Chapter 1
Integrated Waste Biorefinery for Biofuels and Biochemicals

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Abstract This chapter summarizes the recent advances in the processing of waste resources to produce biofuels and platform chemicals. There is a growing concern globally on clean energy and environmental sustainability, which is impelling the search for biofuel sources and other platform chemicals. This chapter examines the prospects provided by organic waste materials and waste water and considers their suitability for alternative fuel and fine chemical production, their sources, residue management, conversion and refining technologies, and the circular economy. In addition, the applied aspects of waste conversion by several thermal, chemical, and biological technologies are discussed.

Keywords Waste biorefinery · Biofuels · Biochemicals · Lignocellulose · Clean energy

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J. K. Saini, R. K. Sani (eds.), *Microbial Biotechnology for Renewable and Sustainable Energy*, Clean Energy Production Technologies,
https://doi.org/10.1007/978-981-16-3852-7_1

1.1 Introduction

The utilization of wastes and agricultural residues is of concern globally in response to confronting climate change and the worldwide endeavor to curtail greenhouse gas (GHG) emissions. Biodegradable wastes and agro-residues have previously been recognized for the production of energy and find a place in the developing biorefinery concepts. India has tremendous waste biomass as a potential feedstock that satisfies most energy needs. The annual consumption of liquid fuels in India is about 50 million metric tonnes. However, it should be borne in mind that the biomass potential and its broad utilization in India can adept to produce double the amount annually. For India, the estimated energy usage for domestic, transport, and industrial sectors are 40%, 40%, and 20%, respectively. The required stake of crude oil and gases has a significant share (90%) for the primary and transport sectors, and the remaining 10% is utilized for the production of industrial chemicals. The escalating prices of crude oil and energy security issues have forced developing countries to search for alternative and cheap energy sources to fulfill their rising energy demand. The Indian energy transition has a long route to go. The wastes must contribute to the bio-economy that uses material and energy in biorefineries and interpose for the energy transition in hybrid technologies, i.e., combing other renewable energies. India foresees installing 175 GW of renewable energy capacity by 2022 with the contribution of solar (57%), wind (34%), biomass (6%), and small hydropower (3%).

1.2 Integrated Waste Biorefinery

The traditional petroleum-based refineries employ fractional partitioning on a raw feedstock to obtain various components. In analogy, biorefinery involves the association of various biomass treatments processed under one umbrella, resulting in the production of different components of commercial use. Subsequently, the entire chain becomes more viable and reduces the waste generated. Biorefineries are envisaged as viable platforms for transforming to a biobased circular economy capable of utilizing a variety of biofuels and platform chemicals. The full-scale biorefinery will also attain sustainability if the basic frameworks are built up. Since the very rationality of biorefinery hands holds sustainability goals, the second generation biorefineries become the main targets. Endowed with huge biomass potential and abundance of lignocellulosic wastes, immense prospects exist in India for the development of 2G biorefineries. These agro-residues reportedly are varied and are available throughout the year in required amounts. However, large agricultural residues, specifically the paddy straw, are burnt in the field due to lack of awareness, policies and, poor valorization. This chapter examines the prospects provided by organic waste materials and wastewaters to consider their suitability for alternative fuel and fine chemical production, their sources, residue management, conversion and refining technologies, and the circular economy. Besides, the applied aspects of waste conversion by several thermal, chemical and biological technologies will be discussed. In summary, the present chapter offers comprehensive and illustrative descriptions of major processing technologies, waste valorization for fuels and chemicals, supply value chain and logistics, techno-economic analysis, and life-cycle assessment, and the circular bio-economy.

Biorefineries aid in the maximum utilization of optimum energy potential of organic wastes and resolve the issues on waste management and GHGs emissions. Wastes can be converted into either gaseous or liquid fuels by suitable enzymatic/chemical treatment. The pretreatment processes involved in biorefining generate products such as paper-pulp, high fructose corn syrups, solvents, acetate, resins, laminates, adhesives, flavor chemicals, activated carbon, fuel enhancers, and undigested sugars. These sources remain generally untapped in the conventional processes. The efficiency and appropriateness of the process rely on their ability to use a wide range of biomass resources obtained from animal or plant materials. The concept of the biorefinery is still in the budding stages in most places of the world due to several factors such as availability of raw material, product supply chain viability, and model flexibility that hamper the progress to commercial scales. Being in a burgeon holds the solution to the optimum utilization of wastes and natural resources that the mankind has always tried to achieve. The onus now lies on governments and corporate organizations to incentivize or finance the research and development in this field.

In the context of increasing global demand for more environmentally friendly sources of energy, biofuels and biochemicals stand on the fore to make different products. Few companies have already explored the production of platform chemicals from these renewable resources. For example, Cargill and Virent Inc. had collaborated to utilize corn dextrose as a feedstock for the production of drop-in low-carbon biofuels and biochemicals. The BioForming® technology of Virent Inc. facilitates the use of plant-derived sugars as feedstocks for renewable drop-in gasoline, lower carbon biochemicals, and jet fuel. Furthermore, bioparaxylene can be produced and used to produce recyclable biopolyester. Comparably Chempolis Ltd., Fortum, and Numaligarh Refinery Ltd., India focused on the bamboo biorefinery concept to convert 300,000 tons into bioethanol, furfural, acetic acid, and biocoal. Biocoal is used as fuel in the combined heat and power (CHP) plant located in Assam, India.

1.2.1 Solid Waste-Based Biorefineries

The substantial growth in population with developed living standards has enhanced the energy demands along with waste generation. The depletion of resources at a faster pace has created innumerable impacts on the environment leading to climate change and global warming. To overcome these drawbacks, various efforts have been made to develop sustainable strategies. A biorefinery is a boon to several industries based on polluting and finite fossil resources and is commercially convenient for the production of biofuels and biopower from biomass. Biorefinery is the sustainable processing of biomass into a spectrum of marketable products and energy (IEA 2008). The concept of biorefinery comprehends a broad range of technologies for the conversion of biomass resources into value-added products integrating biomass conversion processes and equipment. Integrated biorefinery systems aim to optimize the energy use and materials in the total chains from biomass plantation to end-product to ultimate product use, by that the economic viability and sustainability of biorefineries gets developed. Accordingly, tight integration is essential in the integration of platforms, waste and product exchange, application of efficient conversion routes, and optimizing biomass supply chain (Budzianowski and Postawa 2016).

1.2.2 Solid Waste Value Chain and Logistics

In practice, solid waste management begins at the household at the micro-level, firms at the macro level, thereby resulting in a new form of waste. The value chain linkages of solid waste will have distinct dissimilarities with the main manufactured product. While the value chain of the main product will symbolize the value enhancement along its chain, it can be termed as a positive chain, and sometimes, the waste value chain will also exhibit negative value. But the economic performance of waste value chains can be improved by different strategies, such as industrial integration, economies of scale and size, and reducing feedstock logistics. The solid waste value chain holds a significant role in the circular economies to mitigate the challenges of environmental issues. The value chain of several agro-based wastes is depicted in Fig. 1.1.

In developing economies, poor institutional governance, financial crunch, resources shortage, and political matters are some of the important issues in the management of solid waste effectively. Lack of coordination in addressing solid waste management requires a holistic environmental approach to focus upon 3 R: reduce, reuse, and recycle. It could also create employment opportunities, thereby helping economic development. The Thailand waste management experience revealed that different technologies are used for solid waste management (Thiengburanathum et al. 2012). Similarly, a research study on Nigerian experience in handling solid waste and logistics in the performance of the Lagos State Waste Management Authority helped in developing metrics to analyze the efficiency of management (Ayantoyinbo and Adepoju 2018). In Brazil, a reverse logistics network was deployed for the management of solid waste by the Brazilian Waste Management Policy (Ferri et al. 2015).

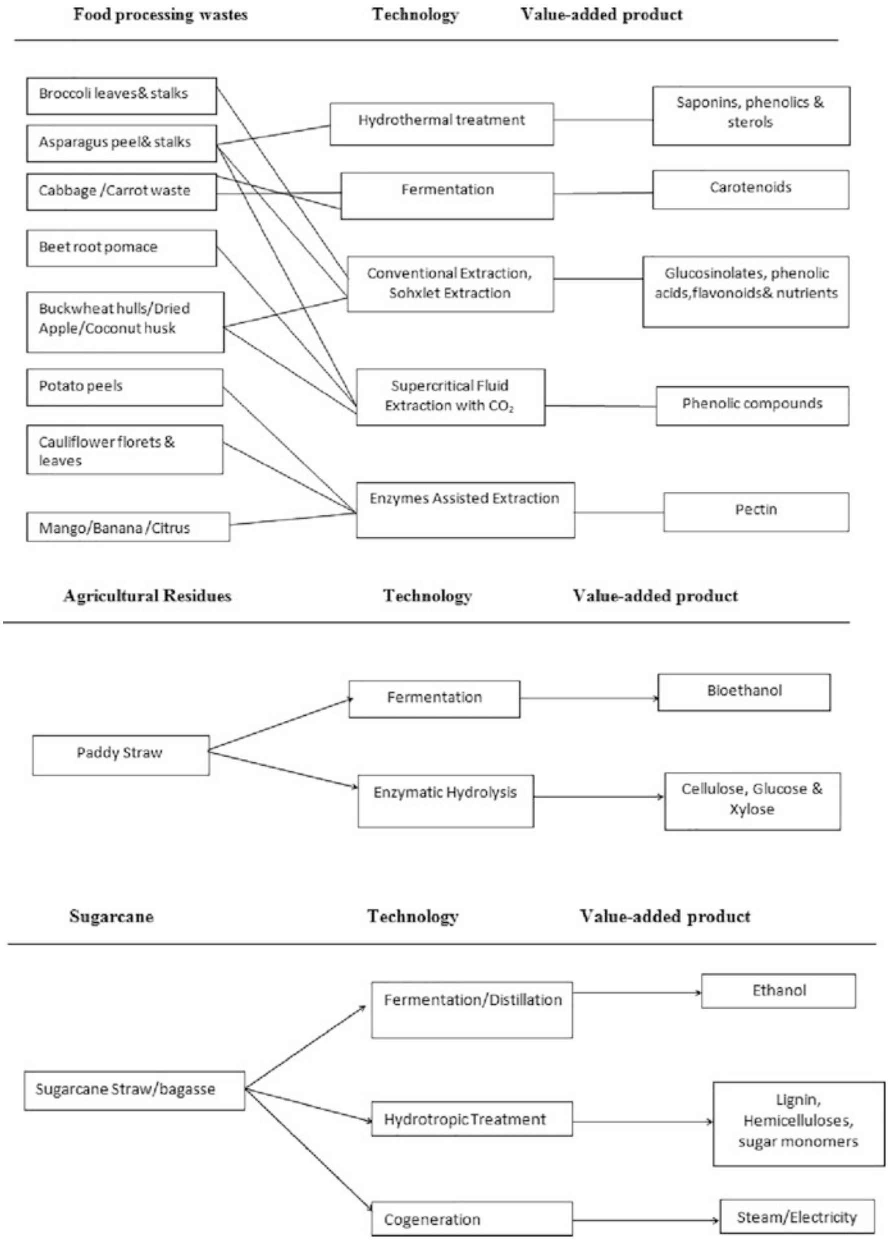

Fig. 1.1 Value chain of various agro-based wastes

1.2.2.1 Mapping of Value Chains

Solid waste generation is linked with various stages of the value chain. Generally, the wastes are generated in various processing operations by converting raw materials into the final products and by-products (Hakim et al. 2017). The following four stages are the sequential process in the mapping of any waste value chains.

- Households/firms involved in the raw material generation,
- Households/firms with manufacturing and production as the prime activities,
- Households/firms engaged in the involved in the logistics,
- The final customers/end users.

While treating the solid wastes, the type and availability of waste materials, processing methods, products recovered, and market conditions are the key determining factors in mapping the value chain process. From the economic point of view, wastes containing appreciable quantities of high-value substances should be converted into valuable building blocks. It also decides the optimal size of the plant to be operated in processing the solid wastes (Muntoni 2019). Some of the waste value chains are presented below.

1.2.2.2 Key Players/Actors

Value chain concept in product/services will be always seen as a value-added stream, where each activity will subsequently adding value. In waste management, there are systems with a negative value in the chain. The households, institutions, markets, and infrastructure are the key players who ultimately decide the efficiency, sustenance, and performance of the waste value chain and logistics. But, in a market economy, the economic agents of this value chain ecosystem compete against each other for individual welfare, resulting in the addition of negativity to the chain. Identifying the systemic constraints that inhibit the performance of these value chains is the foremost concern of the researchers/policy makers. Incorporating a value chain network in solid waste management aims at minimizing the environmental impact of the production process and recycling and minimizing GHG emissions resulting from logistics. To achieve this, the incentives for the key players/actors, opportunities and constraints for the individual players on the value chain, quantification of positive and negative externalities at each node of the waste vale chain should be properly defined. Generating wealth from the waste and identifying existing gaps in solid waste management will lead to fulfilling some of the sustainable development goals of the United Nations.

1.2.2.3 Logistics for Waste Management

One of the new trends in logistics for waste management is effective recycling or reuse of products/services along with transport with minimal damage to the ecosystem. Designing and implementing proper logistics will address most of the environmental and economic aspects of solid waste management.

The conceptual framework for the logistics of solid waste can be as follows:

- Identification and determination of the waste locations;
- Determination of intensity of vehicles and their capacity;
- Estimation of any environmental damage while performing logistics;
- Understanding the demand for solid wastes;
- Determination of costs of operations;
- Preparation of budgets for fleet management;
- Evaluating the effectiveness of the logistical method;
- Final feedback system.

1.2.3 2G and 3G Biofuels

The first-generation biofuels were manufactured from edible feedstocks which appear to be unjustifiable and the controversies on food-versus-fuel appear to be untenable for the commercial use of first-generation biomass. They have significant financial, natural, and political concerns as extensive manufacturing of feedstock demand arable agricultural lands and contributes to ecological degradation. The debate on the food security for the use of biofuels was expunged with the use of second-generation (2G) biomass, which includes the nonedible plant materials, including different feedstocks, i.e., lignocellulosic biomass feedstocks to municipal solid wastes. The variety of biomass feedstocks used for 2G biofuels are wood, organic wastes, food wastes, and specific crop residues. 2G biomass requires to undergo a series of pre-treatment to recover the fermentable sugars embedded in the fibers of the plant. Further, they should undergo fermentation/gasification/pyrolysis to yield ethanol/syngas/ biochar, respectively. The operational cost and the additional steps for the processing of biomass hinder the efficiency. Consequently, third-generation biofuels (3G) gained interest in the field of sustainable energy. They are produced from algal biomass and renders favorable advantages for producing biofuels as they can accumulate large cell lipid content (20–77%) (Jin et al. 2015). The short harvesting cycle and high growth rate of microalgae serve huge potential compared to other biomass. Their low lignin content eliminates the need for pretreatment and increases the production of fuel by transesterification.

1.3 Sources of Wastes

1.3.1 *Potential Economic Utilization of Biomass Waste as Feed Stock*

In India, the potentiality of lignocellulosic biomass for renewable energy production using the latest technologies has been analyzed for the past decades (Mandade et al. 2016). The exigency on energy endowed with global warming has spurred the world to hunt for alternatives. One of the key alternatives is the production of biofuels and biomaterial building blocks from agro wastes, agro-processing industrial wastes, food waste, biomass feedstocks, and liquid wastes. Generally, the pretreatment process was used for different biomass feedstocks to produce liquid or gaseous biofuels such as biomethane, biohydrogen, bioethanol, and biodiesel (Liu and Wu 2016).

The viable characteristic of biorefinery in reducing the processing cost of biofuels can be encouraged and applied for economic sustenance. An estimate shows that the cost of petroleum fuels is still two to three folds lower than that of second-generation biofuels based on energy equivalent aspects (Carriquiry et al. 2011). In the context of reducing the production cost, there are numerous challenges endowed in the production of biofuels and biochemicals from biomass (Hoekman 2009; Luo et al. 2010; Menon and Rao 2012) that need to be addressed. These challenges are in the areas of biomass production and its logistics, development of energy-efficient biofuel production technologies (pretreatment, enzymatic hydrolysis, and fermentation), co-product production, standards for bioproducts, biofuel supply chain network, societal acceptance, and life cycle assessment (LCA) and environmental impact of biofuel production technologies. These challenges necessitate the need for experts from different areas of research starting from crop cultivation to final product production.

Biofuels and biochemicals produced from lignocellulosic biomass feedstocks offer quite a few welfares to the society, such as (1) renewable and sustainable feedstocks, (2) carbon-neutral, (3) local economic growth and rural employment, (4) alternate eco-friendly solutions for air pollution from in situ biomass burning and biomass rotting in fields, (5) supporting bioeconomy concept and energy security for countries and also reduce the oil imports, (6) new employment opportunities (Greenwell et al. 2013). Apart from this, the current potential uses of biomass residues include animal fodder, mulching, thatching, and fuel in different industries and biomass power plants.

1.3.2 *Wastewater as Feed Stocks*

A wastewater-based biorefinery integrates the concept of the biorefinery to wastewater treatment. This biorefinery generates valorized products to direct an economically viable process that enhance resource productivity and simultaneously treats wastewater to acceptable standards. It is focused on bioresource recovery in converting the major organic nutrients and trace elements in the wastewater stream to value-added byproducts and concurrently offering clean water as a product. This system contributes to a potential circular bio-based economy to promote the energy and industrial sectors. Thus, integrating the biorefinery system into a wastewater treatment system will promote an exemplar transference that can enhance the system's profitability and reduce environmental pollution. This system also facilitates a linkage between the end-users of water and those who control the wastewater management and can end in resource recovery in closed-loop cycles that fabricate a circular economy.

One of the major impediments in biofuel generation from algae is their high nutrients requirement and higher downstream processing costs. Spanning algal biomass generation with wastewater treatment will resolve these issues. Algal biomass is a capable alternative feedstock in biorefineries, owing to their higher photosynthetic efficiency (Singh et al. 2011), biomass productivity (Bhola et al. 2011) oil content (Mutanda et al. 2011), and the possibility of daily harvesting of algal biomass (Rosenberg et al. 2011). The algal biomass does not compete with food crops and its cultivable area. Algal biofuels are referred to as third-generation biofuels (Gressel 2008). Hitherto, microalgae are a potential resource for liquid biofuel production due to higher biomass productivity (175 tons/ha/year), possibility to cultivate in wastewaters (Jena et al. 2011), mixotrophic growth (Nagajothilakshmi et al. 2016), and cocultivation of algae (Rakesh and Karthikeyan 2019). Rinna et al. (2017) reported that *Botryococcus braunii* has higher nitrogen and phosphorus removal efficiency in wastewater. Simultaneously, this process generates lipid-rich biomass and algal lipid can be utilized as a potential feedstock for biodiesel production. Generally, about 20% of agro-industrial food wastes are utilized as animal feed and the remaining waste may be disposed of through incineration, composting, or landfilling. Nowadays, agro-industries are facing an increase in their growth around the globe. These agro-industrial wastes are inexpensive, abundant, and micronutrient-rich, but they have disposal problems. These wastes could be potential as a substrate for alternate carbon sources for biofuels and biochemicals production. Increasing global demand for biofuels and biochemicals via utilization of waste biomass resources has driven research toward stable, inexpensive resources with concern over global climate change (Hu and Ragauskas 2012). Vijayanand et al. (2017) used different inexpensive and abundantly available agro-industrial wastes for biobutanol production. They confirmed that pretreatment and glucose supplement enhanced the biobutanol production by *Clostridium beijerinckii*. The distinct feature of algal biomass is the coexistence of mixed or multiple species contributing to an array of products from nutraceuticals such as omega-3 fatty acids to complex recombinant proteins, thereby making a valuable biorefinery processing system (Subhadra 2010). *Nannochloropsis* sp. is a potential biomass candidate for lipid resource to produce biodiesel, biohydrogen, and high added-value compounds. The algal biomass cake after the extraction of oils and pigments can produce hydrogen through the fermentation process (Nobre et al. 2013). Agar is obtained from the pulp of marine red seaweed *Gracilaria verrucosa*, and its process residues may be used as bioethanol feedstock (Kumar et al. 2013). However, there is restricted information available for research on selective microorganisms (bacteria/yeast) to exploit for high value-added products and biofuel production (da Silva et al. 2014).

A microbial fuel cell (MFC) is an electrochemical system for converting the chemical energy of organic materials into electrical energy via redox reaction under anoxic conditions (Ledezma et al. 2015). Several industries utilize a huge amount of fresh water and energy for processing and generate a large quantity of wastewater. Generally, this wastewater is directly discharged to land, resulting in environmental problems such as water and soil pollution. Hence, recently the emphasis has shifted to utilize various industrial effluents for MFC cell feed (Sahu 2019). MFC have the potential to overcome wastewater management issues. It is an ideal technique to use industrial wastes material in wastewater to fuel and hence obtaining electrical energy as the end-product (Pant et al. 2013). The efficiency of microbial fuel cells usually depends on the suitable cathode, an anode (Bi et al. 2018), and cation exchange capacity of the material used to treat wastewater (Rahimnejad et al. 2015). Recently, many industrial wastewaters such as starch processing, brewery, palm oil, paper, and sewage were treated with the MFC concept (Baranitharan et al. 2015; Radha and Kanmani 2017). The complex chemical composition of agro and food processing wastes is a very reliable feedstock in MFCs (ElMekawy et al. 2015). Wastewater treatment sludge consists of a desirable source of microorganisms for microbial fuel cells treating liquid wastes, whereas endogenous microflora can be utilized for MFCs with solid organic waste (Mohan and Chandrasekhar 2011).

1.3.3 Biomass Harvest and Yield

Wastewater-based biorefinery offers new opportunities for both algal cultivation and multiple products generation aspects (Khoo et al. 2019). Harvesting of microalgae is one of the major obstacles to microalgae processing for multiproducts due to its higher initial investment, low biomass concentration, and sedimentation rate (Rakesh et al. 2020). Various methods applied for microalgae harvesting are sedimentation, centrifugation, flotation, and flocculation. Sometimes a combination of two or more methods is used for ideal harvesting (Chutia et al. 2017). Pahl et al. (2013) examined various centrifuges for microalgae harvesting and reported that disc stack centrifuges are extensively used for high-value product recovery from algae in industries. Flocculation of microalgal cells via flocculating agents is one of the desirable methods of harvesting microalgae. The selection of a suitable flocculating agent is an essential condition for this process, i.e., it should be easily available, non-toxic, inexpensive, and should be effective at low concentrations (Branyikova et al. 2018). Rakesh et al. (2014) used multivalent metal salts to initiate flocculation in the microalgal cell suspension.

Jiang et al. (2020) reported that co-flocculation of *Chlorella pyrenoidosa* and *Citrobacter freundii* in the ratio of 1:1.6 showed maximum flocculation efficiency of 97.45%. Autoflocculation is a species-dependent harvesting process that involves interaction between surface molecules of microalgae with the surrounding medium or among themselves. Matter et al. (2019) showed that *Scenedesmus obliquus* autoflocculation efficiency improved from 10.4 to 33.2% when pH increased from 7 to 10. Pandey et al. (2020) evaluated the harvesting of *Scenedesmus* sp. using electro-coagulation-flocculation showed effective harvesting efficiency (>99%) under optimal conditions. Autoflocculation and bioflocculation are found to be inexpensive and effective dewatering techniques for algal harvesting. Autoflocculation has a high sedimentation rate without any addition of the flocculants. The autoflocculation can be enhanced by a high aeration rate, CO_2 concentration, and nitrogen levels. Bioflocculation is also an efficient, eco-friendly, and cost-effective algal harvesting method.

1.4 Industrial Waste Biorefineries

Huge industrialization across the globe has well served to the generation of industrial wastes and harmful environmental pollutants menacing mankind. A waste biorefinery aims at plausible utilization of wastes into a wide spectrum of bio-based products, thereby providing energy security and pollution control with societal development. The biomass waste accumulation from industries and storage systems is crucial for further processing. In the modern era rather than waste disposal methods like incineration and landfill, reuse and recycle are indispensable. Various industries, including cassava, brewing, wood, and sugarcane industries, contribute to starch residues in either liquid or solid waste. The concept of circular economy is being increasingly adopted in both developing and developed countries not only to reduce, reuse, and recycle the wastes but also to produce a plethora of products such as food, feed, fuels, and chemicals through multiple technologies of valorization. This concept of biorefineries (producing various products from one feedstock or mixed feedstock) is developing at a fast pace to meet the socio, economic, environmental, and geopolitical factors of different countries.

Several wastes such as agricultural wastes, forestry wastes, municipal wastes, industrial wastes, food wastes, and animal wastes are suitable for biorefineries. All the wastes have high potential in terms of processing and getting high-value products (Takkellapati et al. 2018). Among the aforementioned industrial wastes belong to the following categories:

Olive oil wastes (including olive oil crop residues and mill wastewater);

Pulp and paper industry wastes (including lignin-rich waste streams, kraft lignin derivatives, etc);

Sugar industry wastes (press mud, bagasse, molasses distillery spent wash, sugarcane tops, etc.);

Coffee industry wastes.

1.4.1 Waste Refinery Based on Sugar and Syngas Platforms

This refinery process falls into a category of two platform biorefinery according to National Renewable Energy Laboratory. The two platforms are (1) The sugar platform in which the wastes are biochemically converted to produce sugars, and (2) The syngas platform where wastes are put into the gasifier to produce syngas. The sugar platform uses biochemical methods such as pre-treatment, hydrolysis, and fermentation to produce sugars. The syngas platform uses thermochemical methods to generate syngas from wastes (Yadav et al. 2019).

1.4.1.1 Sugar Platform

As discussed, the sugar platform involves biochemical steps such as pretreatment, hydrolysis, and fermentation or biological processes into various biofuels and biochemicals. As an example of sugar biorefinery, bioethanol is the major end product produced. Bioethanol can be a renewable resource for various other platform chemical production such as ethylene, propylene, and butadiene and also other chemicals of commercial utility such as acetaldehyde and acetic acid. For example, acetaldehyde and acetic acid are value-added chemicals generated from bioethanol in the sugar biorefinery concept.

1.4.1.2 Syngas Platform

The biomass conversion by the thermochemical process is quite complex and utilizes several component configurations and operating conditions for transforming biomass into synthesis gas or oil. High energy gas production by partial oxidation of industrial wastes at 500–800 °C is referred to as syngas. Initially, the wastes are pretreated to remove unwanted materials, then gasification proceeds with partial oxidation, leading to syngas production. Syngas primarily consists of carbon monoxide (CO) and hydrogen (H_2). The gas composition of syngas depends on the components of biomass feedstocks, the gasifier operational parameters, and gasifier types (Puigjaner 2011). Unpurified syngas also contains small amounts of impurities such as tar, CO_2, and other gases. Hence, most of the syngas platforms use cleaning as the third step in cleaning and purifying syngas to remove impurities. Syngas can produce multiple products such as ammonia, methanol, ethanol, methane petrol, diesel, and chemicals. This can be achieved through different processes including syngas fermentation, Fischer-Tropsch synthesis, methanol synthesis, and ammonia synthesis synthetic natural gas production. Syngas can be a renewable feedstock for the generation of bioethanol by both biochemical and thermochemical routes. The biochemical route involves using microorganisms. For example, *Clostridium autoethanogenum* and *Rhodospirillum rubrum* convert syngas into bioethanol and biohydrogen, respectively. The added advantages of the syngas fermentation method over conventional fermentation are that it needs no pretreatment, utilizes entire biomass; in it reactions occur at ambient conditions, ethanol yield is higher, and no costly enzymes are used. However, poor mass transfer properties of the syngas and low ethanol yield of biocatalysts are the major hurdles for the commercialization of this technology (Munasinghe and Khanal 2010).

1.4.2 Waste Refinery on Cellulosic/Starch-Based Biofuels

The lignocellulosic biomass has candidacy to be transformed into energy-rich hydrocarbon and fine chemicals through thermo-chemical and biochemical pathways. For the industrial wastes considered, the basic waste bio-refinery may consist of a biodigester. Crops with copious quantities of starch such as corn, wheat, and cassava can be employed for enzymatic hydrolysis to yield a sugar solution, which can subsequently ferment and be processed into biofuels and biochemicals. On the other side, the by-products from the processing of starch-rich crops are animal feed with rich proteins. If appropriate technology is applied for sweet sorghum stems, liquid biofuels (e.g., bioethanol, biobutanol), and wood-plastic composites can be generated (Yu et al. 2012). Generally, the plant oils contain fatty acids with 8–24 carbon length chains (Octave and Thomas 2009). Oilseeds can be a rich resource for alternative petroleum products (fuels, chemicals, lubricants, and detergents), which can produce biofuels and high-value fatty acids. Oils of soybean, palm fruits, rapeseeds, and canola seeds are popular to produce biodiesel (Demirbas 2007). Bouaid et al. (2010) scrutinized an integrated process for producing low and high-molecular-weight methyl ester fractions from coconut oil for the production of biodiesel/biolubricants/bio solvents. Rincón et al. (2014) developed an integrated approach for producing biodiesel by transesterification of palm oil, palm wastes, and crude glycerol or methanol from syngas.

1.4.3 Conversion of Sugars from Waste to Hydrocarbon Chemicals

Hydrocarbons are long-chain containing alkanes formed by condensation or head-to-head condensation of fatty acids involving various steps as depicted in Fig. 1.2. They are similar to high octane jet fuel. Sugars produced from wastes can be used to produce hydrocarbons (Ladygina et al. 2006). Sugar-based biorefineries are applicable for different sugar crops such as sugarcane, sugar beet, or sweet sorghum. It is a simple way to extract the saccharose from sugar crops, and it is further processed to produce bioethanol and biochemicals using appropriate technologies. In Brazil, the biorefinery was applied to sugarcane crops to produce bioethanol and biopower using sugar juice and sugarcane bagasse (Mariano et al. 2013). In India, Godavari

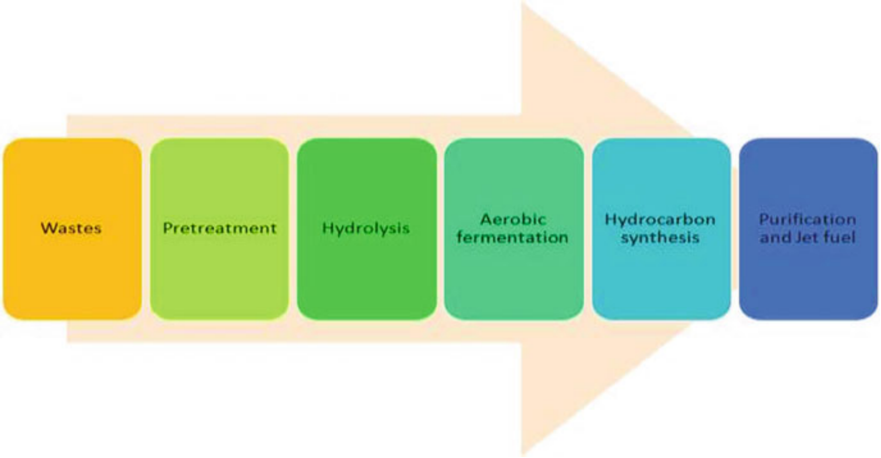

Fig. 1.2 Steps involved in hydrocarbon production

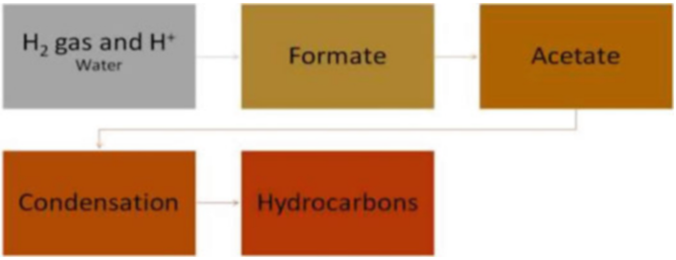

Fig. 1.3 Pathway of hydrocarbon production (Adapted from Ladygina et al. 2006)

Biorefineries Ltd. operates two sugar refineries to produce sugar, bioethanol, and electricity from sugarcane coupled with more than 20 renewable feedstocks. In Colombia, sugarcane biorefineries operate to produce sugar, bioethanol, and electricity from cane juice, molasses, and bagasse, respectively. It helps in establishing a profitable and sustainable biorefinery and offers several benefits such as acceptable GHG emissions, low stillage effluent production, waste minimization, and new job opportunities for both rural and educated people (Moncada et al. 2013).

In the developed nations, the bioethanol pilot plants are used with a small modification to produce hydrocarbons. Initially, the biomass is processed and pre-treated with dilute sulfuric acid. The pretreated biomass is subjected to enzymatic hydrolysis produced onsite and the pathway of hydrocarbon production is depicted in Fig. 1.3. The difference between bioethanol and hydrocarbon is an important aerobic process. The reactor is supplemented with aerators to increase the mass balance ratio of the medium. Another difference is the removal of solids in hydrocarbons production. The majority of microorganisms viz., Cyanobacteria *N. muscorum, Anacystis nidulans*, Gram-negative anaerobic sulfate-reducing bacteria *Desulfovibrio desulfuricans,* Gram-positive aerobic bacteria (eubacteria) *Bacillus* sp., and Yeast *Saccharomyces*, *Penicillium* sp. are capable of accumulating intracellular and extracellular hydrocarbons.

1.5 Food Industry Waste Biorefinery

The exponential growth of the global population poses threat to finite resources and also surges the sum of waste generated. Among the most generated biowastes, food waste (FW) is of global concern. The ineffective waste management strategies lay a step for a waste generation along the food supply chain accounting for 1.3 billion tons of waste. It is approximately equivalent to one-third of edible parts of food for human consumption (FAO 2019) and total waste generation is projected to increase by 44% by 2025. FW, being rich in moisture content and nutrients (proteins, carbohydrates, and lipids) putrefies upon accumulation, thereby serving as a ground for disease-causing organisms and poses serious environmental threats contributing to 10% of greenhouse gas emissions (IPCC 2019). Given the collective challenges of food wastage with demand for green energy and diminishing fossil fuels, a sustainable biorefinery strategy is the need of an hour for the utilization of this potential feedstock toward assorted product production. An appropriate biorefinery of FW can increase the efficiency of the food supply chain and obtains value-added products by various means such as extraction, biological/chemical conversion, and synthesis.

1.5.1 Energy Recovery and Waste Treatment

The lignocellulosic nature of FW has attracted interest among renewable energy scientists for its conversion into commercially important products. The organic fraction composition of FW endows the high bio-degradability that reduces the need for pre-treatment methods. Energy recovery from the wastes can be employed by either of the processes including combustion, pyrolysis, anaerobic digestion (AD), and gasification. These processes involve the conversion of wastes into energy which may in the form of heat, fuel, or electricity. Various energy recovery processes of FW are depicted in Fig. 1.4. AD serves as a key for reduction, stabilization, and biogas production from FW (Algapani et al. 2017). AD of FW has less environmental impact than incineration and landfilling. However, AD involves complex processes and relies on important parameters such as nutrient contents, particle size, inhibitory compounds, and process parameters like pH, temperature, retention time, organic loading rate, agitation, and inoculum, while various innovations are being developed to enhance and optimize product yield. Two-stage anaerobic digestion of food waste was studied by De Gioannis et al. (2017), which resulted in enhanced methane production as well as associated H_2 production. Co-digestion of FW with sewage sludge has been gaining interest to increase the efficiency of AD. FW sludge

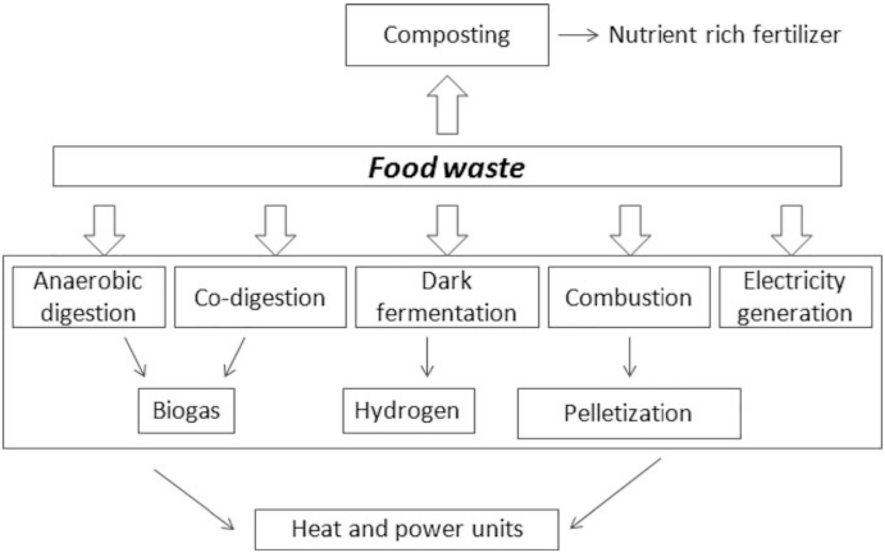

Fig. 1.4 Energy recovery from food wastes

co-digestion with chemically enhanced pre-treated sludge was found to improve methane (CH_4) recovery (Chakraborty et al. 2018). The energy balance of wastewater treatment plants can be enhanced by co-treatment of municipal wastewater with FW associated with increased methane yield (Guven et al. 2019). Co-digestion with animal manure or sewage sludge supplies the needed alkalinity and micronutrients required for the AD. Another common type of co-substrate being used is carbon-to-nitrogen (C/N) ratio rich lignocellulosic biomass, which also helps to prevent rapid acidification in AD using food waste as a single substrate. Co-substrate should have a good C/N ratio, total solids, and enough buffering capacity to sustain pH drop in methanogenesis of FW under dry conditions.

Micronutrient availability plays a pivotal role in the performance and stability of food waste digesters. Improving the design of the digester and operating strategies solves the issue of rapid acidification of FW and the inhibition by methanogens. Appropriately, two-stage systems have been anticipated in which CH_4 production and acid production are divided into two reactors to prevent pH inhibition (Grimberg et al. 2015). Various modifications were applied in a two-stage system to diminish digestion time (Fuess et al. 2017), reduce hydrogen sulfide and CO_2 content, increase methane content (Li et al. 2017), biohydrogen production, or sulfate removal (Yun et al. 2017). Further, a study on three stages of anaerobic digestion of FW with horse manure accelerated the solubilization of organic matters and volatile fatty acid formation with a 23% increase in methane yield (Zhang et al. 2017).

Food waste pre-treatment for AD aims to: (1) improve the lipids/protein digestibility in short retention time, (2) reduce the rapid acidification rate, (3) modifies the physicochemical characteristics of FW to eliminate process inhibition, while the strategy for dark fermentation aims to (1) solubilize complex carbohydrates and make easy access for hydrogen-producing bacteria (HPB), (2) inactivation of hydrogen consuming and non-hydrogen producing microbial communities, and (3) selective enrichment of HPB (Parthiba Karthikeyan et al. 2018).

1.5.2 Food Waste Processing for Platform Chemicals

Management of huge FW seems to be critical for many countries worldwide. It is estimated that supply chain waste alone contributes to 40 percent of waste in food processing (Dahiya et al. 2018). This problem is more aggravated in low-income countries where the infrastructure is not proper. Currently, anaerobic digestion of food wastes is practiced in many parts of the world. However, a high organic load with more fatty acid content reduces the methane yield. Hence more value-added chemical production through biorefinery (tabulated in Table 1.1) is an important option. The large volume and unstable nature of FW pose more risks in the valorization of FW. For instance, fruits and vegetable waste during processing constitute the largest part of the food waste they can be an excellent source for the production of pectin and phenols and gelling agents. Similarly, kefiran, an exopolysaccharide rich in glucose and galactose, can be produced from milk industry wastes. Proteins extracted out of meat and the meat processing industry have a high market value. Platform chemicals are the prime feedstock for the production of secondary chemicals, intermediates, and final products.

1.6 Agroindustry Waste Biorefineries

The agricultural strength in the country provides a huge amount of biomass which is used as feedstock in agro-industries. The diverse variety of lignocellulosic biomass available around the year provides an opportunity for multidrop biorefineries for different bioproducts production.

1.6.1 Problems with Agro-Residues

There are two types of agro-residues viz., crop residues and agro-industrial residues. Crop residues are non-edible parts of the plant collected in the field after the harvest of the main crop. Agro-industrial residues are engendered from different unit operations used in the post-harvest processes. For example, waste residues from wood and food processing industries (Mande et al. 2005). The comprehensive statistical data on the availability of agricultural residues is a must for developing

Table 1.1 Valorization of FW into various value-added products and platform chemicals

Products	Substrate	Pre-treatment/conversion process	Inoculum	Product yield	References
Biofuel	Instant noodle waste	Simultaneous saccharification and fermentation, and chemical trans-esterification	*Saccharomyces cerevisiae* K35	61.1 g/L	Yang et al. (2014)
	Waste cake	Grinding, hydrolysis and centrifugation	*Saccharomyces cerevisiae*	46.6 g/L	Han et al. (2019)
Hydrogen	Canteen waste	Solid-state fermentation (SSF) and dark fermentation (DF)	*Biohydrogenbacterium* R3	52.4 mL H_2/g	Han et al. (2015)
	Canteen waste	Potassium ferrate pretreatment + DF	Municipal solid waste	173.5 mL/g	Kuang et al. (2020)
Butanol	Pea pod waste	Saccharification with acid pre-treatment (1.3% H_2SO_4)	*Clostridium acetobutylicum* NRRL B-527	6 g/L	Nimbalkar et al. (2018)
	Orange peel waste	Steam explosion	*C. acetobutylicum* NCIM 2877	19.5 g/L	Joshi et al. (2015)
	Cassava waste residue	Acid hydrolysis	*C. bifermentans* PNAS- 1	3.36 g/L	Johnravindar et al. (2017)
Ethanol	Citrus peel waste	Simultaneous saccharification and fermentation	*Saccharomyces cerevisiae*	39.6 g/L	Wilkins et al. (2007)
Protease	Bread waste	Autoclaved	*Rhizopus oryzae*	2400 U/g	Benabda et al. (2019)
	Brewery waste	Centrifugation	*B.subtilis*	9.77 U/mL	Blanco et al. (2016)
α-Amylase	Potato peel		*Bacillus subtilis*	600 U/mL	Shukla and Kar (2006)
	Orange peel	Dried and pulverized	*B.amyloliquefaciens*	220 U/mL	Uygut and Tanyildizi (2018)
Bioplastics	Canteen waste		*Serratia ureilytica*	54 ± 3% dry cell weight	Reddy et al. (2015)
	Pineapple waste	Acid hydrolysis	*Ralstonia eutropha* ATCC-17679	88 mg L/L	Vega-Castro et al. (2016)
Lactic acid	Pineapple waste	Ground and filtered	*Lactobacillus delbreuckii*	0.82 gg^{-1} sugar	Idris and Suzana (2006)

	Apple pomace	Dried, milled and autoclaved	*L.rhamnosus*	0.88 gg^{-1} sugar	Gullón et al. (2007)
Citric acid	Pomegranate peel waste	Dried, pulverized followed by SSF	*Aspergillus niger*	278.5 g/kg dry peel	Roukas and Kotzekidou (2020)
	Banana peels	Untreated	*Enterococcus faecium*	15.9 L^{-1}	Abdel-Rahman et al. (2019)
Succinic acid	Fruit and vegetable waste	Hydrolysis by enzyme and SSF	*A. niger* and *Rhizopus oryzae*	27.03 g/L	Dessie et al. (2018)
	Wheat bran	SSF	*Actinobacillus succinogenes*	0.88 gg^{-1} sugar	Du et al. (2008)
	Bread waste	SSF		47.3 gL^{-1}	Leung et al. (2012)

any management strategy. In most of the cases, it is estimated as product yield of crops and residue to crop ratio. The agriculture sector generates billions of tons of non-edible residues every year. These residues create high environmental pollution, management, and economic problems due to improper handling and untapped potentials. Hence, the usage of agricultural residue as a source of high-value products is highly encouraged.

The lignocellulosic agro-industrial wastes are generated in tons every year by most of the developing and under-developing countries (Bhatia et al. 2012). However, various feedstocks with different characteristics pose challenges in collection, transportation, and handling. These wastes are usually burnt freely, which not only causes loss of agricultural biomass but also creates environmental pollution. The major environmental issues may occur due to the poor logistics and mismanagement of the wastes. Therefore, the same can be utilized to produce a variety of bioproducts through proper biomass conversion technologies (Ramesh et al. 2019b). Lignocellulosic agro-industrial wastes mainly comprise cellulose, hemicellulose, and lignin. The cellulose and hemicellulose can be easily converted into fermentable sugar and further fermented to produce bioethanol. The lignin acts as a physical barrier hindering the fermentation for bioethanol production (Ramesh et al. 2018).

1.6.2 Pretreatment of Agro-Residues for Biofuels

Pretreatment of lignocellulosic biomass involves the conversion of complex lignin structures into simple sugars to remove lignin, preserve hemicellulose and reduce the cellulose crystallinity. The pretreatment choice for the biomass depends on the composition and desired products as a result of pretreatment. There are various methods of pretreatment as shown in Fig. 1.5 and aim to attain the formation of sugars by hydrolysis, avoid the loss of fermentable sugars, control the excess inhibitory compounds production, reduce energy consumption, and minimize biofuel production cost.

1.6.3 Agroresidues- Sources, Availability, and Collection

Generally, the cultivation of crops yields not only farm produces but also agro residues or crop residues. There are two types of wastes generated: field and crop processing residues. The field residues mean wastes collected after the harvesting of crop/farm produce. Stem, stalks, leaves, trashes, and straws fall into this category. In crop processing residues, wastes are generated during the processing of farm produce to get the final product or value-added product. The quantities of these agro wastes vary from crop to crop and climatic conditions. These major compositions of these wastes are similar to other lignocellulosic feedstocks, such as cellulose, hemicellulose, and lignin. According to the National Policy for Management of

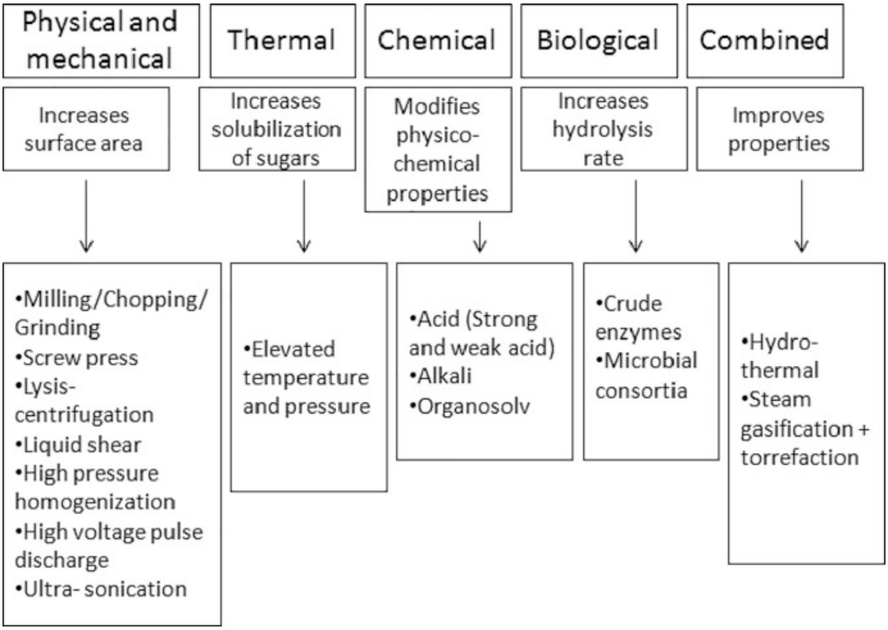

Fig. 1.5 Different types of pre-treatment methods for the production of bio-fuel

Crop Residues (NPMCR) report, the first three states contributing agro-residue generation are Uttar Pradesh (60 Mt) Punjab (51 Mt), and Maharashtra (46 Mt). Among them, 70% of residues were contributed by rice and wheat crops, and out of 500 Mt, 92 Mt of crop residues were burnt in a year (NPMCR n.d.). The collection of agricultural wastes depends on the type of residues generated. Earlier, the residues were collected manually, which is a labor-intensive process. Due to the low bulk density of agro wastes, transportation cost is higher, and sometimes its cost more than the price of residues. The wastes collected from the agricultural field could be achieved through different types of machinery. In the case of straw collection, the baling machines are used to make square or circular-shaped bales of straw. This step can reduce transportation charges due to the higher bulk density of balers. Size reduction types of machinery are commercially available for easy handling of agro residues. Shredder/chopper can be used to reduce the plant materials (e.g., oil palm fronds) into smaller sizes.

1.6.4 Biofuel from Agro-Residues

Agro residues are the most abundant renewable resources on earth. They consist of cellulose 50%, hemicellulose 30%, and lignin 20%. The carbohydrates in the biomass can be biochemically processed through pre-treatment, hydrolysis, and

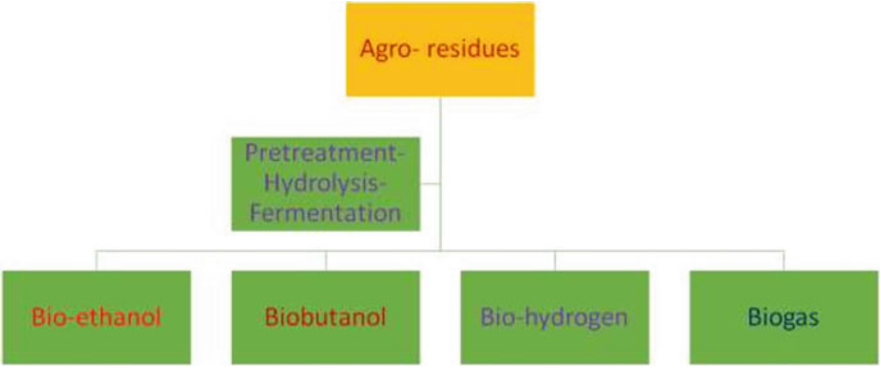

Fig. 1.6 Biofuels from agro-residues

fermentation, resulting in different types of fuels as depicted in Fig. 1.6 (Ramesh et al. 2019a).

1.6.5 Case Study with Paddy Straw

Paddy straw is one of the residues produced in rice cultivation. It can be used for several purposes ranging from animal feed to building blocks. Generally, 1 kg of paddy grain can produce 1.0–1.5 kg of straw (Maiorella 1985). Therefore, larger quantities of straw are generated. However, the length of the straw depends on harvesting methods. Abraham et al. (2016) proposed the paddy straw biorefinery concept based on the thermochemical and biochemical platforms. Thermochemical platforms use any one of the processes such as pyrolysis, hydrothermal liquefaction, gasification, and combustion to get the final product as bio-oil/syngas/ heat/electricity. They also suggested biochemical conversion pathways for biogas gasoline, aromatics, phenolic and liquid biofuels, 5- hydroxymethylfurfural (HMF), and other furfurals. The pretreatment is a pivotal production step for the biochemical conversion technology used for lignocellulosic biomass for biofuel production. It is obligatory to break the biomass structure to make cellulose more accessible to the enzymes, which helps the conversion of carbohydrate polymers to fermentable sugars. Sreekumar et al. (2020) studied straw biorefinery for bioethanol production and heat generation and calculated that production of 1 L of bioethanol requires 3.37 kg of rice straw-based overall mass balance approach.

1.6.6 Case Study with Sugarcane Trash

Sugarcane is one of the important cash crops produced globally. Harvesting of sugarcane leaves enormous quantities of residues in the field itself. For instance, a study conducted by TIFAC India in collaboration with CSIR-NIST states that sugarcane tops are the major residues generated in the county with an annual production of more than 100 MMT. Often, its potential is not realized and it is left in the field for low-value products of compost or many times burnt directly in situ causing serious environmental threats.

One case study was conducted in Brazil on sugarcane trash utilization for fuel and compost production. Dried sugarcane leaves had more nutrients than tops were found by simple enzymatic means. The high moisture content of 82.3% and heating value of cane trash, and heating value make trash an excellent source for biofuel production.

A case study was conducted in India to evaluate the alternative utilization of sugarcane trash. The results indicated that rash utilization reduced the ethanol break-even selling price (BESP). The scientists also studied the percent of retention in soil and their contribution to BESP. The results showed that 50% retention of trash could be beneficial as it doesn't linearly increase the ethanol ESP. More than 50% retention reduced the BESP of Ethanol. As the trash is added to the soil, it reduces the fertilizer requirement for the next crop and increases the crop yield. Reduction in GHG emission was also correlated and transportation due to GHG was calculated. It was revealed that fertilizer saving has more GHG reduction than transportation. However, the study did not include the benefits of the environment, irrigation saving Life cycle analysis. Overall trash utilization can have a beneficial effect on ethanol price and increase soil fertility was reported (Vikash et al. 2018).

1.6.7 Agro-Industry Waste and Sustainable Rural Development

The biorefinery mode operates for converting agro-wastes into a spectrum range of products such as biofuels, biohydrogen, biochemicals, etc., through a cascade of advanced approaches such as pyrolysis, gasification, and other catalytic processes. Such development helps in stabilizing the economy of rural areas by conferring clean energy by the replacement of fossil fuels. Due to the lack of awareness and knowledge on the management of surplus agro-residues, these wastes are frequently ruined on a mass scale for waste management instead of being used in other productive ways (Hiloidhari et al. 2020) Many of the rural areas are equipped with biogas (methane gas) with agro-industrial waste as substrate via anaerobic digestion for various purposes like water heating, broiler operation, drying of grains, etc. (Obi et al. 2016). Methane production via anaerobic digestion makes disposal and treatment of a huge quantity of agro-industrial wastes easier and also reduces the foul smell problem.

Agro-industrial wastes are nutritionally rich in composition and comprise many of the bioactive compounds, which can be utilized as raw material for the production of value-added products viz., biogas, mushroom, biofuel, etc. Many of the valuable products are generated through solid-state fermentation with the help of suitable microbial growth on agricultural residue (Sadh et al. 2018). Gowda and Manvi (2019) utilized agro-residues as a substrate in mushroom cultivation and are also developed simple and low-cost pasteurization equipment for small-scale rural mushroom growers. Vazquez-Olivo et al. (2019) converted lignocellulosic agro-industrial waste to value-added products such as bioactive molecules, phenolic compounds, antioxidants, etc. with a zero-waste process (Um et al. 2017). Hence, the agro-based biorefinery approach will not only produce value-added products but also help in the sustainable development of rural India efficiently.

1.7 Cost Economics of Waste Biorefineries

Cost economics is a must to evaluate the sustainability and financial feasibility of any industry. As the global population swells every year, the rate of increase in waste generation poses major environmental threats and resource crunch. If there are proper directives for waste management, wealth can be generated through recycling or converting them into value-embedded products. The biological source of wastes accumulated in low-income economies is about 50% higher than that in well-developed economies. Hence, for the economic development of emerging economies, waste-based biorefineries are very crucial. Solid waste biorefineries, if properly integrated, would result in generating new entrepreneurs, creation of job opportunities, reduced cost in waste management, waste to value-added products, and lower emissions. Besides capital intensive, most of these biorefinery technologies are energy-centric; hence, there may be scope for emission acting as a negative externality.

1.7.1 Cost of Biomass

Considering the agricultural sector, waste generated from energy crops depends upon the land extent under each crop, its yield potential, production cost, logistics, handling, and proximity to the nearest biorefinery. Mostly, the sources of biomass can be broadly classified into three categories: They are crop residues, energy crops, wastes of industrial origin. Energy crops are those dedicated crops serving as stock materials for biorefineries. The resultant products are the first-generation (1G) biofuels. Corn, soybean, cassava, sweet potato, sugarcane, barley and palm oil are the energy crops used for these purposes around the globe. The demand and supply for these crops are dwindling, according to the market and nonmarket factors.

Crop residues are the organic wastes generated as byproducts obtained during post-harvest processing of field crops which are again classified into primary and secondary residues. The primary residues are the ones obtained on the production site which have alternate applications and the secondary residues are mainly the byproducts obtained while processing. Secondary residues are much cheaper to serve as feedstock in waste biorefineries as they find no alternative applications. Developing economies generate vast industrial wastes. Huge amounts of wastewater from households and industries, wastes from processing industries, animal wastes can be a source of feedstock in the biorefineries.

1.7.2 Cost of Logistics

The commercial viability of waste biorefineries is much dependent upon the location of the site from the biorefineries, harvesting and collection of biomass, transportation mode, time duration of transportation, and processing of biomass. The bulkiness of low energy content of biomass creates logistics much difficult. Cost economics of waste logistics is much dependent on distance, time of travel, the density of biomass, etc. Travel time influences the cost involved in hiring manpower and wear/tear of the vehicles. Biomass density is another prime concern as the requirement of low-density biomass but its huge volume, in turn, falls heavy on the cost of logistics. Figure 1.7 depicts several costs incurred while processing the waste biorefineries.

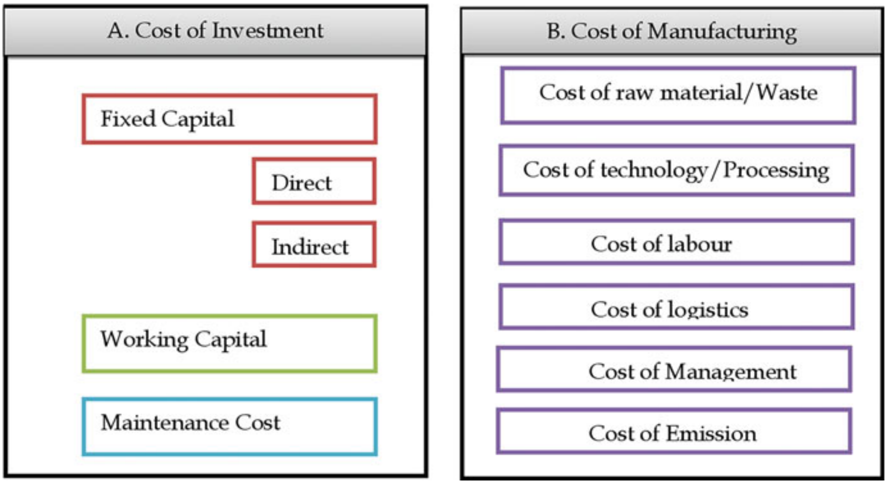

Fig. 1.7 Various costs incurred upon waste biorefinery processing

1.7.3 Economic Assessment of Waste Biorefineries

The economic assessment is an important criterion for evaluating the quality of the waste biorefineries. The required parameters for the economic evaluation of any waste biorefineries on cost streams are investment cost, maintenance cost, interest, taxes, insurance, material cost, logistics, labor cost, management cost, emission cost, etc. and on the revenue side, the quantum and sale of energy products from waste biorefineries. Markets for bio-based products are characterized by high-value innovative chemicals and materials with high energy security with low processing costs and also with a minimal environmental cost. The commercial viability is much dependent on technical, commercial, and sustainable issues.

The estimation of food waste generation at the manufacturing stage for various products through biorefineries and a techno-economic and profitability analysis of routes for their valorization indicated that the markets for the energy products, processing, logistics, and the prices of competing fossil fuel-based products are the key determinants for the commercial viability of the waste biorefineries (Cristóbal et al. 2018). The technical, economic, and environmental assessment case studies conducted by the International Energy Agency (2019) revealed that all the case studies of sugars to lignin, biogas, lipids, and pulp to lignin depicted the potential environmental benefits accrued from developing biobased products through biorefinery processes.

Commercialization, creation of markets, and the economic feasibility of these biobased products are still under investigation as the lower cost of competing for fossil counterparts in the energy markets. The commercial feasibility and the economic viability of lactic acid with biogas through an integrated biorefinery process are more efficient than as a single process. The integrated biorefinery resulted in a minimal amount of waste generated and increased value-added products (Demichelis et al. 2018). The cost of biomass is determined by the selling price, raw material cost, cost of storage, and logistics and transportation cost and confined to place and time (Thorsell et al. 2004).

1.8 Energy Footprint and Life Cycle Assessment of Waste Biorefineries

The economic, as well as the environmental benefits of using agro/industrial wastes, would be further enhanced by the joint production of chemicals and energy products. To convert wastes into wealth, the following are the necessary conditions.

- The product mix should have the highest economic value;
- It should yield the highest benefit; and
- The feedstock requirements should not be bulky to handle.

Generally, the Life Cycle Assessment (LCA) is meant to analyze the resource use pattern and the environmental impacts of the process involved in a production cycle to obtain the final products from raw materials. To estimate the associated energy footprints, carbon dioxide emissions from various feedstock sources are in corporate in the LCA framework. Then, the emissions from various components are added up to decide the aggregated to decide the footprint of the entire system. Direct and indirect emissions are reported separately to improve the system boundaries in terms of energy use and education in emission rate.

1.8.1 Key Issues in Life-Cycle Assessment of Waste Biorefineries

Increased energy consumption owing to rapid urbanization resulted in more GHG emissions leading to unpredictable climate change. Urbanization triggers the enhanced energy consumption and accumulation of more solid and liquid wastes. The amount of waste generated is alarmingly increasing affecting the ecosystem. Hence, it is necessary to identify efficient strategies to reduce ever-increasing environmental hazards. Waste biorefineries have created aspirations aimed toward integrating various conversion technologies for waste management to generate an array of energy products resulting in circular and low-carbon bioeconomy.

1.8.2 Case Studies in Life-Cycle Assessment of Waste Biorefineries

Increased energy consumption owing to rapid urbanization resulted in more greenhouse gas (GHG) emissions and climate change. Urbanization is one of the chief criteria leading to enlarged energy consumption and the accumulation of more solid and liquid wastes. The amount of waste generated is alarmingly increasing at a faster rate affecting the ecosystem. Hence, efficient sustainable waste management strategies are the need of an hour to reduce ever-growing environmental hazards.

The life cycle assessment for the calculation of the greenhouse gas emissions in the organic livestock production systems of Spain has concluded that organic livestock farming is a feasible strategy for reducing GHGs (Horrillo et al. 2021). The results of the ecosystem model for agricultural carbon footprint used for the US Western Corn Belt region showed an enlarging negative carbon footprint due to crop land expansion and associated carbon cost of grain production (Lu et al. 2018). Wang et al. (2015) studied the excessive use of nitrogen fertilizer and its impact on agriculture, and they found that several parameters such as grain yield, input energy, greenhouse gas emission, and carbon footprint were increased with an increase in nitrogen rate.

The GHG emissions of crop production from a life-cycle assessment perception concluded that intensive crop production aiming at economic optimum nitrogen supply helped to mitigate GHG emissions (Torres-Dorante et al. 2009).

1.9 Conclusion and Future Perspectives

With the current availability of 500 million metric tonnes of biomass, India has a potential of about 18 GW of energy from biomass and constitutes 32% of the total primary energy used. Higher than 70% of the country's population relies on biomass for energy needs. The estimated surplus biomass availability per year in India is about 120–150 million metric tonnes of agricultural and forestry residues (equivalent to 18,000 MW). Backward and forward integration at different levels should be considered to advance the overall efficiency of multi-product integrated portfolios. The economic and environmental performance of the biorefinery systems stands at the fore of the evaluation.

Overall, the efficient biorefinery system could provide energy generation, land saving, new business with employment generation, landfills cost savings, reduction of GHG emission, and savings of natural resources. Waste biorefineries are not only the way forward to sustainability but also generate crucial environmental benefits.

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