuña et al., 2019).

Pretreatment is required to convert organic food waste to bio-plastic. Pretreatment strategies enhance the chemical, physical and biological properties of food waste (Tsang et al., 2019). In a fermentation process (7.5L), *Alcaligenes* sp. NCIM 5085 produced 70.89% of PHB by utilizing cane molasses. The optimized process yielded productivity of 0.312 g/L/h (Tripathi et al., 2019). The biomass from enriched activated sludge utilized distillery spent wash of rice and jowar grain as substrate and yielded 40% and 42.3% of PHA. The yield of PHA was found to be increased to 67% by the addition of di-ammonium hydrogen phosphate (Khardenavis et al., 2007). Bagasse, wheat straw, and wood hydrolyzate were used as a substrate by *Ralstonia* and *Burkholderia* species for the production of PHA by a fermentation process. It was reported to yield 65%, 72%, and 51.4% PHAs respectively (Al-Battashi et al., 2019).

In a fed-batch fermentation strategy, wheat straw hydrolyzate serves as a source for PHB production and yielded 105.0 g/L and 135.8 g/L of polymer accumulation and biomass (Cesário et al., 2014). Furthermore, *B. cepacia* utilized woody hydrolyzate as a substrate and yielded 51.4% dry cell weight and 8.72 g/L of PHA content in 96 h (Al-Battashi et al., 2019). NaC+NaS pretreated Kenaf biomass hydrolyzate was employed as a feedstock for polyhydroxybutyrate (PHB) synthesis using *Ralstonia eutropha*. They recorded a 70.0% PHA accumulation and 0.488 g/g of PHB yield in 36 h of fermentation (Saratale et al., 2019).

Corn stover was reported as the favorable substrate for the production of PHAs by *Paracoccus* sp. It was found that the enzymatically hydrolyzed corn stover without any detoxification resulted in 9.71 g/L of PHAs (Sawant et al., 2015). Kovalcik et al. (2020) reported that fermentable sugars and oils derived from grape pomace can be utilized for the production of PHAs by several bacterial species. *Cupriavidus necator* produced 63% of PHB in a 2-L bioreactor in 29.5 h. The polydispersity and weight of the polymer were recorded to be 1.2 and 512.2 kDa respectively (Kovalcik et al., 2020).

In comparison to conventional food crops algae are 5 to 10 times faster in biomass production along with its promising potential of biopolymer synthesis in photobioreactors. Microalgae-derived-biopolymers are cost effective and eco-friendly substitute of petroleum derived polymers. The operating cost of photobioreactors (PBR) was estimated to be around USD $22.7 million per year, including fixed cost, nutrients cost, CO_2, electricity, and clean-in-place (CIP) system expenses. The cultivation cost in PBR system is 57% lower as compared to open pond system. In terms of economy, bioplastic industry had contributed to economic growth with an income of around USD $15 billion in 2016 and was expected to arise from 4.2 to 6.1 million tons bioplastic production capacity by 2021 (Devadas et al., 2021).

5.2. Biosurfactants

Biosurfactants are surfactants of biological origin prominently produced by bacteria (Gaur et al., 2019a; Tripathi et al., 2020) and fungi/yeast (Gaur et al., 2019b; V K Gaur et al., 2021). The production of biosurfactant from various natural and feasible sources has become an alternative method that has gained potential significance in the present scenario (Gaur and Manickam, 2021a, 2021b; Markande et al., 2021)). Biosurfactants derived from organic sources exhibited several properties such as reduction in surface tension and high emulsification capacity. The surfactant extracted from organic compounds is amphiphilic in nature with a wide range of promising applications (Akbari et al., 2018; Kumar et al., 2021a). Waste generated from different sources such as oil, agro-industries (lactic whey, molasses), distilleries contains a large amount of carbohydrates, lipids, and fats and thus had been effectively used as a feedstock for the production of biosurfactant which is cost effective and environment friendly (Table 2) (Kaur et al., 2015; Varjani et al., 2021).

Globally, the generation of waste cooking oil (WCO) was approx 4.1 kg per person yearly so as per today's population it is considered that about 29 million tons of WCO are generated per year which leads to difficulties in the disposal of untreated wastes in the environment. Waste cooking oils such as kitchen or restaurant waste oil is harmful to the environment and human health and can be utilized as a sustainable carbon source for the synthesis of biosurfactant. The microbial surfactant produced from these sources possesses several properties that can be significantly used for the removal of toxic heavy metals (Maddikeri et al., 2015; Md et al., 2019). In India, a large amount of oil waste like olive, sunflower, soybean, groundnut, safflower, sesame, rapeseed, palm, and coconut is generated from industries causing pollution. The oil waste from these industries has high lipid content and other nutrients that can be utilized as the cheapest source for the production of secondary metabolites (Makkar et al., 2011). Plant based oils like mesua oil, jatropha oil, castor oil, ramtil, and jojoba oil can also be industrially used for the synthesis of biosurfactant. The production of biosurfactant from agro-industrial wastes using molasses and whey as a growth substrate was found similar to that with glucose. The use of molasses reduces production costs and is a readily available resource (Rane et al., 2017). It was also suggested that the growth of microorganism and the rate of biosurfactant production using distillery and whey waste as a substrate was better than the synthetic medium. Agro-industrial wastes obtained from potato processing industries such as potato, orange peels are rich substrates for microbial growth and biosurfactant production using *Bacillus subtilis* (Rivera et al., 2019). *B. licheniformis* KC710973 was found to preferentially produce the highest amount of biosurfactant i.e. 1.8 g/L by utilizing 4% orange peel as compared to potato peel and banana peel. Interestingly, 3% orange peel yields more rhamnolipid suggesting that the strain and type of waste affect the yields (Kumar et al., 2016; Rivera et al., 2019). *Psuedomonas aeruginosa, Bacillius subtilis,* and *Starmerella bombicola* yielded rhamnolipid, surfactin, and sophorolipid at 8.78 mg/L, 3.1 mg/L, and 41.6 g/L respectively by utilizing olive and sunflower oil refinery wastes. Soy molasses, a byproduct of soybean oil processing was utilized as a substrate by *Candida bombicola* and yielded upto 21 g/L of sophorolipid (Makkar et al., 2011).

It was reported that *P. aeruginosa* when supplemented with 7% (v/v) molasses and 0.5% (v/v) corn steep liquor as carbon and nitrogen source respectively yielded 25 g/L rhamnolipid. Dairy waste (whey) enhances microbial growth and can be used as a cheaper source for the synthesis of biosurfactant. *Pseudomonas aeruginosa* was reported to produce 0.92 g/L of biosurfactant by utilizing whey as a substrate and causes a significant reduction of surface tension from 72 to 27 mN/m with good emulsifying property (Kaur et al., 2015). *Bacillus subtilis* utilized cassava flour as a substrate for biosurfactant production and it was found that the surface tension of the medium reduced from 49.5 to 26.6 mN/m with a yield of 3.0 g/L (Pekin et al., 2005). Another strain of *Bacillus* sp. produced 5.35 g/L of crude biosurfactant by growing on used cooking oil (Md et al., 2019). *Pseudomonas fluorescens* showed maximum biosurfactant yield by utilizing olive oil and ammonium nitrate as a carbon and nitrogen source. It was found that this biosurfactant exhibits several properties such as reduction in surface tension, stability at different pH, temperature, and salt concentration and showed good emulsification properties (Gaur et al., 2020b; Makkar et al., 2011**.** *Pseudomonas aeruginosa* LBI produced 9.5 g/L of rhamnolipid by utilizing 2% (w/v) waste derived from soybean refinery (Rivera et al., 2019). The biosurfactants derived from different sources were reported to possess different therapeutic applications (Table 3).

5.3. Biofuel(s)

The production of biofuels by utilizing renewable resources is crucial for environmental sustainability and reducing climate change globally (Kumar et al., 2020). The production of biofuels has been reported by several renewable resources such as fruit, vegetable*,* sugar beet pulp, corn stillage, rice straw, cellulose, etc. (Mazumder et al., 2020; Rahman et al., 2018; Rulianah et al., 2020; Sindhu et al., 2020). *Saccharomyces cerevisae* yielded 7.3% (v/v) bioethanol after 48h of incubation during alcoholic fermentation of kitchen waste, majorly comprising of fruit and vegetable peels (Rahman et al., 2018). Furthermore, 2% (v/v) culture of *S. cerevisae* produced 0.316 g bioethanol from fruit and vegetable waste (Sindhu et al., 2020). A recent study showed that sequential cultivation of thermophilic bacteria, *Geobacillus thermoglucosidasius* and *Thermoanaerobacter ethanolicus* for the production of biofuel yielded 70.1 L bioethanol production per ton of dry food waste. The scaling up of the production process from 1 L to 40 L reactor yield 18.4 g/L bioethanol (Bibra et al., 2020). Cieciura-Włoch et al. (Cieciura-Włoch et al., 2020) investigated dark fermentative hydrogen production using sugar beet pulp and corn stillage, fruit, and vegetable waste. The highest biohydrogen yield of approximately 52 cm^3/g VS was observed from fruit and vegetable waste. Microbiological analyses showed *Lactobacillaceae, Coriobacteriaceaeae and Mogibacteriaceae* were the dominant species during the process (Cieciura-Włoch et al., 2020). *Citrobacter sp. E4* was studied for the production of bioethanol by utilizing fruit waste It was recorded that strain E4 produced 0.13 g of ethanol/g of waste whereas 0.30 g of ethanol/g waste was produced after optimizing the process parameters (Sarkar et al., 2019).

Jugwanth et al. (2020) reported the valorization of sugarcane bagasse for bioethanol production by *Saccharomyces cerevisae* through saccharification and fermentation process, the yield was recorded to be 4.88 g/L (Jugwanth et al., 2020). Corn stover hydrolyzed by cellulose and xylanase and fermented by *Thermoanaerobacterium thermosaccharolyticum* W16 produced biohydrogen at productivity of 11.2 mmol/L/h (Ren et al., 2010). A recent finding showed that mesophilic bacteria, *Staphylococcus epidermidis* B-6 produced 30 L biohydrogen by utilizing one kg of rice straw acid hydrolysate (Mazumder et al., 2020). Pretreated de-oiled rice bran yielded 7.72 g/L of biobutanol *Clostridium saccharoperbutylacetonicum* N1-4. Results also showed that when enzymatic hydrolyzate of de-oiled rice bran was treated with XAD-4 resin, then acetone-butanol-ethanol productivity and yield were 0.1 g/L/h and 0.44 g/g, respectively (Al-Shorgani et al., 2012). The co-cultivation of microalgal-bacterial consortium is a promising economic and environment friendly choice for microbial-based biofuel production in conjunction with bioremediation of nutrients-rich municipal wastewater. A total nitrogen removal efficiency of 94.45%, 0.241 g/L lipid production and biomass production of 1.42 g/L was attained in synergistic microalgal-bacterial incorporation in wastewater remediation (Leong et al., 2019). It was estimated that glucose derived biodiesel costs USD $3.79/L whereas agriculture waste and food waste derived biodiesel costs USD $2.6–3.0/L and $0.6/L (Silva et al., 2021).

6. Waste derived economy: Roadblocks and future perspectives

Waste(s) polluting the environment is being available in large amount(s) which is now recognized as a useful element and are expected to replace conventional and expensive resources up to a greater extent. The waste derived economy is regenerative and restorative which can be strengthened by implementing suitable technologies and strategies. A balanced switch from linear to circular bioeconomy is of significant importance as it provides advantages to waste management, revenue generation, and environmental preservation (Mohan et al., 2020). Core principles of circular bioeconomy demonstrate the use of natural resources, lengthening its function, decreasing waste generation, and thus closing loops.

The concept of waste derived circular economy presents ecological, socio-economic development focusing on environmental awareness by enhancing policies of eco-innovation. Based on this concept, some notions stated that circular bioeconomy is not always linked to the framework of 3R (reduce, reuse and recycling) but only with the view of recycling. The circular bioeconomy does not rely upon a change of the state of affair, but also requires some modification in system perspectives. The relationship between sustainable development and circular looped bioeconomy is enfeebling because the standard of environmental attributes and economic wealth are contemplated but the impact of these on social equity is not yet evaluated. Waste derived circular bioeconomy will aid in attaining the highest value for the resources through the use and recycling of cascading biomass, by preserving the natural resources. This action will expedite to some perspectives for governance; intervention of policies should be accelerated to promote the depletion of environmental burden and stress along with intact value chain; technological revolution should be implanted, which will handle the product utilization and waste management; biological approaches should be implemented to maximize the profit of biodegradable products (Chew et al., 2021; Peter et al., 2021).

Implementation of circular bioeconomy would aid in initiating the programmes and policies in developed or developing countries. The need and transition towards the concept of waste recycling in society should be promoted for the development of a resource efficient and low carbon circular economy. Awareness in consumers to support the manufactured products in view of circular economy will create a framework by introducing some legal provisions and enabling re-use of waste biomass. The roadmap will be campaigned on the principle of calculating and analyzing the approach of waste valorization. It is also essentially important to nourish the innovative ideas about the coupling of fundamental technologies to circular bioeconomy. To overcome the dominating models of take, make, and dispose, circular bioeconomy originates with the concept of take, make, and recycle.

Innovative ideas for diminishing energy and material used should be prioritized which will aid in reducing pressure for biomass production and anticipating uninvited consequences. It is conceived that sustainability needs improvement as it supports wellbeing and prosperity. Services from the market and companies should be understood to integrate with products derived from waste. The future of the circular bioeconomy will not sustain if the community doesn’t acknowledge the pertinence of this green economy, so narration and communication are needed for better public participation. The economy driven by waste and its management bears the tendency to restore environmental burden while furnishing employment and comprehensive development, so the blueprint for *no venture, no gain* should be taken into consideration.

7. Conclusions

Implementation of technologies for producing bio-based products would improvise the environmental structure by decreasing the health hazards of the pollutants present in industrial waste. Food, agriculture, and oil industries generate a huge amount of waste that is primarily organic and causes serious human and environmental health hazards. The traditional waste management approaches do not efficiently resolve the concern of reducing environmental pollution and the health hazards of the pollutants. The present sustainable treatment approaches include valorization and bioremediation. In this context, the use of microorganisms has proven an indispensable tool for the reduction and management of these wastes. Bacterial and fungal species while growing on waste produces several economically important compounds such as biofuels, bioplastic, and biosurfactants. The major constrain in this perspective is the efficiency and economy of the process. The environmental sustainability, roadblocks, and future perspectives covered in different sections of this paper would pave a way for waste derived circular bioeconomy with reduced health hazards and provide systematic in-depth information to the researchers working in this area.

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Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figure captions

Figure 1: Wastes as resource in circular bioeconomy

Figure 2: Bioremediation approaches for waste management

Figure 3: Routes for organic waste generation and its valorization

Table Legends

Table 1: Microorganisms involved in waste management and mitigation

Table 2: Production of biosurfactant from different industrial wastes

Table 3: Multifarious therapeutic applications of biosurfactants

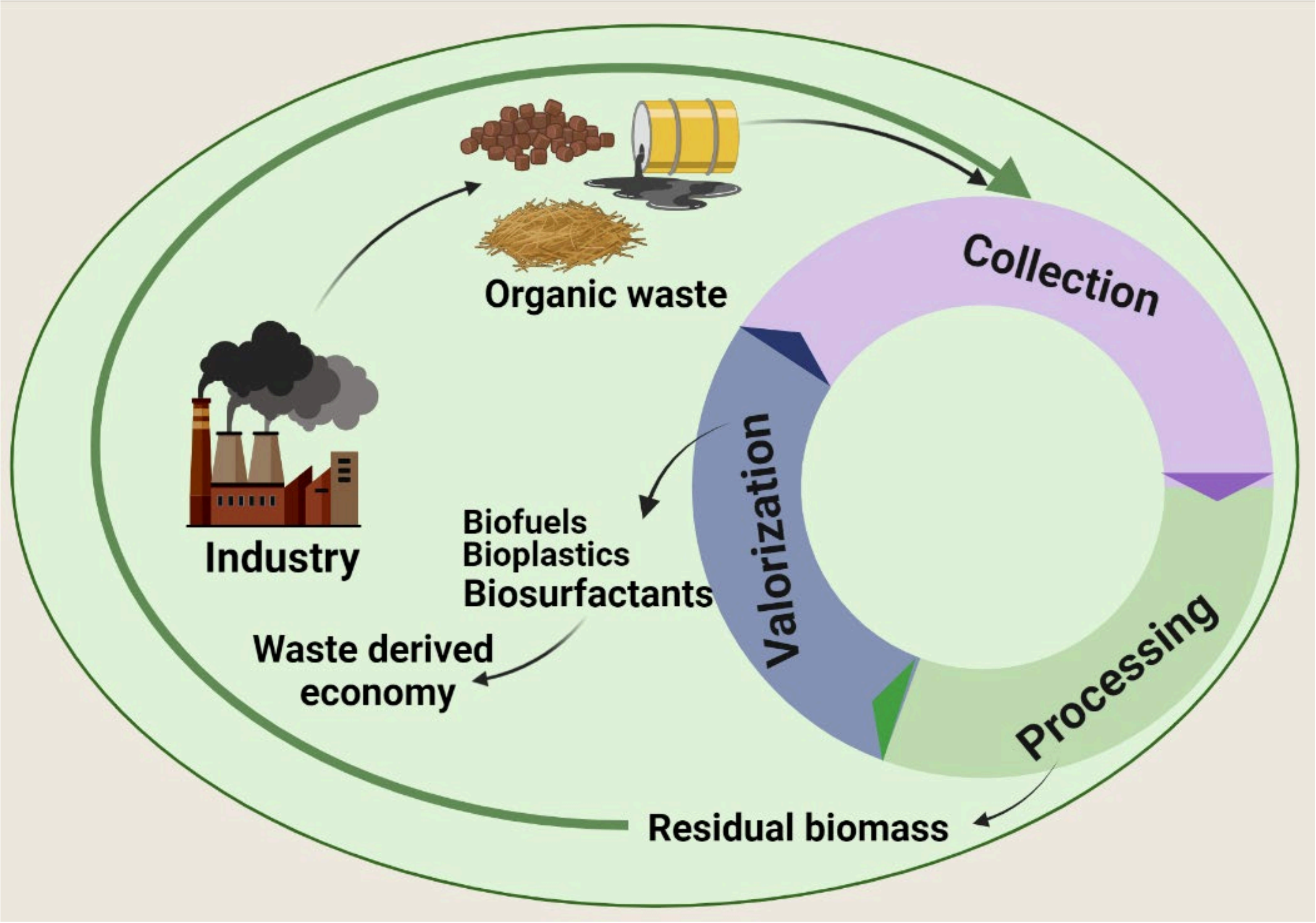
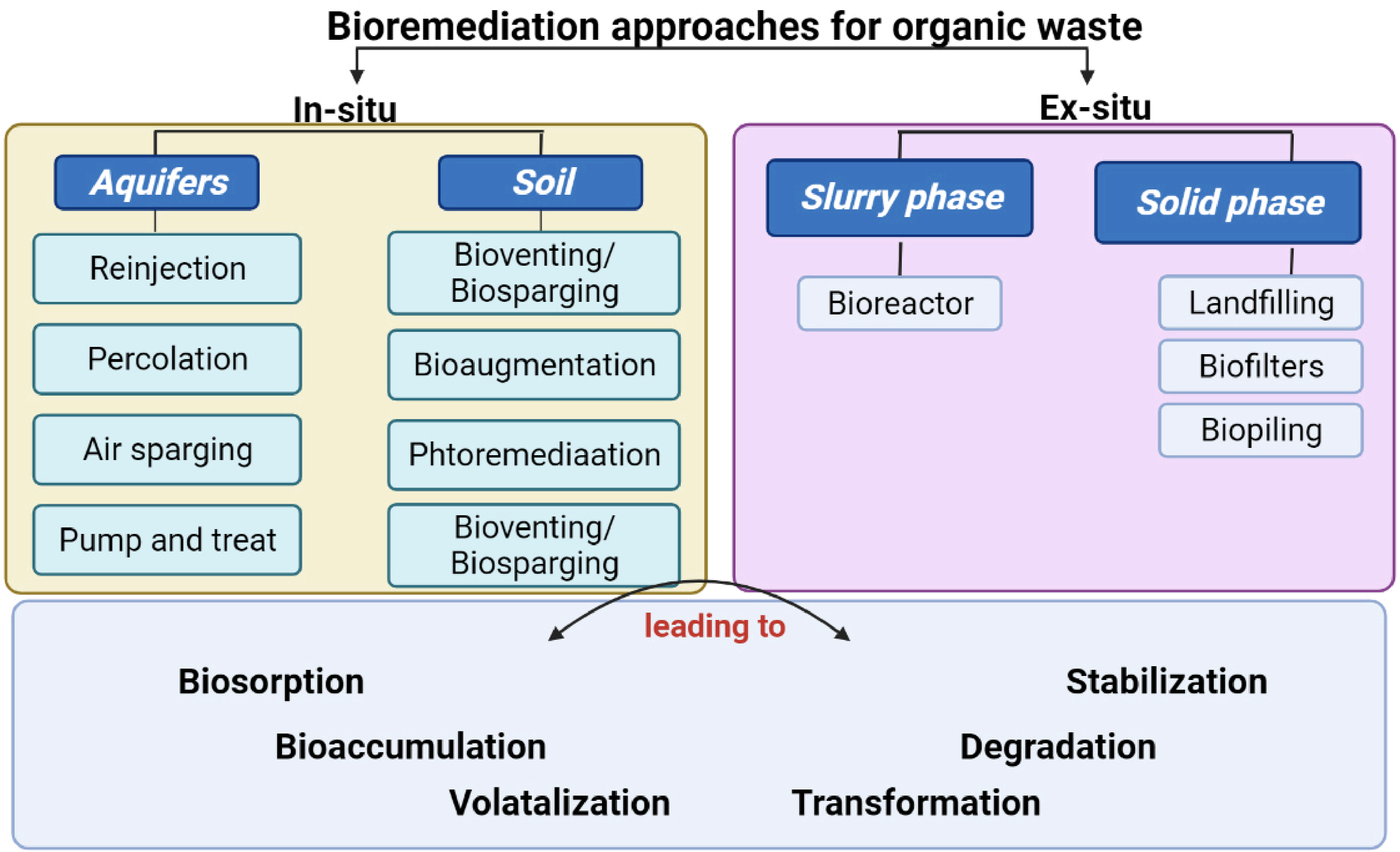


Figure 1. Wastes as resource in circular bioeconomy



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1238 **Figure 2.** Bioremediation approaches for waste management

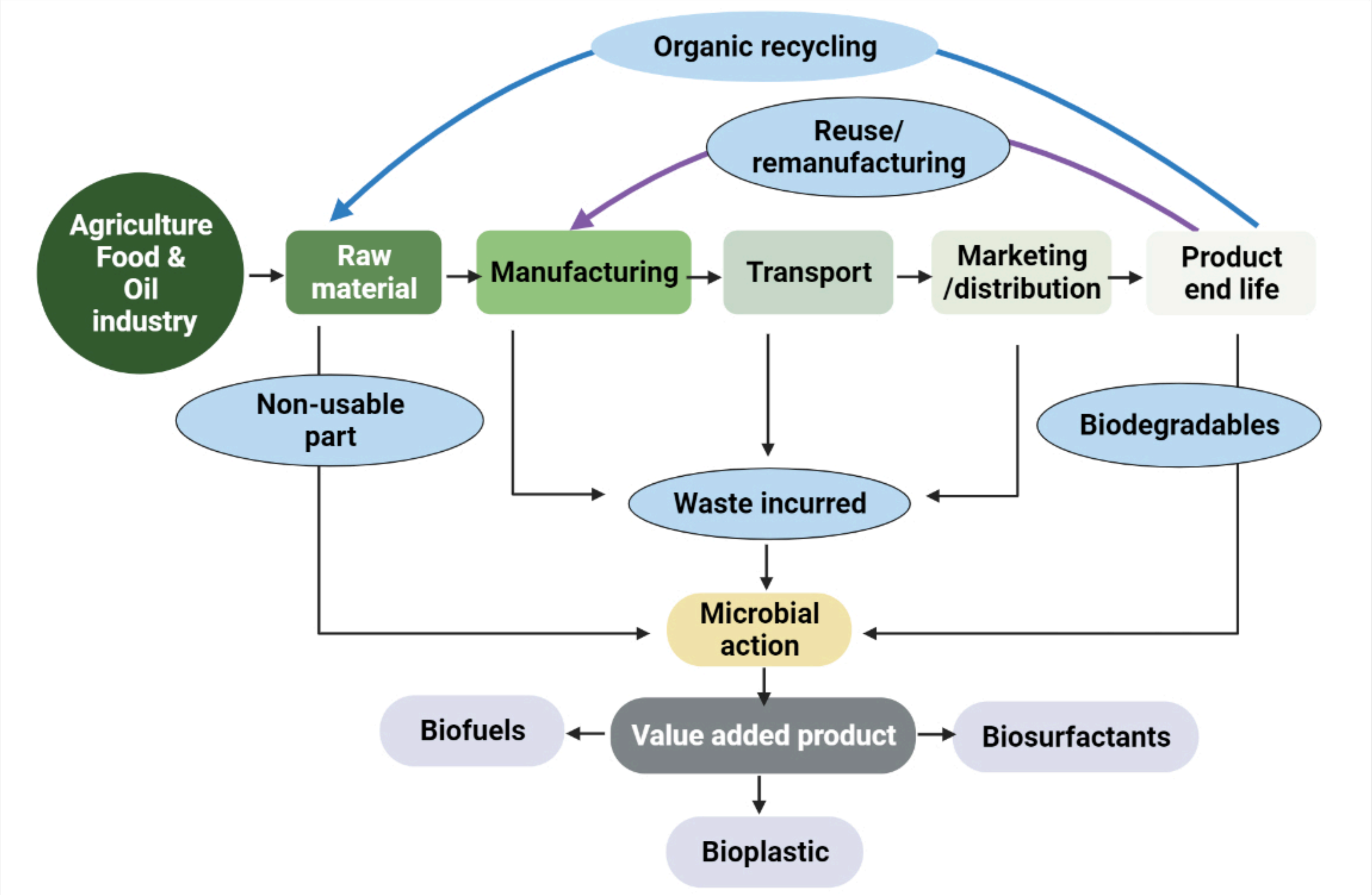

Figure 3. Routes for organic waste generation and its valorization

Table 1: Microorganisms involved in waste management and mitigation

Waste biomass	**Microorganism**	**Waste management strategy**	**Process efficiency**	**Reference**
Post consumption food waste	*Brevibacillus borstelensis*, *Bacillus licheniformis*, *B. thuringiensis* and *B. cereus*	Biocomposting	42.95% degradation.	(Awasthi et al., 2017)
Organic domestic waste	Psychotrophic bacteria	Biocomposting	Enhanced biodegradation of organic matter.	(Hou et al., 2017)
Heavy metals co-composted with agrowaste	*Phanerochaete chrysosporium*	Biocomposting	Enhanced passivation of heavy metals (Cu, Cd, and Pb).	(Chen et al., 2019)
Paddy straw	*Trichoderma harzianum*	Biocomposting	Composted.	(Yaacob et al., 2019)
Domestic food waste	*B. subtilis*, *B. licheniformis*	Biodegradation	43% degradation.	(Msarah et al., 2020)
Sewage sludge and food waste	*Bacillus thermoamylovorans* SW25	Biodegradation	67% organic matter degradation.	(Ivanov et al., 2004)
Pre and post consumed food	*B. subtilis*, *B. licheniformis* and *B. thuringiensis*	Biodegradation	64.38% degradation.	(Awasthi et al., 2018)

Lignin from corncob	*Phanerochaete chrysosporium*, *Lentinusedodes* and *Pleurotusostreatus*	Biodegradation	96.88% lignin biodegradation.	(Mahyati et al., 2013)
Dairy wastewater	*Pseudomonas aeruginosa*, *B. subtilis*, *Lactobacillus delbrueckii*, *Staphylococcus aureus*, *Enterococcus hirae* *Alternaria* sp., *Fusarium* sp. and *Aspergillus* sp.	Biodegradation	Increased degradation.	(Al-Wasify et al., 2017)
Diesel	*P. aeruginosa* and *B. subtilis*	Bioremediation	*P. aeruginosa* and *B. subtilis* degraded 87% and 75% hydrocarbon respectively.	(Safdari et al., 2017)
Crude oil	*B. subtilis*, *B. velezensis* and *B. licheniformis*	Bioremediation	*B. subtilis*, *B. velezensis* and *B. licheniformis* degraded 88%, 92% and 97% hydrocarbon respectively.	(Prakash et al., 2021)
Crude oil	*Aspergillus niger*, *Saccharomyces cerevisiae*, *Candida glabrata* and *C. krusei*	Bioremediation	94% biodegradation by *A. niger*.	(Burghal et al., 2016).
Polychlorinated biphenyls	*Pleurotusostreatus*	Bioremediation	50.5% PCB from rhizosphere.	(Stella et al., 2017).

Wheat bran	*Ralstoniaeutropha* NCIMB 11599	Biotransformation	62.5% Poly-3-hydroxybutyrate (PHB) production.	(Annamalai and Sivakumar, 2016)
Mango peel	*Bacillus thuringiensis* IAM 12077	Biotransformation	51.7% PHB produced.	(Gowda and Shivakumar, 2014)
Fruit pomace and waste frying oil	*Pseudomonas resinovoran*	Biotransformation	12.4% medium chain length-Polyhydroxybuytyrate (mcl-PHA) production	(Follonier et al., 2014)
Wood hydrolysate	*Burkholderia cepacia*	Biotransformation	54.1% PHB produced.	(Pan et al., 2012)
Banana peel	*Enterobacter* sp. EtK3	Biotransformation	23.6% yield of ethanol was obtained.	(Sarkar et al., 2017)
Sweet lime pulp waste	*Komagataeibacter europaeus* SGP37	Biotransformation	38g/L bacterial nano-cellulose production.	(Tiwary and Dubey, 2018)
Olive oil mill wastewater	*Aureobasidium thailandense* LB01	Biotransformation	139 ± 16mg/L biosurfactant production.	(Meneses et al., 2017)

Table 2: Production of biosurfactants from different industrial wastes

Substrate	Microorganisms	Biosurfactant type	Production	References
Soyabean oil	*Pseudomonas aeruginosa* AT10	Rhamnolipid	9.5g/L	(Rivera et al., 2019)
Molasses and corn steep liquor	*P. aeruginosa* GS3	Rhamnolipid	0.25g/L	(Kaur et al., 2015)
Cassava flour-processing effluent	*B. subtilis* LB5a	Surfactin	3.0g/L	(Kaur et al., 2015)
Orange peel	*Pseudomonas aeruginosa* MTCC 2297	Rhamnolipid	9.18g/L	(Kaur et al., 2015)
Groundnut oil	*Candida lipolytica*	Lipopeptide	4.5g/L	(Makkar et al., 2011)
Palm oil	*Pseudomonas alcaligenes*	Rhamnolipid	2.3g/L	(Makkar et al., 2011)
Soyabean soap stock waste	*Pseudomonas aeruginosa* LBI	Rhamnolipid	11.7g/L	(Makkar et al., 2011)
Soy molasses	*Candida bombicola*	Sophorolipids	21g/L	(Makkar et al., 2011)
Peanut oil cake	*Lactobacillus delbrueckii*	Glycolipid	5.35 mg/ mL	(Thavasi et al., 2011)
Olive oil	*Pseudomonas aeruginosa* M40	Rhamnolipid	12.6g/L	(Ji et al., 2016)

Used cooking oil	*Bacillus sp.* HIP3	Surfactin	5.35g/L	(Md Badrul Hisham et al., 2019)
Cheese whey and Olive oil	*S. bombicola* ATCC 22214	Sophorolipid	6.2g/L	(Ma et al., 2020)
Cat fish residues	*S. bombicola*	Sophorolipid	21.8 g/L	(Wang et al., 2019)
Sunflower acid oil	*C. bombicola*	Sophorolipid	41.6 g/L	(Jadhav et al., 2019)
Soyabean flour and rice straw	*Bacillus amyloliquefaciens*	Lipopeptide	50mg/g	(Zhu et al., 2013)
Passion Fruit oil	*Pseudomonas aeruginosa* LBI	Rhamnolipid	9.2g/L	(Costa et al., 2006)
Cheese whey	*Lactobacillus pentosus* CECT-4023	Biosurfactant	1.4g/L	(Rodrigues and Teixeira, 2008)
Dairy waste liquor	*P. aeruginosa* BS2	Rhamnolipid	0.92g/L	(Kaur et al., 2015)
Low-solids (LS) potato process effluents	*B. subtilis* ATCC 21332	Surfactin	0.39g/L	(Kaur et al., 2015)

Table 3: Multifarious therapeutic applications of biosurfactants

Biosurfactant Type	**Source organism**	**Effective concentration**	**Test pathogen**	**Therapeutic applications**	**References**
Lipopetide	*Bacillus circulans*	10 µg/mL	*Alcaligens faecalis* NCIM 2105	Antibacterial	(Das and Mukherjee, 2007)
Lipopeptide	*Klebsiella pneumoniae*	10 µg/ml	*Micrococcus luteus*	Antibacterial	(Bhosale et al., 2014)
Lipopeptide	*Staphylococcus* sp.	3.37 mg/mL	*Bacillus subtilis ATCC 6633*	Antibacterial	(Eddouaouda et al., 2012)
Rhamnolipid	*Pseudomonas aeruginosa* SS14	500 µg/mL	*Trichophyton rubrum*	Antifungal	(Sen et al., 2019)
Rhamnolipid	*Pseudomonas aeruginosa DS9*	100 µg/mL	*Colletotrichum falcatum*	Antifungal	(Goswami et al., 2015)
Rhamnolipid	*Pseudomonas aeruginosa*	10 µg/mL	*Phytophthora capsici*	Antifungal	(Kim et al., 2000)
Sophorolipid	*Candida bombicola* ATCC 22214	0.5 µg/mL	*Phytophthora sp.*	Antifungal	(YOO et al., 2005)
Rhamnolipid	*Psedomonas aeruginosa* IGB 83	0.2 µg/mL	*Pythium sp.*	Antifungal	(YOO et al., 2005)
Surfactin	*Bacillus amyloliquefaciens* WH1	-	Splenocytes from mice	Adjuvant	(Gao et al., 2012)
Sophorolipid	*Candida lipolytica* UCP0988	12µg/mL	*Streptococcus mutans* HG985	Antibacterial	(Rufino et al., 2011)

Not identified	*Rhodotorula*	10 µL	*Aspergillus niger*	Antifungal	(Gharaghani et al., 2020)
Surfactin	*Bacillus subtilis*	25 mM	*Mycoplasma hyorhinis*	Antimycoplasma	(Vollenbroich et al., 1997)
Surfactin	*Bacillus subtilis*	30 mM	*Mycoplasma orale*	Antimycoplasma	(Vollenbroich et al., 1997)
Rhamnolipids	*Pseudomonas aeruginosa* MR07	25.87µg/mL and 31.00µg/mL for mono- and di-rhamnolipids	MCF-7 human breast cancer cells	Anticancerous	(Rahimi et al., 2019)
Surfactin	*Bacillus subtilis*	30 to 64 mM	ML (mink lung), Hep2 (human larynx), 293 (embryonal kidney), and CV1 (African green monkey kidney)	Cytotoxic	(Vollenbroich et al., 1997)
Sophorolipid	*Candida lipolytica*	100 µg/mL	Influenza virus strain, murid gamma herpes virus	Antiviral	(Borsanyiova et al., 2016)
Lipopetide	*Bacillus cereus*	0.52 mg/mL	*Staphylococcus aureus*	Antibacterial	(Basit et al., 2018)
Glycolipid	*Lactobacillus acidophilus* NCIM 2903	625 µg/mL	*Bacillus subtilis*	Antibiofilm	(Satpute et al., 2018)
Glycolipid	*Staphylococcus lentus*	20mg/mL	*Vibrio harveyi,* *Pseudomonas aeruginosa*	Antibiofilm	(Hamza et al., 2017)
Not identified	*Lactobacillus paracasei*	50 mg/mL	*Lactobacillus reuteri* ML 1	Anti-adhesive	(Gudiña et al., 2013)

Fellutamides C	*Aspergillus versicolor*	3.1 to 33.1 µM	XF498 CNC cancer, SK-MEL-2 skin cancer, A549 lung cancer, HCT-15 colon cancer, SK-OV-3 ovarian cancer cell lines	Cytotoxic	(Lee et al., 2011)