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Zero Waste Biorefinery

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Preface

Energy demand has been rising remarkably due to the increasing population and urbanization. The global economy and society significantly depend on energy availability because it touches every facet of human life and activities. Transportation and power generation are the two major examples. Without millions of personalized and mass transport vehicles and the availability of 24×7 power, human civilization would not have reached contemporary living standards.

The International Society for Energy, Environment and Sustainability (ISEES) was founded at the Indian Institute of Technology Kanpur (IIT Kanpur), India, in January 2014 to spread knowledge/awareness and catalyze research activities in the fields of energy, environment, sustainability, and combustion. Society's goal is to contribute to the development of clean, affordable, and secure energy resources and a sustainable environment for society and spread knowledge in the areas mentioned above and create awareness about the environmental challenges the world is facing today. The unique way adopted by ISEES was to break the conventional silos of specializations (engineering, science, environment, agriculture, biotechnology, materials, fuels, etc.) to tackle the problems related to energy, environment, and sustainability in a holistic manner. This is quite evident by the participation of experts from all fields to resolve these issues. ISEES is involved in various activities such as conducting workshops, seminars, conferences in the domains of its interests. Society also recognizes the outstanding works of young scientists, professionals, and engineers for their contributions in these fields by conferring them awards under various categories.

The Fifth International Conference on 'Sustainable Energy and Environmental Challenges' (V-SEEC) was organized under the auspices of ISEES from December 19 to 21, 2020, in virtual mode due to restrictions on travel because of the ongoing COVID-19 pandemic situation. This conference provided a platform for discussions between eminent scientists and engineers from various countries, including India, Spain, Austria, Bangladesh, Mexico, USA, Malaysia, China, UK, Netherlands, Germany, Israel, and Saudi Arabia. At this conference, the eminent international speakers presented their views on energy, combustion, emissions, and alternative energy resources for sustainable development and a cleaner environment. The conference presented two high-voltage plenary talks by Dr. VK Saraswat, Honorable Member, NITI Ayog, on 'Technologies for Energy Security and Sustainability' and Prof. Sandeep Verma, Secretary, SERB, on 'New and Equitable R&D Funding Opportunities at SERB.'

The conference included nine technical sessions on topics related to energy and environmental sustainability. Each session had 6–7 eminent scientists from all over the world, who shared their opinion and discussed the trends for the future. The technical sessions in the conference included emerging contaminants: monitoring and degradation challenges; advanced engine technologies and alternative transportation fuels; future fuels for sustainable transport; sustainable bioprocessing for biofuel/non-biofuel production by carbon emission reduction; future of solar energy; desalination and wastewater treatment by membrane technology; biotechnology in sustainable development; emerging solutions for environmental applications' and challenges and opportunities for electric vehicle adoption. Five hundred plus participants and speakers from all over the world attended this three days conference.

The conference concluded with a high-voltage panel discussion on 'Challenges and Opportunities for Electric Vehicle Adoption,' where the panelists were Prof. Gautam Kalghatgi (University of Oxford), Prof. Ashok Jhunjhunwala (IIT Madras), Dr. Kelly Senecal (Convergent Science), Dr. Amir Abdul Manan (Saudi Aramco), and Dr. Sayan Biswas (University of Minnesota, USA). Prof. Avinash K Agarwal, ISEES, moderated the panel discussion. This conference laid out the roadmap for technology development, opportunities, and challenges in energy, environment, and sustainability domain. All these topics are very relevant for the country and the world in the present context. We acknowledge the support received from various agencies and organizations for the successful conduct of the fifth ISEES conference V-SEEC, where these books germinated. We want to acknowledge SERB (special thanks to Dr. Sandeep Verma, Secretary) and our publishing partner Springer (special thanks to Ms. Swati Meherishi).

The editors would like to express their sincere gratitude to a large number of authors from all over the world for submitting their high-quality work on time and revising it appropriately at short notice. We would like to express our special gratitude to our prolific set of reviewers, Dr. Sakar Mohan, Dr. G. N. Nikhil, Dr. Anjireddy, Dr. Omprakash Sarkar, Dr. Sumer Singh Meena, Dr. Kashyap Dubey, Dr. Abhishek Chandra, Prof. A. K. Jain, Dr. Krishna Kadirvelu, Dr. M. D. warakanath, Dr. D. Prabha, Dr. Sri Shalini, Dr. R. Selvakumar, Dr. Godvin Sharmila, Dr. R. Yukesh Kannah, Dr. M. Dinesh Kumar, Dr. P. Balasubramanian, Dr. Dhanya M. S., Dr. Khetan Shevkani, Dr. S. Shantha Kumar, Dr. P. Senthil Kumar, Dr. Rajeev Pratap Singh, Dr. C. Sivaraman, Dr. V. Preethi, Dr. Divya Subhash, Dr. Ritu Singh, Dr. Rashmi Kataria, Dr. K. Sivagami, Dr. R. Arthur James, Dr. S. Sudalai, Dr. Mukesh Awasthi, Dr. Sushma Yadav, Dr. Lakhvinder Singh, Dr. Neelam Yadav, Dr. Sartaj Bhat, Dr. Hardeep Rai Sharma, Dr. V. V. Tyagi, Dr. S. Adish Kumar, Dr. Manpreet Singh Bhatti, Dr. Divya Nair, Dr. Anoop Yadav, Dr. Kiran Bala, Dr. Anju Malik, Dr. Somvir Bajar, Dr. Minakshi Suhag, Dr. Naresh Rawat, Dr. Navish Kataria, Dr. Anita Singh Kirrolia, Dr. Mona Sharma, Dr. Asheesh Kumar Yadav, Dr. Poonam Yadav, Dr. Richa Kothari, Dr. Kashif Kidwai, Dr. Kavita Sharma, Dr. K. V. Yatish,

Dr. G. Velvizhi, Dr. Simranjeet Singh, Dr. Kulvinder Bajwa, Dr. Renu Singh, Dr. Atin Kumar, Dr. Arti Devi, and Dr. Harmohan Singh who reviewed various chapters of this monograph and provided their valuable suggestions to improve the manuscripts.

This book is a compilation of process, technologies, and value-added products such as high-value biochemicals and biofuels produced from different waste biorefineries. The book is sectioned into four categories where few chapters in Part I provide a comprehensive outlook about zero-waste biorefinery and technologies associated with it. The emerging technologies that potentially put back the lignocellulosic waste, municipal solid waste, and food waste into intrinsic recycling for production of high-value biochemicals and bioenergy, along with associated challenges and opportunities, are compiled up in Parts II and IV. Algal biorefineries leading to sustainable circular economy through production of broad spectrum of bioactive compounds, bioethanol, biobutanol, biohydrogen, biodiesel through integrated biorefinery approach are discussed in Part III. The book includes few chapters on conversion technologies and mathematical models applied for process optimization. Chapters include recent results and are focused on current trends of waste biorefineries. In this book, readers will get a sound foundation about the underlying principles of biorefineries and a up-to-date state-of-the-art-based overview on the latest advances in terms of scientific knowledge, techno-economic developments, and life cycle assessment methodologies of integrated waste biorefinery. The book is envisioned for a broader audience, and the editors hope that the book would greatly interest the professionals, postgraduate students, and policy makers involved in waste management, biorefineries, circular economy, and sustainable development.

Bathinda, India — Yogalakshmi Kadapakkam Nandabalan
Bathinda, India — Vinod Kumar Garg
Nagpur, India — Nitin K. Labhsetwar
Samba, India — Anita Singh

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Dr. Yogalakshmi Kadapakkam Nandabalan is currently working at Central University of Punjab, as Associate Professor in the Department of Environmental Science and Technology. She holds a Master's and Ph.D. degree in Environmental Science from Anna University, Chennai, India. She has about 12 years of teaching and research experience. Her areas of research interest include water and wastewater management, energy generation from waste and wastewater, solid waste management, and nanobioremediation. She has authored around 15 book chapters and 40 research and review articles in peer-reviewed, high-impact factor journals. She has developed a number of e-content modules. She has completed three sponsored research projects funded by various agencies as Principal Investigator. She is a member of several professional and scientific bodies.

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Dr. Nitin K. Labhsetwar is a Ph.D. with over 34 years of research experience in environmental and energy-related research. He has been actively working on cleaner energy generation including photocatalytic hydrogen generation, bioenergy, carbon capture, chemical looping combustion, CO_2 reforming, automobile emission control and rural energy (development and deployment of improved biomass cook stoves), etc. He has worked as STA/JSPS Fellow and Visiting Overseas Researcher at NIMS, Tsukuba, Japan, and as Visiting Professor at Kyushu University, Japan, under the Global COE Program on Novel Carbon Resource Sciences. He has over 170 research publications with over 6800 citations and 22 international patents and 8 design registrations in addition to a few contributions in books. He has so far contributed to more than 75 R&D projects.

Dr. Anita Singh is working as Assistant Professor, Department of Environmental Sciences, Central University of Jammu, India. She has over 8 years of teaching and research experience. Dr. Singh pursued her Ph.D. on bioethanol production from lignocellulosic biomass from Guru Jambheshwar University of Science & Technology, India. Her post-doctoral research was at the University of Georgia, USA, on selective removal of inhibitors from lignocellulosic biomass. She has published 40 research papers in international and national journals and 6 book chapters in various edited books. She has guided 33 master's dissertation and is currently supervising 4 Ph.D. students. She was awarded CSIR-SRF and CSIR-RA fellowships for research during Ph.D. and UGC Raman Post-doctoral Fellowship for doing research in the USA. She is working in the field of biofuel production and value-added product production from lignocellulosic biomass.

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Part I
General

Chapter 1
Zero Waste Biorefinery: A Comprehensive Outlook

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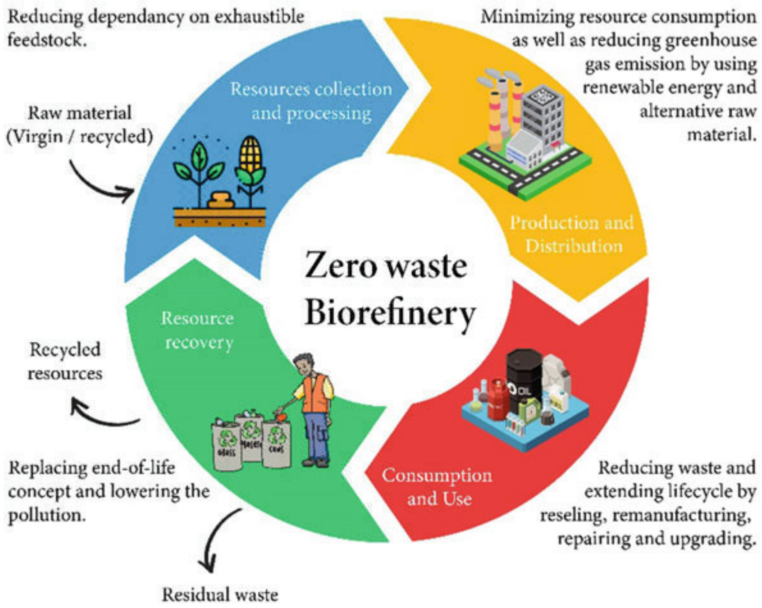
GRAPHICAL ABSTRACT



1.1 Introduction

The contemporary world is undergoing prodigious expansion in human population. On an average 81 million people are added annually to the existing 7.9 billion people (Worldometers.info 2021). In such circumstances, the availability of resources such as water, food, energy, forest, and biodiversity that are necessary for human survival has become scarce in addition to exacerbation in energy demands, pollution, waste generation, and climate change leading to an unsustainable habitat (Pimentel and Pimentel 2003). To cope with this ever-increasing trend in population and limited supply of resources, countries across the world have proclaimed their focus on strengthening sustainable and carbon-free alternatives to the conventional production mechanisms. One such substitute is "Biorefineries" which are infrastructural establishments that aim to convert biomass into numerous commercial commodities or energy in a sustainable manner (Kamm and Kamm 2004; Fernando et al. 2006; Cherubini 2010; Jong and Jungmeier 2015; Mohan et al. 2016). Biorefinery is not a modern concept; biomass has been exploited in the pulp and paper industry, fuel industry, and food industry for a considerable time. Biomass includes all sorts of organic materials from renewable sources. However, the efficacy and on-field existence vary significantly for different classes of biorefineries (as listed in Table 1.1). Towards future biorefineries, the scientific community seeks alternate substrates with

Table 1.1 Types of biorefineries based on the type of feedstock and their significance

Substrate	Type of biorefineries	Products	Significance
Sugar/Starch crops	One-platform (C6 sugar) biorefinery	Bioethanol Animal feed	+ The primitive attempt replaces non-renewable resources − Compete with food and feed supply
Oil crops	One-platform (oil) biorefinery	Biodiesel Animal feed Glycerin	
Lignocellulosic biomass	One-platform (syngas) biorefinery	Biofuels Chemicals (alcohols)	+ Lignocellulosic biomass is the most abundant available substrate in the environment with no competition for food and feed production + Wide range of established pre-treatment methods – Complex structure/chemical composition
	Four-platform (lignin/syngas, C5/C6 sugar) biorefinery	Biofuels Animal feed Bioethanol	
Grasses/Algae	Green Biorefinery	Biomethane Chemical building blocks (lactic acid and amino acids) Biomaterials Fertilizer	+ Grasses/algal biomass is the second most abundant available substrate that naturally occur in environment + Reduction in greenhouse gas emissions − Difficult to maintain cultivation requirements

cleaner conversion techniques to transform biomass into a range of value-added products. Building such an eco-efficient technology will not only pave way for a sustainable living but also a way out for current concerns such as waste management, and increasing greenhouse gas emissions (Angouria-Tsorochidou et al. 2021).

The concept of the biorefinery is analogous to traditional oil refineries except for the fact petroleum-based refineries make use of non-renewable (fossil fuels) feedstocks which liberate greenhouse gases imposing detrimental impacts on the environment. On contrary, an enormous variety of biomass (such as edible crops, algae, and residues from industries) is available that can be transformed using physical, chemical, or biological processes for generating a wide range of products or energy to suffice the demands of mankind (Uellendahl and Ahring 2010; Kumar et al. 2013; Hernández et al. 2014; Salvachúa et al. 2016; Gnansounou and Pandey 2017; Ichikawa et al. 2017; Hingsamer et al. 2019; Bittencourt et al. 2019; Monte et al. 2020). Besides environmental and economic benefits of organic energy sources, food security menace and recurring shortfall of input resources limit the implementation of the biorefineries in reality (Espinoza Pérez et al. 2017; Gírio et al. 2017; Byun

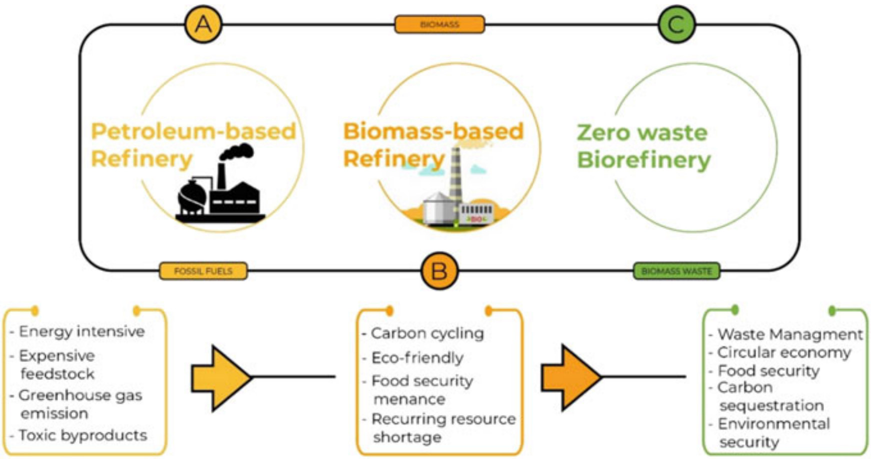


Fig. 1.1 Transition from petroleum biorefineries to zero waste biorefineries

and Han 2020). In this regard, residues from industries/biorefineries are often overlooked but they are the quintessential alternative to the aforementioned biorefineries. Wastes in solid, liquid, or gaseous form have net positive energy incorporated, which holds propitious capabilities to be transformed into bioproducts and biofuels (Oliveira and Navia 2017; Zheng et al. 2020; Venslauskas et al. 2021). The waste utilization approach attributes to repeated use of the substrates which further brings down the limitation of finite resources and emphasizes zero waste generation. Moreover, the concept adds auxiliary value along with improved resources utilization efficiency (Byun and Han 2020). These zero waste bio-based refineries open the door for the paradigm shift from linear mass production involving extraction, manufacturing, utilization, disposal to a closed-loop system and thus evolving to a sustainable bioeconomy as illustrated in Fig. 1.1 (Nizami et al. 2017; Venkata Mohan et al. 2019; Ubando et al. 2020). The rational idea behind sustainable biorefineries solely depend on reusing and recycling the residues, which require a thorough understanding of gaps in technical and biological proceedings. On that account, the present chapter focuses on providing a comprehensive overview of carbon-neutral biorefinery systems using feedstocks such as lignocellulose, algae (micro-, and macro-algae), residue (solid waste, paper, food, manure), and improvised treatment processes.

1.2 The Zero-Waste Biorefinery Concept

Biorefineries are the consolidated system of physical, chemical, and biological processes in well-defined order which can convert biomass or residues to marketable services viz., chemicals, feed, fuels, energy, etc. Biomass is regarded as a renewable source of energy that can effectively contribute to global energy demand through fuels and economic prosperity by producing high-value products (Zetterholm et al. 2020). Analogous to petroleum refineries, biomass-based refineries also account for certain downsides. The major pitfall are limited space and added waste generation. To overpower these foregoing issues, residues or wastes from biorefineries unfold the possibility to reuse and recycle using effectual mechanisms which can be termed as zero waste biorefineries (Brunklaus et al. 2018). Zero waste biorefineries are expected to develop an effective circular bioeconomy by directly benefitting society and the economy (Venkata Mohan et al. 2019; Ubando et al. 2020). Figure 1.2 illustrates how biological-based products revolve in a closed and re-circulating loop system. According to Ellen MacArthur Foundation (2013), a compact circle establishes maximum savings on raw material, capital, and energy (Ellen MacArthur Foundation 2013). The circular model of consumption and production epitomizes multiple re-use of initial feedstock material across the loop, and diminishing the need for fresh feedstock. Aside from economic benefits, the zero-waste biorefinery can also strengthen climate change control by utilizing carbon dioxide into efficacious bio-feedstock.

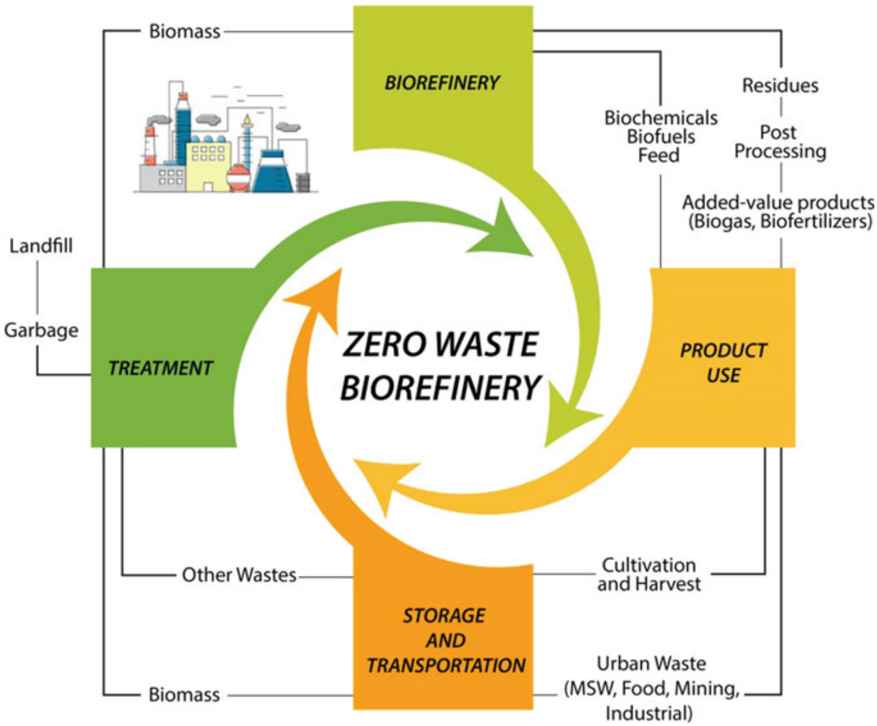


Fig. 1.2 Zero-waste biorefinery—Circular and carbon-neutral system of production and consumption

Bioeconomy and circular bioeconomy are often interchangeably used; however, the two terms differ slightly in their principles. The term bioeconomy was originally defined in 1998 with a target of developing bio-commodities using renewable sources of input and replacing oil-based commodities (Enriquez 1998). The published literature so far promises to curb climate change effects by providing renewable biomass together with generating opportunities and employment (Ubando et al. 2020). Whereas circular bioeconomy endorses circular economy framework, wherein bio-based products are generated using a variety of biomass. The circular loop ensures economic viability, waste reduction, and sustainability (Carus and Dammer 2018).

1.2.1 Lignocellulosic Biorefinery

Lignocellulosic biomass attribute to the plant dry mass which consists of cellulose (35–48%), hemicellulose (22–30%), and lignin (15–27%) (Yousuf et al. 2020). This is the most abundant and cost-effective raw material present, which includes agricultural and forestry residues. For a long time, lignocellulosic biomass has been transformed into marketable commodities via physical, chemical, and biological processes. However, the prime focus has been extracting and exploiting polysaccharides to manufacture alcohol, methane, phenolic compounds, furans, etc., and on the other hand, lignin is either transformed into low-quality aromatic products or burnt to generate heat. On account of ineffective handling of the lignin component limit the functioning of biorefineries. Nonetheless, several studies affirm that lignin with little or no degradation can yield high-value chemicals and fuels. The development of eco-friendly and milder procedures for structural degradation of lignin into beneficial products is the need of the hour. Garlapati et al. (2020) scrutinized biological and chemo-catalytic processes for the effective valorization of the lignin component. It was concluded that bioconversion of lignin using peroxidases, laccases, and other auxiliary enzymes gained a victory over chemical processes. Keeping in mind the concept of "Zero waste biorefinery" in lignocellulose biomass-based refinery, the scientific community explored limited bottlenecks (as depicted in Fig. 1.3). Qiu et al. (2021) peeked into alternatives of traditional oil plants, such that the efficacy of production-consumption can be elevated. The study found *Litsea cubeba* as an ideal substitute as it holds the potential to produce oil in addition to value-added products. Citral, being the dominant component, the applicability of *Litsea cubeba* can be extended to the perfume industry, pharmaceutical industry (anti-oxidants, antimicrobial, inflammatory), and food industry (food flavoring). Another innovative approach explored the efficacy of adsorbents fabricated from renewable polysaccharides residues (Zuin et al. 2017). Mesoporous carbonaceous sorbents formulated using starch (Starbon), alginic acid (Algibon), and pectin (Pecbon) were manifested as suitable substrates due to their functional and structural flexibility. Among three sorbents, starbon overpowered the other two as its fabrication required limited steps and had an improved environmental footprint.

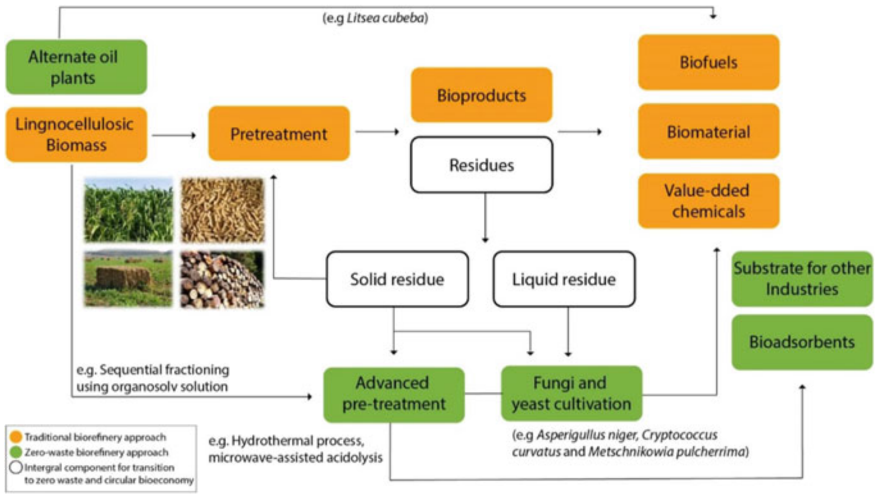


Fig. 1.3 Zero-waste biorefinery processes for lignocellulosic biomass

Another major bottleneck in lignocellulose biorefinery is the selection of a meticulous pretreatment method (Liguori and Faraco 2016; Arevalo-Gallegos et al. 2017; Galbe and Wallberg 2019). An effective treatment technology is crucial for lowering down the production cost involved and making the process more sustainable. Recently, a study conducted by Squinca et al. (2018) opened the doors for utilizing liquefied materials in cultivations of *Aspergillus niger* using enzymatic pretreatment. The findings of the study concluded that using the above-mentioned combination can cut down the cost of enzyme production and attain a closed-loop within the biorefinery. Following the same trend, waste pomegranate peels were digested via the hydrothermal procedure and the residue was further treated with enzymes aiming to increase the overall efficiency of the system (Talekar et al. 2018). During the initial phase of the setup, a substantial yield was achieved with 18.8–20.9% of food-grade quality pectin and 10.6–11.8% of phenolic compounds. The residual biomass was subjected to enzymes which in turn generated 95% of glucose. A primitive study focusing on unconventional pre-treatment technology was conducted by Abdelaziz et al. in 2015 where an organosolv aqueous solution was investigated for sequential fractioning of the forest residues (Abdelaziz et al. 2015). The organosolv consists of 2-methyltetrahydrofuran and oxalic acid as organic solvent and catalysts respectively. At the end of the experiment, the researchers successfully fractionalized the components in their compact form. A new method of pretreatment i.e., rapid microwave-assisted acidolysis was scrutinized and further residual biomass was investigated for potential as yeast substrate (Zhou et al. 2017). Three types of lignocellulosic biomass were considered including herbaceous, hard, and softwood, out of which softwood on treatment liberated lignin component with 93% purity. Furthermore, two yeast strains (*Cryptococcus curvatus* and *Metschnikowia pulcherrima*) were able to proliferate on the residual biomass from the first proceeding. In recent years, it is observed that the association of two or more treatments methods has been a preferred choice to integrate into the circular economy. Dávila et al. (2017, 2019) proposed a combination of hydrothermal treatment followed by delignification and enzymatic saccharification to segment different components of vine shoots as the lignocellulosic biomass. Under optimized conditions, the study was successful in extracting 82 wt. % of lignin along with deceased cellulose degradation (35 wt %) (Dávila et al. 2017, 2019). Another progressive study made effort to omit sulfur from the traditional fractioning methods by using steam explosion and hydrotropic extraction (Olsson et al. 2019). Hardwood was first subjected to steam pre-treatment where hemicellulose was solubilized and subsequently, the biomass was subjected to hydrotropic extraction to extract lignin, leaving behind a solid mass rich in cellulose.

1.2.2 *Algal Biorefinery*

Algae are unicellular aquatic photosynthetic organisms that lack root, shoot and stem characteristics. Based on morphology, algal species can be macroalgae (rich in carbohydrates) and microalgae (rich in lipid content). Owing to the macromolecule abundance and relatively cheaper cost to edible crops, algae became an emerging feedstock for biorefineries. However, the conventional biorefineries were pronounced to manufacture one class of commodities, but with progression in technology, a wide range of high-value products are developed (Rajak et al. 2020). Incorporating the concept of zero waste biorefinery, algal residues (solid or liquid) serve as a prime asset as illustrated in Fig. 1.4 (Mitra and Mishra 2019). Solid residual mass can be utilized as a feedstock to other industries or as a sustainable adsorbent to remediate a polluted

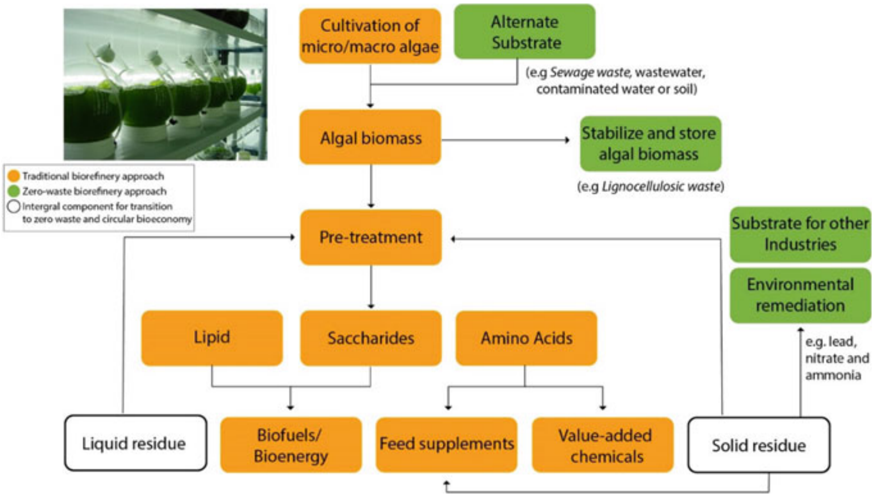


Fig. 1.4 Zero-waste biorefinery processes for algal biomass

environment. Additionally, biomolecules and nutrients present in the residues can be reused or recycled to generate biofuels and valuable co-products (Gifuni et al. 2019). In 2016, Tedesco and Stokes evaluated the biogas production of six indigenous algal-treated biomass for the production of biogas. And it was observed that *Laminaria* and *Fucus* spp can produce 187–195 mL CH_4 gVS^{-1} and 100 mL CH_4 gVS^{-1}, respectively (Tedesco and Stokes 2016). Recently, a study proposed a mechanism using *Fucus spiralis* as a feedstock in the circular bioeconomy. Algal biomass was put to use for the generation of economically benefiting services and the leftover residue was utilized to remediate lead (Pb(II)) contaminated environment (Filote et al. 2019). For a long time, algae have been used to produce marketable commodities, therefore the focus of the study was to evaluate the efficiency of contaminant removal and further using the biomass as biochar, thus fulfilling the "zero waste biorefinery" concept. The optimistic results of the studies expand our horizon for biofuel and biochar co-production in an environment-friendly manner (Filote et al. 2019; Bhowmick et al. 2019). Also, encourage industries to opt for green resources to make the transition from the traditional linear economy. Wuang et al. (2016) exploited the remediation capability of S*pirulina platensis* as a feedstock in aquaculture and further facilitated the residue as fertilizers for leafy vegetables. The study depicted optimistic results, indicating the high removal capacities of ammonia and nitrate in water from aquaculture. Moreover, the residual biomass also enhanced the growth of vegetables, in comparison to the controls.

A prominent economic barrier in algal biorefinery is the seasonal variation in the production of biomass. Wendt et al. (2017), Jarvis et al. (2018), and Wahlen et al. (2020) collectively, explored the methods to stabilize and store algal biomass for off-season requirements. The primary study conducted by Wendt et al. (2017) and Wahlen et al. (2020) blended corn stover and yard waste respectively with algal strains. The results showed effective preservation of the blended biomass for upto 30 days. Also, the organic acid produced during the storage remarkably increased its proportion in the biomass that can be extracted later. Jarvis et al. (2018) established a synergistic effect of blended biomass of algae and lignocellulose. Usually, certain oils are used as a buffer to stabilize the blend, however in this case organic acids from algae substituted the need for an external buffer source. The results depicted an increased yield of biocrude that can further be processed for value-added products.

For sustainable production using algal biomass as feedstock, the primary focus depends on cultivation and harvesting techniques. In this regard, a couple of researchers have made an effort to use inexpensive substrates for the growth of algae and subsequently producing high- value products. A study in 2019 evaluated the algal residue for the absorption of contaminants in the environment (Sadhukhan et al. 2019). The experiment was designed in a way, where the growth of algae was carried out using the contaminated water/soil inputs which could effectively remove toxic components via phytoremediation, and then algal biomass can be utilized further for the generation of energy, chemicals, and other beneficial products. Another study investigated sewage waste as its growth medium for algae to substitute freshwater dependency. The results affirmed positive outcomes to generate high-value services which further make biorefinery more cost-effective and self-sustainable (Wuang et al. 2016; Mishra and Mohanty 2019). To reduce the cultivation cost, Sachdeva et al. (2018) estimated nitrite as an alternative to nitrate in the culture medium of A*rthrospira* sp in photosynthetic biorefineries using wastewater as input material. The algal strain could assimilate up to 120 mM nitrate in the form of urea in the biorefinery without any ill effects on the products. Moreover, utilizing wastewater can effectively sequester carbon dioxide along with cost reduction by 35–86%. In terms of the economic prosperity of utilizing inexpensive feedstock, Judd et al. (2017) evaluated the relationship between algal productivity and production cost. The analyses reveal that production cost can be minimized to $1 per liter, in addition, to harnessing beneficial components from the waste sources under optimized conditions. The aforementioned processes manifest a win-win situation with economic and environmental stability. However, these approaches are still in their infancy stage and require elaborative analysis at the pilot scale to substantiate feasible zero waste algal biorefinery.

1.2.3 Integrated Biorefinery

So far, the studies mentioned capsulate the advancements in the biorefineries that drive the traditional economy to circular bioeconomy and zero-waste concept. This section of the chapter includes the integration of lignocellulosic biomass and algal biomass to compensate for each other's downsides. De Bhowmick et al. (2018a) were pioneers who researched an innovative solution where fermentation (dark/photo) of lignocellulosic biomass was combined with cultivation of microalgae (Bhowmick et al. 2018a). The results of the study established a cost-effective cycle where lignocellulose and algae were completely degraded to produce bioenergy (hydrogen, gasoline, diesel, and ethanol), and carbon dioxide emission was reduced. Based on Taguchi's approach of experimental design, rice husk, pinewood, and *Sargassum* sp. were selected to produce biochar and the process parameters were further evaluated (De Bhowmick et al. 2018b). Temperature (500 °C) and algal ratio (70%) were critical parameters in enhancing the yield, surface area, ash content, and thermal stability of biochar produced. Another integral biorefinery involved oil palm residues and microalgae cultivation for bioenergy, bioproducts, bioactive compounds, and biopharmaceutical production (Abdullah and Hussein 2021). The study was recognized as an environmentally friendly technique for reducing the emission of greenhouse gases. The integrated system enhanced the economic competitiveness and paved the way to achieve a zero-waste biorefinery approach.

1.2.4 Residue Biorefinery

Residue or waste-based biorefineries are a consolidated system of cascading processes to produce biochemicals, bioactive agents, biopolymers, biofuels, and many more (summarized in Table 1.2). With rapid expansion in economic activities and urbanization, waste has been recognized as a resource that will never lessen. Therefore, the production of commercial commodities from wastes bring forth advantages such as reduction in greenhouse gas emissions, waste management, decrease landfill costs, and other economic benefits (Caldeira et al. 2020). Additionally, residual biomass as substrate can impart solution to food-energy indecision, and thus advocate sustainable design in comparison with traditional biorefineries. Broadly, wastes can be characterized as agricultural, industrial, food, biomass, and municipal wastes, however, the composition is highly susceptive of geographical location.

Globally, it is estimated that 2.01 billion tons of municipal waste are generated by the nations, out of which 33% of the wastes remain as such and compound modern issues related to sustainable living (Datatopics.worldbank.org 2021). Therefore, waste biorefineries are advocated as an integral component to extend its boundary into circular bioeconomy (Oliveira and Navia 2017; Dahiya et al. 2018; Zabaniotou and Kamaterou 2019; Lappa et al. 2019; Yadav et al. 2020; Nawaz et al. 2020; Alfio et al. 2021). To counterbalance the ominous effect, the extraction process limits the development of zero waste biorefineries (Villacís-Chiriboga et al. 2020). Li et al. (2019) explored an innovative transformation for the extraction process that accounts for the major expenditure in the production of bioactive compounds from the biomass. The authors utilized vegetable oils and their derivatives to effectively extract volatile, as well as non-volatile compounds from rosemary leaves with keeping in mind the concept of zero waste biorefinery. The study concluded that oleo-extraction using soybean oil reduced the need for separation processes, which hold the potential to substitute traditional methods. Fish waste from aquaculture is also considered a potent hurdle. With the expansion in the market for salmon derived products, the co-stream and fish waste have been becoming more evident, as the residue generation is not seasonal but produced throughout the year. Considering the issues, a study evaluated a two-way approach for the sequential extraction of profitable commodities (Venslauskas et al. 2021). Firstly, the residual biomass was subjected to mild pretreatment to extract high-value oil and the further enzymatic process was applied to efficiently separate oil and protein content. Once all the chemicals are extracted, the solidified biomass can be used as feed to animals. Economic and environmental assessment of the approach concluded that the two-way method can increase the return on investment along with decreasing the environmental footprint.

Food waste generated from the agro-industrial processes is of major concern and requires adequate steps for sustainable management. The cascading approach has emerged to be one of the beneficial approaches where primary products such as bioethanol, biodiesel, tannins, phenolic compounds along with secondary products as feedstock for energy generation, biochar, and carbon material can be obtained (Dahiya et al. 2018). This approach not only suffices the maximum resource utilization but also integrates biorefinery into a closed-loop pattern of the economy. Jin et al. (2020) explored the efficiency of grape pomace in lead remediation. In conventional biorefinery with the grape as substrate, a larger portion of the residues persists in the landfills, thus reducing the efficiency of the system. Therefore, the authors