BIOREMEDIATION OF FOOD WASTES

Abstract

Various types of food wastes (FW) are generated in large quantities worldwide after their processing which consists of high level of polysaccharide materials. Majority of such wastes are discarded by the public and industries thus creating environmental nuisance. Therefore, such wastes should be treated properly. Bioremediation of food wastes is a modern technique where the wastes are transformed naturally or biologically in which contaminants are altered by microbes from their original state. These processes have own advantages as various sustainable products can be generated from the food wastes nowadays. The implementations of such methods are cost-effective, eco-friendly and can be adapted by all class of people. Although, bioremediation of food processing waste is not a new concept, but incorporation of genetic engineering and microbiology gives a valuable path to tackle with environmental contaminants. These techniques can be executed both in industries and laboratories. Herbicides, pesticides, insecticides and cleaning chemicals are new emerging contaminants which can be transformed into non toxic substances by bio remediating via autotrophic organisms. . This chapter represents the general idea of bioremediation techniques and generation of value-added products from food wastes.

Keywords: Food wastes, Bioremediation, Composting, Valorisation, Microbial activity, Recycling, Polysaccharides, Value–added Products

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I. ABBREVIATIONS

BOD	:	Biological Oxygen Demand
COD	:	Chemical Oxygen Demand
DO	:	Dissolved oxygen
EPA	:	Environmental Protection Agency
FAO	:	Food and Agriculture Organization
FW	:	Food Waste
FWF	:	Food Waste Footprint
GHG	:	Green house gases
MC	:	Moisture content
MSW	:	Municipal Solid Waste
PAH	:	Polycyclic aromatic hydrocarbons
SS	:	Suspended solid
UNDP	:	United Nations Development Programme

II. INTRODUCTION

Since last few decades, peoples are very much focused on the development of their daily needs with the progress of industrialization process. On this regard, various problems arise because of landfills during the development of industrialization and even after their settlement which leads to other environmental issues like soil and water pollution. Various reasons are considered responsible for the pollution of environment such as waste, waste sludge disposal and leakage of toxic substances [1]. Among them, fertilizers, insecticides and pesticides used in agricultural fields may be the major reasons for pollution of soil or land followed by water resources. Water pollution is considered as most crucial and serious issue because of deficiency in good quality of fresh water in various regions worldwide [2]. The accidental discharge from petrochemical tanks, continuous percolation of untreated sewage, uncontrolled waste deposits, pesticides, insecticides and other pollutants into aquifer leads to pollution of ground water and this is becoming widespread rapidly with time. Besides ground water, the surface water resources also get polluted especially the coastal area due to the contaminants like oil nutrients, heavy metals, radio nuclides, synthetic organic compounds, litter, microbial organisms, etc.

Numerous amounts of wastes are generated yearly during various agricultural activities like handling and processing of agricultural products. Such agricultural wastes include rice husk, rice straw, banana rachis, wheat straw, corn stalks, sugarcane bagasse, etc; and nowadays many of them are being investigated as a promising feedstock for the generation of several value-added products namely biofuel and nanofiber. Nevertheless, a different kind of wastes generated from food processing industries remain unutilized which should be explored for further beneficiation. "Food wastes" is defined as the reduction in quality and quantity of food which generally results from the decision as well as actions by retailers, food service providers and consumers [3]. These are food-by-products, residue of high organic load and falls in the category of bio-wastes. Such wastes may results in solid or liquid form. The solid wastes include the portion of raw material which are unable to be utilized in the intended products manufacturing such as fibers, skin, leaves, pips, etc, of fruit after their processing for juice making, which often referred as pomace [4]; sugar beet residue after processing of sugar beets and kitchen wastes.

The losses of enormous amount of edible part of food biomass occur at every stage of food supply chain or value chain (production - postharvest processing - preparation of foods - retailing or distribution - consumption) and thus get discarded to the landfills. According to Food and Agriculture Organization (FAO) of United States, around one-third ($1/3^{rd}$) of food which is made for consumption by humans are getting lost or wasted worldwide and it amounts to about 1.3 billion tons/year. Even so, 40% of Indian food gets wasted according to UNDP (United Nations Development Programme), which a whole UK (United Kingdom) can consume. On the other hand, almost 25% of the world's food wastes (FW) are generated in south and south-east Asian countries. Japan, China, and South Korea which are considered as highly industrialised, generates up to 28%. Therefore, Asian countries alone contribute nearly 55% of the total food waste which can feed almost 100 billion people. This amount may refer to either of food waste and food losses or both.

Food wastes have adverse impacts on the environment and thus needs proper treatment, minimization and preventive measurements during their disposal. However, various value-added products are producing nowadays from FW and thus gaining attention of researchers. Bioremediation of food waste means the minimization of waste material as well as food loss so as to improve nutrition and food security, reduce the pressure on water and land resources, to reduce greenhouse gases (GHGs) emission, to increase productivity and economic growth. However, very few techniques are available for recycling, reusing and production of sustainable cost effective products but certain projects such as FAO's Food Waste Footprint (FWF) are being launched nowadays. This book chapter mainly focuses on the bioremediation techniques of solid FW which are executed by microbial action and also on the extraction and application of various sustainable products.

III. FOOD WASTES

1. **Solid wastes:** The solid food waste is usually generated from the five different phases, namely, production of agricultural crops, handling after harvesting, storage, distribution process, and consumption. Among these, the solid food waste from processing, distribution, and consumption is much higher than others. Solid food waste or by-products of food industries can be referred to as the non-edible or undesirable parts of food which come from the dairy, milling, winery, meat, fruits and vegetables, grain, and marine industries [5]. Basically, such wastes include the household and commercial food waste, stem, seeds, peels or skins or non-edible portions of fruits and vegetables, expired packaged food, cakes, retentate, feathers, and bones. The food industries have been continuously working on disposal or reuse or recycle of their solid wastes to resolve the problems of the landfill [6].

   Environmental Protection Agency (EPA) has estimated that solid FW of 40.7 million tons was generated in the year 2017. In addition to that, these type wastes contributed 15.2% to that of municipal solid waste (MSW) [7]. The annual amount of 278 to 416 million tonnes from 2005 to 2025 is expected by the urban food waste generation in the Asian countries [8]. Such wastes can be found with the moisture content (MC) of 74-90%, C:N value of 14.7–36.4, and volatile solids: total solids of 80–97%, as per the reports of Vakalis et al., (2022)[9]. However, such wastes can be decomposed and recycled easily, but it requires accurate planning, management, and implementation on a large scale with minimum expenses. The collection and sorting of food waste from other waste plays an important role in its decomposition [10]. An approximate estimation of waste production globally in the year of 2020-2021 from different type of fruit and vegetable wastes are illustrated in Table 1.

Table 1: Global Report of Amounts of Fruits and Vegetables Production and Waste Generation from Them in MT (Million Tonnes) in the Year 2020-2021

Vegetable/Fruit	Total global production in MT	Waste generated	Ref
Apple	81.6	Approx. 25–35% of the dry mass = 20.3 – 28.5 MT	[11]
Grape fruit	25.9	Approx. 9.4 MT of grape fruit waste	[12]
Lemons and limes	9.5	Approx. waste = 4.9 MT – 6.4 (half of the fruit)	[13]
Tomatoes	38.9	3 - 7% is of products is lost as waste during processing; Approx. waste 1.16 MT – 2.72 MT were generated in 2021	[14]
Oranges	50.2	Almost 70% of global production wastes generates in juice making, marmalades etc. waste = 50 – 60% of fresh fruit weight = 24.2 – 29.1 MT	[12]
Potatoes	391.3	Peel waste can be 15 – 40%, based on the application of processing methods. Approx. waste generated per year = 58.6 – 156.5 MT	[14]
Sugar beet	252.9	For every 1T (tones) of processed sugar beet = produced exhausted dried pulp of 70kg/produced exhausted pressed pulp of 250kg Wastes production of pressed SBP (sugar beet pulp) or dry SBP = 57.1 MT or 22.8 MT respectively	[15]
Olive	2.9	"Black water" production of 50-110kg per 100kg of processed olives for oil extraction. Fresh olive (approx. 20% of the weight) = 0.58 MT waste	[16]
Pineapple	2.8	40 – 80% waste. 45% of produced waste amounts to 1.2 MT/year	[17, 18]
Grapes	6.8	Approx. waste as grape pomace during wine making (20% of grape produced)	[14]
Banana	120	30 – 40% waste	[18]

2. **Liquid wastes:** Food industries produce much more liquid waste or wastewater compared to other industries. The liquid waste is mainly produced by the dairy, oil and marine, beverage, meat, poultry, winery, and brewery industries, whereas the dairy industry is effectively responsible for the wastewater. The liquid waste comprises whey, blood, curd, wastewater, chemicals, oils, milk sludge, and these may contain the dry solids less than 5% [19]. The wastewater refers to the water which is used for cleaning processes in food industries and is the main source of wastewater. The cost for the treatment, its limited post-application after treatment, and difficult processes promote the higher generation of liquid waste. The liquid waste of food industries has a higher concentration of biochemical oxygen demand (BOD), suspended solid (SS), chemical oxygen demand

(COD), and has variable pH depending upon the constituents of food and wastewater [20]. The rate of generation of FW can be considered as a function of the socioeconomic status of the country. The low-income countries produce higher FW which leads to numerous amount of liquid waste generation, and in the case of high-income countries, the rate of generation of food waste is comparatively low [21].

IV. SOURCE

The sources of food waste are categorized and explained according to the industries as follows.

1. **Household wastes:** The production of FW at the household level is caused due to bad and insufficient storage conditions, inappropriate purchasing, over-preparation, cooking, and portioning. The generation of household FW is dependent on consumption behaviour, socio-demographic properties of the household, consumer income, and food pattern. Around 50% of municipal solid waste is from household food waste [21-23]. However, FW at household level is ranged from 25 to 50% of the total purchased and cooked food.

   These types of waste mainly comprises of cooked food, fruits and vegetable waste or by-products, and wastewater. In some developing and most undeveloped countries, household food waste is not collected properly and efficiently by the municipal corporation due to the absence of advanced facilities and landfill grounds in major cities. Thus, lack of planning, management facilities, and available statistics of such waste could potentially increase the risks of production of greenhouse gases from waste landfill [24, 25]. The carbohydrates enriched household FW can be used for production of methane gas where cooked rice is the main contributor to these wastes. Apart from cooked rice, carrot, cabbage, and other vegetables also contribute significantly, and this can be composted easily with the help of a bulking agent [26].

2. **Fruit and vegetable industry:** The different unit and processing operations in fruit and vegetable industries produce the by-products or wastes such as peel, pomace, skin, seeds, leaves, sludge, pulp cake, etc. Although, these all by-products contain bioactive and pharmaceutical compounds and can be recovered or extracted by using different novel techniques. But the extraction processes of these compounds are extremely expensive, and very few industries go for the costlier techniques. At the same time, most of the industries throw these by-products and treat them as waste [27]. By-products of fruits and vegetable industries contain 80 to 90% moisture content and have acidic pH value [28]. These by-products or wastes generally come from canning industries, fruits, and vegetable dehydration industries. The different fruits and vegetable wastes possess a high percentage of COD, BOD, and SS, as given in Table 2 [29]. The chemical composition of waste depends and varies according to processed fruits and vegetables.

   The waste or by-product of fruit and vegetable industries is rich in hydrocarbons and relatively richer in fat and proteins. The hydrocarbons refer to sugars, cellulose, hemicellulose, pectin, and nitrogen present in the waste. The wastewater of fruit and vegetable industries includes cleaning chemicals, herbicides, pesticides, and dissolved compounds. Therefore, waste of these industries is allowed for composting by using bulking agents for example bark, sawdust, rice hulls, mature compost, paper, coffee residuals. Sometimes, chemical nitrogen is also added as a bulking agent to the waste.

These bulking agents neutralize the pH of waste, which causes a best condition for microbial growth. Those bulking agents also reduce the bulk density and increase porosity of waste, and this allows the removal of water up to 4-5% by gravity flow and 10% by pressing [27, 30]. The porosity of fruit and vegetable industry waste also raises C:N value of compost due to the high content of carbon. On the other hand, main limiting factor of composting the waste of fruit and vegetable industries is their higher moisture content. This causes anaerobic respiration, and consequently, it gives odour problems [27].

Table 2: Composition of fruits and vegetables waste

Fruits and vegetables	pH	COD	BOD	SS
Apples	5.9	18700	9600	450
Carrots	8.7	2300	1350	4120
Cherries	605	2500	2550	400
Corn	6.9	2500	1550	210
Grapefruit	7.4	1900	1000	250
Green peas	6.9	1650	800	260
Tomatoes	7.9	1500	1025	950

3. **Grain processing industry:** Grain processing industries also contribute to the landfill waste as they produce different types of by-products or waste during their operations. This waste comprises of hulls, pods, cobs, chaff, stems, weeds, and leaves from the corn, wheat, rice, oats, barley, etc. The waste of grain industry has low moisture content and high porosity whereas their composition depends upon the origin from where they are derived, maturity stage of grains, and their moisture content. The composting methods of grain processing waste include static pile and windrows. Granary waste using wood and cardboard are used to increase the porosity of compost of these kind of wastes [27].

4. **Olive oil industry:** The olive oil mill industries produce numerous amount of wastewater in Mediterranean countries. Their liquid waste are of dark colour which comprises of organic substances like polyalcohol's, sugars, pectin, lipids, tannins, organic acid, etc. High composition of BOD, organic substances, and COD restricts the decomposition of their wastewater [31]. The chemical composition of organic fraction present in olive oil industry wastewater is shown in Table 3 [29].

Table 3: Composition of Various Chemical Components of Wastes Produced from Olive Oil Industries

Components	Values (%)	Parameters	Values
Lipids	1.00-1.50	pH	3.50
Pectin, colloids, tannins	1.00-1.50	TS	6.39%
Organic acid	0.50-1.55	SS	65000 mg/l
Total nitrogen content	1.20-1.50	COD	100000 mg/l
Sugar	2.00-8.00	BOD	43,000 mg/l

Both aerobic and anaerobic processes are used for biological treatment of wastewater come from olive oil industry. The aerobic treatment is carried in presence of oxygen, which is supplied to wastewater in pure form or simply in the open atmosphere. This process is difficult in operation and requires more time. Aerobic treatment works efficiently only when the concentration of wastewater is in the order of 1 g COD/L [32]. The process for polyphenols and lipids removal from wastewater was developed by Zahi et al., (2022) prior to aerobic treatment [33]. The presence of polyphenols and lipids in wastewater of olive oil industry causes difficulty in biodegradability and thus compost becomes unusable. Alternatively, anaerobic wastewater treatment shows better results compared to aerobic treatment in presence of polyphenols, lipids, sugars, pectin, and organic acids. The growth rates of microorganisms during this treatment are slower than the aerobic treatment. Many anaerobic processes like up-flow anaerobic sludge blanket, anaerobic contact, and anaerobic lagooning have been studied and implemented to treat these wastes [33].

5. **Fermentation industry:** Three main categories of fermentation industry are brewing, distillation, and manufacturing of wine. All these categories produce liquid wastes, which has a high concentration of BOD and COD [27]. Collectively, fermentation industries produce waste such as wastewater, carbon dioxides, tartrate, grape pomace, grape stalks, vine pruning, residual yeast, spent grains, and grape seeds [5]. High concentrations of organic acid, tannin, and phenol are present in the wastewater of fermentation industry. The anaerobic treatment of this wastewater was reported as an effective treatment by Kiani et al., (2022) as anaerobic treatment reduced COD content up to 97% and aerobic treatment reduced the COD up to 76% [34]. Kumar et al. (2022) has performed the optimization of temperature and acidity of the process for biodegradation of brewery wastewater by using anaerobic treatment [35].

The load and amount of distillery waste depend upon the raw material used. The molasses produces three times the biological load than that of resins is a perfect example of dependency of load and amount of distillery waste on raw material used. The conditions such as carbon source, pH, and nutrients were affecting wastewater treatment to reduce the concentration of COD and ammonium content of wastewater [36]. The treatment methods for winery are also similar to brewery industries, as discussed earlier. The reduction of COD up to 98% was possible in winery industries when multi-stage, modular, and full-scale activated sludge treatment plants were used [37]. Presence of vinasse in wastewater of winery creates problems in treatment method, and it needs to be treated to decrease the concentration of COD [38].

6. **Dairy industry:** Dairy industries are mostly responsible for the total wastewater generation. Wastewater of dairy industry also pollutes the environment by contaminating the soil and water. Generally, dairy wastewater contains SS and organic load, which are fatty substances in the high amount with a pH of 4.2–9.4. Such wastewater also contains cleaning chemicals, salts, nitrogen, phosphorous, proteins, and lactose [39].

The detergents present in the wastewater of dairy may be acidic or alkaline and used for cleaning purposes. The detergents of salts of hydroxides are responsible for the alkaline nature of dairy. The acids are used to eliminate alkaline solids such as milk stones from pipes and takes of the dairy industry. Thus, wastewater contains both acids and alkaline liquids. The cleaning agents such as phosphoric acid, citric acid, and sometimes both in the combinations are used in milk industry, and consequently, they increase the presence of nitrogen and phosphorous in wastewater of dairy. Globally, the load of 3337–5217 tonnes of nitrogen and 850–1788 tonnes of phosphorus per annum is produced from dairy industries. The presence of phosphorus as well as nitrogen in wastewater hardly increases COD as compared to milk, whey, or cream [40]. Therefore, treatment of wastewater of dairy industries is a comparatively difficult process due to the presence of detergents. Khumalo et al., (2022) have reported about 90% reduction of COD by using a laboratory-scale anaerobic batch reactor [41]. Guo et al., (2022) has also found that there was a removal of 85 and 65% of COD for the loading rates of 500 and 900 g COD/m^3 h, respectively[42].

7. **Meat and poultry industry:** Fish, meat, as well as poultry industries generate highest waste loads in food industries. Slaughter houses are most important unit where waste such as fat, blood, manure, meat, bones, residue from intestines, and paunch grass are generated [29]. Slaughter house wastewater has high nitrogen content and moisture content (90-95%). The wastewater of meat industry possesses odour with high BOD and their pre-treatment is employed to increase the porosity by reducing moisture content up to 60-70%. Bulking agents also help in making the waste more porous for aeration. Sometimes, use of a bulking agent is not sufficient at the high moisture content as large quantities are necessary; thus increases cost of the method. On the other hand, the processing sludge or waste contains a pathogen, which also needs the pre-treatments [29].

   Fish waste is very problematic when it comes to the odour, as it gives a high unpleasant odour level. The odour of nitrogen-rich waste can be minimized by composting, and products made from this can be marketable. The residue of fish industry can be varied from 5 to 65%, depending upon the methods of processing of fish [38]. Such wastes include whole fish, skin, tails, heads, fins, bones, and other fish offal. Fish waste has a high moisture content, alkaline pH, high nitrogen, and low solids. The advantage of fish waste is that there is no need for quantities of bulking agents for composting [27]. Waste of poultry is equally as problematic as the meat industry wastewater because of slaughtering process. Starkey (1992) reported that treatment for wastewater of poultry depends on the treatment work discharge, land application systems, land availability, conventional waste treatment systems, and previous site history. Like other waste, this waste also needs a pre-treatment for minimization of moisture content and to increase the porosity [43].

V. COMPOSITION OF FW

The use of FW in the energy conversion is a challenging task for many reasons which include its low calorific values, high moisture content, heterogeneous compositions. These reasons impede the development of a large scale, robust, and highly effective method for processing [44]. Composition of food waste mainly depends upon the type of industries where it is originated; the consumer's eating habits, consumer's purchasing power, impurity content, and type of unit operations done on food material. Collection and sorting also influence the composition of food waste. The food waste contains 74-90% moisture, 14.7–36.4 C:N (carbon to nitrogen) ratio, and 80–97% volatile solids to total solids ratio as per the review conducted by Thi et al. (2015). Furthermore, in deeply, FW also comprises of lipids and proteins of all types, bioactive compounds, and the highest percentage of carbohydrates than other constituents [45]. The method for predicting ten constitutional parameters of food waste compost has been developed by Chang and Hsu (2008) [10]. The parameters include the final and lowest pH values, percentages of material losses in terms of weight fractions of fat and proteins, highest temperature, acidification times after composting, cumulative CO_2 evolution, etc.

VI. ADVERSE IMPACT OF FW ON ENVIRONMENT

Food waste in its solid form is a matter of concern to the environmentalists due to its volume regardless of their harmful nature like liquid wastes. Food waste inevitability destructs the natural ecosystem, and its treatment is deemed as important and challenging. Industries and factories simply dump their wastes in nearby area. Because of the high moisture content and nutrient available in such wastes, the growth of micro-organisms occurs and fermentation takes place in that area which may cause bad fouling and other environmental issues. Therefore, solid wastes are to be managed properly to mitigate the harmful impacts.

In certain cases, the wastes are transported to the landfill sites to dispose them, which may lead to addition costs as landfill disposal fees depending upon various countries' waste management rules [46]. In order to manage the waste in the landfill and industrial dumping sites, usually incineration is carried out. However, because of very low calorific value and high moisture content of FW, huge amount of energy is required which may not be a cost-effective management process. Alternatively, incineration process also leads to generation of some toxic gases like, carbon dioxide (CO_2), carbon monoxide (CO), methane, ozone, nitrous oxide, water vapour, hydrocarbons and aerosol which causes serious air pollution [47]. These gases are emitted and absorb the radiant energy, thus, impacting global warming and climate change [45]. The burning of heap and dumps of food waste also cause the smog formation in the surrounding air and increase air pollution [45]. The food waste can pollute the soil, water, and crops with disrupting the disruption of biogenic cycles [24].

VII. BIOREMEDIATION AND ITS ADVANTAGES

Bioremediation is an emerging technology used for removal of pollutants from air, contaminants or unwanted substances from soil, water, sediments, and from food waste materials by the application of living microorganisms [48-50]. The main principle of bioremediation involves the breakdown of toxic or hazardous substances by organisms to less toxic or nontoxic substances [51]. It has different approaches for remediation. One kind of approach can be classified based on the location as either *ex situ* (with excavation) or *in situ* (without excavation) [51, 52].

Table 4: Beneficial Aspects of Bioremediation

Sl. No	Merits
1.	A natural biological method
2.	Toxic substances are eliminated or destroyed from the ecosystem
3.	Can completely destroy a wide range of contaminants.
4.	Can alter or convert contaminants to non-toxic materials
5.	Can be performed onsite with minimum disruption to normal activities.
6.	No transportation or excavation costs are required for *in* situ Bioremediation method.
7.	Low energy consumption unlike other technologies
8.	Manual supervision is not required for micro-organisms

The other variety of approach in bioremediation process achieved either by bio-stimulation or bio-augmentation. Bio-stimulation approach involves the stimulation of naturally occurring microbial communities to break down the contaminants either by nutrients or by controlling other parameters some of which are aeration, pH, moisture, electron acceptors, electron donors, etc). In bio-augmentation, selected organisms with high degradation capacities are used to inoculate the contaminated site [51]. This type of waste management technique offers minimum damage of ecosystems, economic feasibility, enhanced competence and eco-friendliness [53]. There are number of advantages are enlisted in the following Table 4 [52].

VIII. METHODS FOR BIOREMEDIATION OF FW

Bioremediation of FW can be performed in several ways. However, all these methods have their own advantages and disadvantages which are listed in Table 5.

Table 5: Merits and Demerits of Various Types' Bioremediation Technique

Method	Merits	Demerits	Applications	Ref
Land farming	Simple process; Inexpensive; Presently established technique.	Slow degradation rates; High exposure risks; Residue contamination often removed; Require extensive incubation periods	Aerobic process; Surface contamination; Low to medium contamination levels	[54-58]
Slurry bioreactor	Incubation periods = days to weeks; High - quality control over parameters; Enhance desorption of soil compounds; Good microbe/ compound contact; speedy degradation rates;	High capital outlay; High risks of exposure; Limited by reactor size;	Contamination of surface; Recalcitrant compounds; Aerobic and anaerobic processes; Soil that binds compound tightly;	[59-61]
Composting	Inexpensive; High reaction rates; Self-heating.	Residual contamination; Requires aeration; Requirement of bulking agents; Incubation periods = months to years; High exposure risks; Nitrogen addition often necessary.	Aerobic process; Surface contamination; Sewage sludges, Human and agricultural wastes; Yard wastes; MSW, industrial wastes.	[54, 55, 62, 63]
Intrinsic bioremediation	Comparatively less expensive; No need of Excavation, Low exposure risks.	Low rate of degradation; Needs good hydro-geological site characterization; Less control over environmental parameters; Incubation periods = months to years.	Deep contamination; Contamination levels = Low to medium; Aerobic or nitrate reducing conditions; Oil and gasoline; Chlorinated hydrocarbons; Chlorinated aromatics.	[57,64, 65]

1. **Land farming:** It is a remediation treatment method introduced in the scientific research articles so as to remove the organic pollutants or heavy metals from contaminated soils and/or total hydrocarbons in refinery sludge [50, 66]. This technique is also applicable for the treatment of industrial waste and controlling the bio-cycling of natural compounds

[29, 67]. Land farming process is performed either *ex situ* or *in situ* depending upon location and according to the configuration in particular outdoor or indoor. The indoor area is usually surrounded by a greenhouse whereas outdoor is an open area. In *in situ* land farming, a remediation performed when polluted soils arises at original contaminated site, while in *ex situ*, excavation and transportation process are performed to transfer the contaminated substances to treatment facility sites [68-71]. Generally, *in situ* land farming is employed to the upper surface of soil layer at depth up to 50 cm, but it can be achieved in most soils at less than 30 cm for effective oxygen diffusion. Bulking agents are added with the purpose of enhancing the porosity of contaminated soils; and thereafter mixed the soil periodically to ensure a proper aeration, after which water is added to increase the activity of microorganisms. A successful *in situ* land farming mainly depends upon the characteristics of soil (soil texture, pH, number of microbial species, MC) and atmospheric conditions (temperature, wind, rainfall) [68, 72]. On the other hand, in *ex situ* land farming, the bulking agent (mostly used industrial wood waste) is mixed with excavated contaminated soil nutrients until a layer is formed up to a depth of 0.5m. To obtain an appropriate aeration and homogeneity of the mixture, contaminated material is periodically tilled. It improves the contact between contaminants and microorganisms [68, 73-79]. Depending on the soil alkalinity or acidity, optimal pH can be adjusted by adding up elemental sulphur and ammonium sulphate or lime while moisture content is maintained by adding water [66, 68, 71].

Land farming method recently became a large scale commercial application in polycyclic aromatic hydrocarbons (PAHs) removal because of its simplicity, cost-effective and more ecofriendly nature than other soil remediation methods [66]. Mineral Processing industries extensively use this process to remediate soils which are contaminated due to oil spills, treatment of oil sludges settled in oil storage tanks [68, 80, 81]. For successful land farming, well-drained soil, abundant presence of microorganisms, biodegradability of pollutants by existing microbes and a closed greenhouse system are required to reduce the soil erosion, control air emission and to rain-off from rainfall. Nonetheless, appropriate environmental conditions are also needed such as moisture content, pH, availability of nutrients, temperature [81].

2. **Composting:** This is a natural process in which biological aerobic decomposition of organic matter transform into a stable, solid-like product by the action of thermophilic microorganisms under controlled conditions [29, 82, 83]. In this process, rate of decomposition is a prominent factor which depends on the material properties and use of microorganisms. To clearly understand the composting method, a typical process flow is shown in Fig. 1 [27].

   For industrial purpose, to increase the decomposition rates, it needs to optimize the microbial growth [29]. Generally, thermophilic bacteria work at temperature 50-60ºC, which facilitate the growth of media. Further increase of temperature (more than 70ºC) leads to lowering the activity of microbes. In this case, the conditions need to be optimized so as to attain maximum efficiency. The optimizing parameters are concentration of oxygen, MC, C:N, pH, and particle size [82, 83]. Wood chips and vermiculite as bulking agents for this case are used to improve the porosity in compost [62]. Willow (1992) reported that volume of material substantially decreases from 25-40% during composting, while others observed it may even exceed 50% [84]. Composting is employed for stabilization and minimization of industrial wastes, sewage sludges, municipal and yard wastes. Nonetheless, it is also applicable for treatment of petroleum waste, hazardous waste like explosives [85-87]. The most commonly used composting methods are classified into three following categories and illustrated in Table 6 [27, 84]:

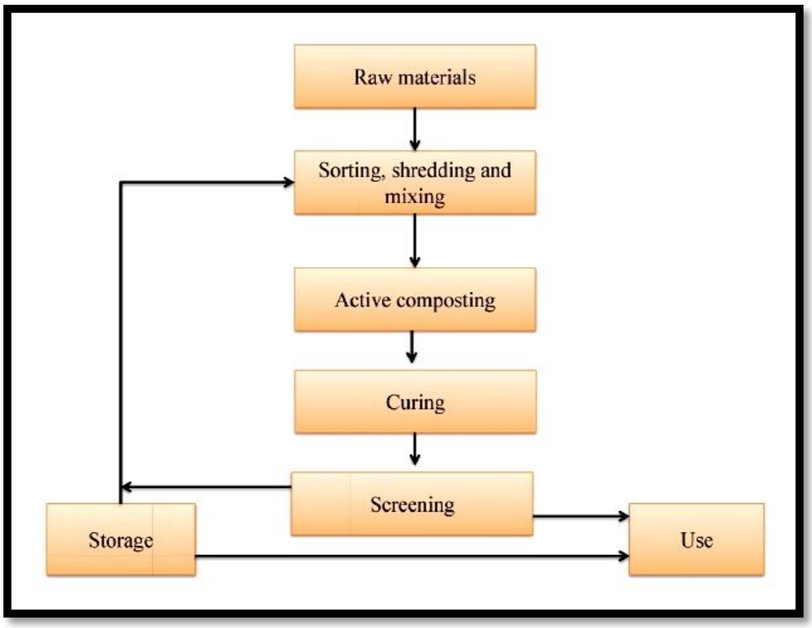

Figure 1: Flow-Diagram of Composting Method

- Aerated piles
- Windrow
- In-vessel

Table 6: Classification of Composting Methods

Method	Composting time	Treatment	Cost
Windrow	8-24 weeks for municipal solid waste	Used mainly for curing the compost in combination with in-vessel technique	Low
Aerated piles	6-12 weeks	Sewage sludges, MSW, Industrial organic wastes and yard wastes	Medium
In-vessel	Less than 7 to 15 days	All type of wastes	High

3. **Intrinsic bioremediation:** It is a type of remediation method defined as "cleaning up the contaminants by nature itself without taking human help" [88]. It is also known as natural attenuation; this process includes chemical, physical, and biological transformation such as anaerobic or aerobic biodegradation, oxidation, co-metabolism, reduction, volatilization, adsorption, and dispersion.

It has been believed that aerobic as well as anaerobic biological degradation (intrinsic bioremediation) are important to take into account for both reduction of contaminant concentrations as well as containment of the contaminant plume which are dissolved in the waste biomasses [89, 90]. Aerobic biodegradation depends on dissolved oxygen (DO), in which the subsurface microbial species are used as electron acceptor. Unlike in anaerobic biodegradation processes, nitrate, ferric iron [Fe (III)], carbon dioxide (CO_2), and sulphate are used as terminal electron acceptors. Interior of a contaminant plume is usually dominated by anaerobic biodegradation [91-93].

4. **Slurry bioreactor:** It is a mechanized aerated vessel reactor system, in which slurry is formed due to mixing of excavated contaminated soils and water.The components of the reactor is agitated to enhance desorption of soil contaminants, promote breakdown of soil aggregates, increase oxygenation rate of the slurry, and enhance contact between microbes and wastes [62]. Unlike, dispersants, surfactants and supported materials for microbial growth are added to increase biodegradation capability and improve the treatment of contaminated soil [66]. Biomass concentration is an important factor to maintain the degradation for both in the beginning and during processing and in such cases microorganism may be added to the slurry. Dangol et al. (2022) conducted a research on pilot scale slurry bioreactor for the decomposition of FW [94]. The time taken to complete the operation was 90 days, where continuously food wastes was added (750 g per day) and successfully achieved 91% reduction of food waste, decomposed inorganic carbon without intermittent removal of SS. Researchers observed that the microorganisms actively grew during 20 days of operation and reached a stationary phase with cell concentration 5×10^{-10} cells ml^{-1}, where utilized FW act as respiratory substrate during this phase. However, slurry bioreactors is expensive than *in-situ* system in view of high degree of mechanization. On the other hand, it has a great advantage of faster biodegrading rates of same compound compared to any other *in-situ* method [95, 96].

IX. VALUE-ADDED PRODUCTS FROM FW

The management of solid FW can be executed in various ways. Several research works has been done for producing value-added products from different type of FW [46, 97]. Carbon-nitrogen ratio, moisture content, composition, particle size, oxygen supply (aeration rate), temperature, quantity of bulking agent, porosity, microbial succession are the key factors during reutilization of FW [98-102]. These key parameters highly influence the efficiency of the production process.

1. **Animal feed:** Food waste can most commonly utilized as animal feed, mainly as cattle feed. The wastes are dried under sunlight and make them into pallets form [12, 103]. The pellets of wastes are sold in the market as animal feed. However, the application has several limitations depending on the quality of FW. Wastes from olive oil industry and sugarcane bagasse are highly rich in lignin content which hinders the utilization process as it may be difficult for animal to digest the food [46]. Food wastes with low protein content may not also be ideal for animal feeding. On the other hand, if the food wastes are not sun-dried then some additional charges are required for drying up the waste and to convert those into pellet form. This even costs more than the selling price of the waste. However, potato waste is suitable for cattle feed (not for other animals) as it has high potassium content. The rapid degradation of apple waste makes them suitable unless immediate drying takes place after its processing [104].

2. **Fertilizer:** Food waste can also be utilized as fertilizer. The untreated FW are spread on the soil which helps to increase soil microbial biomass. Therefore, the food biomass degraded into simpler form by microbial activity which can be easily taken up by plants and also increases the organic content of soil. The citrus wastes show fungi static behaviour which inhibits fungal growth in the fruits and vegetables on the agricultural field. Fertilizer from FW can also be prepared by composting and it is one of the easier methods to reutilize them. By composting, the food waste becomes a steady substance and it is known as compost [98, 99, 105]. Such fertilizers also known as organic fertilizers or soil amendments [106]. Composting process is very slower than other reutilization techniques such as anaerobic digestion, thermo-chemical conversion, fermentation etc. However, it is cost-effective, environment friendly and sustainable procedure which can be alternative to incineration, combustion and chemical conversion of landfill waste [107]. Therefore, it is widely used at the local or household levels. The efficiency of the organic fertilizers can be increased by co-composting where other organic materials are incorporated into it [108]. Anaerobic digestion can be another process for fertilizer production. Fertilizer generation by composting process is shown in Figure 2.

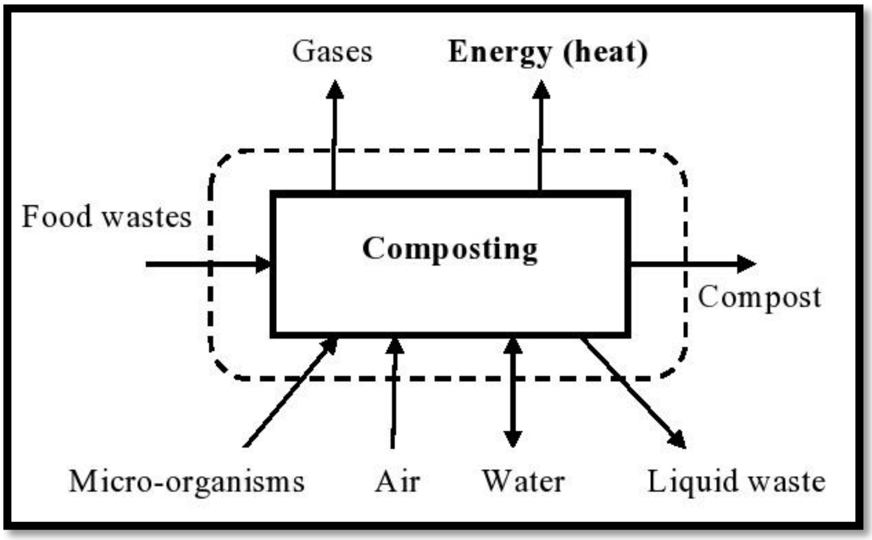

Figure 2: Fertilizer Manufacturing Via Composting

3. **Dietary fibers:** Dietary fibers are defined as the carbohydrates which are not digestible or absorbable by the human body’s enzymes. It is most commonly found in fruits, vegetables, nuts, cereals, lentils, dried peas and grains. These kind of fibers can be extracted from FW and have various applications in many fields. Dietary fibers have various beneficial aspects such as [109, 110]:

- It has ability to prevent the constipation
- It helps in maintaining a healthy diet and thus human body weight
- It minimizes the risk of diabetes by controlling blood sugar level
- It helps to reduce the risk of cardiovascular disease and colorectal cancer.

Dietary fibers can be extracted by from banana peels [110], apple pomace [111], grape waste [112], sugar beet pulp [113], sweet potato [114].

4. **Phenolic compounds:** Phenolic compounds have various advantages and can be extracted from several vegetable, beverages and fruit wastes. These are referred to as photochemical compounds. Its antimicrobial, antioxidants, anticancer compounds and anti cardio-vascular properties makes them helpful for human body [115]. The concentration of phenolic compounds may differ according to the type of food waste. For example, apple pomace contains lower concentration of phenolic compounds such as 20µg/mg, whereas, red grape pomace have comparatively higher concentration such as 100 µg/mg [116].

5. **Biofuel**

- **Biogas:** Biogas generation from FW is a very effective way to treat the waste and simultaneously the generation of fuel. High water content and biodegradable nature makes food waste suitable for this process. Bio-methane is the major and most important component of biogas. However, carbon-dioxide and hydrogen also be part of biogas [117]. Therefore, biogas generated from various FW can be utilized as fuel. The efficiency of the bio-methane generation can be enhanced by reducing the particle size and optimization of growth of micro-organisms. Bio-hydrogen (H_2) can be generated by bio-photolysis, photo-fermentation, and anaerobic fermentation or by integrating these processes. The process is shown in Figure 3.

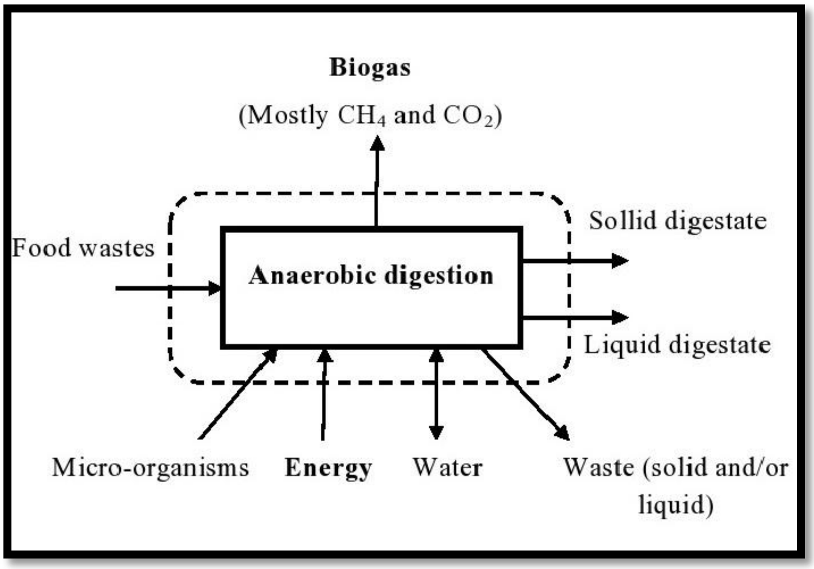

Figure 3: Biogas Generation by Anaerobic Digestion Process

- **Bioethanol:** The composition of FW varies with the location and geographical conditions. It can be found from one study that average food waste comprises of 35% starch, 20% protein, 25% lignocelluloses and 10% lipid [118]. However, the moisture content also varies with source of food waste generation. Another study shows that 27-47% (w/w) of FW are comprised of organic material [119]. The main components of FW were 23.5-18.3% (w/w) proteins, 16.2-29.4% starch, and 25.7–33.2% (w/w) lipids on dry wet basis [119]. Production of sustainable materials by fermentation process is a new and important research. Bioethanol can be generated by fermentation process by using microbial activity with controlled conditions. Food waste must be sterilized before fermentation process to avoid the contamination. Sterilization is considered as an energy intensive process and desired product can be extracted by controlling the microbial growth with the sterilized food materials.

6. **Nanocellulose:** A recent and sustainable material named nanocellulose can be extracted from FW such as rice husk [120], sugar beet pulp [121], banana peel [122], cassava root bagasse [123], tomato peel [124], soy hull and wheat straw [125], citrus waste [126]. This nanocellulose can be either nanofiber or nanocrystals. Both can be utilized for manufacturing food packaging applications. Nanocellulose has achieved great demand due to its renewable, biodegradable, biocompatible and nano-properties which is suitable for biocomposite applications. For the extraction of nanocellulose, various methods such chemical treatment, steam-explosion, chemi-mechanical treatments, mechanical defibrillations and enzymatic treatments are applied [127-130]. The structure of nanofiber is shown in Figure 4 [131].

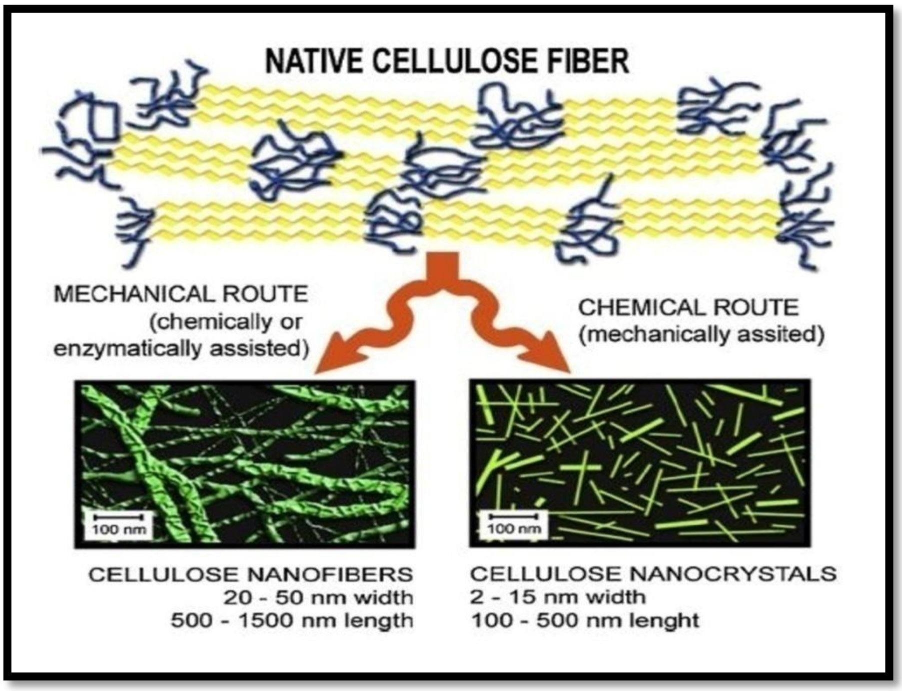

Figure 4: **Structure of Nanocellulose**

X. FUTURE PROSPECTS ON FOOD WASTE VALORISATION

The loss and waste of food occurs at every stage of the food supply chain, from manufacturing to consumption, as previously mentioned. Recycling and bioconversion of FW into biofuels and value-added products or biofuels can help to minimise this problem. Many researchers have found ways to extract biofuels and other value-added products from FW using a variety of approaches. In order to maximise the profitable product output at a low cost, new technologies and methodologies need to be explored. Many scientists have been working recently to find ways to increase output while consuming less energy. This immediately affects the cost of producing the product. FW should be encouraged to be fully utilised or integrated into a biorefinery, since this will significantly lower the cost of FW management.

The most viable and ground-breaking approaches to valorise FW should be devised by combining scientific fields. For innovative FW valorisation that recovered high-calorie biofuels and value-added goods. Adopting energy-efficient pre-treatment's before recovering biofuels and other value-added products from FW will increase product yield and income. Post-treatment of FW is a future technique that will improve efficiency. Complete bio-based product recovery or integrated biorefinery of FW is economically advantageous. The biorefinery concept might repurpose FW into a bio-based product for the circular bio-economy. Organic-rich FW is a valuable waste that can generate revenue due to its biological content. At each level of the food supply chain, from production to consumption, FW should be reduced.

XI. CONCLUSION

The extensive amount of FW is generated through the activity of household as well as food industries. The amount of FW would be increased in the future, and it needs to be utilized or discarded for maintaining the ecosystem. The FW composition varied according to the food waste source and the stage of processing. It has been shown from various literature and experimental data that FW is a compositional and promising feedstock for the generation of various sustainable products. Besides this, it is also shown that bioremediation is a valuable technique for mitigating environmental issues by converting various agro-chemicals into non-toxic substances (herbicides, pesticides, insecticides, etc.) and FW into simpler adoptable materials.

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