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Biosynthetic Technology and Environmental Challenges

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Biosynthetic Technology and Environmental Challenges

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Preface

Biomass is a renewable organic material and a continuous source of sustainable energy. The bio-based economy is getting more and more interest, and there is a need for innovative and low-emissions economy for the production of industrially important chemicals through a green approach. The biorefinery concept development is based on the techno-economic viability of the proposed process considering raw materials, process options, mass and energy management, market constraints, etc. Stable technologies are required for the proper management of industrial waste. Collaboration between biotechnologists, microbiologists, environmental scientists, biochemical engineers, molecular biologists and modellers is required for sustainable environmental development.

The first international conference on 'Sustainable Energy and Environmental Challenges' (SEEC-2017) was organized under the auspices of 'International Society for Energy and Environmental Sustainability' (ISEES) by the 'Center of Innovative and Applied Bioprocessing' (CIAB), Mohali, held from 26 to 28 February 2017. ISEES was founded at IIT Kanpur in January 2014 with the aim of spreading knowledge in the fields of energy, environment, sustainability and combustion. The Society's goal is to contribute to the development of clean, affordable and secure energy resources and a sustainable environment for the society and to spread knowledge in the above-mentioned areas and spread awareness about the environmental challenges, which the world is facing today. ISEES is involved in various activities such as conducting workshops, seminars and conferences in the domains of its interest. The Society also recognizes the outstanding works done by the young scientists and engineers for their contributions in these fields by conferring them awards under various categories.

This conference provided a platform for discussions between eminent scientists and engineers from various countries including India, USA, South Korea, Norway, Malaysia and Australia. In this conference, eminent speakers from all over the world presented their views related to different aspects of energy, combustion, emissions and alternative energy resources for sustainable development and cleaner environment. The conference started with four mini-symposiums on very topical themes, which included (i) New Fuels and Advanced Engine Combustion,

(ii) Sustainable Energy, (iii) Experimental and Numerical Combustion and (iv) Environmental Remediation and Rail Road Transport. The conference had 14 technical sessions on topics related to energy and environmental sustainability and a panel discussion on 'Challenges, Opportunities and Directions of Technical Education & Research in the Area of Energy, Environment and Sustainability' to wrap up the three-day technical extravaganza. The conference included 2 plenary talks, 12 keynote talks, 42 invited talks from prominent scientists, 49 contributed talks and 120 posters. A total of 234 participants and speakers attended this three-day conference, which hosted Dr. V. K. Saraswat, Member NITI Ayog, India, as a chief guest for the award ceremony of ISEES. This conference laid out the road map for the technology development, opportunities and challenges in this technology domain. The technical sessions in the conference included Advances in IC Engines and Fuels; Conversion of Biomass to Biofuels; Combustion Processes; Renewable Energy: Prospects and Technologies; Waste to Wealth—Chemicals and Fuels; Energy Conversion Systems; Numerical Simulation of Combustion Processes; Alternate Fuels for IC Engines; Sprays and Heterogeneous Combustion of Coal/Biomass; Biomass Conversion to Fuels and Chemicals—Thermochemical Processes; Utilization of Biofuels; and Environmental Protection and Health. All these topics are very relevant for the country and the world in the present context. The Society is grateful to Prof. Ashok Pandey for organizing and hosting this conference, which led to the germination of this series of monographs, which included 16 books related to different aspects of energy, environment and sustainability. This is the first time that such voluminous and high-quality outcome has been achieved by any Society in India from one conference.

The editors express their sincere thanks to the authors for submitting their work in a timely manner and revising it appropriately at a short notice. We are grateful to the reviewers for reviewing various chapters of this monograph and providing their valuable suggestions to improve the manuscripts. We acknowledge the support received from various funding agencies and organizations for the successful conduct of the first ISEES conference SEEC-2017, where these monographs germinated. These include Department of Science and Technology, Government of India (special thanks to Dr. Sanjay Bajpai); TSI, India (special thanks to Dr. Deepak Sharma); Tesscorn, India (special thanks to Sh. Satyanarayana); AVL India; Horiba, India; Springer (special thanks to Swati Mehershi); CIAB (special thanks to Dr. Sangwan).

The involvement of scientific knowledge, biofuels and biorefinery industries in future can be the replacement of chemical market with bio-derived bulk and fine chemicals. The book gives detailed information on biosynthetic approaches for the production of various industrially important chemicals and products and the environmental challenges for its production under biorefinery approach. There are several books on industrial biotechnology or on waste remediation; however, there is hardly any comprehensive book covering these two interrelated topics in a single book. This is a state-of-the-art book providing interdisciplinary aspects on the subject matter, which deals with 'green processes' for production of chemicals, fuels and processes involving biotechnological interventions for remediation.

The book shall include chapters on different aspects of biosynthetic technology from well-known experts in the field, both from within India and internationally. Some of the topics covered shall include bioprocesses for the production of 2,5-furandicarboxylic acid; production, characterization and applications of microbial poly-γ-glutamic acid; recent advances in composting of organic and hazardous waste: a road map to safer environment; computational modelling and prediction of microalgae growth focused towards improved lipid production; perennial energy crops on drained peatlands in Finland; environmental assessment of biorefineries; oil palm biomass and its kinetic transformation properties; management of agro-industrial wastes with the aid of synthetic biology; plant biosynthetic engineering through transcription regulation: an insight into molecular mechanisms during environmental stress; bioremediation by microalgae: current and emerging trends for effluent treatments for value addition of waste streams; recovery of nutraceuticals from agri-food industry waste by lactic acid fermentation; advances and tools in engineering yeast for pharmaceutical production; biosynthesis and technological advancements of biosurfactants, etc. This book shall provide a synthesis of scientific literature on biosynthetic technology and related environmental challenges for researchers and academicians working in this area globally.

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Thiruvananthapuram, India — Binod Parameswaran
Nagpur, India — Sunil Kumar
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About the Editors

Dr. Sunita J. Varjani is Scientific Officer at Gujarat Pollution Control Board, Gandhinagar, Gujarat, India. She holds M.Sc. degree in Microbiology (2009) and Ph.D. in Biotechnology (2014). Her major areas of research are Industrial and Environmental Microbiology/Biotechnology and Molecular biology. She has authored 35 publications, including 1 book, 19 book chapters/reviews and 15 original research papers. She has won several awards and honours, including Young Scientist Award at AFRO-ASIAN Congress on Microbes for Human and Environmental Health, New Delhi, (2014) and Best Paper Awards for oral presentations at national and international conferences in 2008, 2012 and 2013. She is a member of the editorial board of Journal of Energy and Environmental Sustainability.

Dr. Binod Parameswaran is currently working as Scientist in the Microbial Processes and Technology Division of CSIR-National Institute for Interdisciplinary Science and Technology, Trivandrum, India. He obtained his Ph.D. in Biotechnology from Kerala University, Trivandrum, in 2008, and after that, he did his postdoctoral studies at Korea Institute of Energy Research, Daejeon, South Korea, in the area of lignocellulosic biofuels. He has nearly 85 publications including research papers, reviews and book chapters. In 2001, he received Young Scientist Award from International Forum on Industrial Bioprocesses (IFIBiop), and in 2014, he received Kerala State Young Scientist Award. His research interests include bioprocess and bio-products including biofuels, biopolymers, biochemicals of industrial importance and Enzyme Technology.

Dr. Sunil Kumar is Senior Scientist in Solid and Hazardous Waste Management Division of CSIR-NEERI, Nagpur. He has extensive experience in the field of solid and hazardous waste management. His major research interests include a wide range of environmental science and engineering fields, which include municipal solid waste management, hazardous waste management and environmental impact assessment. He is Honorary Director of Institute of Chartered Waste Managers, Jaipur, India. He has more than 80 publications/communications, which include three books and eight book chapters. He has provided industrial consultancy for various projects in Indian/international industries. He is an editorial board member of Bioresource Technology and Associate Editor of Journal of Hazardous, Toxic and Radioactive Waste, USA, and Environmental Chemistry Letter.

Prof. Dr. Sunil K. Khare is presently working as Professor of Biochemistry at the Department of Chemistry, IIT Delhi. He received his Ph.D. from IIT Delhi, carried out postdoctoral research at National Food Research Institute, Tsukuba, Japan, and has been DBT Visiting Scientist at Northern Regional Research Laboratory, Illinois, USA. He has been working in the area of solvent-tolerant and halophilic class of extremophiles and their enzymes, especially understanding the structural and molecular bases of their stability. The applications of these extremozymes in various biotechnological and industrial bioprocesses have far-reaching implications. His current noteworthy contributions have been in differential proteomics of solvent-tolerant and halophilic class of extremophiles and deciphering nanotoxicity mechanisms in microbial and plant systems. The work has led to 135 publications with high impact, 2 patents, 12 book chapters to his credit, besides a large number of conference publications. A large number of culture deposits in Microbial Type Culture Collection, India, and GenBank submissions to National Centre for

Biotechnology, USA, have also been made. The h-index for his work is 32 with a total of 3609 citations. He has guided 14 Ph.D. and 40 master's students. Several awards have been conferred on him, and noted amongst them are United Nations Amway Award; Fellow United Nations University; Fellow International Forum on Industrial Bioprocesses, France; Fellow Biotech Research Society, India; and Member National Academy of Science, India. He is General Secretary of the Biotech Research Society, India, Joint Secretary of Association of Microbiologists of India, member of many national committees and professional societies including DBT committees, DST task force, Academic council member of AMU, Central University of Haryana, Indraprastha University and Visiting Faculty for University of Blaise Pascal, France.

Part I
General

Chapter 1
Introduction to Biosynthetic Technology and Environmental Challenges

Sunita J. Varjani, Parameswaran Binod, Sunil Kumar and Sunil K. Khare

Abstract Bio-based processes and products are getting more and more acceptance nowadays mainly because of the environmental friendly process. Many current petroleum-derived products would be replaced by less expensive and better performing products based on renewable materials in near future. This will help for achieving economic and environmental sustainability. Bioeconomy is now emerging as a major industrial breakthrough and new biomass-based products are emerging due to the advancement in technologies. These potential benefits of bio-based products could justify future public policies that encourage a transition to renewable raw materials for production of organic chemicals, fuels and materials. Biosynthetic approaches for production of various industrially important chemicals and products through microbial and plants routes have been discussed in this book. The environmental challenges for its production under biorefinery approach and the various methods for addressing the environmental issues have been discussed in detail.

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Keywords Biochemicals · Biofuels · Biosurfactants · Biopolymers
Biopharmaceuticals · Prebiotics · Nutraceuticals · Biorefinery
Waste management

Lignocellulosic biomass is one of the most abundant renewable resources available on earth. Huge amount of lignocellulosic biomass is generated from agricultural and food industries as a waste material, commonly known as agro-industrial waste. It has low value for industries and also a big problem as environmental pollutant, therefore its proper management is needed. Several technologies have been applied to recover maximal quantity of valuable product from agro-industrial waste but applications of emerging synthetic biology in production of high value product seem to be more promising for its management. Agro-industrial waste is a good source of carbon and energy for the growth of microorganisms. The lignocellulosic biomass can be converted easily to fermentable sugars and these sugars can be converted to valuable products such as biofuels, bioactive molecules, rare sugars, prebiotic oligosaccharides, biochemicals and many more by applying engineered enzymes or organisms.

The complete utilization of lignocellulosic biomass for various products leads to the emergence of biorefinery concept. This also leads to more advanced interdisciplinary area of techno-economic analysis. The development of the biorefinery concept is based on the techno-economic feasibility of the proposed process considering raw materials, process options, mass and energy integration, market constraints, etc. Nevertheless, along with all these considerations, the environmental assessment must be taken into account at the same time, and concepts like sustainability, land uses, environmental impacts and other related issues must be included in the biorefinery design. A detailed information on this aspect based on different case studies covering a wide range of raw materials and products is also presented in this book. Comparing technological options for biorefinery development is usually done based on economic criteria, but environmental aspects have gained a key role in addition to economic factors for the selection of the best production scheme. Although different approaches, methodologies and data bases are available, the combined consideration of economic and environmental factors can be used as a right tool for decision-making.

Microorganisms such as bacteria, fungi, yeasts and algae are used for production of various chemicals of industrial and pharmaceutical importance. Biopharmaceuticals are important part of modern medical biotechnology and current commercial market of pharmaceutics show annual growth rates between 7 and 15%. The microbial production systems offer several advantages in production of pharmaceutically important proteins due to its unicellular nature, easy gene manipulation, cost-effective and fast growth. Recently major industries focus on biological method for production of chemicals such as 2,5-Furandicarboxylic acid, 1,3 propanediol, biosurfactants, etc. Biopolymers are another important entity of commercial importance. Poly γ-glutamic acid is a promising biodegradable polymer from bacterial sources with intense applications in the field of medicine, wastewater treatment, food and cosmetics, etc. Another polymer having wide application is Pullulan. This microbial pullulan acts as the promising biomaterial that is currently used for packaging of readily oxidized food materials, controlled drug delivery, tissue engineering and can also function as artificial molecular chaperones. Biosurfactants also constitute an important compound having wide application. The realm of surfactant activity widespread to different industries including food, environmental remediation, textiles, fuel extraction, biotechnology, antimicrobials and many more. Recent developments in the production of these chemicals and polymers are described in this edition of book.

The enormous amount of by-products produced in food and agricultural sector and current attention towards sustainability is attracting researchers to look into possibilities of its utilization in recovery of nutraceuticals. Nutraceuticals are food or food products that confer health and medical benefits, and are instrumental in prevention and treatment of diseases. The agri-food industry by-products are an excellent source of proteins, lipids, fibre and other bioactive compounds. Among different methods used for extraction of these bioactive compounds (nutraceuticals), fermentation by lactic acid bacteria is one of the economical and eco-friendly approaches. During fermentation, chemical changes induced in organic substrate by action of microorganisms aid in formation of bioactive compounds, either by a process of hydrolysis of large polymers to simple molecules or transformation of substrates. One of the chapters in this book discusses the role of lactic acid fermentation in transformation/hydrolysis of by-products for efficient recovery of nutraceuticals. The bioprocess of nutraceuticals recovery from waste by lactic acid fermentation with better efficiency adds value to food waste, reduces environmental pollution and has positive impact on the economy.

Prebiotics constitute non-digestible food ingredient that promotes growth of beneficial microorganisms in the intestines. The oligosaccharides are highly stable and are used as dietary supplement possessing prebiotic, antioxidant activity and potential immune-modulating properties. A detailed information on manno-oligosaccharides has been included in one of the chapters in the book.

Plants also constitute an important source for biosynthetic products. They are well responding to environmental factors and endow rapid adaptation for survival under multiple environmental stress. These various environmental perturbations not only affect productivity of plant but also cause different variations in plant morphology and anatomy, growth, development and metabolism as well. During commencement of environmental stress, majority of biological processes are directly affected, such as photosynthesis, transpiration, respiration, stomatal conductance, pigment concentrations, energy and metabolism. To improve plant secondary metabolism production, it is essential to understand its biosynthetic pathway at the transcription level.

Energy crops such as Miscanthus, switchgrass, etc., represent important sources for biofuel production. The cultivation of perennial bioenergy crop on a drained peatland is an interesting approach. Peatlands are globally important because of their high carbon content. While the use of peatlands as an economic resource was deemed necessary, the fact that such land use (drainage) leads to environmental problems is increasingly being realized the world over since the 1990s. Hence, continued attempts are being made to find suitable land use options for drained peatlands after their intended land use. Simply abandoning these lands is considered environmentally untenable. Therefore, several options have been suggested as after-use options: intensive forestry, rewetting, restoration to a functional peatland, creation of artificial wetlands, use of cutover peatlands for agriculture and cultivation of energy crops, etc. Decision on which option to use at a given drained peatland is complex. As an after-use option on a cutover peatland, the cultivation of a perennial bioenergy crop on a drained peatland in eastern Finland was explored during 2004–2011. The long-term measurements of greenhouse gas exchange from this study site showed that the benefits from bioenergy crop cultivation vary strongly depending on the climatic conditions during the crop cultivation phase.

Another plant-based residue is the oil palm biomass from oil palm mills which need a proper waste utilization application. Pyrolysis is the commonly used method to utilize this waste. The kinetics of this process and the recently available kinetic models such as lumped and distributed models are discussed in detail in one of the chapters in this book.

Cultivation of microalgae has appeared as an emerging alternative approach for removing pollutants and heavy metals present in the water bodies. Biomass production in the alga depends on rapid utilization of the organic content and other nutrients present in the effluent and can be considered as an attractive and eco-friendly means for treating waste streams, other than removing the pollution load, algal cultivation adds value to the process by production of commercially valuable products such as fuels and various chemicals from biomass. The recent developments and perspectives in bioremediation of waste streams by algae for removal of various pollutants for value addition of waste have been discussed in the book. Various computational modelling methods applied to microalgae growth in various environmental conditions have been reviewed. The possibility and potential of employing these models for better lipid production have also been highlighted, as better predictability of models can lead to better transgenic algal platform.

Increasing amount of waste due to urbanization, lifestyle and shift of huge masses from rural to urban largely contribute for the need of waste management. This developed a need of categorizing the waste into municipal waste, industrial waste, agricultural waste, hospital waste, etc., which would make it easy for the proper disposal, reuse and recycling of waste so determined effort should be taken for management of waste. Vermicomposting is the biocomposting process of organic waste by earthworms and bacterial action directing the stabilization of organic matter. The final product produced in this process is known as vermicompost and it assists in enrichment of soil as well as useful for sustainable agriculture. This technology is a boon for recycling of the solid waste generated from various sources including aquatic weeds. Vermicompost production from water hyacinth (*Eichhornia crassipes*) and its application to a commercial crop groundnut (*Arachis hypogaea*) for total yield and biomass production have been described in one of the chapters. Deliberation on the variations of life cycle computation of solid waste management that involved to different global warming potential of composting is also a topic of discussion in this book.

Another important issue in waste management is handling and disposing the hazardous wastes as antibiotics residue, municipal solid waste and agricultural waste. These wastes contain lots of organic matter and nutrients, while also contain various kinds of toxic materials or elements (e.g. heavy metals, pathogens and antibiotics). The improper disposal of these wastes would result in environmental pollution and potential risk of human health. One chapter in this book discusses benefit and challenge of composting of organic and hazardous waste. It also discusses current method to promote the compost quality and reduce the environmental risk.

Water bodies are subject to a considerable pressure from sewage and industrial wastes. Monitoring methods adopted so far have helped in assessment level of contaminants in water but not interaction of these pollutants with living organisms. Water quality testing programs use two traditional methods for water quality assessment that includes physico-chemical parameters and bio-monitoring. Looking at the limitations of these two traditional methods, a new method known as 'biomarkers of pollution' should be adopted. Evaluating various biomarkers in sentinel species can be of great help in environmental monitoring program as they forecast various risks and hazards associated with the habitats of aquatic animals. The major advantage of biomarkers is that bioavailability or potential exposure to toxicants can be demonstrated which is not possible in chemical analysis.

The topics are organized in five different sections: (i) General, (ii) Biosynthetic approaches and products and (iii) Environmental assessment and waste management.

Part II
Biosynthetic Approaches and Products

Chapter 2
Management of Agro-industrial Wastes with the Aid of Synthetic Biology

Lokesh Kumar Narnoliya, Jyoti Singh Jadaun and Sudhir Pratap Singh

Abstract Biomass is the renewable organic material and it can serve as a continuous source of sustainable energy by passing through proper channel. Lignocellulosic biomass is one of the most abundant renewable resources available on earth. Huge amount of lignocellulosic biomass is generated from agricultural and food industries as a waste material, commonly known as agro-industrial waste. It has low value for industries and a big problem as environmental pollutant, therefore its proper management is needed. This agro-industrial waste could be used to generate other valuable products which aid on its value as well as manage agro-waste substances. Thus, several technologies have been applied to recover maximal quantity of valuable products from agro-industrial waste but applications of emerging synthetic biology in production of high-value products seem to be more promising for its management. Synthetic biology is a combination of engineering and biology which is helpful in designing novel biochemical pathways, organisms, or redesign existing, genetic circuits, biological modules, and natural biological systems. Generally, bacteria or yeast biological systems grow easily and are able to produce altered enzymes very efficiently with desired modifications in their genome. These engineered organisms are able to convert agro-industrial waste into valuable products. Nowadays, several valuable products are produced by using synthetic biology approach from industrial waste generated from agro-food industries such as sugarcane bagasse, apple pomace, and citrus peel. Here, we will discuss about agro-industrial waste, biosynthetic tools, and case studies of application of synthetic biology to produce valuable products from agro-industrial waste such as production of prebiotics, nearly calorie-free sugars, and bioactive compounds.

Keywords Agro-industrial waste · Synthetic biology · Lignocellulosic waste Prebiotic oligosaccharides · Biofuels

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1 Introduction

In India, agriculture has the main socioeconomic impact on business development of the country. More than 50% population are still completely dependent on agriculture for their livelihood. After harvesting crops, there is a huge amount of agricultural residues left in the fields, which remain unused and often burnt causing serious environmental hazards. This leftover organic material contains significant quantity of carbon, which can be used in production of alternative sources of food, feed, and energy being a low-cost raw material for value-added molecules (Matos-Moreira et al. 2012; Kulkarni et al. 2015; Díaz et al. 2017). Thus, development of biosustainable and renewable resource technology for management of agro-industrial waste has immense importance with respect to environmental concerns. Lignocellulose and starch are the most abundant agro-industrial waste as well as renewable organic biomass on the earth, which are produced every year in all over the world through photosynthesis in wide area from the forest to sea (Da Silva 2016).

Lignocellulosic waste could be decomposed by microbes and later transferred into environment which finally becomes a part of carbon cycle operating in ecosystem, where it is converted into CO_2 and H_2O. However, natural decomposition of lignocellulosic waste is a time-consuming process, it will take so many years for degradation of even currently present amount of lignocellulosic waste. Furthermore, the value of natural lignocellulosic feedstock is in demand due to recycling economy and sustainable development of energy sources. The research aspects on lignocellulosic biology are flourishing rapidly and this area is expanding for biosynthesis of bioactive compounds from biomass (Hongzhang 2014). Lignocellulosic biomass consists of mainly three types of polymers such as cellulose, hemicellulose, and lignin, which are strongly intermeshed and bonded by covalent cross-linkages and non-covalent forces (Singh et al. 2012). Microbial organisms degrade lignocellulosic biomass mainly through two enzyme systems: hydrolytic and ligninolytic. Hydrolytic enzymes are responsible for cellulose and hemicellulose degradation, whereas ligninolytic enzymes degrade lignin and open phenyl rings (Dhillon and Kaur 2016). In recent years, several technologies have been developed to manage lignocellulosic biomass. Synthetic biology is a combinational branch of engineering and biology containing several disciplines such as biotechnology, molecular biology, genetic engineering, systems biology, molecular engineering, evolutionary biology, and computer engineering. Synthetic biology is used to design novel biological pathways, organisms, or redesign existing, genetic circuits, biological modules and natural biological systems. Microbes, especially bacteria, are the key organisms used as bioengineered system for biosynthesis of valuable compounds from agro-industrial wastes (Cameron et al. 2014; Hongzhang 2014).

Array of genes encoding beneficial enzymes from various sources is available which could be transferred into targeted microbes via synthetic biology approach. The enzymes from microbial factories are useful bio-tool for treating the agro-industrial waste to generate high-value bioactive substances. Bacteria has a simple genomic structure, their genetic manipulation can be controlled efficiently, and they can be grown easily and rapidly to produce huge amount of desirable enzyme or bio-product. Substantial efforts have been made to produce high-value biomolecules from agro-industrial wastes including agriculture waste, food wastes, fruit waste etc., by employing synthetic biology approaches. Synthetic biology has received significant attention since last two decades, after forthcoming of computational era (Cameron et al. 2014; Andrianantoandro et al. 2006). Synthetic biology is successful in altering the biochemistry and physiology of an organism by using modern bioengineering technologies, so they can perform new tasks or existing tasks more efficiently according to need. Reports are available showing applications of synthetic biology in transforming agro-industrial residues and by-products into products such as prebiotics, zero calorie sugars, and herbal medicines.

2 Source of Agro-industrial Waste

The source of agro-industrial waste is the agriculture residues generated from agriculture and fruit industries wastes, such as sugarcane bagasse, fruit pomace, wheat bran, rice straw, corn cob, and wheat straw (Dhillon and Kaur 2016). Agro-industrial wastes are the highly abundant and cheapest natural carbon source and their disposal is a big concern for environment. These wastes are mostly disposed in landfills causing soil pollution and gradually these are drained out in water prompting water pollution. Soil microbes degrade these wastes, generating intolerable and awful smell, thus generating air pollution. Use of the inexpensive agro-industrial wastes and surplus by-products in production of valuable products has double benefit of providing additional livelihood opportunities to farmer as well as addressing environmental issues. This approach gives opportunity to develop products from less-valued materials and the green solution worthwhile for environment protection.

Food and agriculture-based industries generate waste residues after vegetable and food processing steps, grain industries produce spent grains including breweries, distilleries as well as fruit, sugar cane, pulses, oil-based industries also produce huge amount of waste. Broadly, we categorized total waste into three categories based on their production sources such as agriculture, fruit, and food waste.

2.1 Agriculture Wastes

It is generated as a result of agriculture practices either in the field or during processing of agricultural products in the industries. For example, huge vegetative biomass waste is generated during the cultivation of crops such as rice, wheat, corn, barley, oats, rye, etc., after grain harvest. Agriculture waste comprises the largest proportion of total agro-industrial waste. In agriculture, more than 50% part of plant is directly not in use as food and is generally attempted to be used for animal feed, however, a major proportion of this biomass is left as waste. Half of the world's population consumes rice as a staple food and rice cultivation generates rice straw and rice husk as major waste materials, which have negligible commercial values. Rice straw is produced as half to same quantity as rice produced and fifth part of harvested rice is husk. The quantity of rice crop waste is often more than rice grain and it is considered as poor animal feed due to presence of silica, which is not liked by animals (Singh and Sidhu 2014; Dhillon and Kaur 2016). The chemical composition of rice straw is 42–49% of cellulose, 26–32% of hemicellulose, 12–16% lignin, 15–20% of ash, and 9–14% silica (Garay et al. 2009). In India, most of the farmers burn the rice crop leftover on their field for preparation of next crop which results in excessive air pollution (Binod et al. 2010).

Wheat straw consists of approximately 40% of cellulose, 20% of lignin, 20% of xylose, and 3–5% arabinose. It is generally used for animal feed and has been explored for production of compressed agricultural fiber, resins, paper, and bioethanol (Kristensen et al. 2008). Another food crop is corn in which after harvesting of corn seeds, the rest of the plant becomes waste and corn cob is the main post-harvest waste. The application of corncob is not much more explored, except its use as feed for poultry farms, however, significant opportunities are being discussed in different publications to produce valuable products from this abundant biomass. Recently, corncob has been demonstrated as feedstock for production of furfural chemical and bioethanol (Jerry et al. 2016). There are three main steps to produce bioethanol from agro-industrial waste, physicochemical pretreatment, cellulose saccharification, and finally monosaccharide fermentation (Jeffries and Jin 2004).

2.2 *Fruit and Vegetable Wastes*

Fruits and vegetables residues belong to the highest wastage rates at consumer and retail levels. Vegetable wastes can be used as low-cost feedstock for production of fermentable sugar through various treatments (Díaz et al. 2017). The vegetable wastes, such as cabbage leaves, cauliflower leaves, tomato pomace, baby corn, etc., have been explored to be used for production of value-added product through aid of synthetic biology technique. The fructose sugar present in the cauliflower foliage can be converted into nearly zero calorie rare sugar, D-psicose (Patel et al. 2016). Recently, dual production of bioethanol and D-allulose from vegetable residue has also been demonstrated (Song et al. 2017).

In the past decades, consumption of fruit juices has increased rather than consumption of whole fruits, which led to rise in fruit processing industries. Fruit processing wastes include citrus fruit skins, pineapple residues, sugarcane bagasse, apple pomace, and other fruit residues. Now fruit waste became a problem in big cities as huge municipal solid waste which has negative impacts on environment (Cheok et al. 2016). Currently, fruit wastes are managed by landfilling or incineration. However, this approach is limited by emission of methane and carbon dioxide gases during landfilling, and incineration and simultaneously generates pollutant and other toxic substances (Dhillon and Kaur 2016; Deng et al. 2012). Suitable biotechnological solutions are required to address the abundant fruit and vegetable residues.

Huge amount of apple pomace (30% of original fruit) is produced in apple industry which is mainly subjected to landfill (Vendruscolo et al. 2008). Its use as animal feed is currently avoided due to high sugar content, low digestibility, low vitamin, and mineral content. However, its pretreatment with enzyme complex, containing amylase, cellulase, and proteases makes it a superior feed grade (Dhillon et al. 2013; Vendruscolo et al. 2008). Further, several valuable products have been demonstrated to be produced using apple pomace as feedstock, such as organic acids, high protein feed, bioethanol, aroma compounds, antioxidants, phenolics, fibers, etc. Bio-synthetically engineered cells and enzymes can efficiently transform these low-cost residues into high-value bio-products (Vendruscolo et al. 2008). The sugars present in fruit pomace wash can be transformed into high-value functional sugar, e.g., D-fructose to D-psicose (Patel et al. 2016), and the remaining fibrous material may be used in other food or feed products. Banana is a popular fruit rich in nutrients such as sugars, minerals, antioxidant molecules, and dietary fibers. However, banana cultivation generates about 10–40% waste in the form of peel, pseudostem stalk, leaves, and banana fruit skin (Sharma et al. 2017). Thus, banana is also a potent source of lignocellulosic waste which could be valorized by transforming it into animal feed or utilizing the biomass into bioethanol production (Velásquez-Arredondo et al. 2010). Bioprocessing of banana stem juice led to the development of a health drink (CSIR-CFTRI). By employing suitable enzymes, the nutritive scale of the drink may be improved (Sharma et al. 2017). After citrus juice extraction, pulp residues remain which is made up of peel, internal tissue, and seeds. Citrus pulp consists of water and soluble sugars which make it digestible. It can be used as feedstock for ruminants but due to high fiber content, it is not liked by monogastric animals (Dhillon and Kaur 2016). Pineapple pomace is produced after processing of pineapple juice and it accounts $\sim$60% weight of total harvest. It contains soluble sugars, fibers, and pectin which can be easily digested so it is used as ruminants feed. Other fruits also generate significant level of lignocellulosic waste such as melon peels and pulp, mango peels and seed kernels, carrot pulp, sugar beet pulp, and grape. Fruit waste is composed of lignocellulose biomass which can be used to produce valuable products such as biofuel, food materials (prebiotics and zero calorie sugars), bioactive compounds, enzymes, etc. (Sharma et al. 2016, 2017). Engineered enzyme or microbial systems (bacteria or yeast) are developed by synthetic biology which is directly able to convert agro-industrial waste into commercially important products in efficient manner with low cost and minimum time (Fig. 1). Thus, it upgrades the value of raw material (agriculture or fruit or food) and helps in the agro-industrial waste management.

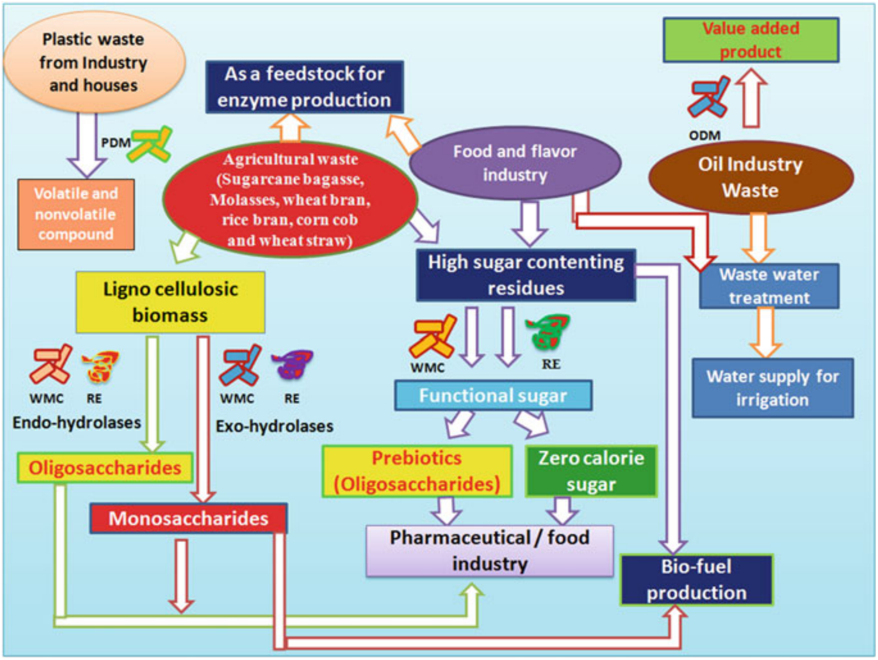

Fig. 1 Different routes of bioprocessing of agro-industrial waste through synthetic biology approach. *WMC* whole microbial cell, *RE* recombinant enzyme, *PDM* plastic degrading microbes, *ODM* oil-degrading microbes

2.3 Other Wastes

Food wastes are produced by households, food manufacturing industries, and food service sectors. A huge quantity of waste is produced in the form of liquid and semisolid by food processing industries, bakery industries, milk-based industries, livestock, and poultry farms, appropriate management of which is a challenge for scientists, engineers, and industrialists (Ravindran and Jaiswal 2016). The residues produced from grain processing (maize, barley, wheat, triticale, sorghum, rye, and oats) and sugar industries (cane and beet) are majorly used for bioethanol production; whereas, oilseed wastes (rapeseed, jatropha, canola, palm oil, soybeans, castor, and neem) are used for production of biodiesel. Production of liquid biofuel as bioethanol and biodiesel also produces massive amount of by-products as waste. Bioethanol waste directly can be used as animal feed and biodiesel by-products are used for animal nutrition as a protein source (Dhillon and Kaur 2016). The pretreatment of lignocellulosic biomass by enzymatic hydrolysis is able to release maximum quantity of sugar which could be used in making isomers and oligomers of health significance. Nowadays, industrial ecology concepts are considered as leading principle for eco-innovation aimed to "zero waste economy" in which waste materials of industries are again used as raw material for new products.

3 Synthetic Biology and Its Applications for Management of Agro-industrial Waste

Synthetic biology combines both engineering and biology streams at a single platform. Biological transformation involves use of native or engineered organism or biocatalyst for conversion of agro-industrial waste into precious chemicals or products. Biological transformation is more favorable mode of conversion because chemical conversion needs high temperature and pressure (Brar et al. 2014). Generally, engineered organisms are used in fermentation techniques to generate value-added products from waste. There are a lot of fermentation-based products in market like chemicals, biofuels, biopolymers, organic acid, amino acids, antibiotics, and pharmaceuticals. Nowadays, utilization of biocatalyst is significantly increased toward transformation of renewable resources due to their high specificity, selectivity, high yield, and less by-product production (Brar et al. 2014). Role of synthetic biology came in notice when system biology and genetic engineering disciplines are evolved up to significant status. System biology explores omics such as genomics, transcriptomics, proteomics, and metabolomics which provide valuable gene/enzyme information rapidly which could be used in enzyme engineering. Genome or transcriptome resource of any living system will provide genetic information related to novel enzymes or a new source of enzyme which might have enhanced activity (Sangwan et al. 2013; Narnoliya et al. 2017).

These newly identified enzymes can be directly used or they can be engineered for better performance as per demand. Engineered enzymes are able to catalyze direct or preprocessed agro-industrial waste into valuable products. Enzyme engineering comes under genetic engineering discipline which uses biotechnology, molecular biology, and metabolic engineering branches of biology. Engineered enzymes acquire higher catalytic efficiency, thermal and pH tolerance than wild enzymes for better functionality to convert agro-industrial biomass into precious products such as prebiotics, calorie-free sugars, bioactive compounds, biofuel, lipids, biosurfactant, pigments etc. These modified enzymes either alone or in combination with other enzymes may be integrated in genome of a suitable host organism to perform better biotransformation of waste substances. Although biological transformation through synthetic biology approach provides high-value products from agro-industrial waste but still there are problems associated with downstream and upstream processes such as pretreatment, sterilization, aeration, agitation, product recovery, and temperature control which are needed to be resolved. Since, last decade utilization of agro-industrial waste increased in a notable manner as renewable resource alternative of petroleum fuels and some other industrial process.

Example of such utilization of agro-industrial waste is production of catechol and adipic acid from glucose present in agro-industrial waste through recombinant *Escherichia coli* (Draths and Frost 1994). Engineering of *Saccharomyces* sp. which is able to produce bioethanol from glucose and xylose present in lignocellulosic waste was a good step for conversion of low-value substrates to high-value products (Sedlak and Ho 2004). Algae is used for biodiesel production through lipid extraction, and the remaining algal biomass can be explored for carbohydrates, crude glycerol, pigments, proteins, and others products (Brar et al. 2014). Likewise, citrus fruit waste are used to produce ethanol, fibers, essential oils, carotenoids, cellulose as well as bioactive molecules like hesperidin and hesperetin which possess significant activities such as anti-inflammatory, anticarcinogenic (Simmons 2016). Brewery waste and apple pomace are the good sources of ligninolytic enzymes such as laccases, manganese peroxidase, and lignin peroxidase which are responsible for lignin degradation (Gassara et al. 2010).

4 Case Study on Production of Valuable Products from Agro-industrial Waste

4.1 Productions of Biofuels from Agro-industrial Waste

The sources of fossil fuel are limited and world population is continuously increasing so in upcoming few years, we may face energy crisis. Fossil fuels also generate pollution, therefore new and cleaner alternative energy sources are required for the future. Biofuels provide a good source of renewable energy and are also safer for environmental concern (Balat and Balat 2009). For growing population, we need more food as well as fuel so we have to increase the proportion land area for crop production but for fuel production, we also need land. Land is becoming a limiting factor in fuel production and biofuel is the only alternative source for accessing the fuel requirement. Thus, there is little bit imbalance situation between “food and energy” therefore new technologies are emerged which will be able to produce biofuels from agro-industrial waste (Jeihanipour and Bashiri 2015). The cost of agro-industrial waste is almost zero so the raw material for biofuel has no limitations. The biodiesel conversion from agro-industrial waste is carried out by transesterification of branched triglycerides into smaller straight-chain esters (Leiva-Candia et al. 2014).

Biofuels are classified into four categories based on their production technology as first to fourth generation biofuel. First generation biofuel used food crop (sugar, starch, vegetable oils) and second generation used nonfood crops (wheat straw, corn, wood, solid waste) as feedstock and produced bio-alcohols, biodiesel etc. Third generation used algae to produce vegetable oil and biodiesel, and the fourth generation biofuel used vegetable oil and biodiesel to generate Biogasoline (Demirbas 2009). Brazil and the USA are the leading countries which produce bioethanol. Several microorganisms such as bacteria, fungi, yeast, and algae contain the ability to store lipids under specific cultivation conditions. Agro-industrial waste is good source for growing such microorganisms because it contains different types and high level of carbon source (Fig. 1). For enhancing efficiency of these microbes, synthetic biology can give a solution. System biology provides information regarding responsible pathway and enzymes which can be modifying by recent genetic engineering techniques. Some yeast species retain high oil content compared to algae or bacteria and their growth rate is also fast therefore they can be easily used for biofuel production. Some oleaginous yeast strains such as *Rhodosporidium* sp.*, Lipomyces* sp.*, Cryptococcus* sp., and *Rhodotorula* sp., accumulate significant level of lipids especially when glucose is used as carbon source (Hu et al. 2009).

A well-known yeast *Saccharomyces cerevisiae* genus was used for bioethanol production. A remarkable level (more than 50 g L^{-1}) of bioethanol production was achieved by recombinant *S. cerevisiae* from glucose and xylose as source which was extracted from agro-industrial waste after pretreatment process (Alfenore and Molina-Jouve 2016). Agro-industrial wastes such as molasses, cheese whey, crude glycerol, meat product waste, and waste oil possess significant quantity of carbon and these yeast species can use these sources as substrate for growing. *Candida* sp. uses molasses as carbon source and could be able to store 60% (w/w) lipid content. *Cryptococcus curvatus* strain uses crude glycerol, cheese whey, and molasses as carbon source and produces significant level of lipids (Leiva-Candia et al. 2014). For yeast, lignocellulosic waste is not a suitable food without pretreatment. It can be pretreated by enzymatic, acidic, basic, thermal, or combination of these methods. Therefore, sweet sorghum bagasse, wheat straw, cassava starch, Jerusalem artichoke extract, corn cob, and rice straw could be used as potent carbon source for lipid storages microbes (Leiva-Candia et al. 2014; Jeihanipour and Bashiri 2015; Alfenore and Molina-Jouve 2016). A number of sources available such as cassava bagasse, raw residual coconut milk, raw residual pineapple juice, grape and sugar beet pomaces, rice straw and corn stalks, sugar cane molasses, soy molasses, corn fiber xylan, etc., were used for biofuel production through engineered organisms as mentioned in Table 1.

E. coli is the most common host for genetic manipulation studies and possesses suitable system such as to grow in salt condition, anaerobic condition, and utilize array of carbohydrates substrates, polyols, and fatty acids (Clomburg and Gonzalez 2010). Glycerol dissimilation pathway and *Zymomonas mobilis* ethanol production pathway was introduced in *E. coli* by aid of synthetic biology and this metabolic engineered *E. coli* produces 20–40 g L^{-1} ethanol (Durnin et al. 2009; Yomano et al. 2008). Several pathways responsible for synthesis of isobutanol, 1-propenol, 1-butanol, 2-methyl-1-butanol, 3-methyl-1-butanol, isopentenol, and fatty alcohols were introduced in *E. coli* and significant yield of respective alcohol was obtained (Clomburg and Gonzalez 2010). Besides *E. coli*, *S. cerevisiae* and *Z. mobilis* were also engineered and extensively used for ethanol production. *E. coli, Pichia stipitis* and *Klebsiella oxytoca* can use pentose sugar for ethanol production. Xylose