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Elements of Bioeconomy

Edited by Krzysztof Biernat

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Published in London, United Kingdom







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Elements of Bioeconomy
http://dx.doi.org/10.5772/intechopen.78099
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First published in London, United Kingdom, 2019 by IntechOpen
IntechOpen is the global imprint of INTECHOPEN LIMITED, registered in England and Wales,
registration number: 11086078, The Shard, 25th floor, 32 London Bridge Street
London, SE19SG – United Kingdom
Printed in Croatia

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Additional hard and PDF copies can be obtained from orders@intechopen.com

Elements of Bioeconomy
Edited by Krzysztof Biernat
p. cm.
Print ISBN 978-1-78923-861-7
Online ISBN 978-1-78923-862-4
eBook (PDF) ISBN 978-1-83962-355-4

Meet the editor

Krzysztof Biernat Ph.D. (Mech.Eng.) is a professor of the Automotive Industry Institute (PIMOT), acting as President of the Polish Biomethane Council, a Coordinator of Polish Technology Platform for Biofuels, and a member of the Coordinating Committee of Society Cluster of Bioeconomy. He is also a lead expert of the International Renewable Energy Agency and an expert in many operational programs. He specializes in chemical thermodynamics of environmental processes as well as obtaining technologies, quality evaluation, and the use of exploitative liquids, including biofuels, and biorefinery systems. He is an author of above 200 publications in the area of properties and exploitative conditionings of fuels, biofuels, and other liquids as well as environmental protection. He is a member of many national and international scientific societies including the American Chemical Society and American Association for the Advancement of Science.

Contents

Preface

Bioeconomy, as a new branch of industrial processes, was created as a result of the analysis of methods of using raw materials, technological processes in the use of these raw materials, and receipt of various types of material goods. Without questioning the legitimacy of the need to produce many products, technologies that use natural resources pose a serious burden to the environment. For these reasons, the concept of bioeconomy as a new industrial branch was introduced in 2012. Bioeconomy is based mainly on raw materials of biological origin, including so-called waste biomass. By definition, bioeconomy should include a wide range of raw materials and the development of technology for their processing, with a minimum environmental burden. Initially, it was assumed that bioeconomy technologies would completely eliminate the production of waste. According to recent research and views, it is theoretically possible to significantly reduce post-production waste in bioeconomic processes. However, known technological processes using biomass as a raw material require an energy supply. This, in turn, causes emissions of carbon dioxide into the atmosphere, regardless of whether this energy comes from coal and oil, or from the use of biofuels and bioliquids. It is also possible to use other renewable energy sources, such as wind, water, or solar energy, but the LCA analysis of these sources also shows emissions in this cycle. Therefore, complete elimination of all waste, including waste heat as one of the forms of mass and energy exchange, from technological processes or the possibility of their full use is not possible. Therefore, bioeconomic processes require in-depth analysis taking into account such criteria as: rational use of available resources of raw materials, the necessary environmental needs for these raw materials, progressive climate change, preservation of biodiversity, soil condition, water, and air. These criteria fall into the category of environmental criteria. In the category of social criteria, we can distinguish: access to clean air, access to food, preservation of soil ownership, process transparency and access to information, employment, and health protection. In the economic criteria category, there is one important criterion regarding the cost and efficiency of bioeconomic processes. The rational use of available raw materials requires the development and implementation of appropriate technologies that should take into account environmental, social, and economic criteria. For this reason, the need to develop a book with the working title "Bioeconomy" that covers the basics and legitimacy of conducting activities in this field was recognized. This book organizes definitions and presents the updated research in the scope of possibilities of implementing bioeconomic processes. Unfortunately, the degree of research development in the scope of these processes is still at the level of discussion in the area of bioeconomy development strategy, and even concepts and their interpretations. Out of many proposed chapters, nine studies were selected. These nine chapters fall within the scope of criteria covering bioeconomic processes. The accepted chapters cover various but partial aspects of these processes. This resulted in the title of the book presented being "Elements of Bioeconomy". Due to various aspects of bioeconomic processes covered in the accepted chapters, it was impossible to divide the content of the monograph into relevant thematic sections.

The first chapter is the introductory chapter. This chapter presents the general concept of bioeconomy, its origins, and planned effects. The possibility of obtaining the status of bioeconomy as a completely circular economy has been critically discussed.

Chapter two deals with life cycle assessment (LCA) as a tool for implementing sustainable development principles in bioeconomic processes. This chapter also presents examples of LCA analysis for bulky waste.

The third chapter concerns the analysis of a very important group of processes in bioeconomy. These processes fall within the concept of biorefineries as a basic element of biorefinery technologies and lead to the production of biofuels through the WtL and WtE processes. The authors provide an overview of these processes.

The technological processes of biomass transformation, enabling its further use as a raw material, require many complex preparatory processes. In chapter four, the authors review the processes of enzymatic biomass transformation, enabling sustainable energy recovery to obtain biofuels or bioliquids.

In the fifth chapter, the authors have analyzed the use of agricultural waste as raw material in developing countries. These processes can also significantly improve the purity of water in these countries.

Chapter six covers the analysis of the possibility of using biosorbents as materials that enable effective recovery of metals from waste, mainly from printed circuits. The research part presents the possibility of recovering gold (I) from these circuits using appropriate biosurfacants.

The seventh chapter presents the possibilities of using digital solutions in rationalization of forest management. The use of digital techniques can allow stock assessment, timber demand planning, and real-time order status tracking. This can improve the sustainability of forest management.

Chapters eight and nine cover, respectively, the analysis of the possibilities of developing the bioeconomy in Spain and a review of biotechnological processes, mainly in the field of cultivation for bioeconomic purposes, implemented in sub-Saharan Africa. The choice of bioeconomy countries is not accidental and allows for comparison of the bioeconomy status in a developed country and in developing countries.

The state of advanced research on bioeconomy, especially technologies in this area, is at an early stage. I hope that it will be possible to return to the initial intention of the publishing house and soon develop a book covering all the conditions of bioeconomic processes, taking into account all environmental, technical, and socio-economic aspects.

On behalf of the authors, I thank Ms. Sandra Maljavac, Author Service Manager at IntechOpen, for her great commitment and patience in managing this project. This led to the publication of this important book.

I also thank Dr Piotr Wieczorek from the Automotive Industry Institute for the verification of the English versions of the materials contained in this book.

I devote this book to the memory of my wife Danuta.

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Chapter 1

Introductory Chapter: Objectives and Scope of Bioeconomy

Krzysztof Biernat

1. Introduction

As a result of the review of the implementations and research works conducted in many countries aimed at intensifying the processes of using RES, it turned out that these works are dispersed and do not bring the expected effect, both in the environmental aspect and in terms of energy conversion savings. For this reason, the vision of an industry based on raw materials of biological origin was created in the European Union, which also included waste substances from primary and secondary processes of biomass utilization and processing, as defined in Directive No. 28. The implementation of this vision should lead to the transition toward the so-called "post-oil" society, by clearly separating economic growth from resource depletion and environmental impact.

After consultations conducted in the member states, the need to separate a new industrial branch defined as a bio-based industry ("Bio-Based Industries") [1] was defined, which should strive to optimize land use and food safety through sustainable, efficient (effective) raw materials and to a large extent limit the amount of waste generated and industrial processing of the European renewable raw materials into a wide range of products of biological origin such as:

- Advanced transport fuels
- Chemicals
- Materials
- Food and feed ingredients
- Energy

As a result, "bio-industry," which is one of the core elements of the EU economy known as "bioeconomy," will play an important role in stimulating sustainable growth and making Europe more competitive through the reindustrialization and revitalization of rural areas, thus providing tens of thousands of jobs in the areas of research, development, and production over the next decade.

The bioeconomy program for Europe is going to be an evolutionary program. It is planned to develop the so-called value chains, whose implementation will eventually lead to the so-called biorefinery, which will process biomass in a comprehensive and waste-free manner. Thus, the most important technological, political, and market challenges will be before the commercialization of innovative solutions on a full scale. These challenges cannot be overcome by individual companies or the dispersed industry, so a systemic approach to the entire biomass management system is necessary. This is important due to the need to reverse the current trend of significant bioeconomic investments in non-European regions where conditions seem to be more attractive. A long-term research and innovation program jointly funded by public and private entities can help solve this problem. This process will be implemented through the creation and implementation of appropriate value chains, which will lead to a reduction of investment risk in demonstration projects in the field of implementation of innovative processes.

This study is the result of analytical work of the Author's Team, completed with an internal report [2] and publication [3].

2. The concept of bioeconomy

Bioeconomy is defined in various ways. Therefore, the definition of the bioeconomy included in the Communication of the European Commission on 13 February 2012 of the European bioeconomy was adopted as a basis. According to this definition, the bioeconomy involves the production of renewable resources of biological origin on land and in the sea and the use of these resources and waste streams to produce value-added products such as food, feed, bioproducts, and bioenergy. Bioeconomy based on the use of renewable resources of biological origin is to gain a new character due to:

- Renewable resources
- Resources with low greenhouse gas emissions or neutral in this respect
- Resources repeatedly used (cascade) in production processes
- Resources with high potential for beneficial properties with respect to end products, such as lower or no toxicity, higher stability, higher durability and strength, limited water consumption, etc. [4]

The bioeconomy should include the agricultural, forestry, and fisheries sectors and all related sectors of the economy (production of food, feed, wood and paper, biofuels, etc.). The new approach to this economy should strive to implement innovation (research and innovation at the interface of many different sectors and industries) in combination with the industrial application of biotechnology [5]. The priority of the bioeconomy should be the economic growth achieved on the basis of traditional and new (emerging) industries based on biosurants. This increase will be realized through the creation of new value chains based on resources of biological origin that will provide high value-added products to the market.

The activities necessary for the development of the bioeconomy include, above all, research and innovations going beyond particular sectors, a coherent policy, and defined bioeconomy strategies at the level of countries and regions as well as international and intersectoral cooperation. The basis for the development of the bioeconomy should be intensified primary production. The goal and tool will also be the creation and development of new markets and the likely increase in the competitiveness of the entire economy. **Figure 1** presents the optimistic evolution of the economy in relation to the resources on which it is based [6].

The emergence of the post-oil society is, however, subject to many conditions related to the current state of the technology of converting fossil resources into

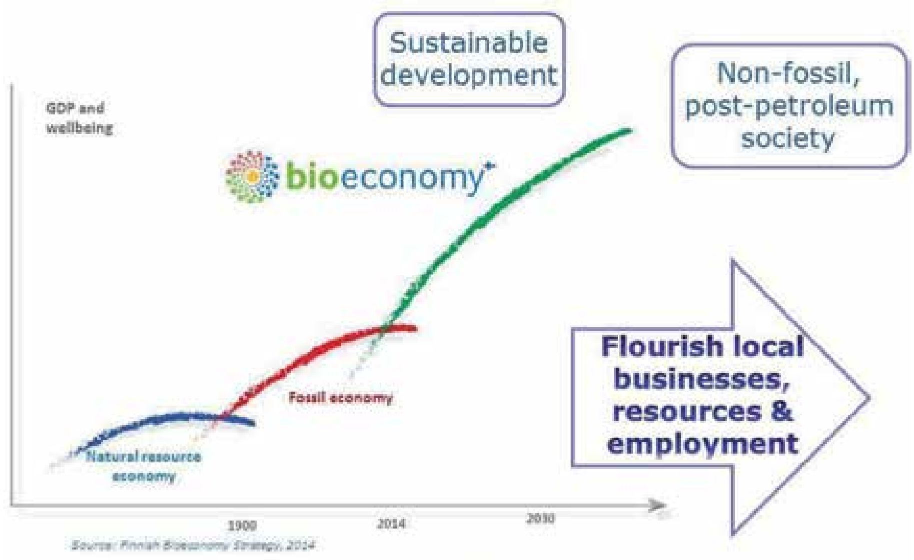

Figure 1.
The concept of transition through successive stages of economic development in relation to resources [6].

widely used products, as well as the continuous development of these technologies in terms of obtaining protection of growing social needs. Processing of fossil resources is a huge area of the global economy, whose transformation or extinction of specific sectors of this economy may be difficult or even impossible. Biomass resources as the basis for the bioeconomy, and more broadly the so-called "green economy," can be a substitute for fossil fuels, not only for energy applications but also for the production of chemicals and materials. However, biomass is also of great importance in natural environmental processes. Estimates of biomass availability for industrial purposes usually do not take into account environmental needs and are definitely overestimated. Biomass is traditionally used as a raw material for the production of, for example, wood products, in the cellulose-wood industry, and natural fibers, and as a raw material in the biofuel industry (oily, starchy, and sugar raw materials). Therefore, taking into account the environmental needs necessary to meet environmental needs, only waste from the above areas of biomass utilization should be used, and substitute materials in these industries should be considered to reduce the demand for primary biomass. Therefore, the vision presented in **Figure 1** will probably be shifted on the timeline, and the shape of the bioeconomy curve will probably be significantly flattened. Nevertheless, in a modern bioeconomy, one should strive to ensure the sustainability of biomass production and utilization processes, the efficiency of these processes, and the scaling effect in relation to mobilizing possible environmentally safe resources [5].

The bioeconomy should respond to the following challenges [4]:

- Feeding the growing population (9 billion people by 2050)
- Launch and use of the production potential of the seas and oceans
- Economic strengthening of coastal and rural areas
- Intensive development of markets based on resources of biological origin

3. Implementation of the concept of bioeconomic processes

The implementation of bioeconomic processes requires a change in the approach of both the industrial sector and the policy of governments in individual countries. It is also necessary to deepen the transformation of social awareness toward the need to consume products from these processes. In European Union countries, the implementation of bioeconomic processes through public-private partnership began. This partnership is to operate in the following areas, through:

1. Construction of new value chains based on the development of sustainable biomass collection and supply systems with increased efficiency and better use of biomass resources (including cogeneration and by-product management) while using and valorizing waste and biomass

2. Adaptation of existing value chains to a new level, by optimizing the use of raw materials and industrial side streams while offering innovative value-added products, thereby creating market demand and strengthening the competitiveness of EU forestry and industry

3. Bringing technologies to the state of advancement through research and innovation, as well as through the modernization and construction of demonstration and flagship biorefinery installations that are already processing biomass in the direction of obtaining innovative products of biological origin [7]

Taking into account the limited resources of biomass and the need for its processing by the agri-food industry, technological processes should be implemented in a way that does not limit the production of food of an appropriate quality and quantity.

In pursuing the set goals in accordance with the developed value chains, the partnership shall ensure the availability of sustainable and safe supplies of biomass, both for food and feed applications and for the production of chemicals, materials, fuels, and energy. It is also necessary to increase the productivity and efficiency of biomass from agricultural land and forests, but in a sustainable way, while taking advantage of the potential of residues and by-flows as well as waste. Currently, it is desirable to work on the optimization of the use of the existing raw material (forest and agricultural biomass), the development of new raw material supply chains (e.g., forestry waste, agricultural waste, lignocellulosic or special crops), and the use of side streams of organic industrial and municipal waste. Providing new markets for biomass producers will strengthen rural economies and allow for further development and investments in a sustainable production system. Because the efficient processes of biomass and biodegradable waste conversion have not yet been developed in a way that enables their commercialization, it is necessary to plan solutions to these problems by conducting further research and creating demonstration technologies.

4. Strategic Innovation and Research Agenda (SIRA) in the area of bioeconomy

As part of the preparatory work for launching European activities in the field of bioeconomy, the Strategic Innovation and Research Agenda (SIRA) plan was developed. This document proposes a coherent set of actions that should lead to an intensification of the implementation of the bioeconomy development concept:

- Implementation of projects aiming at the integration and implementation of technologies and results of scientific research and the introduction of technology on a commercial scale through the implementation of demonstration and flagship projects

- Implementation of development projects aimed at filling gaps in research and technological innovation

- Supporting projects addressing cross-sectoral challenges

Schematically, the value chains are shown in **Figure 2**.

In the Strategic Innovative and Research Agenda (SIRA), these chains have been defined as follows:

1. From the lignocellulosic feed to advanced biofuels, chemicals, and biomaterials, through the selection of raw material base and technology for the new generation of fuels, chemicals, and materials

2. Utilization of the full potential of forest biomass through rationalization of afforestation and rebasing as well as creation of new markets and value-added products

3. The use of agro raw materials enabling durability of production through effective agricultural production as well as new markets and value-added products

4. Waste management, through the implementation of sustainable technologies to transform waste into valuable products

5. Integrated biorefineries as a means of sustainable production of bioenergy, including biofuels, biomaterials, biochemicals, etc.

The first value chain includes new or improved profitable lignocellulosic biomass sources with higher efficiency in production (fertilizers, water use, logistics) and/or improved processing properties in biorefineries. This will reduce the amount of industrial waste and improve environmental impact, helping to reduce pressure on natural resources, as well as European dependence on imports, and increasing rural development. Financial incentives will be created that favor higher incomes for farmers and forest owners, producing biomass at a competitive price. This chain should end with a demonstration of advanced technologies for the hydrolysis and conversion of lignocellulose.

The goals of the second value chain will be achieved by creating new value-added products from the current raw material base by increasing the mobilization of raw materials (forest waste) and improving the use of by-products and waste streams. For this purpose, new innovative and efficient technologies will be implemented, and innovative products will be developed, as well as by-products and residues and valorization of side streams. This will improve the competitiveness of European value chains based on forest industry while reducing pressures on biomass resources. Products from this value chain have a much smaller impact on climate change by exchanging fossil materials for bio-based materials with positive social impact. It will meet both market and consumer requirements and will create new markets by demonstrating the paths and concepts of processing new innovative materials into new products.

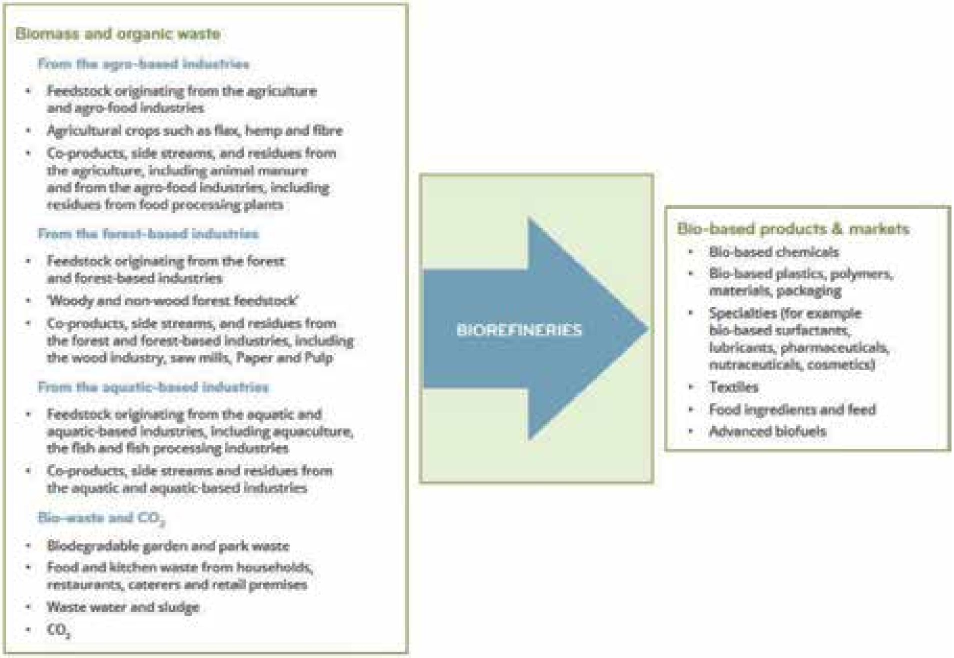

Figure 2.
Value chains in the bioeconomy [8].

The third value chain will be achieved by creating more value-added products from the current raw material base by increasing raw material production and flexibility and making better use of side streams and residues. In addition, new and improved profitable crops with higher productivity in production (use of fertilizers and water, logistics) will reduce industrial waste and improve environmental impact. Innovative and efficient cultivation, harvesting, and logistic technologies will be introduced for existing and new crops, and innovative products will be developed with the use of by-product and residue valorization.

The development and demonstration of value chains based on currently unused streams (side ones) and wastes from various sources of biological origin (agriculture, forestry, sewage management, sediments, municipal organic waste, garden waste, food processing waste, etc.) are the aim of the fourth chain value. The costs of implementing competitive value-added value chains will contribute to creating solutions for the environmental problem of ever-increasing waste flows (partly due to urbanization) while reducing the pressure on unprocessed natural resources and increasing the competitiveness of the industry.

The implementation of the fifth chain should demonstrate an improvement in the stability and economics of bioenergy production through the conversion and integration of biorefineries. The creation of a whole range of value-added products and bioenergy from raw materials will allow a full use of biomass, including unused biomass resources, and will increase the competitiveness of the bioeconomy.

The concept of creating value chains in the “Bioeconomy for Europe” program is shown in **Figure 3**.

The implementation of these value chains should also contribute to the intensification of the so-called primary production, which may result in the potential development of the bioeconomy as a different industrial branch based on the resources of biomass, mainly waste.

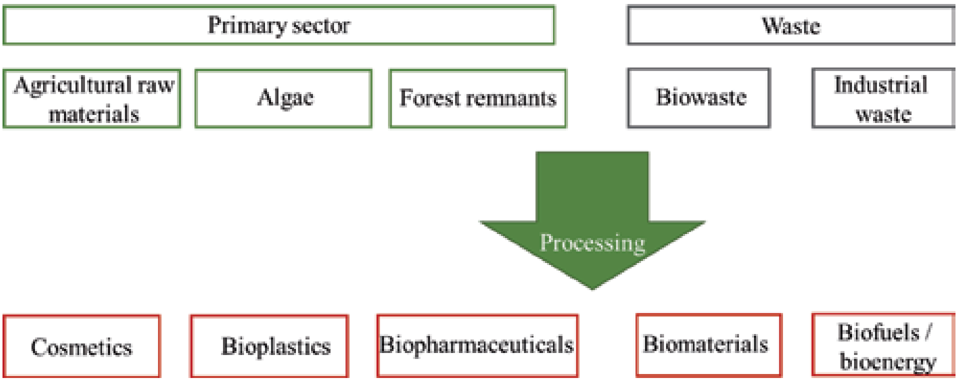

Figure 3.
Examples of value chains based on renewable energy resources [5].

As already mentioned, the proposed value chains capture biomass as the basic source of raw materials in the bioeconomy, also referred to as the "green economy." However, according to the International Energy Agency, the report "IEA Bioenergy, Task 42, Biorefineries" [9] shows that to ensure that the so-called National Indicative Targets can be met for the replacement of conventional fuels with biofuels from biomass, Europe is the second region outside the Japan, which must import biomass as a raw material for the production of these fuels. Irrespective of this, it is not clear what share of waste biomass from natural processes can be used as a raw material for bioeconomic processes, without creating environmental threats for the proper course of these processes. Also in the field of energy carriers, other sources of waste biomass as the main raw material are considered, i.e., waste biomass from industrial processes, including biodegradable waste from agriculture, wood management, food industry, etc. For the same reason, it is proposed intensifying the development of production technologies for other alternative fuels (other than biofuels), which may enable more efficient use of biomass as a shortage resource, mainly for the production of semifinished and high value-added products, replacing and then displacing petroleum and coal.

5. Bioeconomy in the circular economy cycle

In terms of the concept of economic development of highly industrialized countries, in order to meet the requirements related to sustainable development taking into account environmental requirements, it is proposed to create an economy with the so-called circular economy, which is to complete the life cycle of the product characterized by "life cycle assessment" (LCA) for this product. In short, you can define this cycle as a succession of processes: obtaining raw materials; production; operation; and utilization of post-mining waste, i.e., from cradle to grave (CtG). The closed cycle economy proposes the "cradle to cradle" (CtC) cycle, reusing post-mining waste to produce new (new products). This approach will result in reducing raw material consumption, reducing the amount of waste deposited and increasing the waste stream used for recovery and recycling. The course of such a cycle has been illustrated in several contemporary publications, while the economic closed loop can be considered interesting. In this perspective, the bioeconomy can mean much more than the circular economy, because agriculture, forestry, and fisheries or the primary sectors of the economy are the source of production of the raw material, i.e., biomass. In accordance with the anticipated value chains of bioeconomic processes, waste biomass should be processed primarily for value-added products such as food and feed, chemicals, and materials from which bioproducts are produced, and biofuels and bioenergy should be obtained from the untraceable residue at today's level of technological profitability. However, it is not entitled that the bioeconomy means more than a circular economy, as shown in **Figure 4**.

As shown in **Figure 2**, all value chains lead to high value-added products through the so-called biorefinery processes. These processes lead to obtaining, through various technological variants, substitutes for hydrocarbon mixtures, which can be used to synthesize or compose the desired products using various technological processes. The analysis shows that it is possible to obtain many products with the desired and high added value, as shown in **Figure 5**. However, obtaining these products from waste biomass, coming from various industrial processes, may still generate waste substances, whose further processing is required. It will be the development of new technologies; in each case the processing of energy carriers causes emissions to the atmosphere, which in the full and real technical life cycle are usually greater than the absorption of carbon dioxide in photosynthesis processes. Regardless of the emission of carbon dioxide, it is also possible to emit other gases depending on the type of technological processes. Practically, a fully closed-loop economy lasted until the primitive human used natural stone or wooden branches as tools. From the stage of wood and stone processing, the era of waste generation began, and, therefore, the circular economy has ended. While the waste from woodworking was subject to natural biodegradation, wastes from stone processing and later from the manufacture and treatment of metals increased the effect of charging the environment with wastes resulting from the needs of humanity, up to the industrial era, which lasts until now. For these reasons, a fully circular economy seems to be impossible to achieve, because each new type of technology creates a new group of waste, for which another new technology is required for processing,

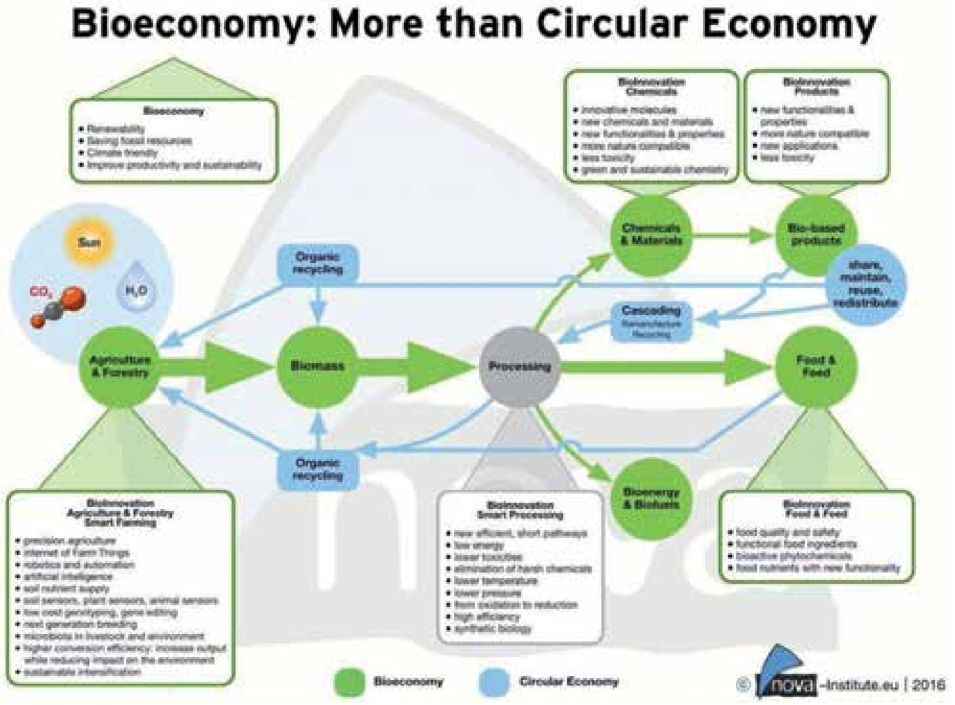

Figure 4.
Bioeconomy in the circular economy system [10].

including waste, etc. It is only possible to reduce the amount of waste by increasing efficiency of processes or modifications of technological processes toward the production of semi-products that can be directly used. One should therefore strive for an economy with a closed circulation so that the waste migration gap is as small as possible. For the above reasons, it can be concluded that the biorefinery processes presented in **Figure 5** are aimed at the so-called bioeconomy with a closing circle.

Biorefinery processes in terms of adherence to the principle of optimal use of resources from the so-called renewable sources have been widely discussed in [12]. In the current state of progress in the field of technology, assessed on the basis of bibliography [12, 13], the item [12] also includes thermodynamic aspects of biomass transformation as a natural source, and own works allow to determine the basic and desirable directions of technological use of biomass (waste) according to the initial LCA analysis carried out, as shown in **Figure 5**.

As can be seen in **Figure 6**, there are currently three paths for using waste biomass. The first of these paths proposes the transformation of biomass into

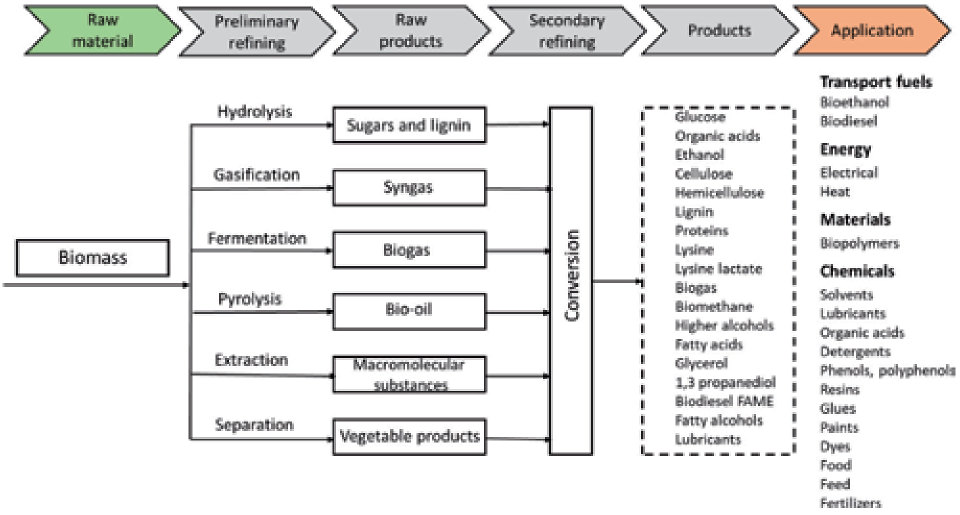

Figure 5.
Technological paths for obtaining products from biorefinery processes [11].

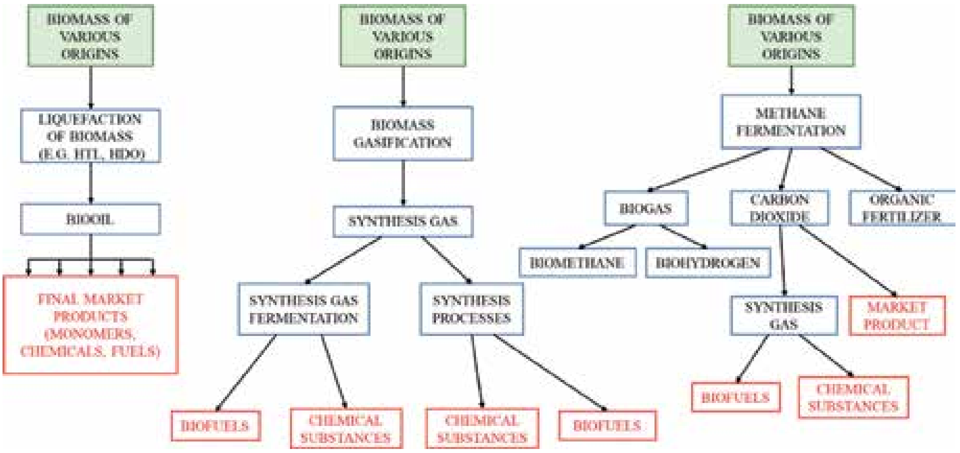

Figure 6.
Currently possible directions of biomass conversion in bioeconomic processes [14].

a so-called "biosurge," having characteristics of petroleum. Without going into the complexity of further processes, it is possible to convert bio-oil into products analogous to products obtained from crude oil, using comparable technologies. The second path is the path of biomass gasification, which results in synthesis gas fermentation processes leading also to the formation of isoprene structures and the possibility of further synthesis of various types of chemical compounds as well as biofuels in processes. The third track is based on the use of methane fermentation processes, which is important in many processes of using waste biomass from agricultural processes and wastewater management.

6. Conclusion

The concept of bioeconomy in the full range of potential possibilities of this industrial branch has not yet been clearly defined, especially as regards the availability of raw materials, their types, and technological possibilities of their processing while minimizing environmental impacts. In available sources, as well as in this monograph, the proposed paths of bioeconomic processes concern mainly biofuel technologies, not including identification of other bioproducts and technologies for their production. In the teams dealing professionally with the problems of the bioeconomy, two basic concepts are being clashed. The first one involves the transformation of biomass toward the production of biofuels or bioliquids, and post-process residues convert to biochemicals and other value-added products. This view is motivated by the already mastered technologies of "biomass to liquid" (BtL) and "waste to liquid" (WtL) processes, while biomass processing technologies for biochemicals, bio-plastics, and other products are just being developed. The second concept involves the implementation of processes leading to the separation of possible value-added products from biomass and the remainder subjecting WtL and "waste to energy" (WtE) processes to obtain energy carriers or directly energy for process purposes.

The economic efficiency of bioeconomic processes is still small. Due to the technological complexity, comprehensive technological processes, especially full biorefinery systems, still require research, which makes their implementation more expensive. It seems advisable to gradually adapt or retrofit existing oil refineries and petrochemical plants to the possibility of converting biomass to bio-oil [biosecure, e.g., in "hydrothermal upgrading" (HTU)] and further processing into fuels and value-added products using existing installations and technologies used, which would significantly reduce costs.

Bioeconomic processes may contribute to increasing the use of land, not yet used up to around 35% in 2030, which may cause an increase in biomass supply. The results of the implementation of the bioeconomy program may also contribute to the maintenance and further development of a competitive knowledge-based rural economy and the creation of new qualified jobs, including more than 80% in rural areas, relatively underdeveloped.

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Chapter 2

Life Cycle Assessment as a Tool to Implement Sustainable Development in the Bioeconomy and Circular Economy

Izabela Samson-Bręk, Marta Gabryszewska, Justyna Wrzosek and Barbara Gworek

Abstract

In this chapter, the life cycle assessment was presented as a tool to implement sustainable development in the bioeconomy and circular economy. Bulky waste includes large items such as furniture, doors, flooring and mattresses. The management of bulky waste is a serious problem for European countries. The URBANREC project proposed a solution to this problem through the use of new technologies for the bulky waste processing. The aim of the URBANREC project is to implement an eco-innovative, integrated system of bulky waste management and demonstrate its effectiveness in various regions of Europe. The project has received funding from the European Union. In this chapter, the LCA environmental analysis was performed for the technology of grinding bulky waste using a water jet by the Ecofrag company. The calculations were carried out using SimaPro 8.5.2.0. The LCA analysis shows that the reuse of foams and mattresses contributes to the avoidance of their targeted production, which is related with the reduction of greenhouse gas emission and consumption of fossil raw materials.

Keywords: LCA, sustainable development, bioeconomy, wastes, recycling

1. Introduction

Environmental life cycle assessment (LCA) is a technique designed to assess the environmental risks associated with the product system or activity either directly by identifying and quantifying the energy and materials used and the waste introduced into the environment or indirectly by evaluating the environmental impact of such materials, energy and waste. The assessment relates to the whole lifespan of the product or activity, from the mining and mineral material processing, product manufacturing process, distribution, use, reuse, maintenance, recycling up to the final disposal and transportation. LCA directs the study of environmental impact of the product system to the area of ecosystems, human health and the resources used.

In this chapter, the LCA method will be presented as a one of the tools to implement the principle of sustainable development in the bioeconomy and circular economy. In the economic model currently proposed in the European Union, resources are to be used more sustainably. Closing the life cycle of products by boosting the level of recycling and waste reuse will be highly beneficial, not only to the environment but also to the economy.

Taking into account the dynamically developing economies of the European Union Member Countries, and thus increased demand for raw materials and energy, the European Commission has adopted a new ambitious circular economy package. It is intended to help European businesses and consumers move to a stronger economy, where waste will be a valuable resource base for production processes. The proposals cover the whole life cycle of products: from production and consumption to waste management and the secondary market of raw materials. Implementation of the above strategies will allow for maximizing the use of all raw materials, products and waste and will be conducive to energy savings and reduction of greenhouse gas emission. In this chapter, the results of the life cycle analysis of a large-scale waste recycling, conducted as part of the URBANREC project, are presented as an example of the LCA method application.

2. Sustainable development in the economy

Since some years concerns have been raised about the economic development, the current rate of which can no longer be maintained that, in turn, may result in the incapacity to meet the demands of modern societies. Particular concerns are associated with the predatory use of natural resources, rooted in the incessantly growing consumerism and the lack of constraints on resource use. It is hoped that sustainable reconstruction of industrial society [1] may provide a remedy to mitigate the effects of human pressures. Within this context, the ‘economy of sustainable development’ has found its place in shaping a new social, economic and economic order.

Traditional economics itself is a social science characterized by a comprehensive spectrum of research problems of varying importance, from fundamental to detailed ones, from theoretical considerations to application recommendations [1]. Until recently, the economy was mainly interested in the pursuit of solutions that will enable the economic and social development. However, the newly emerging and hitherto unknown problems, with which the traditional economy is unable to cope, have led to the advent of new research projects that helped to single out the new types of economics, including the economy of sustainable development. They are collectively defined as sustainable science.

One of the main questions that the modern economy is trying to answer, is how to manage natural resources to ensure that all human needs are met and, at the same time, the regeneration of the natural environment and biosphere functioning are not affected? The economy of sustainable development also seeks to define conditions that would ensure a high ecological (environmental), economic and sociocultural standards, for both the present and future generations, within the limits of tolerance and regeneration of the nature, thus implementing the principle of intra- and intergenerational justice.

Economists dealing with sustainable development can see very clearly the relationship between the condition of the natural environment and the intensity of using its resources, as well as between the economics and the economy. The following major relationships and problem areas referring to the sustainable development economy can be enumerated:

- Climate warming → lack of economic stability

- Destruction of ecosystems → insufficient satisfaction of basic people’s needs, increase in prices of goods

- Overexploitation of nonrenewable resources (mainly energy raw materials) → inflation, economic imbalance, dependence on raw material supply, economic development slowdown and increase in prices of goods and services

- Overpopulation → increase in prices of land and basic goods, insufficient satisfaction of basic needs of people (mainly water and food)

Numerous studies by environmental economists have proved the existence of socioeconomic factors that prevent the wise management of natural resources [1–6]. The following groups of determinants can be identified [1]:

1. Environmental costs, subject to externalization

2. Natural resources treated as public and openly accessible goods

3. Other socioeconomic factors, such as world population growth, continuous economic development, consumerism and, ultimately, psychological barriers

In order for the market self-steering mechanism to work, it is important that all costs associated with the production, use and disposal of a given good (including the costs of damage to the natural environment) are included in the final price of the product. If this is not the case, because part of the costs has been externalized or transferred to other entities (taxpayers, future generations or nature itself), then they are misallocated, and the goods are sold below their real price.

Reasons underlying cost externalization are numerous. The key ones include, first of all, the fact that environmental resources are treated as open access goods implying that anyone can use them unrestrictedly and shifted the responsibility for resulting damage onto others, in this case, onto the future generations. People are not willing to incur the costs of environmental impacts, in the hope that others will pay them.

Natural resources are often regarded as public goods, which can be used without major restrictions. We do not handle common goods rationally, economically and with due care as we deal with private property. This is, naturally, based on an erroneous assumption that has become evident particularly at present, when we have to deal with the overuse of nonrenewable raw materials, and consequently, with growing competition over access to these resources. Natural resources are slowly becoming rare goods that are already reflected in their market price. This price will gradually increase, and it is the future generations that will be hurt with a highest burden, being additionally charged with the follow-up costs. We are capable of predicting and estimating these costs; however, the prospect of the future for the present generations is so remote that we are far from long-term thinking and preventing future costs right now. Thus, one of the fundamental principles of sustainable development regarding the intergenerational justice is being violated.

In environmental economics, in addition to cost externalization and the problem of treating natural resources as public goods, there are the so-called other socioeconomic determinants, which include, among others, world population growth, continuous economic development, consumerism and, finally, psychological barriers.

The steady population growth globally entails a number of problems resulting mainly from the rapidly increasing demand for food, drinking water, energy resources, habitable land and advancing deterioration of the natural environment. In the fight against the ongoing degradation of the ecosphere, limiting the population growth seems to be indispensable. However, these are the radical actions that countries in the world are not yet ready for.

Another important determinant is the exponential increase rate of economic development and of related consumerism. Continual growth of needs of modern society translates into unimaginable resource exploitation and environmental burden. Developed countries are at the cutting edge of certain styles and trends that strongly affect developing countries. However, the desire to possess seems overwhelming at the moment, while demand and supply will continue to grow.

The so-called psychological barriers [1] constitute an interesting social phenomenon. This is a relatively new aspect, since the interest in the environment and its condition has also a short ancestry. People are reluctant to change their routines and habits, and fear of the unknown is often a limiting factor when introducing changes. Only a small percentage of people are willing to engage in new activities. A good example is entrepreneurs who, under the Environmental Protection Act, are obliged to incur the so-called fees for economic use of the environment (introduction of dust and gases into the air, water intake, waste generation, etc.).

In most cases, the entrepreneurs consider this obligation to be another legislator's invention, which was created to make their life more complicated. They are unaware that they are obliged by the statutory 'polluter pays' principle [7], while the environment is a public good, which does not mean that it is no one's good.

It should be clearly emphasized that the damage to the environment in the twenty-first century consists primarily in the predatory economy of fossil raw materials. This is due to the socioeconomic and economic factors mentioned above. One of the goals of the economics of sustainable development is to identify the most important economic and economic problems, define their causes and propose socially acceptable or necessary solutions. It is also important to undertake attempts at monetary evaluation of the environment and its resources as well as the goods produced. Thanks to the introduction of economic aspects into the idea of sustainable development, it is possible to lay new foundations of economic thinking, and to define economic conditions that will ensure appropriate economic, social and environmental standards.

3. Circular economy—contemporary economics of sustainable development

Circular economy (CE) is a concept that has forced its way into the dictionary of European business, at the same time increasingly displacing the term 'sustainable development', well-known for many years. CE is to be a response to the multiple challenges of the modern world, economic, environmental and social ones.

This new economic model is based on the assumption that the value of products, materials and resources in the economy is to be maintained for as long as possible to ultimately minimalize waste generation. Efficient use of resources is the priority of the circular economy. In this concept, raw materials are repeatedly recycled, often passing from one branch of industry to another. Therefore, it is about closing the product life cycle and transition from the linear economy model (raw material acquisition-production-use-waste use as raw material) to the closed circuit model (production-use-use of waste as raw material in the next production cycle).

Preventing and reducing food waste in households should be a key priority for both scientists and politicians. To achieve the goal of reducing global food wastage, a campaign should be implemented raising awareness on the gravity of food waste problem and the need for prevention. In Europe, the reduction of food waste is a key area of the circular economy [8, 9]. A huge challenge in this context is recycling of plastics. Equally important is the social acceptance of new products made of recycled plastic [10]. The concept of circular economy is now widely discussed within the

European Union (EU); however, the implementation of its assumptions in the Member Countries faces difficulties due to market and political barriers. The main legal barriers to the circular economy include regulatory provisions that hinder the implementation of the concept and the lack of global consequences. The main market barriers comprise low prices of primary materials on the market, limited standardization and high initial investment costs [11]. Companies do not tend to engage in activities for environmental protection as the latter have not been identified with increasing the company's profit and competitiveness [12]. Technological progress in the field of digitization may accelerate the transformation towards a more sustainable circular economy [13].

The response to the legislative needs of the above mentioned new management model was the set of proposals, announced by the European Commission (EC) in 2015, as the circular economy package. The proposals included in the package aimed at reconciling environmental and business interests. The package was a clear signal for business entities that using all available tools to fully implement the new ecological and raw materials policy was one of the European Union's priorities.

The package includes a strategy to make plastics and plastic products easier to recycle and biodegrade, as well as to reduce the presence of hazardous substances in plastics and to significantly reduce the amount of marine waste.

The package proposes also new rules on fertilizers to encourage nutrient recycling, while ensuring the protection of human health and the environment. A number of actions have also been foreseen for water reuse, as well as the review of legislation concerning ecolabelling (Ecolabel) and Eco-Management and Audit Scheme (EMAS).

The CE package includes also proposals to set new waste management targets to be achieved by 2030, aiming at a significant increase of the levels of waste recovery and recycling as well as a significant reduction of municipal waste landfill. Packaging waste, in addition to, among others, food waste, construction and demolition waste, biomass and bioproducts have been included in the priority areas requiring special attention of the EC.

The potential contained in waste is not only a great opportunity but also a challenge for attaining the vision of the European economy—sustainable, low emission and resource efficient, where raw materials are returned to circulation and waste generation is minimized. Unfortunately, still more than half of the waste generated in EU households ends in landfills or in waste incineration plants.

The EU waste legislation already provides a good foundation for building a circular economy model. The waste management hierarchy, which has been binding the EU countries for years, was formally defined by the Waste Framework Directive of November 19, 2008 (2008/98/EC). The directive instructs the order of implementing priorities, set in legal regulations and strategies, highlighting the importance of waste prevention and management. Only further priorities are assigned to waste recycling and recovery (including energy recovery) and finally neutralization, i.e., storage or thermal disposal (combustion without energy recovery) [14].

According to EU Directive 2018/851 of 30 May 2018 [15], Member Countries should introduce measures to promote the prevention and reduction of food waste. They should seek to achieve an indicative Union-wide target for reducing food waste by 30% by 2025 and by 50% by 2030. Those Member Countries that prepared for reuse and recycled less than 20% of municipal waste in 2013, or submitted landfill of more than 60% of municipal waste, should be able to decide whether to extend the periods to achieve targets for preparing for waste reuse and recycling set for 2025, 2030 and 2035. In the EU Directive of 2018, new targets were set for municipal waste preparation for reuse and recycling, a minimum of 55% by 2025, a minimum of 60% by 2030 and a minimum of 65% by 2035. Member Countries will implement a selective collection of at least paper, metal, plastics and glass, and from 1 January 2025—textiles.

According to official EU statistics, the aggregated amount of waste generated in the EU countries by all sectors of the economy as well as households amounted to 2.5 billion tonnes in 2014. It was the largest amount recorded in the years 2004–2014. Nearly 35% of the above was generated by the construction sector. The mining sector and mining activities are responsible for the next 28% of waste, while industrial production and wastewater treatment are responsible for 10% and 9% of waste mass, respectively. Household waste is only in the fifth position—with 8.3% of the total weight of waste generated in Europe.

One of the EC's priorities will be finding effective options to manage municipal waste. Unfortunately, as many as 54% of municipal waste in the EU is subject to landfilling or thermal transformation. Only about 28% is recycled and another 16% composted.

How the amount of waste generated in the EU countries has changed is shown in **Figure 1**.

Growing population numbers and increasing production of consumer goods make the life span of products shorter, thus causing an increasing problem with emerging waste. It can be assumed that the amount of waste generated

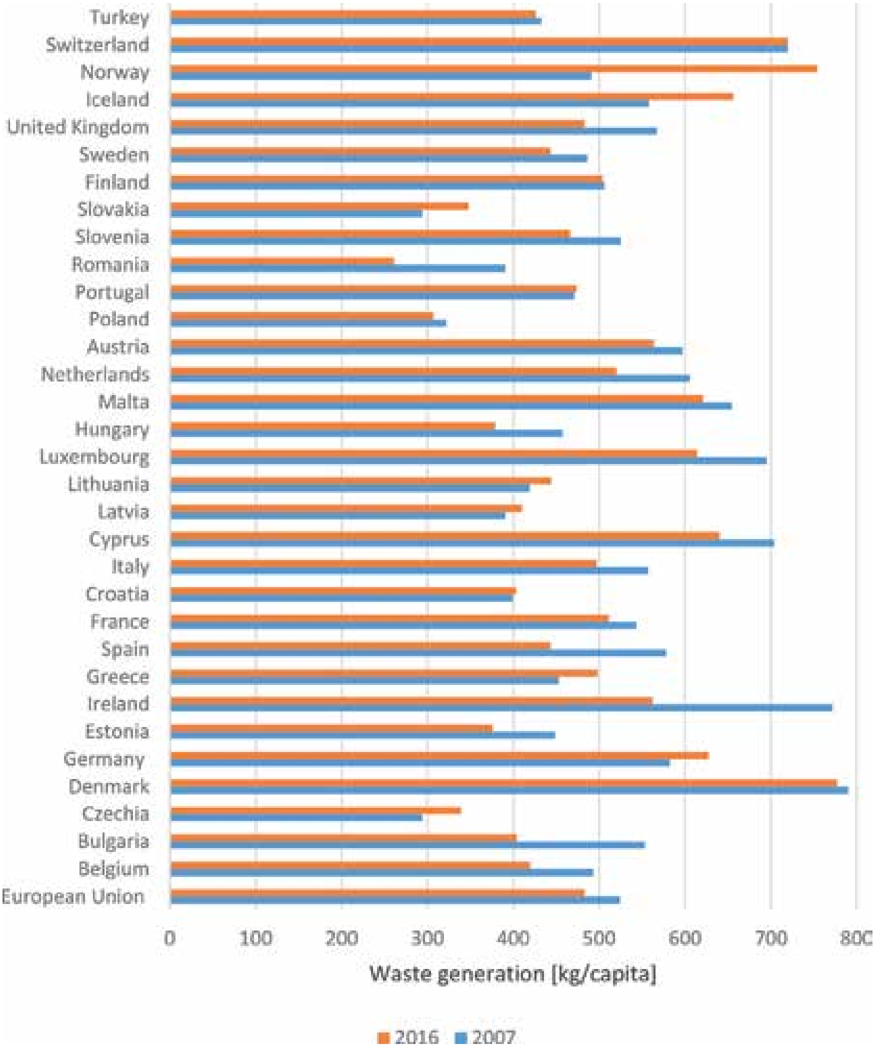

Figure 1.
Per capita waste generation by country, comparison between years 2007 and 2016 (data from Eurostat [16]). In the case of Ireland, data are for 2007 and 2016.

approximates, to certain extent, the gross national income per capita in a given country. In Poland, the per capita amount of waste in 2007 was 322 kg, while in 2016—307 kg, whereas in Denmark these amounts were by half higher, 790 and 777 kg, respectively (**Figure 1**) [16]. The lowest per capita amounts of waste, in 2007–2016, were recorded for Romania, Poland, the Czech Republic, Slovakia, Latvia and Estonia (**Figure 1**). The group of countries where waste generation is highest embraces the more developed countries, such as Denmark, Norway, Switzerland and Iceland. At the turn of 2007–2016, in most European countries, a reduction in the amount of waste generated per one inhabitant was observed, including in Belgium, Bulgaria, Poland and Ireland. In the same period, in other countries, there was an increase in the amount of waste generated (Norway, Iceland, Greece and Germany) [16].

The indicator (illustrated in **Figure 2**) measures man-made emissions of greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons, nitrogen trifluoride (NF_3) and

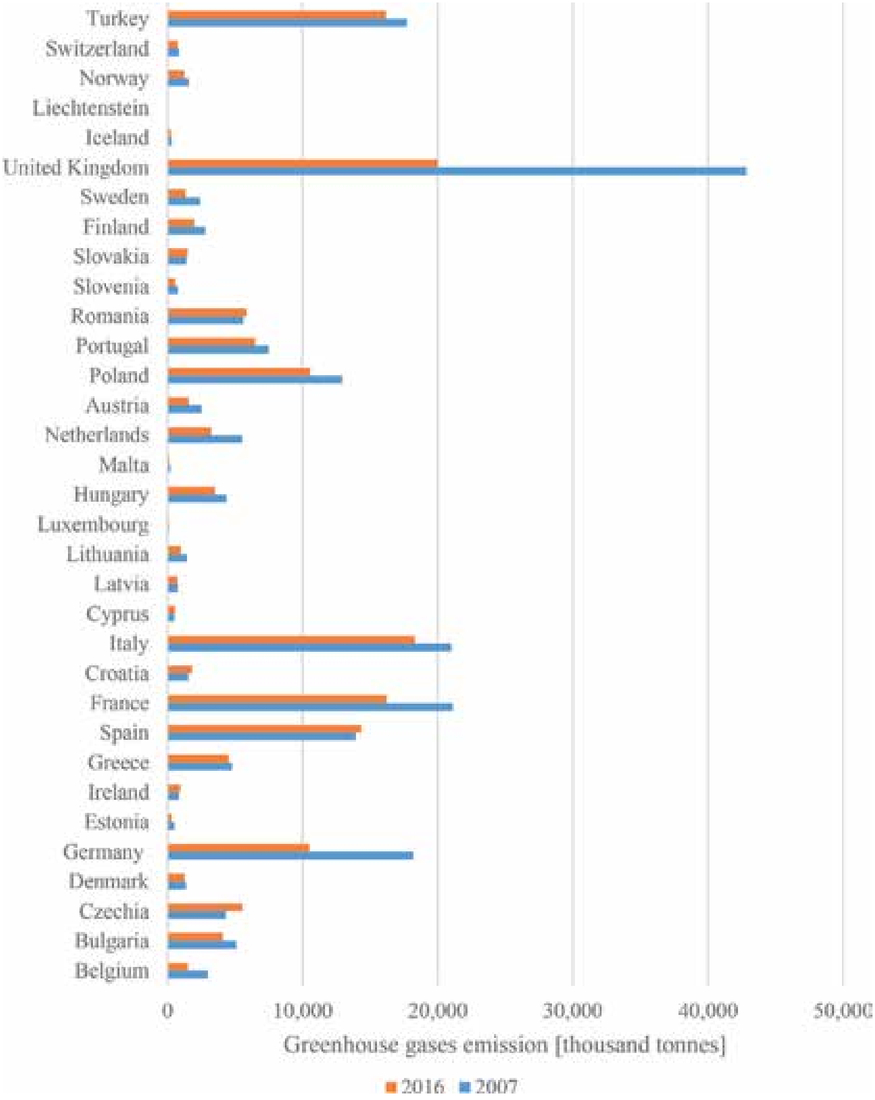

Figure 2.
Greenhouse gas emission from the waste management sector expressed in CO_2 equivalent (Source: Eurostat [16]).

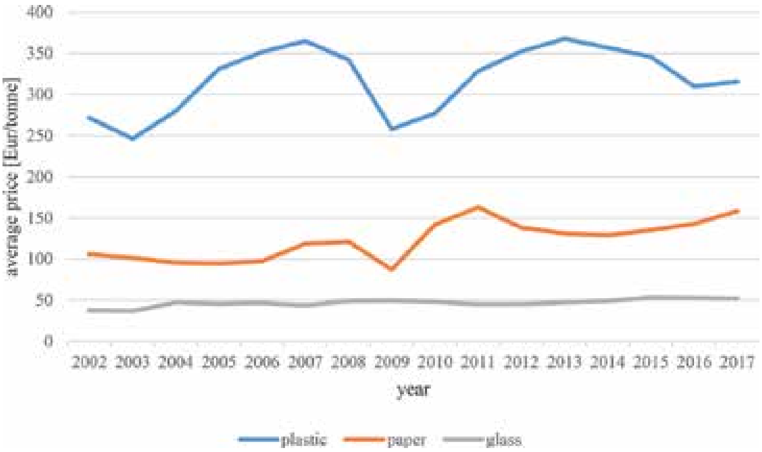

Figure 3.
Price changes of recyclates: plastic, paper and glass (data from Eurostat [17]).

sulphur hexafluoride (SF_6). The global warming potential (GWP) is for each gas individually integrated into a single indicator expressed in CO_2 equivalent units. This also indicates that, when there is a proper waste management, the greenhouse gas emission might be lower in the countries generating large amounts of waste, as compared to those producing low waste amounts, e.g., Denmark and Spain.

In the USA, the US Environmental Protection Agency noted that greenhouse gas emissions from waste landfills amounted to 115.7 Mt of carbon dioxide equivalent in 2015 [18].

The way to reduce greenhouse gas emission and to efficiently use raw materials is the closed circuit waste management. One of the waste management methods is recycling. Apart from being beneficial to the environment, recycling delivers financial profits to waste management companies. In **Figure 3,** the trends are shown for prices per ton of paper, plastic and glass over the past 15 years. Despite a significant drop in prices in 2009, one can notice an upward price trend per ton of recycled waste.

4. Environmental life cycle assessment in the circular economy

Environmental life cycle assessment (environmental LCA) is defined as a methodology to identify and assess potential environmental impacts associated with all the stages of a product's (good's) life. The life cycle should be holistically understood: from extraction of raw materials necessary for the production of a given good through the production process, transportation and distribution to the final management of the waste generated [19–23].

One of the most frequent definitions of environmental LCA, encountered in the subject literature, is the definition proposed by Fava et al. [24]; consistent with this definition, the environmental LCA is a method designed to assess environmental risks associated with the product system or activity, either directly, by identifying and quantifying the energy and materials used and the waste introduced into the environment, or indirectly, by evaluating the environmental impacts of such materials, energy and waste. The assessment embraces the whole lifespan of the product or activity, from the mining and mineral material processing, product manufacturing process, distribution, use, reuse, maintenance and recycling up to the final disposal and transportation. LCA directs the study of environmental impact of the product system to the area of the ecosystem, human health and the resources used [24].

The basic advantage of the above method is its versatility. LCA has typically been used to evaluate environmental technologies or production processes within boundaries of the 'from cradle to gate' or 'from cradle to grave' systems. The life cycle analyses within the framework of the circular economy concept shall embrace boundaries of the 'from cradle to cradle' system [25].

Depending on the adopted degree of detail of the analysis, it is possible to link all of the unit processes and to assess their impact on the environment, which is particularly important in the case of closing the circuits [26]. It is also possible to quantitatively identify all materials and energy used to produce the product, along with the release of dust and gas emission, noise and radiation emission, as well as the resulting waste, which allows for effective management of the production process and minimizing economic and environmental costs. The life cycle assessment allows for identifying the processes, which generate the largest environmental burden, and consequently, for modifying these processes in order to reduce environmental impacts. Moreover, LCA allows for reducing the economic costs by optimizing the consumption of raw materials (the so-called life cycle cost (LCC)) [27–29]. That is exactly why such a comprehensive and systematic approach to the production process as the LCA has gained wide attention and become a broadly used management method.

In Poland, LCA remains a rather novel method in the environmental management. It is used mainly for R&D purposes and has been developed by R&D centres. Considering the requirements imposed by the EU legislation, as regards minimization of adverse environmental impacts of the fuel industry, LCA seems to be a useful tool for meeting these requirements. The LCA may encompass the whole life cycle of fuel, from raw material mining, all the way through its manufacturing, use, to the processes involved in fuel handling [22].

In Turkey, the LCA analysis was used, for example, to demonstrate which waste management strategy is better from the viewpoint of environmental protection. The results obtained provided evidence that landfilling and incineration were the worst alternatives of waste disposal, while composting and material recovery showed a better performance [30]. Based on the LCA study carried out in Denmark, it was found that the assessment was a good tool for evaluating the household organic waste management system at the Danish-German border, where waste management systems were entirely different [31]. Helene Slagstad and Helge Brattebø demonstrated that waste composition constitutes an important uncertainty in the waste management LCA [23]. Waste composition can affect the total environmental impact of the system, taking into account, especially, the global warming, nutrient enrichment and human toxicity via water impact categories [32].

5. Bulky waste management in the circular economy—LCA results

Considering the constantly growing consumption, and hence the mass of post-consumer waste, there arises a significant problem of waste management. This chapter focuses on bulky waste considering the significant problem of its management.

Bulky waste is a term to describe waste that is too large to fit in ordinary containers. This includes, among other things, furniture, carpets and mattresses. Improper management of bulky waste can pose a large environmental and logistic problem. The waste is atypical since it is largely made of a variety of materials, which have different composition, and thus each may have different effect on the environment and should be treated differently. Considering the above, the main and preferred options for bulky waste management include recycling and energy recovery.

Material and energy recycling issues have been taken as subjects of the European URBANREC project. The project has received funding from the European Union's Horizon 2020. This project will demonstrate solutions for bulky waste management challenges. For the first step, technical solutions will be implemented in two representative European regions: Valencia (Spain) and Harelbeke-Flanders (Belgium). The results obtained will be spread out to other regions. In the first instance in Warsaw (Poland) and Izmir (Turkey), bulky waste management is evaluated in the course of the URBANREC project. The URBANREC project aims to develop and implement an eco-innovative and integral bulky waste management system and demonstrate its effectiveness in different regions. In URBANREC project, Northern, Mediterranean, Eastern and Southeastern areas in Europe are represented by Belgium, Spain, Poland and Turkey, which have very different urban waste recycling rates, from around a 60% in Belgium, 25–30% in Spain or 20% in Poland to less than 5% in Turkey. The URBANREC project aims to advance the separation and disassembling of bulky waste. The project will develop modern waste treatment technologies, such as fragmentation (3D cut). The waste treatments considered in the project include: rebounding and chemical glycolysis for the PUR materials, to prepare renewable adhesives, needle felt to obtain isolation panels from textiles, fibre reinforced composites from textiles, wood plastic composites and catalytic hydro-gasification with plasma for mixed hard plastics to obtain chemicals or fuel. Based on the results obtained, recommendations will be proposed for the new EU regulations as regards bulky waste.

The LCA focuses on demonstration of laminated cutting technology (fragmentation) for separated materials and products. The technology owner is the Ecofrag company.

In URBANREC project, a selection based on waste streams will be made in the civic amenity site located in Valencia to improve the quality of fractions obtained. Critical parameters for selection are defined depending on the waste stream. For mattresses, it is necessary to separate foams as latex, polyurethane or mixed foams. In textiles, different compositions can be obtained like cellulosic fibres—predominantly (cotton, viscose, flax and sisal) and thermoplastic material (PET, PP, PA, multicomponent PET with others, cellulose/thermoplastic blends). Hard plastics will be divided into polyolefin or non-polyolefin. Between the different technologies, laminated cutting technology for grinding will be selected and demonstrated in Valencia. This technique is developed by Ecofrag, and currently is employed as a novel system for fragmentation of PU foam, mixed textiles, mixed plastics, tyres and wood. The recovered fractions that cannot be reprocessed economically within an acceptable quality range (e.g. coated textiles, mix of different types of foams and wood) will be sent to the catalytic hydro-gasification process.

One of the main advantages of the fragmentation system includes lower CO_2 emission due to the reduction of energetic consumption (40–50% in energetic cost), in view of the use of high pressure water as a cutting system. Regarding the fractions obtained, this technology combines two major advantages:

- Clean and differentiated components
- Greater flexibility in sizes and textures that makes easy to recycle obtained fractions

The LCA analysis focuses on the environmental assessment of grinding technology for bulky waste treatment with the use of water stream. As a functional unit, 1 Mg of bulky waste of various types (e.g. PU foam, mixed textiles, mixed plastics or tyres) was adopted. The input data for analysis were provided by the project partner—Ecofrag enterprise.

As a generally applied and common tool, the programme SimaPro 8.5.2.0, developed by Dutch PRé Consultants, was used for the LCA analysis. Within the SimaPro programme, there is an option to select between several dedicated methods of the life cycle impact assessment. The methods vary from one to another, thus when selecting, it is necessary to specify priorities for a given LCA analysis. When selecting the life cycle impact assessment (LCIA) method and impact categories, it is important to take special account of the aim and extent of the analysis [19] and, additionally, of the following way of presenting the end results, way of weighting the individual impact categories, time frame indicated, geographical range, degree of accurateness of the method as well as impact categories included.

Bearing in mind the above, and after analysing the methods available in the SimaPro programme, the ReCiPe (mid-point and endpoint) method was considered to be the most appropriate.

ReCiPe is the most recent and harmonized indicator approach available in the life cycle impact assessment. The primary objective of the ReCiPe method is to transform the long list of life cycle inventory results into a limited number of indicator scores. These indicator scores express the relative severity on an environmental impact category. In ReCiPe we determine indicators at two levels:

- Eighteen mid-point indicators (focused on single environmental problems, for example, climate change or acidification)

- Three endpoint indicators (showing the environmental impact on three higher aggregation levels, being the (1) effect on human health, (2) biodiversity and (3) resource scarcity)

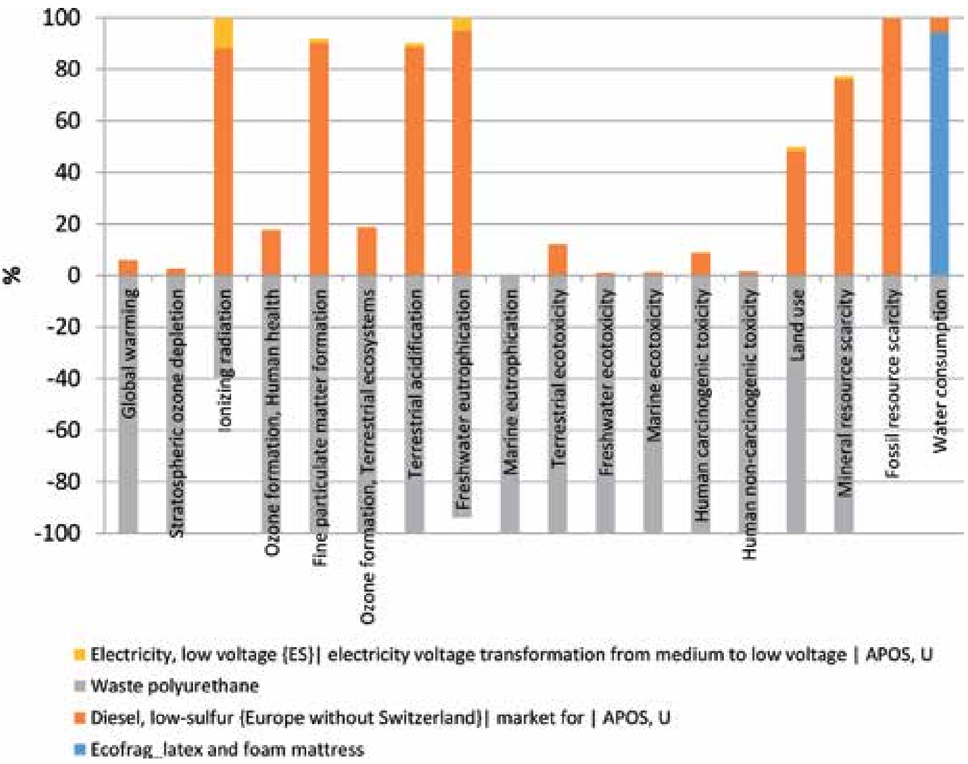

Figure 4.
Results of life cycle impact assessment method applied for ECOFRAG technology, used to treat latex mattresses and PU foam, for the individual impact categories within the framework of ReCiPe 2016 approach (characterization).

Each method (mid-point, endpoint) contains factors according to the three cultural perspectives. These perspectives represent a set of choices on issues like time or expectations that proper management or future technology development can avoid future damages.

- Individualist: short term, optimism that technology can avoid many problems in future.
- Hierarchist: consensus model, as often encountered in scientific models, this is often considered to be the default model.
- Egalitarian: long term based on precautionary principle thinking.

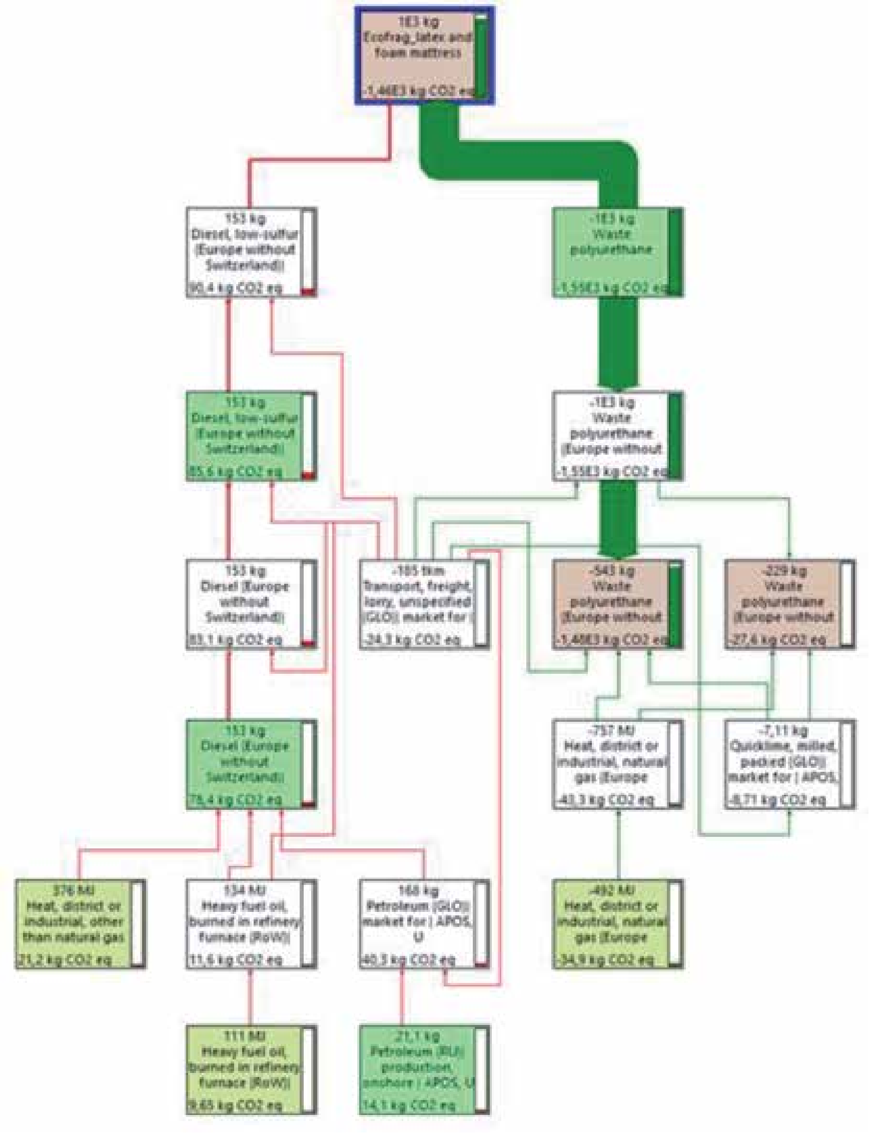

Figure 5.
A fragment of material-energy balance (the Sankey chart).

Considering the aim and extent of the analysis in question, the hierarchist variant was chosen, in view of the balanced time perspective, taking into account both long- and short-term perspectives.

The results of LCIA analysis are illustrated in **Figures 4** and **5**.

As it can be inferred from **Figure 4**, the largest environmental burden is linked with using diesel oil (DO) in electricity generators. Diesel oil combustion causes an increased emission of dust and greenhouse gases to the air that has consequences on increased global warming, ozone layer depletion, water eutrophication, acidification of the environment and increased dust pollution. The impact on water resources of Ecofrag technology is high, but the impact is reduced by the recirculation of water in the installation.

The use of net power generates a significantly lower environmental effect. It should be emphasized that the technology examined has a net positive effect on the environment owing to the application of waste materials as substrates. Recirculation of used PU foam and mattresses contributes to avoidance of emission and generation of waste involved with their target production. Such results have been confirmed by the fragment of the material-energy balance. The Sankey chart is presented taking into account processes/factors, whose impact is not lower than 0.56%.

In **Figure 6**, the results of LCA are given regarding the endpoints such as human health, ecosystem quality and depletion of natural resources, within the framework of the ReCiPe method applied. From the figure, it can be seen that the highest negative load is ascribed to the point 'nonrenewable resources'. This is closely related to the use of diesel oil (as a fossil energy carrier) for generating electricity necessary in the cutting process. On the other hand, a definitely positive impact is observed on human health and the quality of the ecosystem. This result is dictated by the application of Ecofrag technology for waste raw materials.

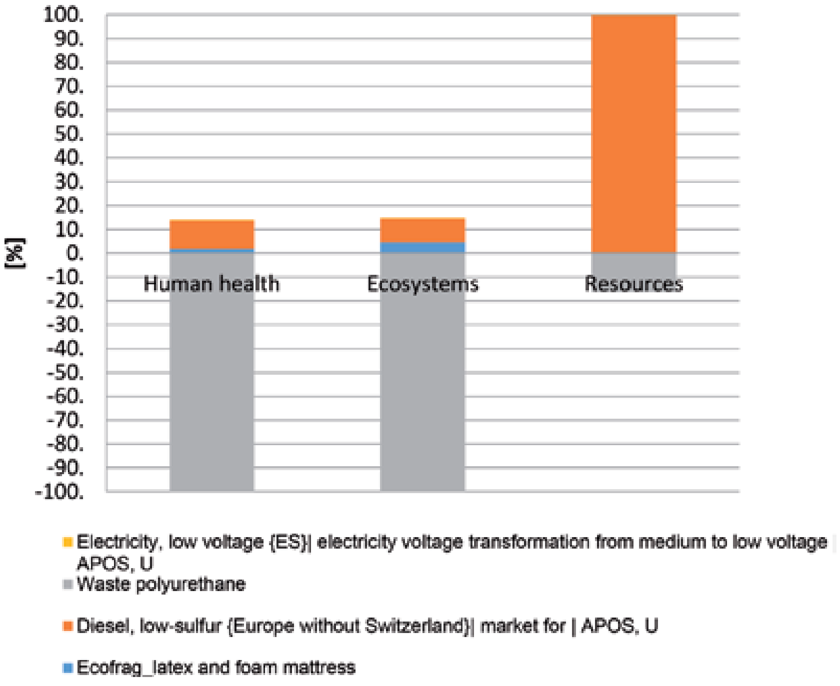

Figure 6.
The results of environmental life cycle assessment in relation to end-points within the framework of ReCiPe 2016 method.

Based on the results obtained, it has been demonstrated that material recycling brings numerous environmental benefits. This is mainly due to the reduction of environmental burdens associated with the intentional production of foam and mattresses, which has an impact on negative indicators of fossil raw materials consumption and reduction of greenhouse gas emissions.

6. Conclusions

The circular economy (CE) is a concept aiming to address activities that enable the reuse of products, focusing on positive society-wide benefits, among others. CE assumes development of a system in which the product does not end up in a landfill and is reused in the same or different form or is recycled. The remodelled hierarchy of waste management is to indicate the order of priorities in the policy and regulations regarding waste prevention and management. Prevention is of crucial importance; it applies to both product producers and consumers. It aims to reduce waste by reusing products or extending their lifespan. Another advantage of such an economy is the reduction of the waste adverse impact on the environment and human health. The circular economy is regulated by the European Directive, which sets specific goals to be achieved by Member Countries in the given years.

The management of bulky waste poses a significant problem for European countries. Under the URBANREC project, a solution to this problem was proposed through the use of new technologies for the bulky waste processing.

In this chapter, the LCA environmental analysis was carried out for the technology of grinding bulky waste using a water jet by the Ecofrag company. The analyses have shown that the reuse of used foams and mattresses contribute to the avoidance of their targeted production, which is associated with the reduction of greenhouse gas emission and consumption of fossil raw materials. The next step under execution of the URBANREC project is to perform the life cycle cost analysis, for the purpose of optimizing economic costs.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690103.

Conflict of interest

Authors declare that they do not have 'conflict of interest'.

Acronyms and Abbreviations

CE	circular economy
DO	diesel oil
EC	European Commission

EU	European Union (EU)
LCA	life cycle assessment
EMAS	Eco-Management and Audit Scheme
R&D	Research and Development
LCC	life cycle cost
LCIA	life cycle impact assessment

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Chapter 3

Review of Biofuel Technologies in WtL and WtE

Bruno B. Garcia, Gonçalo Lourinho, Paulo Brito and Pedro Romano

Abstract

Processing of biomass feedstocks to produce energy, fuels, and chemicals via a combination of different applied technologies is considered a promising pathway to achieve sustainable waste management, with many environmental and economic benefits. In this chapter, we review the current state of the main processes associated with energy recovery and biofuel production under the concept of waste biorefineries. The reviewed technologies are classified into thermochemical, biological, and chemical, including combustion, gasification, steam explosion, pyrolysis, hydrothermal liquefaction, and torrefaction; anaerobic digestion, fermentation, enzymatic treatment, and microbial electrolysis; and hydrolysis, solvent extraction, transesterification, and supercritical conversion. Their brief history, current status, and future developments are discussed within a perspective of valorization and managing of current waste streams with no solution.

Keywords: biorefineries, biofuel production, energy recovery, waste-to-fuels, waste-to-energy, circular economy

1. Introduction

Waste can be defined as any substance or object that has no further use and is intended to be discarded [1]. In this sense, waste production is inevitable in a society based on consumption, making waste management a huge challenge taking into account the enormous quantities of residues that are produced globally. In fact, about 2.6 billion Mg of waste were produced in the European Union (EU) during 2014, from which 41% was discarded in landfills, 36% was recycled, 10% used in earthmoving operations, 7% treated in wastewater treatment plants, and 6% incinerated either for energy production or for destruction. Based on this, in recent decades, humanity is shifting their focus of traditional waste management from the concept of “collection and disposal” in favor of pyramid-based management of the waste hierarchy in order to increase sustainability [2]. However, even when environmentally-friendly practices such as recycling and reuse are accomplished, much of the operations are performed “downcycling,” meaning that the recycled product has an economic value below its original purpose. As such, the linear economy model based on the pyramidal hierarchy of wastes that we tend to use nowadays also has limitations. Actually, there are still opportunities for efficiency gains in many industrial processes, but these gains will probably be increasingly marginal and undifferentiated.

The future adoption of the concept of circular economy is, therefore, a necessary change of paradigm, in contrast to the current linear model. This new concept is increasingly viewed as a source of innovation in products, processes, and business models, opening excellent opportunities that should be seen by companies and organizations as competitive advantages in a dynamic and global market [3]. Specifically, with a circular flux in the consumption of resources, every waste generated is a potential raw material for another process, introducing novel ways of valorization and development of second and third generation products. The benefits are clear as few wastes would be generated and disposed of without treatment, potentially reducing environmental pollution.

Updated knowledge of current technologies is a crucial factor in determining the most suitable processes to valorize different types of wastes in future biorefineries. These waste biorefineries are facilities that integrate the necessary technologies in order to convert biomass feedstocks and other wastes into usable products, ensuring that circular economy transitions from theory to the real world. The available waste streams can either be transformed by technologies producing biofuels (waste-to-liquids, WtL) or energy (waste-to-energy, WtE) with both categories expected to be a key element in future waste management. Based on this, in this chapter, we briefly review the current state of main WtL and WtE technologies within a perspective of their use as tools for managing post-process residues and by-products. The review ends with a brief discussion on future developments regarding mentioned technological options.

2. WtL and WtE technologies: historical and technological overview

Biorefineries are a way to achieve sustainable waste management with many environmental and economic benefits. However, waste streams are often very selective in terms of the technological option most suitable for their valorization. As such, a complete understanding of each technology is a fundamental resource to determine if the different wastes available can be viewed as a raw material for valuable products. **Tables 1–3** summarize the different thermochemical, biological, and chemical processes discussed. A brief description of each technology follows.

2.1 Incineration/combustion

Combustion is the most common waste energy recovery technology used in the production of heat, steam, and electricity. Historically, this technology is considered one of the most "dirty" and polluting processes in waste management and disposal; however, advances in the treatment of emissions in the late 1980s and early 1990s, along with the development of command and control technologies and the pretreatment of waste, have led to combustion once again attracting the attention of researchers and investors around the world. In general, a modern incineration facility consists of pretreatment and/or sorting line from where the wastes are continuously and uniformly fed to a furnace (**Figure 1**). The furnace operates at very high temperatures to ensure complete combustion. The combustion parameters are continuously controlled, and emissions are treated in a set of filters to ensure the removal of the toxic pollutants. As a WtE technology, combustion is very mature with the most recent studies focused on the recovery of energy and ashes resulting from the co-combustion or co-incineration of different wastes in nonspecialized equipment [4]. In fact, this process is widely used for thermal energy recovery of waste forms with good calorific value [5]. In 2016, for example, 28% of municipal solid waste (MSW) generated in the EU-28 was incinerated [6]. Furthermore, about 13.1% of hazardous waste was incinerated with and without energy recovery [7].

Technology	Benefits	Limitations	Products and by-products	Applications	TRL/CRI/demonstration projects
Combustion/ incineration	Reduction of mass (70%) and volume (80%), fast and simple process, energy recovery	High capital cost, public opinion objection, toxic slag production, air pollution (dioxins)	Heat for boilers and furnaces. Potential metal recovery from slag	Heating, electricity	TRL9/CRI4
Gasification	Wide range of applications and feedstocks, high conversion efficiency	High capital cost, high sensibility processes, low flexibility, risk of mechanical failure, tars production	H_2, CO-rich syngas Biochar for soil remediation	Heating, electricity, transportation, fuels and high-value chemicals	TRL9/CRI3 Energos, Norway; Vaskiluodon Voima, Finland
Explosive decompression	Transformation of lignite, solubilization of hemicellulose	Production of toxic compounds, partial degradation	Sugars, digestible products	Heating, electricity, transportation, fuels, and high-value chemicals	TRL9/CRI2
Pyrolysis	High yield, reduced syngas treatment, reduction of waste volume (90%)	High capital, maintenance and operation costs, high bio-oil viscosity	Bio-oils, biochar, syngas	Additives, high-value chemicals, transportation, heating, and electricity	TRL8/CRI2 ABRITech, Canada; Ensyn Several, Canada; Metso, Finland; Rise, Sweden
Hydrothermal liquefaction	Higher LHV bio-oil and low moisture content	Low conversion efficiency (20–60%), higher pressure equipment and higher capital cost	Heavy oil, intermediate value chemicals	Additives, high-value chemicals, transportation, heating, and electricity	TRL7/CRI1 Steeper Energy, Denmark; PNNL, USA; Genifuel, USA; PilotABP, Spain; TERAX, New Zealand
Torrefaction	Homogeneous and stable products, easy pelletizing, high LHV, hydrophobic	Low-energy density, high ash quantity	Torrefied biomass	Heating, electricity	TRL7/CRI1 Torplant, Switzerland; ECN, Netherlands; Norris Thermal Technologies, Vega Biofuels, USA

TRL, technological readiness level; CRI, commercial readiness index.

Table 1.
Comparative summary of different thermochemical conversion technologies [8–10].

Technology	Benefits	Limitations	Products	Applications	TRL/CRI/ demonstration projects
Anaerobic digestion	Solid waste reduction, high moisture content feedstock, methane- and carbon dioxide-rich biogas, low-cost organic fertilizer as by-product	Need to treat and clean the biogas; unstable system; large facilities are unattractive	Biogas, bio-digestate	Heating, electricity, transportation, fuels, and high-value chemicals	TRL9/CRI3
Fermentation	Does not contribute to increase of greenhouse gas emissions	Limited to sugar, starch, or cellulose-rich feedstocks	Liquids and CO_2	Additives, high-value chemicals, transportation, heating, and electricity	TRL9/CRI2-3
Photofermentation	The photosynthetic bacteria can use a range of the electromagnetic spectrum	Low efficiency, inhibited in the presence of oxygen	Hydrogen, carbon dioxide, organic acids	Additives, high-value chemicals, transportation, heating, and electricity	TRL6/CRI1
Dark fermentation	Capable of converting a wide range of wastes, scalable technology, independent of light	Low theoretical limit, immature technology	Hydrogen, acetic acid	Additives, high-value chemicals, transportation, heating, and electricity	TRL5/CRI1 DiSAA Milan, Italy; LanzaTech, New Zealand
Enzyme treatment	Low power consumption, low by-product production, does not require toxic catalysts, can result in a reduced solvent	High cost of the enzymes, slow reactions, necessity of high purity, limited in temperature and pH range	Ethanol, amino acids	High-value chemicals, transportation, heating, and electricity	TRL9/CRI2 PROESA™, Italy; Kalundborg Bioethanol, Denmark
Microbial electrolysis	Hydrogen production, low-energy consumption, effluent degradation	High internal resistance, high capital cost, production greatly affected by substrate composition	Hydrogen, methane, acetate, formic acid	Wastewater treatment, high-value chemicals, transportation, heating, and electricity	TRL6/CRI1

TRL, technological readiness level; CRI, commercial readiness index.

Table 2.
Comparative summary of different biological conversion technologies [8–10].

Technology	Benefits	Limitations	Products	Applications	TRL/CRI/ demonstration projects
Hydrolysis	Less aggressive low-cost substances	Slow and inefficient, high alkalinity or acidity, formation of inhibitory salts	Cellulose, hemicellulose, and lignite	Additives, high-value chemicals	TRL9/CRI5
Solvent extraction	Moderate temperatures, reuse of solvents, high selectivity of solvents, pH control	Intermediate products, solvent saturation	Primary and secondary metabolites	Additives, high-value chemicals	TRL9/CRI3
Transesterification	No modification of equipment is necessary, reduction of air pollution, less toxic, easy to use, decrease in CO_2 emissions	Weak supply chain, high viscosity, high cost, odor	FAME	Transportation, electricity	TRL9/CRI5
Super critical conversion	Uses cheap and abundant solvents; fast, lower thermal degradation; better purity of the compounds	High pressures required, supercritical state, difficult to maintain, complex maintenance and cleaning	Chemicals	Wastewater treatment, high-value chemicals, transportation, heating, and electricity	TRL7/CRI-1 Thar Technology, USA; Integrated Plantrose Complex, USA; New Oil Resources, USA

TRL, technological readiness level; CRI, commercial readiness index.

Table 3.
Comparative summary of different chemical conversion technologies [8–10].

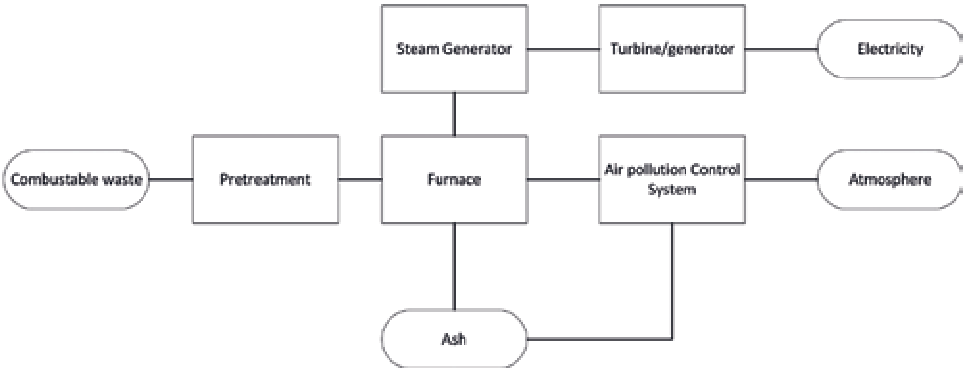

Figure 1.
Example scheme of incineration/combustion technology.

2.2 Gasification

Gasification is a thermochemical decomposition process which occurs without the presence of sufficient oxygen for a complete combustion and allows the transformation of waste feedstocks into a combustible gas known as syngas, a fuel with many potential applications (**Figure 2**). As a technology, gasification has a several-centuries-old history with progress made by advances and stalls. Widely used during industrial revolution in the 1850s to illuminate factories, streets, and houses, this technology fell into disuse during the twentieth century and only recently gained a continuous support for its development due to energy security threats and climate change.

Among WtE processes, gasification is one of the most promising with some specific barriers explaining its lack of penetration in the domestic and commercial sectors [11]. An extensive review on technology progress identified 50 companies offering "commercial" gasification plants in Europe, the USA, and Canada, mostly downdraft and fluidized bed systems (75 and 20%, respectively) [12]. Moreover, in 2013 there were more than 272 operating gasification plants worldwide with more under construction and planned until 2019 [13].

Supply chain development, waste pretreatment (drying/grinding/pelletization), and the potential need for treatment of syngas are usually pointed out as the main barriers to be overcome. Conventional drying systems are known to be expensive and energy intensive. In addition, complete drying of the biomass represents a decrease in

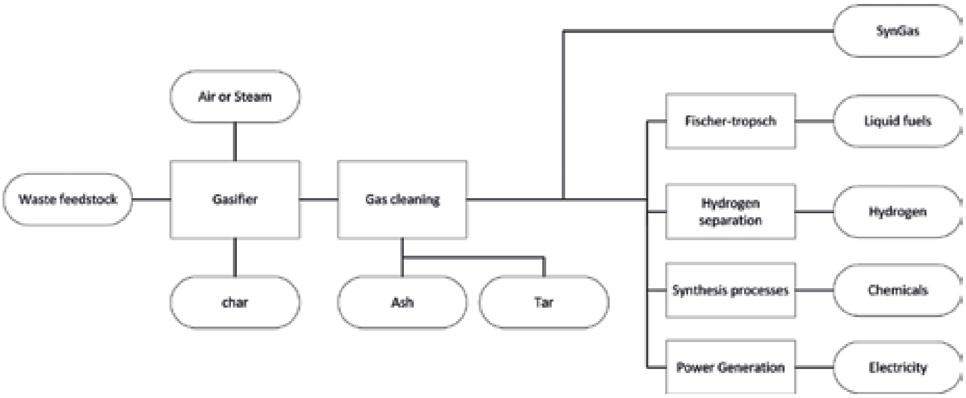

Figure 2.
Example scheme of gasification technology.

the amount of hydrogen that is potentially producible during gasification. Solar drying, though inefficient, is cheap and should be studied and viewed as an alternative. The potential presence of tars, particulate emissions, SO_x, NO_x, and NH_3 in the syngas also limits its range of use. Filtration of the syngas is important to obtain a syngas free of contaminants but requires constant cleaning of the filters as a way to prevent blockage and pressure drops. Tars are seen as the most complicated contaminant. In addition to filtration, it is also possible to resort to thermal decomposition and catalytic cracking as a form of treatment [14]. Thermal decomposition leads to melting of the ashes, which can also result in mechanical problems. Catalytic treatment is seen as the most effective for dealing with tars but ineffective against particles and other toxic gases. The combination of various forms of treatment is the best solution [15].

Pretreatment of the waste and biomass to be gasified, as well as reactor design and optimization of operational conditions, has been proven to be of great importance to maximize conversion efficiency, viability, and profitability [16]. In this regard, procedures such as sorting, grinding, and sifting are simple but essential. Fluidized bed reactors are considered the most suitable for a good and efficient process. Fluid bed material consisting of natural rocks such as dolomite and olivine is usually the best option due to reasonable prices. As for optimized conditions, mathematical models using 2D computational fluid dynamics (CFD) confirmed that gasification temperature has a key influence on the calorific value of the syngas produced [17]. Co-gasification of several wastes has been reported with promising results [18–20]. Inorganic additives such as calcium oxide (CaO) have been observed to decrease CO_2 and increase the quality of the syngas [21]. Integrating gasification and co-gasification into solid oxide fuel cells (SOFC) or internal combustion engine (ICE) cogeneration systems is a very promising option and is already considered economically viable [22–24].

2.3 Explosive steam decompression

Explosive decompression is a thermochemical pretreatment process which disrupts the rigid structure of lignocellulosic materials using steam and high pressures. Patented in 1931 by Mason [25], this process consists in heating the waste in hot steam at 285°C and at a pressure of 3.5 MPa for 2 min, before increasing the pressure once again, this time to 7 MPa for 5 s [26]. Naturally, time and temperature are a major influence in the disruption of the fibers composing the biomass, with the pretreatment process potentially resulting in just some grooves in the wood or in the total conversion into pulp. The main application of this technology is as pretreatment of lignocellulosic materials (**Figure 3**) which is essential for making the

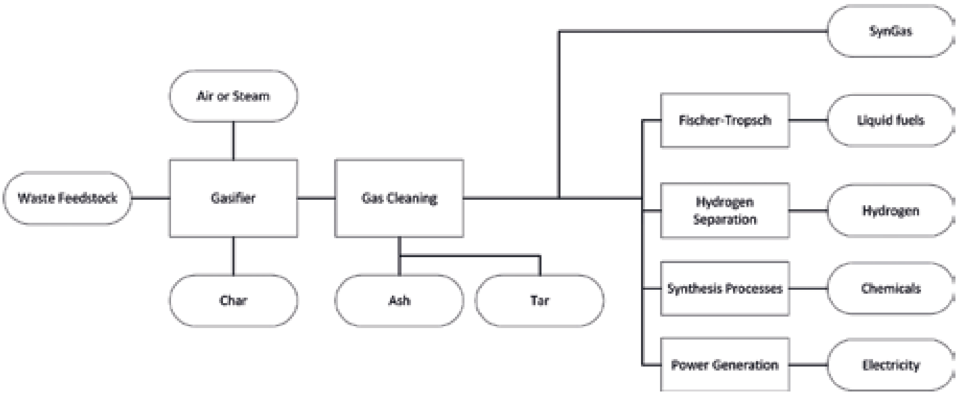

Figure 3.
Example scheme of explosive steam decompression technology.

biopolymers accessible for further treatment via other processes such as fermentation, hydrolysis, anaerobic digestion, and densification. The production of biogas by anaerobic digestion using lignocellulosic wastes, for example, is considered a huge challenge due to its recalcitrant nature (non-biodegradability) [27]. In this regard, the use of explosive steam decompression as a form of pretreatment has been proven to enhance the production of biogas. Moreover, ethanol production and syngas production using lignocellulosic feedstocks have also been reported to proceed with higher calorific value and lower temperatures, respectively, when precluded with steam explosion [28, 29]. A promising solution for continuous steam explosion has been presented by a research team from South China University of Technology [30] allowing for process scale-up and its potential integration in second-generation biorefineries.

2.4 Pyrolysis

Pyrolysis is a thermochemical decomposition process that occurs in the total absence of oxygen and at relatively low temperatures (500–800°C) when compared to gasification (800–1000°C). There are different types of pyrolysis, each favoring the production of three different products: pyrogas, pyrolysis oil, and char (**Figure 4**). The relative proportions of each product depend on the applied pyrolysis method, the type of feedstock, and temperature. Archeological evidence suggests that during the Middle Paleolithic, Neanderthals resorted to pyrolysis to produce a kind of tar which they would use as glue. The use of this process in the production of all types of products was widespread throughout the world until the beginning of the twentieth century. Nowadays, pyrolysis is once again being viewed as one interesting solution to produce energy, fuels, and chemicals using local wastes.

The major advantage of pyrolysis in waste recovery may be in being able to convert low-energy-density materials into high-energy-density products. As an example, pyrolysis has been adopted as an alternative to the treatment of plastic wastes to produce plastic-derived oil (PDO) [31] and pyrogas [32]. PDO has been reported to be similar to diesel (C_{13}–C_{20}) [33]; however, additional processing is needed to deal with aromatic compounds. The use of calcium carbonate ($CaCO_3$) in the pyrolysis of horse manure allows for lower temperatures due to the catalytic effects of $CaCO_3$ as a possible source of CO_2 [34]. Co-pyrolysis of different plastic mixtures [35], as well as the use of catalysts [36–39], has also yield interesting results concerning the productivity and quality of the PDO components.

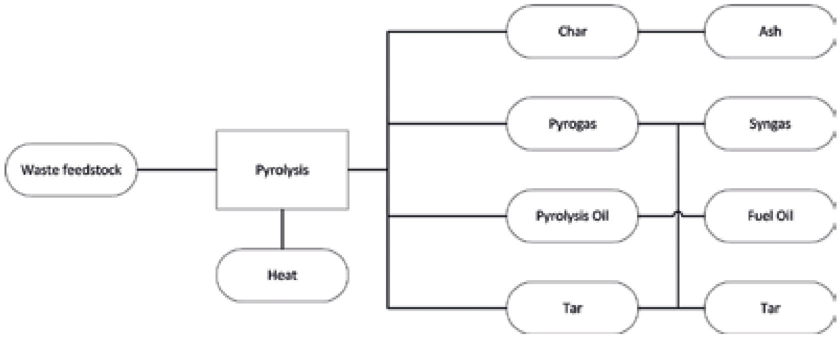

Figure 4.
Example scheme of pyrolysis technology.

2.5 Hydrothermal liquefaction (thermal depolymerization)

Hydrothermal liquefaction or thermal depolymerization is the thermochemical conversion of solid waste into a liquid using moderate temperatures (250–375°C) and high pressures (4–22 MPa). Similar to pyrolysis but occurring with the waste immersed in water at high pressures and temperatures, the process leads to the break of long carbon chains, resulting in a bio-oil with a good calorific value. As a technological option, the process does not need catalysts, but research has indicated that the use of alkaline catalysts allows the formation of high-value chemicals. Hydrothermal liquefaction is attractive because efficiencies greater than 80% are common when converting biomass into fuels and other high-value chemicals [40]. This technology has enormous potential, particularly to produce biofuels and raw materials for further chemical processing.

The concept of hydrothermal liquefaction was first explored in the 1920s and was further developed in the 1950s by H. Heinemann. However, only after the oil crisis in the 1970s did the first efforts to exploit this technology finally emerged, being the concept finally proved at pilot scale with the construction of Biomass Liquefaction Experimental Facility in Oregon, USA [41]. Recently, research regarding this technology has focused on finding new catalysts and developing novel ways of converting the produced bio-oils into high-value products. In practice, hydrothermal liquefaction is valued because it provides rapid conversion of waste biomass into bio-oil, avoiding the high energy cost of drying [42]. Most studies have shown that temperatures between 250 and 370°C are optimal for the production of bio-oil, with no general conclusion given about the effects of reaction time and moisture content [43]. Hydrothermal co-liquefaction is an interesting pathway and should be explored in future studies [44, 45]. Both the addition of potassium carbonate (K_2CO_3) [46] and the reuse of the liquid were reported to increase calorific value and productivity. The addition of solvents was also observed to enhance the process [47], while the addition of metallic catalysts led to deoxygenation and desulphurization of the bio-oil [48].

2.6 Torrefaction

Torrefaction is a form of thermal treatment which takes place between 200 and 500°C in the absence of oxygen. As temperature rises, moisture and superfluous volatiles are gradually released, and biopolymers such as hemicellulose, cellulose, and lignite are partially decomposed, depending on process conditions [49]. At mild temperatures (235–275°C), for example, the degradation of hemicellulose is accelerated, and the release of the volatiles is intensified, while cellulose is only consumed to some degree. On average, the process results in mass losses and decreases in calorific value (20% and 10%, respectively) but yields a more homogeneous waste composition and leads to higher energy densities. Some biomasses have characteristics that hinder their utilization as energy feedstocks; using this process as pretreatment allows the use of a broad spectrum of wastes in other WtE technologies. The main product of torrefaction is, therefore, a waste with improved characteristics regarding its energy use. More than 150 torrefaction installations worldwide with powers from 50 to 700 MWe have successfully tested the co-combustion of torrefied biomass, reducing greenhouse gas emissions and dependence on fossil fuels. It is expected that torrefied biomass could represent 5–10% of industrial applications in Europe [49]. However, the market for torrefied waste products is still very recent, and there is not enough data available about the real use of technology, its implementation, and its evolution.

Among researchers, torrefaction has been viewed as an excellent pretreatment for improving the energy recovery features of several wastes creating products with low oxygen to carbon ratios and high calorific values for co-gasification and co-combustion applications [50]. As an example, the torrefaction of several pomaces [51] and prunings [52] led to very promising results with calorific values increased to near lignite levels. Other interesting results have been reported by researchers [50] dealing with the very heterogeneous nature of MSW which along with high moisture contents make them challenging for application in WTE and WTL processes. Most studies reported a positive correlation between the calorific value and torrefaction temperature.

2.7 Anaerobic digestion

Anaerobic digestion (AD) consists in the conversion of biodegradable organic matter in the absence of oxygen in which a biogas rich in methane is produced [53]. Typically, the resulting biogas is composed of 50–75% CH_4, 25–50% CO_2, and 1–15% of other gases such as H_2O, NH_3, and H_2S. Another by-product of anaerobic digestion is the digestate, an excellent organic biofertilizer. Virtually all types of organic matter have the potential to be digested anaerobically to produce biogas. The most common organic wastes used in AD are agricultural, livestock industry, agroindustry, and municipal solid wastes and wastewater. Woody materials are less suitable because they contain a high proportion of lignite, making it very difficult to decompose biologically.

As a technology, AD is already mature and well developed. Since 2009, the number of biogas plants has greatly increased in Europe with biomethane production growing in line with sector development. In 2016 alone, energy production derived from biomethane increased by 4971 GWh (+40%) within the European countries reviewed [54]. The key to future research is thus the optimization of process parameters that affect efficiency. Temperature change, for example, is known to affect microbial activity and growth rates. Higher digestion temperatures, for instance in the thermophilic range, have been demonstrated to lead to higher biogas productivities, but thermophilic digestion represents a higher investment due to energy costs. On the other hand, digestion of simple substrates often results in a nutrient imbalance that affects the stability of the process. Thus, C/N ratio optimization by co-digestion has been widely tested with good results taking advantage of the synergies between different substrates. This strategy represents the most economical way to improve process productivity nowadays. The use of multiple steps in AD has also been observed to be an interesting solution for achieving the best use of different substrates [55–58].

The integration of anaerobic digestion with microalgae cultivation presents potential benefits [59, 60]. From an economic point of view, costs can be substantially reduced by using the digestate from AD as a source of nutrients for algae growth. However, several barriers will have to be overcome before the scale-up of the process. The main obstacle identified in the reviewed research was the need to find a robust microalga strain capable of binding with organic and inorganic carbon and tolerate extremes of pH.

2.8 Fermentation

Fermentation is an anaerobic metabolic process, in which microorganisms (bacteria, yeast) turn carbohydrates into fatty acids, alcohols, and gaseous products such as H_2 and CO_2 (**Figure 5**). The most common industrial products resulting from fermentation are ethanol, acetic acid, and citric acid (2-hydroxypropane-1,2,3-tricarboxylic

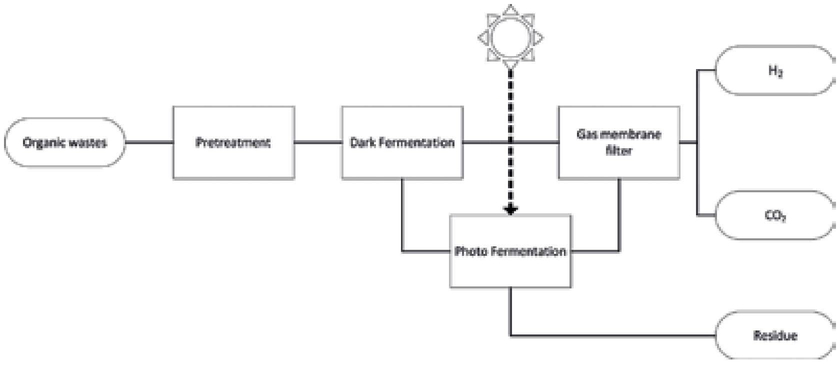

Figure 5.
Example scheme of fermentation technology.

acid). The conversion of sugars into ethanol is the most well-known form of fermentation, producing alcoholic beverages such as wine, beer, and cider. Interestingly, the same fermentation occurs in the production of bread, yogurt, and other foods fermented by the formation of lactic acid (2-hydroxypropanoic acid). In addition, there have been significant advances in the production of bioethanol, biobutanol (butan-1-ol), and bio-hydrogen (molecular hydrogen), among other high-valued chemicals.

Continuous fermentation of syngas using fixed-bed drip reactors for ethanol production has been proven as a valid concept with the highest ethanol concentration (13.2 g L^{-1}) obtained during co-current continuous syngas fermentation at a dilution rate of 0.012 h^{-1} [61]. However, despite being a promising technology, the process has encountered some difficulties in its development on an industrial scale. Besides fixed-bed bioreactors, other efforts related with reactor design have been focused on membranes combined with the formation of biofilms due to enhances in mass transfer. Studies on the production of bio-hydrogen have been focused on bio-photolysis of water using algae and cyanobacteria, photodecomposition of organic compounds by photosynthetic bacteria [62], and dark fermentation of organic compounds with anaerobes [63]. For dark fermentation, special attention has to be given to inhibitors such as the excess of substrate, micronutrients, macronutrients and metal ions, high temperatures, acidic pH levels, and competition from other microorganisms [63].

2.9 Enzyme treatment

Enzymes are macromolecular biological catalysts which accelerate chemical reactions. In 1897, Eduard Buchner resorted to enzymes extracted from yeasts grown in his lab to ferment ethanol, a seminal work for which he received the Nobel Prize for Chemistry in 1907. Industrially, their application lies either in converting substrates into greater value products or as pretreatment for energy recovery and biofuel production. Nowadays, nearly all types of commercially available enzymes are produced by fermentation, being part in virtually every aspect of our lives, from the pharmaceutical industry to laundry detergents. In 2016, an industrial unit including an enzymatic pretreatment started to operate within a perspective of energy recovery from MSW. Specifically, enzymes degrade a fraction of the organics present in MSW so that they can be easily digested anaerobically. The facility is located in Northwich, England, and produces 5 MWe consuming 15 Mg h^{-1} of MSW [64]. Another commercial application with good future perspective is enzymatic saccharification which can be used to produce bioethanol at a low cost. Some studies on bioethanol production from bamboo, for example, indicate that increasing the amount of the enzyme yields little improvement in the process highlighting the need for optimization depending on the waste to be transformed [65]. Other experiments have focused on process enhancement via salt pretreatment. Addition of inorganic salts, for instance, has been reported to improve reducing sugar yields of sugarcane leaf wastes and mustard stalk and straw [66, 67].

2.10 Microbial electrolysis

Microbial electrolysis is a bioelectrochemical transformation where hydrogen or methane is produced from various wastes and wastewaters. Microbial electrolysis cells (MEC) use the metabolic activity of exoelectrogenic bacteria to catalyze redox reactions and promote the flow of electrons between the electrodes [68]. Specifically, the bacteria convert biodegradable substrates at the anode, releasing electrons and protons (**Figure 6**). The electrons are then transferred to the cathode (where hydrogen is produced) inducing an electrical current with electrical potential values (0.2–0.8 V) lower than in traditional electrolysis (1.8–3.5 V) [69]. Microbial electrolysis cells (MEC) have the potential to become one of the most important WtE technologies. However, electrode materials are still costly, and further developments are needed. In this regard, the use of biochar-based electrodes seems to compose an interesting research route [70–72]. Currently, coupling with other technologies for energy generation seems to be its leading application. The use of microbial electrolysis as a pretreatment for AD, for example, has been explored recently with interesting results. In a study focused on the valorization of highly concentrated FW [73], MEC was found to accelerate methane production rate and stabilization. As another example, post-processing of wastewater resulting from hydrothermal liquefaction for recovered hydrogen has also been demonstrated with effective results [74, 75]. As a technology, MEC are still in the early phase of development, and further progress is expected with the use of novel electrode materials and new reactor configurations.

2.11 Hydrolysis

Hydrolysis is probably the most prevalent chemical reaction in multiple WtE and WtL technologies. Hydrolysis is the chemical reaction where the addition of

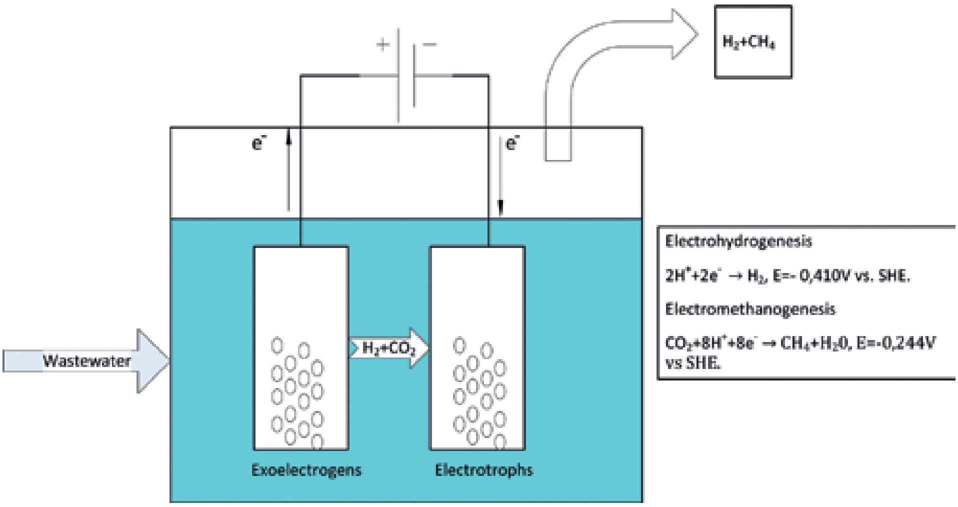

Figure 6.
Example scheme of microbial electrolysis technology.

a water molecule breaks the chemical bond of another molecule and the resulting molecules bind to H^+ and OH^- ions. In 1819, Henri Braconnot discovered that he could produce sugars from cellulose through hydrolysis with sulfuric acid. This hydrolyzed sugar could then be processed and fermented to produce ethanol. The production of ethanol by hydrolysis began extensively at the beginning of the twentieth century, with maximum yields of 190 L Mg^{-1} of biomass. In the former USSR during the 1930s, the industrial growth at the time needed to develop processes of ethanol production that did not use food sources. In 1934, six pilot reactors were built with the objective of optimizing different hydrolysis technologies, not only to produce ethanol but also other products such as xylitol and furfural. After the First World War, this process was no longer economically viable against more conventional methods. With the advances of the last two decades, enzymatic hydrolysis seems to be the most promising application regarding hydrolysis techniques.

2.12 Solvent extraction

Solvent extraction is a relatively modern technology used in the extraction of products from its substrates (**Figure** 7). By choosing a solvent that best dissolves the wanted product, this process usually results in higher yields when compared with other methods. The separation is quick and efficient and most of the solvent can be reused. Extraction of oils via this technology is a common application in the industry, normally used after mechanical extraction. Hexane is the most used solvent, but ethanol and isopropanol have also been proposed as alternative options. The Soxhlet extractor is often the preferred method for lipid extraction due to the simplicity of operation, relative safety, and ease of replicating results on an industrial scale [76]. From research, organic solvents such as chloroform, ethanol, and hexane were found to produce the best results when performing lipid extraction from microalgae. Solvent mixtures were also observed to yield better results

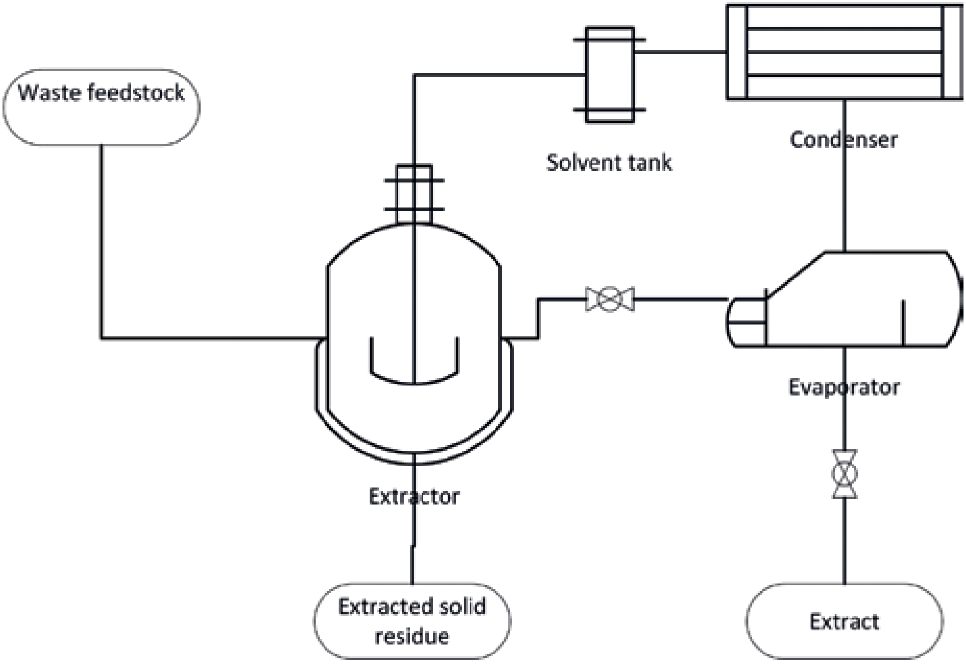

Figure 7.
Example scheme of solvent extraction technology.

than mono-solvent extractions, with a 50/50 mixture of chloroform and ethanol leading to 11.76% lipid extracts. As a mono-solvent, chloroform resulted in the highest quantity of lipids extracted at 10.78% with 3 h showing the best extraction efficiency [77]. Solvent extraction also has the potential to be integrated with other processes like supercritical extraction or pyrolysis in order to produce higher value chemicals from bio-oils [78, 79].

2.13 Transesterification

Transesterification is the main process used in the production of biodiesel in which vegetable oils are broken into methyl or ethyl esters by reacting with an alcohol and catalysts (acids, alkalis, and enzymes) with glycerol as the only by-product. Biodiesel production has increasingly been seen as a carbon mitigation tool, assuming increasing importance in promoting sustainability in European countries. Since January 1, 2010, for example, all commercial diesel fuel sold in Portugal has a 7% incorporation of biodiesel. Biodiesel production is a controversial issue due to the use, availability, and cost of raw materials, as well as greenhouse gases emission and food competition. In this context, the use of waste oils and nonfood crops seems to compose the best option for the widespread production of biodiesel in the future [80]. In Europe, it is estimated that about 4 million Mg of waste cooking oil are to be collected annually, seven times more than the current collected amount [81]. This underdeveloped collection chain led to record level imports in the first 8 months of 2018 with more than 235,000 Mg of waste cooking oil entering the EU from China. Biodiesel market thus does not show signs of slowing down [82]. Although already mature and well established commercially, biodiesel still needs a lot of research and development to achieve significant improvements in its production [83, 84]. In this regard, continued interest in the use of biodiesel as an alternative fuel has led to increased efforts to develop a new generation of biofuels. Heterogeneous catalysts have been increasingly tested since they offer process improvements over homogeneous catalyzed commercial production employing liquid bases. In more detail, the use of solid catalyst facilitates post-process separation and fuel purification, along with the continuous synthesis of biodiesel. The increasing use of low-grade waste cooking oil remains a challenge for existing heterogeneous catalysts since the high concentration of impurities (acid, moisture, and heavy metals) induces rapid deactivation in flow and requires purification. The development of more robust catalyst formulations tolerant to such components is, therefore, a necessity [85]. Cement was recently tested in the transesterification of *Pongamia pinnata* and sunflower oil with somewhat low conversion rates (76%), but research should continue in upcoming years [86]. In terms of process coupling, the blend of biodiesel with pyrolysis oil derived from lignocellulosic wastes is an attractive route as an alternative to diesel fuel [87]. Microalgae are also considered an attractive feedstock alternative to reduce costs in the extraction and conversion of this renewable fuel.

2.14 Supercritical conversion

Supercritical conversion is a new technique that uses high temperature and high-pressure fluids, above their critical point, to achieve the transformation of waste. Compared with conventional WtE and WtL technologies, this method may ignore drying or dehydration pretreatments, reduce reaction temperature, shorten reaction times, and increase product yield. In recent decades, supercritical conversion has gained interest not only for chemical extraction, but also in chemical conversion by replicating processes such as transesterification, gasification, hydrolysis, and others (**Figure 8**). Studies with real biomasses and at larger scales are lacking, but

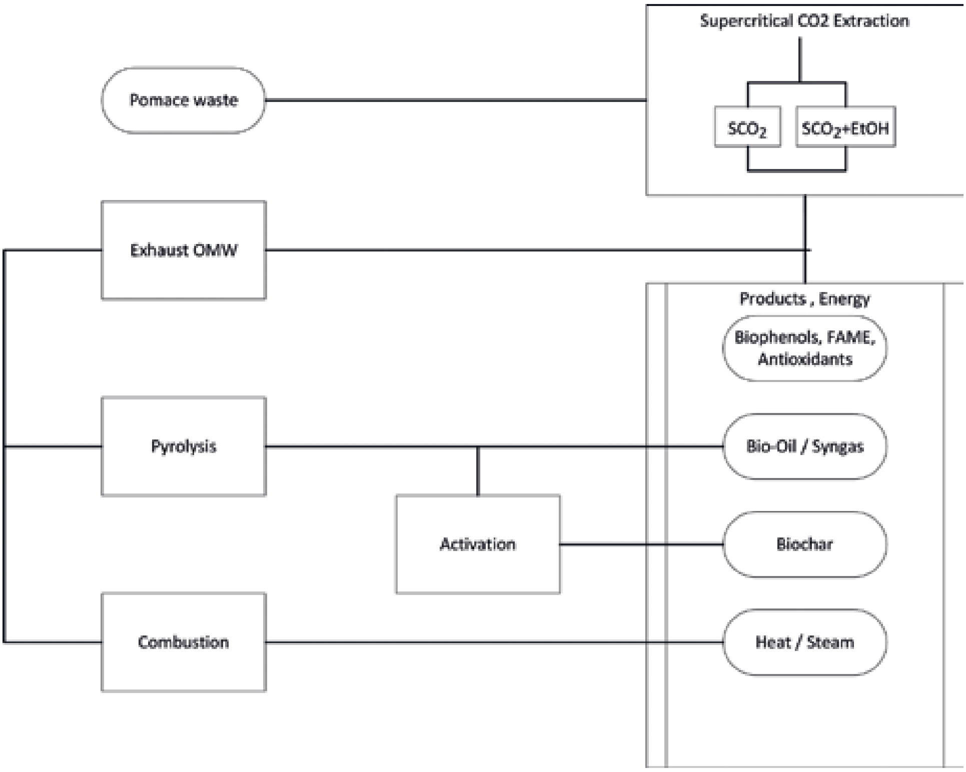

Figure 8.
Example scheme of supercritical conversion technology.

the reviewed research generally suggests that, for example, supercritical gasification in both biorefineries and cogeneration has enormous potential. Supercritical water gasification of olive oil mill wastewater, for example, has been investigated recently with different alkali catalyst types [88]. The tests proved that an increment in catalyst concentration would improve hydrogen yield to a maximum of 76.73 mol H_2 kg^{-1} in specific conditions. Extraction with supercritical carbon dioxide for biodiesel production is another process investigated [89]. In the example study reviewed, the best productivity was 0.312 kg of oil per kg of $seed^{-1}$ at a pressure of 500 bar and 40°C. Fatty acid content was observed to decrease with increasing pressure. In fact, the extraction of fatty acids and transesterification in a single step are considered one of the greatest potentials for this technology [90].

3. Economics of WtE

The most apparent barrier for the implementation of WtE technologies is capital cost, specifically the upfront expense of building and installing the energy generation system. While not enabling a detailed view of project economics, an assessment of capital costs offers simple and clear information which can be used to evaluate the status of different commercial technologies. **Figure 9** shows estimates of capital cost for a range of WtE power generation technologies. Capital costs are low for mature technologies such as cocombustion and anaerobic digestion integrated with ICE or gas turbine (GT). For early-stage technologies, the capital costs are extremely uncertain, and as such many were not included in the analysis. Pyrolysis, plasma arc gasification, and refused-derived fuel (RDF) direct combustion, for

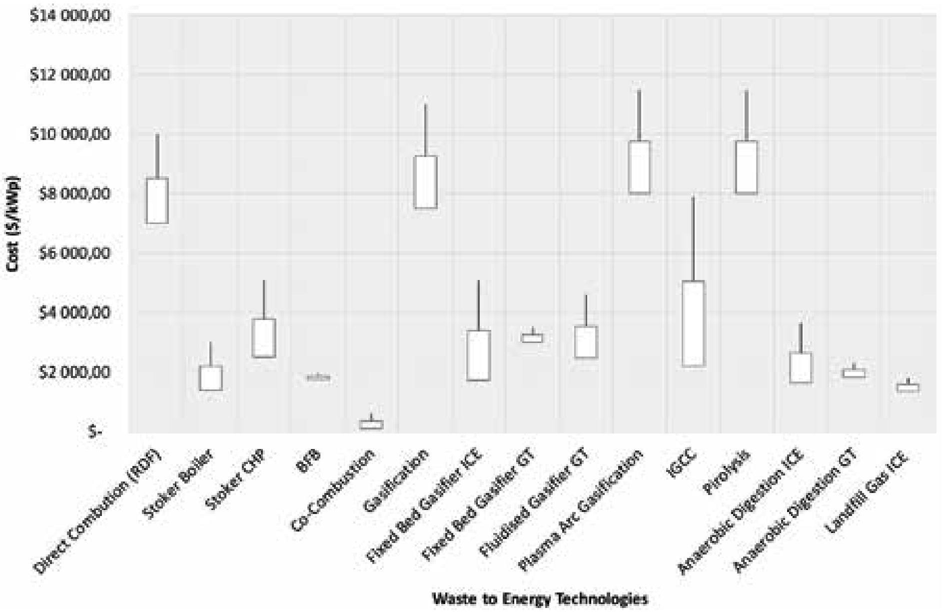

Figure 9.
Capital cost (in $/kW) for selected WtE power generation technologies [91–95].

example, have higher capital costs due to technical hurdles and novelty status. As for integrated gasification combined cycle (IGCC), the costs vary widely as the process is still not established with significant cost reductions expected. The size of cost decline, however, is likely to be very dependent on geographical location and in line to the support given by global policy-makers and national frameworks regarding each technology [91].

4. Conclusions

This chapter explored the possibility of using postprocess residues as abundant biorenewable and low-cost resources in future waste biorefineries. Available waste streams have a complex and varied composition according to its source, requiring new logistic platforms of assortment and valorization. With the exhaustion of the "collection and disposal" linear economy, new waste handling methods are unavoidable in the long term. As such, waste biorefineries that produce green energy and make virtually zero-waste high-value products in a "closed loop" and "up-cycling" approach are the "landfills" of the future. They are expected to be crucial in taking sustainable waste management into the real world allowing game-changing economic growth under the concept of circular economy. However, from the reviewed technologies, it can be concluded that single WtL and WtE processes are almost always limited in their scope, producing many times unwanted products. In this regard, the technology with more potential and scope in single applications is by far gasification; nonetheless, even this process has drawbacks such as reactor design, feeding system, and tar production that require costly posttreatment and/or further technological developments. Conversely, combining multiple WtE and WtL processes in an integrated waste biorefinery will allow the mitigation and elimination of each single process drawbacks. In gasification, for example, some of the unwanted substances generated may be utilized and valued by subsequent chemical processing, and even syngas can be upgraded. This novel waste valuation pyramid will create opportunities for niche technologies such as explosive decompression and torrefaction to make it into practical application by enhancing other technologies that are already well established when used in an integrated approach. Future research should primarily focus on the establishment of a hierarchy of processes to produce the highest value products and then progress gradually to low-cost products and energy production. For this vision to be a reality, however, an increased effort on the part of the researchers will be required with a combined continuous and sustained support from all potential stakeholders. More demonstration projects at pilot or semipilot scale should materialize in the upcoming years, focusing on aspects such as energy balance and cost-benefit analysis guaranteeing the viability of the proposed solutions.

Acknowledgements

Authors acknowledge the financial support received by the projects 0008_ECO2CIR_4_E and 0049_INNOACE_4_E co-funded by ERDF – European Regional Development Fund through INTERREG V-A Spain-Portugal Cooperation Programme (POCTEP). G. Lourinho also gratefully acknowledges FCT - Fundação para a Ciência e Tecnologia - for financial support within the scope of the grant SFRH/BDE/111878/2015.

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Chapter 4

Overview of the Process of Enzymatic Transformation of Biomass

Namita Singh, Anita Devi, Manju Bala Bishnoi, Rajneesh Jaryal, Avni Dahiya, Oleksandr Tashyrev and Vira Hovorukha

Abstract

Cellulase is an enzyme which depolymerizes the cellulose into glucose. Cellulases are produced by a diverse array of microbes including fungi, bacteria, yeast and actinomycetes. Considerable research for understanding the mechanism of cellulases began in early 1950s because of the significant use of these enzymes in various industries. This review provides a general account structure and availability of lignocellulosic biomass, pretreatment strategies for effective digestion, cellulase producing organisms, cellulase activity assay, and enzymology of cellulose degradation. Cellulase production, optimization, purification and characterization studies in addition to the industrial application of cellulase have also been discussed. At last a brief account of present market scenario of cellulases and future prospects of the study are also taken into account.

Keywords: cellulases, lignocellulosic biomass, fungi, pretreatment

1. Introduction

Cellulases are inducible enzymes which breakdown cellulose (the most widely available source of fermentable sugars on earth) into glucose and synthesized during the growth of microorganisms on cellulosic substrates [1, 2]. Cellulase is biotechnological important enzyme due to various industrial applications including biofuel production [3]. Variety of microorganism having cellulose degrading capability, few of them produce considerable quantity of extracellular enzymes. Fungi are the main cellulase producing microorganisms. *Trichoderma* and *Aspergillus* are found to be most potent cellulase producers, to be used for agricultural and industrial purpose [4, 5].

A large number of industries are based upon the agricultural raw materials and it alone accounts for about 10% of the total wages from export. At present, in terms of agricultural production, country holds 2nd position in world (http://www.agrifest.in/aboutagrifest.php). Availability of lignocellulosic biomass varies from one region to another region in our country because of specific patterns of cultivation of crops in different regions. As estimated by the Ministry of New and Renewable Energy (MNRE), Report 2009, Government of India (GOI) every year about 500 Mt/yr residues are generated in India. Out of total residue generated, highest contributor is Utter Pradesh (60 Mt/yr), followed by Punjab (55 Mt/yr) and Maharashtra (46 Mt/yr). Among different crops, cereals crops contribute for the generation of 352 Mt residue followed by fiber crops (66 Mt/yr), oilseed (29 Mt/yr), pulses (13 Mt/yr) and sugarcane (12 Mt/yr). Among the cereal crops up to 70% is contributed by rice, wheat, maize and millets. Rice crop alone accounts for 34% followed by wheat contributing 22% of total residue generated by cereal crops. As depicted above, out of total residues generated from all crops, 13% is contributed by fiber crops. Among fibers, cotton holds 1st position by generating 53 Mt/yr (11% of crop residues) and coconut ranks 2nd with 12 Mt/yr of residue generation. The sugarcane residue (foliage and tops) generates 12Mt/yr, i.e., 2% of crop residues (**Figure 1**) (www.nicra.iari.res.in/Data/FinalCRM.doc).

The amount of crop residues, which have not any valuable uses is either left in the fields to rot or burnt away as such, is termed as surplus biomass. A brief idea about the amount of residue generated in different states of India, surplus residues left behind after conventional use, residue burned as reported by IPCC and [6] is shown in **Table 1**. Two reports dictated the burnt surplus agricultural biomass approximately 83.66 Mt/yr and 92.81 Mt/yr respectively. The data from two reports vary by 11% and this difference can be due to the climatic conditions, geographic separation, sample size and time of sampling used in above mentioned studies. However, in comparison to the total surplus residues, observed difference can be considered as insignificant. Besides biomass a massive quantity of industrial residues is disposed off as such in environment generating pollution and other related problems [7]. This huge amount of lignocellulosic biomass can likely be converted into different valuable products including biofuels, cheap energy sources for microbial fermentation, enzyme production and useful fine chemicals [8].

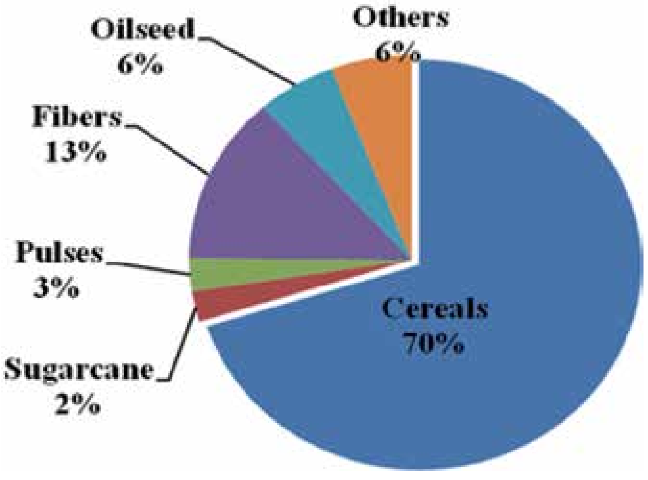

Figure 1.
Contribution of various crops in residue generation (www.nicra.iari.res.in/Data/FinalCRM.doc).

States	Residue generation (MNRE, 2009)	Residue surplus (MNRE, 2009)	Residue burned (IPCC coeff.)	Residue burned [6]
	Mt/yr			
Andhra Pradesh	43.89	6.96	5.73	2.73
Arunachal Pradesh	0.4	0.07	0.06	0.04
Assam	11.43	2.34	1.42	0.73
Bihar	25.29	5.08	3.77	3.19
Chhattisgarh	11.25	2.12	1.84	0.83
Goa	0.57	0.14	0.08	0.04
Gujarat	28.73	8.9	6.69	3.81
Haryana	27.83	11.22	5.45	9.06
Himachal Pradesh	2.85	1.03	0.20	0.41
Jammu and Kashmir	1.59	0.28	0.35	0.89
Jharkhand	3.61	0.89	1.11	1.10
Karnataka	33.94	8.98	2.85	5.66
Kerala	9.74	5.07	0.40	0.22
Madhya Pradesh	33.18	10.22	3.46	1.91
Maharashtra	46.45	14.67	6.27	7.41
Manipur	0.9	0.11	0.14	0.07
Meghalaya	0.51	0.09	0.10	0.05
Mizoram	0.06	0.01	0.01	0.01
Nagaland	0.49	0.09	0.11	0.08
Orissa	20.07	3.68	2.57	1.34
Punjab	50.75	24.83	8.94	19.62
Rajasthan	29.32	8.52	3.58	1.78
Sikkim	0.15	0.02	0.01	0.01
Tamil Nadu	19.93	7.05	3.55	4.08
Tripura	0.04	0.02	0.22	0.11
Uttarakhand	2.86	0.63	13.34	21.92
Uttar Pradesh	59.97	13.53	0.58	0.78
West Bengal	35.93	4.29	10.82	4.96
India	501.76	140.84	83.66	92.81

Table 1.
Residue generated, surplus and burned (www.nicra.iari.res.in/Data/FinalCRM.doc).

2. Lignocellulosic biomass

Lignocellulosic biomass is consist of cellulose, hemicelluloses, lignin, water, protein and other compounds (**Table 2**). Cellulose and hemicelluloses provide strength to fiber and lignin act as the concrete which hold the fibers [9].

Lignocellulosic materials	Cellulose (%)	Hemicelluloses (%)	Lignin (%)	Reference
Sugar cane bagasse	42	25	20	[11]
Sweet sorghum	45	27	21	[11]
Hard wood	40–55	24–40	18–25	[12]
Soft wood	45–50	25–35	25–35	[12]
Corn cobs	45	35	15	[13]
Corn stover	38	26	19	[14]
Rice straw	32.1	24	18	[13]
Nut shells	25–30	25–30	30–40	[15]
Newspaper	40–55	25–40	18–30	[16]
Grasses	25–40	25–50	10–30	[12]
Wheat straw	29–35	26–32	16–21	[17]
Bagasse	54.87	16.52	23–33	[18]

Table 2.
Composition of lignocellulosic materials [10].

About 50% of the CO_2 fixed by plants through photosynthesis get stored in cell wall in the form of cellulose [19]. It is a homo-polysaccharide of glucose residues connected by β-1,4 linkages in linear un-branched fashion (**Figure 2**). Basic repeating unit of the cellulose polymer is a cellobiose unit, made up of two glucose anhydride [20]. The long-chain cellulose polymers are attached to each other by van der Waals and hydrogen bonds which results in packing cellulose chains into microfibrils [21, 22]. Overall structure is found to be consisted of two different types of regions: region where the chains are highly ordered is crystalline and the region with less ordered chain is amorphous [23]. The crystalline regions of cellulose are highly stiff thus these are not easily reachable to endo-cellulases [24]. Amorphous region is more readily hydrated and more accessible to enzyme.

Other significant component of lignocellulose is hemicellulose (**Figure 3**). Hemicellulose usually contributes for about 25–35% of the mass in dry wood, about 28% of softwoods, and 35% of hardwoods [26]. As compared to cellulose these possesses low molecular weight. These are found to consist of comparatively shorter chains of about 500–3000 monosaccharide units as compared to 7000–15,000 glucose residues cellulose [27]. The monosaccharides of hemicelluloses

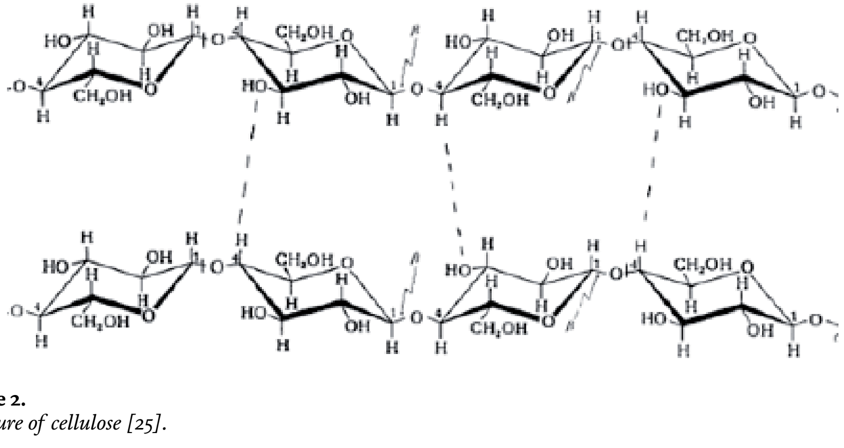

Figure 2.
Structure of cellulose [25].

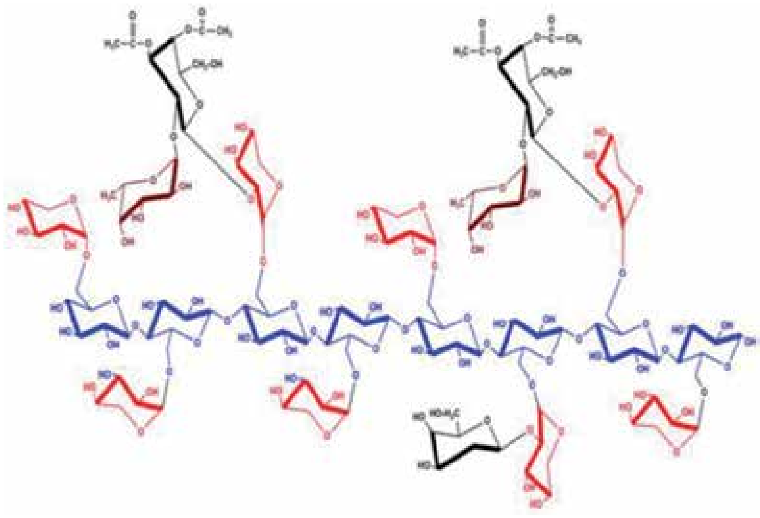

Figure 3.
Xyloglucan: a component of hemicelluloses [29].

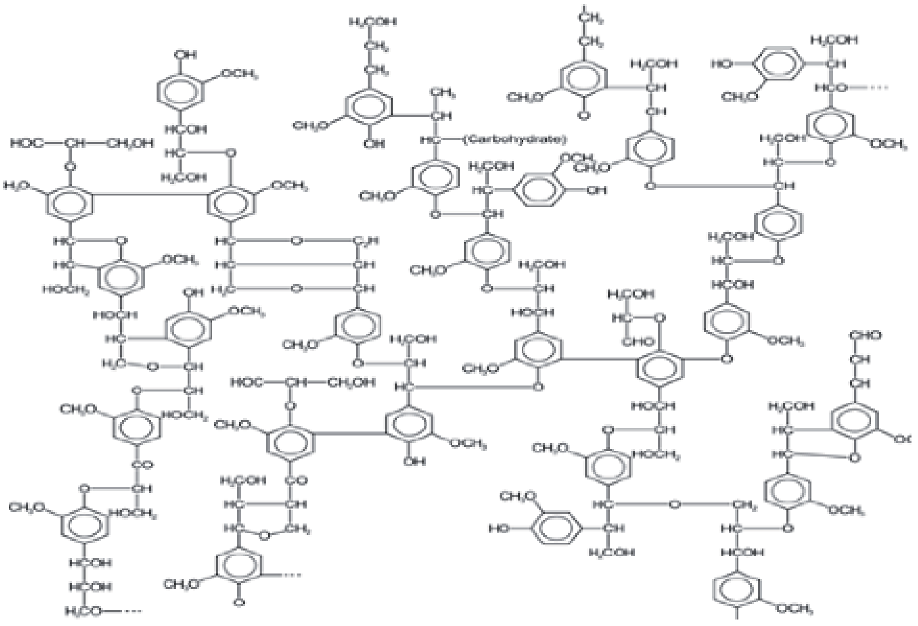

Figure 4.
Chemical structure of lignin (https://en.wikipedia.org/wiki/Lignin).

include pentoses (arabinose, rhamnose and xylose,), hexoses (glucose, galactose and mannose), and uronic acids (D-glucuronic, D-galacturonic acids and 4-o-methylglucuronic). The backbone of hemicelluloses can be a homopolymer or a heteropolymer having β-1,4 or sometimes β-1,3 glycosidic linkages. In hardwood, xylose is the principal pentose sugar but in various agricultural residues and other herbaceous, arabinose is the chief pentose sugar of hemicelluloses [28].

Lignocellulosic microfibrils are found to be surrounded by a complex aromatic heteropolymer known as lignin which provides a tough protective shield to highly energetic cellulose fibers [30]. Lignin comprises of β-aryl ether, biaryl ether, phenylcoumaran, pinoresinol, or diaryl propane linked p-coumaryl, coniferyl and sinapyl alcohol units (**Figure 4**). It is categorized as softwood lignin when the coniferyl alcohol derivatives predominant, hardwood lignin where both coniferyl and synapyl alcohol derivatives exist together and grass lignin where it chiefly consisted of p-coumaryl alcohol derivatives [31].

3. Pretreatment

Lignin is a recalcitrant component of the lignocellulosic biomass. Resistance to chemical and enzymatic attack increases with increase in lignin content [32]. Lignin the natural cement, acts as a ceiling for microbial/enzymatic attack. Hence, it is one of the major hurdles in using lingo-cellulosic materials in fermentation. Pretreatment is one of the most important steps in the process of converting renewable lignocellulosic biomass into useful products. The main target of any pretreatment is to alter or remove structural and compositional resistant to hydrolysis which further enhance digestibility of biomass [33]. It exposes cellulose and hemicellulose chains by breaking the crystalline matrix (**Figure 5**). To remove the obstacles for enzymatic scarification of lignocellulosic material following pretreatment used.

3.1 Mechanical treatment

Major mechanical treatment includes chiping, grinding and milling to reduce the particle size which is responsible to increase surface area and increased surface area responsible for better interaction between substrate and enzyme [21, 35]. Physical treatment includes un-catalyzed steam explosion, hot water pretreatment and high energy radiations. By the process size reduces to 10–30 mm after chipping the biomass and finally after milling or grinding 0.2–2 mm size is attained.

3.2 Steam explosion

Mason [36] first time introduced steam explosion in which biomass is pretreated at 180–240°C under 1–3.5 MPa pressure for 1–10 min with hot steam, followed by

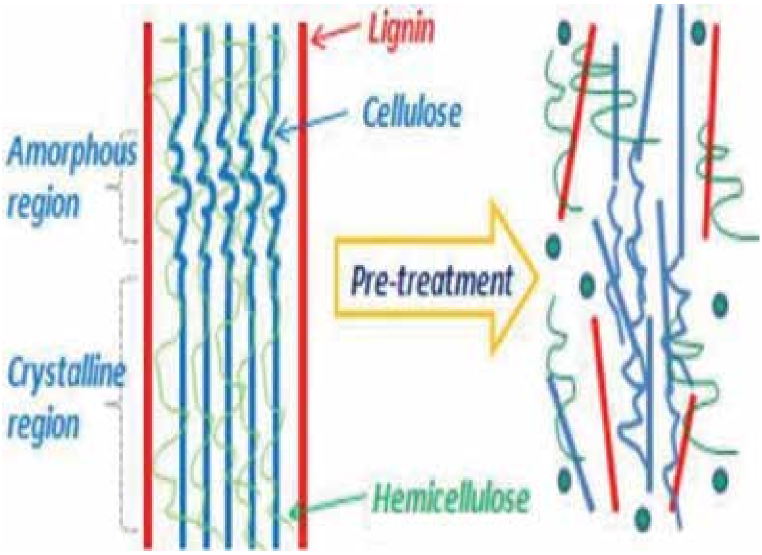

Figure 5.
Effect of pretreatment on lignocellulosic biomass [34].

an explosive decompression which bursts the rigid biomass fibers [37]. Nature of material to be processed and particle size are the determining factor for relationship between temperature and time [38]. Quick expansion in steam explosion vaporizes the saturated water present in fibril structure linkages between molecules, and produces a better lignocellulosic matrix [39]. Recoveries ranged from 46 to 90% indicated that significant autohydrolysis and degradation of sugars can occur during this pretreatment process [40]. Steam provides an effective mean to rapidly attain the required temperature without diluting the resulting sugar syrup. At the end, a rapid release of pressure brings temperature down and arrests the reaction [41].

3.3 Ultrasonic pretreatment

Scanning electron microscopy images reveal that ultrasonic treatment have the capacity to modify structure of lignocellulosic biomass [42]. Ultrasonic waves work by creating pressure difference within a solution [43]. The pressure wave travels through the liquid medium creating alternate regions of high (compression) and low (rarefaction) pressure (**Figure 6**).

3.4 Acid pretreatment

In this method lignocellulosic material is dipped in an acidic solution (typically H_2SO_4), and subjected to optimum temperature. Dilute sulfuric acid had been used at commercial scale for pretreatment of various biomasses such as Switch grass [44] Corn Stover [45] and Poplar [46]. By acid catalyzed hydrolysis (**Figure 7**) most of the hemicelluloses are almost removed from the micro fibrils of the biomass but delignification is achieved to a lesser extent. Dilute acids are highly effective in removing hemicelluloses as dissolved sugars as a result of which glucose yield from cellulose increase to almost 100%. The optimal conditions to attain maximum sugar yield depends on the target to be achieved [47].

3.5 Alkaline pretreatment

It is responsible for the saponification of inter molecule delignification of the hemicelluloses. The biomass is exposed for the enzymatic hydrolysis of cellulose and hemicelluloses. As compared to other methods of pretreatment, alkali pretreatment is carried out for longer duration at low temperature and pressure [39]. It is supposed to act by saponification of inter-molecular ester bonds which are found to present between hemicelluloses and other components [48] (**Figure 8**). It is mainly responsible for

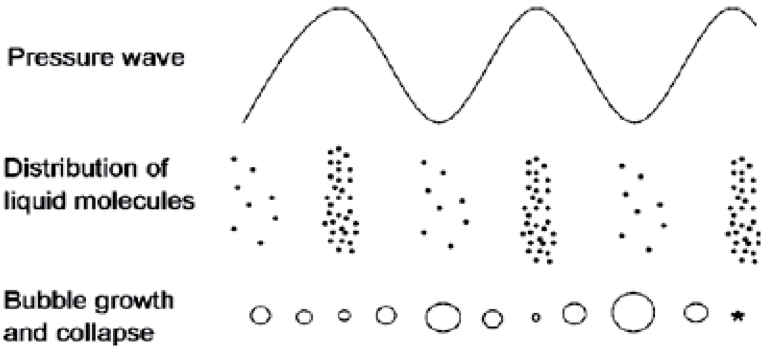

Figure 6.
A pressure wave traveling through a solution [36].

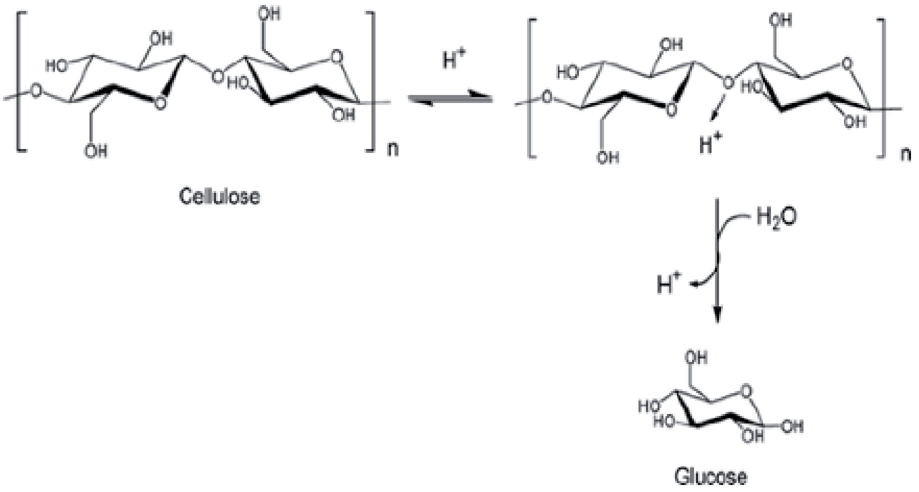

Figure 7.
Cellulose hydrolysis in acidic media [47].

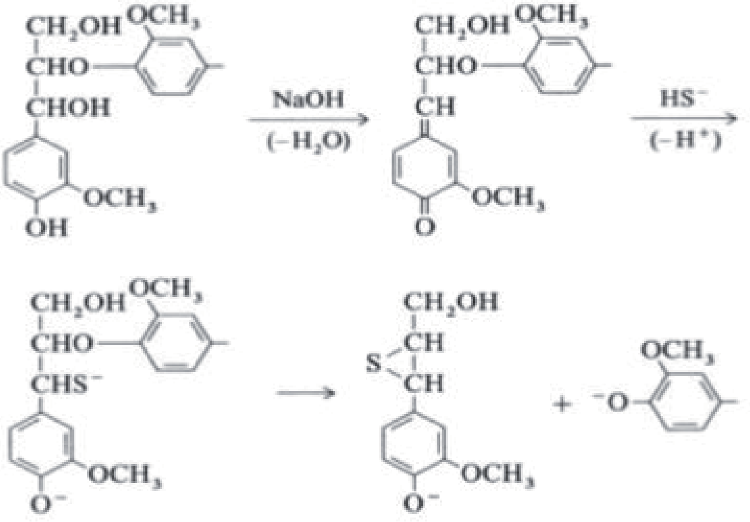

Figure 8.
Ether bond cleavage in alkaline solution [48].

delignification of lignocellulosic biomass. But it also removes some acetyl and uronic acid substitutions on hemicelluloses, which expose the biomass for enzymatic hydrolysis of cellulose and hemicelluloses [49]. A major limitation of alkaline pretreatments is formation of some salts which are either irrecoverable or incorporated as salts into the biomass [50]. Reactor costs for alkali pretreatment are lower than those for acid pretreatments [51]. For a given quantity of biomass, lowest operating cost is for lime pretreatment [39]. However the use of more pricey salts at higher concentrations is the major drawback that poses environmental threats and may also hinder the recycling process [52].

4. Enzymology of cellulose degradation

Cellulases are classified as hydrolases, i.e., they add water molecules to cleave glycosidic bonds. Cellulases purified from different microorganisms found to poses different molecular characteristics including molecular weight, amino acid composition, isoelectric point) absorbability for cellulose, catalytic activity and substrate specificity [53]. Three chief classes of cellulases recognized to date are:

1. Endo-β-1,4-glucanases (Cx) attacks soluble cellulose derivative in a random fashion forming nonreducing ends, producing new chain ends to be attacked by exoglucanases. These enzymes may be processive or nonprocessive. In processive enzymes, enzyme-substrate complex formation is followed by several successive breaks in a polysaccharide chain [23].

2. Exo-β-1,4-glucanases (C1) (avicelase) attack the reducing or nonreducing end of the cellulose polymer. Processive exo-β-1,4-glucanases are named as cellobiohydrolases. The end product of exo-glucanase hydrolysis are cellobiose and glucose units,

3. β-Glucosidases finally breaks cellobiose to glucose.

These enzymes act synergistically (**Figure 9**) [54]. An endo-acting enzyme generates new reducing and nonreducing ends. Exo-acting enzyme releases cellobiose from ends produced by endo-enzymes acting which is finally hydrolyzed by β-glucosidases to glucose [55]. Mainly four types of synergism have been identified [56]:

i. Endo-exo: among exo-glucanases and endo-glucanases.

ii. Exo-exo: among exo-glucanases those processing from different ends (reducing and nonreducing ends).

iii. Synergy between exo-glucanases and β-glucosidases that removes cellobiose.

iv. Intramolecular synergy between catalytic domains and CBHs.

In general cellulases comprise of two distinct domains, i.e., Small cellulose-binding module (CBM) which is noncatalytic, Large domain having catalytic characteristics

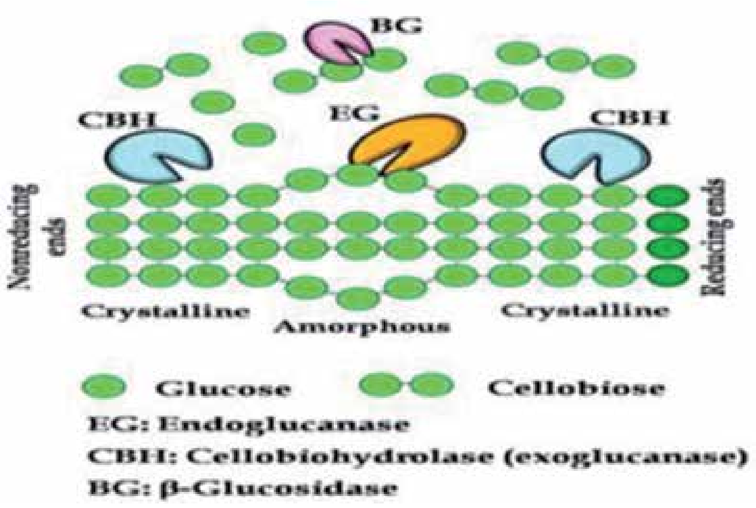

Figure 9.
Mechanism of action of cellulases [54].

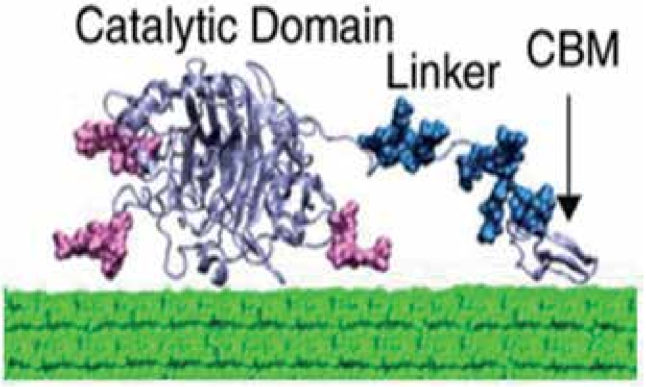

Figure 10.
Cellulases [59].

(CD). Both the domains are found to be connected by a linker region (**Figure 10**) [57]. Till date, about 300 different CBMs have already been identified. CBMs are categorized into 45 families on the basis of their amino acid similarity [58]. This variation in affinity may be due to variation in spatial structure created by the presence of CBMs [60].

4.1 Source of cellulase

Cellulases are the hydrolytic enzymes which are produced by a diversity of microbes like actinomycetes, bacteria and fungi when grown on cellulosic substrates [61]. Among these organisms fungi are studied most extensively [62]. Filamentous fungi are the chief sources known for producing cellulases and hemicellulases [63]. Crude cellulases from *Trichoderma* and *Aspergillus* genera production are commercially available for agricultural and industrial use [64]. Representatives of *Trichoderma* genus secretes comparatively large quantities of endo-β-glucanase and exo-β-glucanase but low level of β-glucosidase, while those of Aspergillus genus secretes moderately high level of endo-β-glucanase and β-glucosidase with low level of exo-β-glucanase [65]. Cellulases isolated from thermophilic fungi are of great interest because of their industrial application on account of thermo stability. Thermophilic fungi producing cellulases include *Chaetomium thermopile*, *Humicola insolens*, *Humicola agrisea*, *Myceliopthora thermophila*, *Talaromyces emersonii* and *Thermoascus aurantiacus* [66]. Unlike thermophiles, cellulase producing alkaliphilic fungi are very rare [67]. The alkaline tolerated cellulases producing marine fungi Chaetomium sp. (NIOCC36) from mangrove leaves. Surprisingly, no any thermophilic archaea showing cellulolytic behavior have been described [68]. Bacterial cellulase generally forms complex systems (cellulosomes). Historically fungal cellulases have been easier to study than bacterial system, as the bacterial enzyme tend to form aggregates. *Cellulomonas*, *Bacillus* and *Micrococcus* spp. isolated from coir retting effluents of estuarine environment were also employed to study endoglucanase activity [69]. Gaor and Tiwari reported organic solvent thermostable cellulases from *Bacillus vallismortis* RG-07 [70]. *Bacillus thuringiensis* strains [71], *Bacillus pumilus* EB3 [72] are also reported as good cellulase producers. Wild-type and mutants stains of *Pseudomonas fluorescens* were used by Bakare and co-workers to produce cellulases [73]. Interestingly, research findings are reported even for the production of cellulases from several species of insects in the orders of dictyoptera, orthoptera, and coleoptera by their own in the mid gut or salivary glands. These findings challenged the traditional view of cellulose digestion that it is mediated by microbial cellulases in the gut of insect [74]. The first endogenous cellulase from insect was discovered in 1998 in the termite (*Reticulitermes speratus*), which was found to be capable for feeding wood even after the removal of its gut fauna [75]. Acquisition of digestive enzymes has also been explored in other xylophagous arthropods, molluscs, including snails, a sea slug, a periwinkle and some bivalves. Various possible sources are reported for these endogenous enzymes such as the hepatopancreas, gastric teeth, and crystalline styles (needlelike structures made of crystalline proteins forming a motor organ in the stomach of bivalves [76].

4.2 Cellulase activity assay

Two fundamental approaches used for measuring cellulase activity are:

1. Measuring individual cellulase (endoglucanases, exoglucanases and β-glucosidases) activities.

2. Measuring the total cellulase (FPase) activity [77].

Quantitatively cellulase activity can be assayed in three ways:

1. Accumulation of products after hydrolysis.

2. The reduction in substrate quantity.

3. Change in the physical properties of substrates.

The first one is ideal for measuring individual cellulase activity within a short time however the third one is a chosen for measuring total enzyme activity within a given time [77].

Total cellulase activity assay is always performed using insoluble substrates having pure cellulosic substrates such as Whatman No. 1 filter paper. The filter paper activity (FPase activity) is the key method for analysis of total cellulase activity which was developed by Mandels, cotton linter, microcrystalline cellulose, bacterial cellulose, algal cellulose and cellulose-containing substrates such as pretreated lignocellulose [78]. This standard filter paper method has been revised by Ghose which was established and published by the International Union of Pure and Applied Chemistry (IUPAC) [79]. He used Whatman No. 1 filter paper (1 × 6 cm strip) as the substrate. It is used as the standard substrate because of its readily availability and inexpensiveness [80].

Commercial avicel is also used for measuring exoglucanase activity because it has a low degree of polymerization (DP) and it is moderately hard to be attacked by endoglucanases [81]. Endoglucanase activity can be measured using a soluble cellulose derivative with a high degree of polymerization (DP) such as carboxymethyl cellulose (CMC). It can be measured by both methods, i.e., reduction in substrate viscosity/increase in reducing sugar. CMCase activity using CMC is measured by determining reducing sugars released after 5 min of enzyme reaction with 0.5% CMC at pH 4.8 and 50°C [78]. Exoglucanases are known to cleave the easily accessible ends of cellulose molecules liberating glucose and cellobiose. β-glucosidases cleaves soluble cellobiose and other cellodextrins having DP up to 6 and liberates glucose as end product [82]. Various chromogenic and nonchromogenic substrates could be evaluated. In chromogenic method, p-nitrophenol-β-glucoside (P-NPG) can be used as the substrate. However, in the case of nonchromogenic substrates different methods used are based on nature of substrates. For example, when oligo or disaccharides (such as cellobiose) are used, released glucose can be evaluated by the GOD (glucose oxidase) method with a commercial kit but when polysaccharide are used a substrate, reducing sugars released is measured by the DNS (dinitrosalicylic acid) method [81].

4.3 Production of cellulases

The technique which are mainly used for the enzyme production are Submerged fermentation (SmF) and solid state fermentation (SSF) [83].

4.3.1 Submerged fermentation

When fermentation is performed with some free flowing nutrient media; it is termed as SmF [84]. In industry, enzymes are produced mostly by SmF, primarily due to the much simplified processes associated with scale-up compared to those involved for scale-up in SSF [85]. In fact, some other important factors like indulgence in controlling process parameters, monitoring and downstream processing makes SmF more significant [86]. Only a few designs are available in literature for SSF based bioreactors. This is principally due to several problems encountered in case of SSF for controlling various parameters like pH, temperature, aeration and moisture content. Fungal cellulase production is largely dependent on media composition and culture conditions. Thus development of a suitable fermentation strategy is necessary for full exploitation of potential of microorganism used for fermentation [87]. Several reports are available for cellulase production using SmF. Karthikeyan et al. [88] reported cellulase production from *Penicillium* strain K-P in liquid medium supplemented with different carbon and nitrogen sources at varying pH and temperature, maximum cellulase activity was observed on fifth day (pH 3.0 and 30°C) in the presence of fructose and ammonium nitrate as carbon and nitrogen source respectively. Narasimha et al. [89] reported maximum cellulase production using *A. niger* on medium (pH 5) supplemented with 1% CMC or sawdust.

4.3.2 Solid state fermentation

When fermentation is performed on nonsoluble materials in the absence of free flowing nutrient media, so that the material used can serve as a platform for support as well as nutrients; it is termed as solid state fermentation. While compared for their potential it was found SSF offers various opportunities over SmF because they are eco-friendly on account of lower energy requirements, produce lesser wastewater and they are based on employment of waste solid biomass [90]. Further advantages of SSF over SmF include prevalence of nonaseptic conditions, a wide variety of substrate are available, low capital cost, inexpensive downstream processing [91], higher product concentration, high reproducibility, lesser space requirements (compact fermenters), easy contamination management [92]. It is observed that production cost was decreased about 10 fold in SSF over SmF.

4.3.3 Fermentation conditions

Fermentation condition play the main role for the standardization of process parameters such as incubation period, inoculum size, pH, carbon and Nitrogen source, metal ions, etc. Maximum cellulase production may vary from 1 day to weeks. It is usually observed that fungal cultures require longer incubation period for cellulase production than bacterial cultures. The highest cellulase level was achieved 96 hrs of the fermentation while using *T. harzianam* and *P. chrysosporium* [93]. Maximum cellulase production was observed after 96 h by *A. niger* [94].

Optimal cellulase secretion from *Aspergillus niger* was achieved at a time of 72 h in maize straw while 96 and 120 h were the growth period in millet and guinea corn straws respectively [95].

The age and concentration of inoculum also plays an important role in the production of cellulases. An increase in inoculum size up to an optimum limits results in rapid proliferation and biomass synthesis which leads to produced higher amount of cellulase [96]. On the other hand higher inoculum volume beyond optimum size leads to increases in the water content of medium in case of SSF creating aeration problems in SSF and it will responsible for reduction in overall yield [97].

Bacterial and fungal cellulase production found to be significantly affected by pH. Milala et al. [95] reported maximum cellulase activity at pH 4.0 by *A. niger*. Devi and Kumar [98] optimized condition of cellulase production in fungal strain *A. niger* against the lignocellulosic bio wastes like saw dust, paper cellulose at varying environmental parameters of pH (4.0–7.0) and maximum activity was observed at pH 5. Gao et al. [99] studied the production of extracellular cellulases by a newly isolated thermoacidophilic fungus *Aspergillus terreus* M11 on the lignocellulosic materials in solid-state fermentation (SSF) and the high-level cellulase activity was observed at pH 3.0. However, the results appeared to contradict previous results reported by Solingen et al. [100] of an alkaline novel *Streptomyces* sp. isolated from east African soda lakes that have an optimal pH of 8.0, highlighting the effect of alkaline environment on the adaptation of these *Streptomyces*.

The fermentation temperature plays a very significant role on the growth and metabolic activity of microbial cells. Optimum temperature for cellulase production under solid-state fermentation by *Trichoderma reesei* RUT C30 was 33°C [101]. Fatma et al. [102] studied ethanol production from rice straw using cellulase produced by *T. reesei* F-418 cultivated in alkali treated rice straw under SSF and reported 162 U/g substrate cellulase activity when fungus was cultivated incubation at 28°C. Maximum enzyme production (3.9 U/ml) was achieved at 45°C temperature by *Aspergillus niger* using paper cellulose [98]. Gao et al. [99] studied production of extracellular cellulases by a newly isolated thermoacidophilic fungus *Aspergillus terreus M11*, on the lignocellulosic materials in solid-state fermentation (SSF) at 45°C. Jang and Chen [103] described a CMCase produced by a *Streptomyces* T3-1 with optimum temperature 50°C. Schrempf and Walter, [104] described a CMCase production by *S. reticuli* at an optimum temperature 55°C.

Various carbon sources such as metabolizable sugars, commercial cellulose and agricultural residues/by-products have been used for cellulase production. Some carbon sources resulted good growth with low enzyme production while some supported good growth along with high yield of enzyme secretion. Commercially available carbon sources used for cellulase production were Powdered cellulose by *A. niger* [105], and CM Lactose by *Mucor circinelloides* [81]. Several studies focused on cellulase use in the bioconversion of agro-industrial waste [106]. Chandra et al. [107] studied effect of several carbon sources including groundnut fodder, wheat bran, rice bran and sawdust on cellulase production by *A. niger.* They found that highest titers of cellulolytic enzymes in solid state fermentation on wheat bran. Azzaz, [108] studied effect of several carbon sources including banana wastes, rice straw, wheat straw, corn stalks and pure cellulose powder on cellulase production by *A. niger* and *A. flavus* NRRL 5521. He observed that wheat straw gave the highest cellulase production when fermented with *A. niger* (0.177 U/mL) while rice straw gave the highest (0.046 U/mL) cellulase production when fermented with *A. flavus* NRRL 5521. The lignocellulosic residues offer cheaper substituent of pure cellulose available commercially for the production of cellulase. Mixed substrates like wheat bran and corn cob are used as best carbon source in case of *A. niger* NRRL3 for cellulase production under SSF [109]. Milala et al. [95] used different agricultural

Supplement	**SmF (U/mL)**		**SSF (U/gDMB)**	
	CMCase	**FPase**	**CMCase**	**FPase**
Carbon sources (5% w/v in SmF and 4% w/w in SSF)				
Control	0.7	0.4	3.7	2
Glucose	1.52	0.54	11.1	6.5
Xylose	1.2	1.42	15.7	6.6
Lactose	3	1.71	18	10.9
Maltose	1.51	1.5	17.5	6.3
Sucrose	1.54	1.51	13.7	6.2

Table 3.
Effect of supplementation of various carbon sources [106].

wastes millet, guinea corn straw, rice husks and maize straw as carbon sources for cellulase production by *Aspergillus niger*. According to Mrudula and Murugammal [85] lactose was found to be the best inducer in SmF and SSF (**Table 3**). Prasanna et al. [110] also reported lactose as the most excellent carbon source for cellulase production by *Penicillium* sp. followed by carboxymethyl cellulose and galactose.

Different researchers studied the effect of various nitrogen sources for cellulase production by employing different microbes. Peptone was reported as most effective nitrogen source for Penicillium sp. [110], *Penicillium waksmanii* F10-2 [111], urea for *A. niger* [89] and NH_4NO_3 for *Trichoderma reesei* NRRL 11460 [112]. Although the addition of beef extract and peptone (as organic nitrogen source) leads to enhanced growth and enzyme production but they were not economically fit because of their higher cost.

Cellulase production by some microorganisms has been found to be influenced by metal ions, chelators, detergents and surfactants. It was reported that usually metal ions such as Ag^+, Cu^{2+}, Hg^{2+}, Fe^{3+}, K^+, Mn^{2+}, Mg^{2+}, and Zn^{2+} are slightly or completely inhibitory of cellulase, whereas metal ions such as Ca^{2+}, Co^{2+} and Na^+ either stimulate or does not affect the cellulase activity [113]. Addition of Tween20 leads to a significant increase in endoglucanase and xylanase production by *Melanocarpus* sp. MTCC 3922 [114]. Cellulase activity increased with Tween80 and reduced with SDS [115]. Enhancement in enzyme production by Tween80 may be due to increase in permeability of cell membrane allowing rapid secretion and synthesis of the enzymes [116].

5. Purification of cellulase

It is an important step to remove any contaminants that are found to be present in the mixture. Hence, it is a vital step required for improving performance/functioning of an enzyme. Enzymes in the culture supernatant could be purified by the conventional methods which include ammonium sulfate precipitation and dialysis followed by column chromatography [117]. The most common matrix for gel exclusion chromatography is the Sephadex with different pore sizes which is employed in the purification of cellulase [118]. The purification folds and % yield are the two most important factors which are used to evaluate the efficiency of purification. First step (ammonium salt precipitation) is based upon difference in protein solubility. The solubility of protein firstly increase and then starts decreasing with increase in salt concentration and finally protein gets precipitate. This process is called Salting out [119]. Ammonium sulfate ($(NH_4)_2SO_4$) is often used for this purpose because of its high solubility in water. Devi et al. [120] reported protein precipitation by addition of solid ammonium sulfate up to 80% saturation. Chen et al. [121] reported precipitation with $(NH_4)_2SO_4$ at 40–60% saturation. Precipitation is followed by a concentrating step that separates proteins from salts called dialysis. For next step chromatographic technique is most widely used for the direct recovery of protein and other charged molecules. Various types of chromatography methods (gel filtration: Sephadex G-100 [73], ion exchange: DEAE-Cellulose [122] and affinity: swollen avicel [123] have been used for purification of cellulase from various fungal strains.

6. Characterization of cellulase

Different researchers reported different temperatures for maximum cellulase production. It is reported that the optimal temperature for cellulase production varies from strain to strain of microorganisms [69]. The optimum temperature of fungal cellulases ranges from 40 to 60°C and pH found to be 4.8. A battery of thermophilic fungal strains are known to produce thermostable enzymes which are stable and active at such high temperature which are not optimum for the growth of the microorganism. Filamentous fungi, e.g., *Talaromyces emersonii*, *Thermoascus aurantiacus* and *Chaetomium thermophilum* are reported to produce cellulases having high-cellulase activity at elevated temperature [124]. The Km value is used for the measurement of enzyme affinity towards the substrate. An increase in substrate concentration made more binding sites available for the enzymes to adhere and the rate at which product formation would be achieved therefore would be faster [125]. In literature, different ranges of Km and Vmax for different fungal species have been reported. Genetic variability may be a factor for the above reported variation [126]. Taha et al. [127] reported cellulase showing optimum activity at pH 6 and 50°C with (Vmax) of $75\ g\ l^{-1}\ min^{-1}\ mg^{-1}$ with its corresponding Km value of 2.5×10^{-5} g/l.

7. Applications of cellulases

According to Sajith et al. [87] on the global enzyme market cellulases occupy the third place (i.e., ≈15%) after amylase (≈25%) and protease (≈18%). Cellulases are currently being produced on commercial scale by several industries all over the world and widely used in various industrial applications [128].

7.1 Paper and pulp industries

Today, 90% of paper pulp is made of wood. Recycling one ton of newsprint and printing or copier paper saves about 1 ton and more than 2 tons of wood respectively [129]. Usually, the industrial process for eradicating wastepaper pollutants involves re-pulping, screening, cleaning, washing and flotation [130]. According to Shrinath et al. [131] the conventional recycling of waste papers is costly and hazardous to the environment due to the use of chemicals (hydrogen peroxide, sodium hydroxide and sodium silicate). Cellulases are mainly used for the pulping and deinking of waste papers. Enzymatic deinking as whole is an environmental friendly process [132]. Cellulase based pulping process is not only energy efficient, environment-friendly but also improve mechanical strength of the final paper product by improving the inter-fiber bonding [133]. When used with hemicellulases, cellulases improve the brightness and quality of the recycled paper [134].

Besides deinking and pulping, cellulases are also used in paper mills for drainage of clogged pipes by dissolving fiber residues [61] and for manufacturing easily biodegradable cardboards, sanitary papers [135].

7.2 Textile industry

Among the application textile industry dominated in the market in 2017. Cellulase application in textile play main role in the growth of textile industry. In textile industry worn-out look is given to the denim using stone washing. But stone washing have some disadvantages. It causes wear and tear of the fabric, huge loss of water due to extensive washing step and high labor cost, etc. Cellulases used for bio-polishing of cotton cloths and enzyme based stoning of jeans to impart stone-washed look for denims. Cellulase treatment gives a smooth and glossy appearance to fabric by removing short fibers, surface fuzziness and improves color brightness, hydrophilicity and moisture absorbance [136]. Most of the cotton and cotton mixed garments tend to become fluffy and dull during repeated washing due to detachment of microfibrils on the surface of garments. Cellulase treatment can restore a smooth surface and original color to the garments by removing these microfibrils [137]. According to a statistics of India Brand Equity Foundation (IBEF), Indian textile market has increased from US$ 99 Billion in 2014 to US$137 Billion in 2016 and exhibited a CAGR of 17.6% during the period 2014–2016.

7.3 Food and feed processing

Cellulases are found to be highly valuable for feed and food Recently BIO-CAT introduced a cellulase (Cellulase C500) at IPPE 2016. The enzyme have been derived from a non-GMO, AAFCO approved microbial strain. Addition of Cellulase to animal feed increases its digestibility (http://www.bio-cat.com/introducing-cellulase-c500-animal-feed-enzyme/).

Use of cellulases in feed processing leads to improvement in feed digestibility and animal performance. As a component of macerating enzyme complex (cellulase, xylanase and pectinase) these are used for extraction and clarification of fruits and vegetable juices, nectars and oils [138]. Along with others, cell wall degrading enzymes cellulases can be used to reduce bitterness and increase the taste and aroma of citrus fruits [61].

7.4 Detergents

Nowadays liquid laundry detergent containing anionic or nonionic surfactant, citric acid or a water-soluble salt, protease, cellulose and a mixture of propanediol and boric acid or its derivatives are employed to improve the stability of cellulases [61]. Cellulases are added to detergents for the breakdown of hydrogen bonding under harsh environmental conditions such as alkaline or thermophilic conditions [139]. Cellulases are mixed with detergents to enhance brightness and hand feel, dirt removal from cotton and cotton blended garments because they are capable of modifying the structure of cellulose fibrils [62].

7.5 Biofuel production

With the fast exhaustion of fossil fuels the need to find a substitute source for renewable energy and fuels is intensifying day by day. Thus interest in the saccharification of lignocellulosic biomass using cellulases and other related enzymes is also increasing [14, 16]. In other words, the cellulase market could be expanded considerably by using cellulases for saccharification of pretreated cellulosic material to sugars which can be fermented further to bioethanol and other bio-based products on large scale [77]. By 2020 biofuels, especially bioethanol from renewable resources is expected to replace 20% of the fossil fuel consumption [140]. Cellulases produced by various filamentous fungi mainly *Aspergillus*, *Trichoderma* and *Penicillium* have a potentially to be used successfully for bioethanol production using sugarcane bagasse, corn straw, rice straw, wheat straw and wheat bran as raw materials [141–143].

7.6 Wine and brewery industry

Microbial glucanases and related polysaccharides are usually used to produce alcoholic beverages including beers and wines by fermentation [144]. In wine production various enzymes such as pectinases, glucanases and hemicellulases plays an important role in improving wine quality and stability by improving color extraction, skin maceration, must clarification and filtration [145]. According to the precedent literature about 10–35% increase in the wine must extraction, a 70–80% increase in the rate of must filtration, 50–120 min decreased pressing time, and 30–70% decreased must viscosity, 20–40% energy saving while cooling thus a considerably improved wine stability. Thus supplementation of enzymes like cellulase and pectinase to the process are expected to enhance the productivity of brewing production [143]. β-Glucosidases can enhance the aroma of wines by modifying glycosylated precursors. Macerating enzymes also improve the juice, press ability and settling of grapes used for wine fermentation. A number of commercial enzyme preparations are now available to the wine industry.

7.7 Medical industry

Cellulolytic bacteria like Bacteroides cellulosilyticus and Ruminococcus champanellensis can be employed for the treatment of phytobezoars disease, which causes concretion of indigestible vegetable and fruit fibers in the gastrointestinal tract that may leads to surgical intrusion [128]. Moreover, cellulases have been utilized as excellent antibiofilm agents against pathogenic biofilms [146]. Further research is required to unravel yet unknown applications of cellulases in medical field.

8. Cellulase market demand

Demand for industrial enzymes in developed countries such as the US, Western Europe, Japan and Canada was relatively stable during the recent times while in developing economies of Asia-Pacific, Eastern Europe, Africa and Middle East regions, demand is increasing day by day [147]. Currently, by dollar volume cellulases are the third largest industrial enzyme globally, because of their extensive applications in animal feed additives, as detergent enzymes, cotton processing, juice extraction and paper recycling. However, cellulases may become the largest quantity industrial enzyme, if ethanol produced from lignocellulosic biomass through these enzymes becomes the major transportation fuel [112, 148]. They contribute to 8% of the worldwide industrial enzyme demand [149]. The international market for biofuel enzymes is expected to reach $9.0 billion by 2017 [150]. Global demand for industrial enzyme's projected to grow 4.0% per year to $5.0 billion in 2021. Key players in the global cellulose market are Amano enzyme U.S.A, Worthington Biochemical Corporation, MP Biomedical LLC, Sigma-Aldrich Co. LLC, Prozmix LLC, Creative Enzymes, bio-WORLD, Amano

Enzyme samples	Supplier	Source
Cellubrix	Novozymes, Denmark	*Trichoderma longibrachiatum* and *Aspergillus niger*
Novozymes 188	Novozymes	*Aspergillus niger*
Viscostar 150L	Dyadic (Jupiter, USA)	*Trichoderma longibrachiatum/Trichoderma reesei*
Multifect CL Genencor	Intl. (S.San Francisco, CA)	*Trichoderma reesei*
Energex L	Novozymes	*Trichoderma longibrachiatum/Trichoderma reesei*
Ultraflo L	Novozymes	*Trichoderma longibrachiatum/ Trichoderma reesei*
Viscozyme L	Novozymes	*Trichoderma longibrachiatum/Trichoderma reesei*
GC 440	Genencor-Danisco (Rochester, USA)	*Trichoderma longibrachiatum/Trichoderma reesei*
GC 880	Genencor	*Trichoderma longibrachiatum/Trichoderma reesei*
Spezyme CP	Genencor	*Trichoderma longibrachiatum/Trichoderma reesei*
Accelerase® 1500	Genencor	*Trichoderma reesei*
Cellulase AP30K	Amano Enzyme	*Aspeergillus niger*
Cellulase TRL	Solvay Enzymes (Elkhart, IN)	*Trichoderma longibrachiatum/Trichoderma reesei*
Econase CE	Alko-EDC (New York, NY)	*Trichoderma longibrachiatum/Trichoderma reesei*
Cellulase TAP106	Amano Enzyme (Troy, VA)	*Trichoderma viride*

Table 4.
Suppliers and sources of enzyme samples [122].

Enzyme Inc., Zhongbei Bio-Chem Industry Co., Ltd., Hunan Hong Ying Biotech Co., Ltd., Genencor and Novozyme are major producers they are known worldwide for cellulase production. All above companies played a noteworthy role for reducing production cost of cellulase several folds by their active research and are still continuing to bring down the cost by assuming novel technologies [112]. A few suppliers and source of enzyme samples are list below (**Table 4**). North America accounted for largest market share in global cellulose production in 2017. Production is depended on the increasing production of biofuel. According to a report by United States Energy information Administration in July 2018, the production of biofuel has increased in the U.S. from 1891 trillion butane to 2332 trillion, increasing at a CAGR of 5.4 during 2013 to 2017.

9. Future prospects

The demand for cellulases is increasing day by day due to its volatile and the rise in oil prices which induced a shift in interest towards the application of cellulases in producing biofuel using lignocellulosic biomass [151]. Enhancing the cellulase activity and reducing the cost of production of enzyme are two key issues regarding the enzymatic hydrolysis of cellulosic biomass. Genetic techniques can be used to clone the cellulase coding sequences into bacteria, yeasts, fungi, plants and animals to create new cellulase producing systems with improved production and activity of enzyme [152]. One of the major drawbacks of SSF is the low thermal conductivity of the solid medium used in SSF which restricts the removal of excess heat generated by microbial metabolism. The elevated temperature in bioreactors may lead to denaturation of thermo labile proteins [153]. Thus the thermo stable, modified fungal and bacterial strains are also good future prospects for cellulase production [62]. Interchangeably more advanced strategy is to engineer microbes for producing all major enzymes involved in cellulose hydrolysis in optimum ratio which may decrease the expenditure greatly [154]. Although the cellulase enzyme cost has dropped due to improvements in expression vectors and on-site production still there is a necessity of engineering a new generation cellulase cocktails that would further reduce cellulase cost. Efforts have to be made via hunting both diversity rich environments and extremophilic niches for identification of novel cellulase producers [150]. It can be made possible through following four approaches:

i. Mining novel cellulase genes via culturable/nonculturable strategies.

ii. Improving production technologies by using novel bioreactors.

iii. Designing novel cellulases through protein and metabolic engineering by understanding molecular mechanism and mode of interaction of cellulases with substrates.

iv. Using mathematical, biophysical and enzymological approaches for cellulase production through consolidated bioprocessing in a cost-effective manner.

10. Conclusion

Lignocellulosic biomass is the most abundant biomass on the earth. They are the potential source of biofuels, and other useful chemicals. But one of the most severe hindrances in this process is the structure of biomass itself. This problem can be resolved up to a greater extent by various types of pretreatments and enzymatic hydrolysis, engineered cellulases and by consolidated bioprocessing.

Consolidated bioprocessing includes cellulose production, hydrolysis of cellulose and fermentation of Pentose and Hexose sugars in a single step which will reduce production cost and increase production/conversion efficiency as compared to the processes performing dedicated cellulase production. A good pretreatment should result in increased cellulose content and decreased hemicelluloses/lignin content of biomass. Another problem is the yield and efficiency of enzyme. Yield of enzyme can be increased by optimization of different parameters involved in enzyme production using one variable or statistical approach (RSM). Alternatively novel proteins with enhanced production can be synthesized by protein and metabolic engineering. Enzyme engineering must be focused on (1) to increase cellulase specific activity on pretreated biomass through enzyme cocktail (2) to increase cellulase stability for cellulase recycling, and (3) to reduce enzyme production costs. Consolidated bioprocessing microorganisms or consortium would simplify the whole process and increase productivity. The above three approaches would be integrated together for maximizing the process for lignocellulosic biomass management/conversion in to value added products.

Acknowledgements

Authors acknowledge CSIR, UGC, DST and HSCST for financial support in the form of fellowship and major research project (DST/INT/UKR/P-14/2015).

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Chapter 5

The Use of Waste Management Techniques to Enhance Household Income and Reduce Urban Water Pollution

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Abstract

Appropriate waste management options are major concerns in the developing world. Current methods include incineration in the open and accumulation of wastes in designated places where they constitute nuisance to the environment. Apart from air pollution from the incinerators, leachates from decomposed wastes are either washed off where they serve as source of pollutants to the adjourning streams and rivers or contaminate groundwater through deep percolation. We present viable options for managing agricultural wastes in this chapter. The options presented are so simple and sustainable such that it can be managed by individuals. Hence, they are independent of the government bureaucratic bottlenecks that have been the bane of the previous government interventions. If embraced, it will also serve as sources of income for the concerned household, hence enhance their livelihood.

Keywords: environmental pollution, water pollution, waste management, waste-to-wealth

1. Introduction

Nigeria is reputed to be the largest black nation in the world, blessed with abundance of natural resources such as nickel, gold, tin, iron ore, bauxite, precious stones, bitumen, crude oil and vast agricultural land. Of all the natural resources, crude oil exploration is well developed. The nation depends on it for more than 70% of her income [1]. Due to instability and recent steady downward fall in crude oil price globally, the government of Nigeria seems to be seeking for diversification of her economy via increase in agricultural production. Several programmes have also been put in place to encourage Nigerians to get involved in agricultural production.

Due to poor infrastructural development in rural areas in developing nations of the world, there is the usual migration of people, especially youths, into the cities where they hope to get a "white-collar job" for a decent life. Unfortunately, the migration continues and the "white-collar job" is more of a mirage than reality. In an attempt to find a means of sustenance, some of these youths end up getting involved in one vice or the other. Due to land tenure system, poverty, lack of incentives, etc., more than 70% of farmers in Nigeria and other developing nations of the world are considered small-scale farmers (land holding of less than 10 ha) [2]. Continuous cultivation of the land has also led to depletion in the nutrient status of the soil. Unfortunately, cost of soil amendments such as mineral fertilizer is gradually getting beyond the reach of average farmer. Hence, if urgent steps are not taken to address the downward trend, developing world will soon be faced with food crises of unimaginable magnitude.

One of the ways of mitigating against this is the step already being experimented by the Nigerian government whereby incentives are provided to encourage women, unemployed youth and other stakeholders to get actively involved in agriculture. This is a right step in the right direction, if pursued to a logical end. However, there must be a holistic approach towards solving this problem. Such approach must include alternative source of input (fertilizer, etc.) that is affordable. It will also be necessary to find a way of forming the farmers into clusters so that processing facilities will be acquired and maximized. The government also must look into the area of packaging and transportation of agricultural produce so as to minimize loss. In a recent survey conducted in selected fruits and vegetable market in Oyo State, Nigeria, the traders complained of losing at least 5% of the purchased products between the farm gate and market due to the way the produce are stacked together during transportation and bad road network. Due to the perishable nature of these produce, a large percentage of the produce will also go into waste. If the traders must break even, they will have no other choice than to increase the price of the remaining items. Hence, buyers will be forced to pay not only for the items bought but also for the spoilt ones. The spoilt ones are usually stacked in designated places within the market community where they serve as breeding ground for disease vectors (**Figure 1**). When it rains, leachates from these dumping grounds are either washed to adjourning streams and rivers where they serve as contaminants to the water bodies or leached down the soil via deep percolation where they serve as contaminants to groundwater. Creating farm clusters will definitely boost agricultural production and encourage siting of medium- to large-scale processing plants that will add value to agricultural produce, thus enhancing the profitability of their products. It will

Figure 1.
Some horticultural waste from Odo-Oba, near Ogbomosho in Oyo State, Nigeria, West Africa.

however lead to generation of large volume of wastes which will serve as nuisance to the communities unless alternative uses have been provided long before they are generated to avoid outbreak of diseases in an epidemic magnitude.

Under normal circumstances, industrial wastes are to be treated to meet some prescribed minimum standards before discharge. The standards are clearly stated by regulating bodies. Unfortunately, most of the industries scattered all over Nigeria, as well as other developing environments, have been reported not to comply with these standards because the enforcement of the prescribed standard is weak and the penalties are too light to serve as deterrent to others [3–5]. These also pose a great risk to waterbodies. Other sources of contamination to waterbodies include leachates from agrochemicals, industrial discharge, etc. In this chapter, however, we will limit ourselves to agricultural wastes and its management.

Poverty thrives in Nigeria, as it is in other developing nations of the world. Nigeria is rated as one of the poorest countries of the world and occupies the 152nd position out of 188 countries on Human Development Index (HDI) ranking [6]. About 80% are reported to be living below poverty line [7]. Pipe-borne water is non-existent in most cities due to the breakdown of public water supply. Hence, several households depend on shallow wells and streams for their potable water. Some are dying of avoidable diseases. Unfortunately, others are ill but are too poor to be able to access health facility. On the contrary, the wastes that litter the place, serving as breeding ground for disease vectors and contaminating the streams and shallow wells, could be turned into income-generating ventures via waste-to-wealth programmes. The government structures are failing in the developing world due to the combinations of factors. Empowering households through waste-to-wealth programme will not only rid the environment of debris, etc. but will also take care of major source of contaminants to waterbodies (surface- and groundwater). Hence, our world will be a better place to live in and pollution will be minimized. Some of the ways of converting the menace of indiscriminate dumping of wastes into money-spinning ventures include but are not limited to:

2. Mushroom production

Across the globe, wastes are being generated from agriculture, industries, etc. To combat food security, efforts are being made to increase agricultural productivity and economic yield with little or no attention given to its disposal. When wastes are poorly managed or disposed, it may result in outbreak of disease and untidy environment, characterized with offensive odors, resulting into increase in the population of rodents and insects that could constitute threat to lives and properties. Over time, what has been considered as wastes in some enterprises, especially in agro industries, is found to be useful, thereby adding value to the supposed wastes.

Mushrooms are a group of fungi and are distinct from green plants because they lack chlorophyll and therefore cannot manufacture their own food as other plants do but rather produce extracellular enzyme which digest various kinds of dead organic matter on which they grow [8]. It contains all the essential amino acids (for humans) as well as most commonly occurring non-essential amino acids and amines. These include phenylalanine, valine, theanine, tryptophan, isoleucine, methionine and leucine [9, 10].

Mushrooms are a good source of protein that can enrich human diets, especially in some developing countries where meat may be rare or expensive. Many mushrooms are considered to be healthy food because they contain large amounts of qualitatively good protein, vitamins (B_1, B_2, B_3, C and D) and minerals (potassium and phosphorus) in addition to folic acid, an ingredient known for enriching the blood stream and preventing deficiencies. They have a low fat content ranging from 0.6 to 3.15%. The protein content ranges between 19 and 37%, depending on the variety [11, 12]. They are conventionally grown on agro-industrial wastes containing lignin, cellulose and hemicelluloses. In Nigeria and other parts of the world, tons of these wastes are generated annually which, if not managed, will constitute a menace to the environment. Different agro-industrial wastes singly and in combination have been used for the cultivation of different mushrooms such as *Volvariella volvacea*, *Pleurotus* species, *Agaricus* species, etc. [13–15]. The waste used in mushroom production includes banana leaves, water hyacinth, sawdust, rice straw, maize stover, corn cob, cassava peels, grass straws, oil palm processing wastes, etc.

The first step in mushroom growing is the choice of which mushroom species to grow. The culture of the choice mushroom can be obtained and prepared into the planting spawn, or the spawn is purchased directly from a mushroom laboratory. The second step is sourcing for a readily available substrate within the grower's immediate environment to cut down production cost. This step is followed by the preparation of the growing medium or substrate which may include chopping, breaking, soaking or moistening, depending on the type of substrate. They can be used fresh (rice straw, maize cob, banana leaves, etc.) or composted (sawdust). Some (straws, vines and wood) may require chopping into smaller sizes of 3–5 cm, while others can be used directly (e.g. sawdust) [16]. It is also required that the growth materials are disinfected to rid them of other inherent micro-organisms and insects by applying heat or chemical treatments [17, 18]. The third step in mushroom growing process is the transfer of the spawn or inoculum (planting material) to the growth medium after disinfection. This is done using a standard method in a laminar flow chamber or a locally fabricated inoculation hood, to avoid contamination of the disinfected substrate by unwanted micro-organisms. After inoculation or planting, the substrates are then moved to a dark room or incubation chamber and left for a period depending on the mushroom species that is being grown; it is a time during which the mushroom mycelium ramifies the entire substrate. After incubation, the substrates are subjected to a fruiting condition where the mushroom fruiting body initials or primordia begin to appear and are harvested after maturity. Mushroom cultivation processes are presented in **Figure 2**.

Figure 2.
Mushroom cultivation processes. (a)–(g) represent substrate preparation, mixing and bagging, actively growing mushroom planting material (spawn), inoculation/spawning of substrate bags, Volvariella volvacea growing on banana leaves, and Calocybe indica (milky mushroom) growing on sawdust substrate and freshly harvested mushrooms, respectively.

Mushrooms are a high-value niche product; its production is a viable source of livelihood and food security. Cost–benefit analysis of different aspects of mushroom production was investigated by [19]. The authors reported a cost–benefit ratio of 2.30, 3.13 and 1.8 on mushroom spawn production, substrate preparation and mushroom fruiting body production, respectively. Celik and Peker [20] and Basanta et al. [21] also reported the profitability of mushroom fruiting body production in Bulgaria and Bangladesh, respectively.

3. Composting

Compost fertilizers are organic fertilizers made from plant and animal leftover that have been decomposed by the existing micro-organism [22, 23]. The main objective of making compost manure is to recycle these nutrients in plants and animal leftover back to the soil for plant growth. The practice improves the soil physical, chemical and biological activities, improving crop yields and nutritional values. It also maximizes the use of available organic resources on the farm and minimizes the use of costly inorganic agrochemicals [24, 25]. Process involved in making compost is referred to as composting. Composting is defined as a biological process in which a micro-organism converts organic materials such as manure, sludge, leaves, peels, animal waste and food waste into a soil-like material called compost in the presence of water and air [26]. It is the main process used to produce stable, high-quality organic fertilizers from organic waste [27]. Composting is done to transform and stabilize organic materials into stable, usable products, to produce uniform organic fertilizer suitable for soil amendment and to remove offensive odors, to kill weed seeds and pathogenic organisms [28]. Compost can be made from crop residues, husks, stovers and agricultural, domestic and industrial wastes that are accessible and available, combined with animal manures. Human wastes can also be composted for crop production, but it is not encouraged due to disease and pathogen transmission [29].

Nigeria is the leading producer of cassava in the world, producing 37 million tons/year on 2.5 million hectares of land [30]. Accompanied with this output is the large volume of cassava peels being released as waste by processing centres all over Nigeria. It is usually burnt or used to feed livestock (most especially small ruminants) as source of protein and roughages. However, not more than 10% of the cassava peels produced is utilized in feeding livestock. The remaining is commonly found in farm and other processing sites as heap that are generally perceived as a nuisance [28]. These materials, however, could be utilized more effectively and sustainably through recycling rather than being destroyed through burning as commonly practiced by many leading to air pollution. Wastes such as cassava peels are rich in crude protein (5.29%) and fat (1.18%) [31]. Utilization of the peels and other agricultural wastes is limited by its low digestibility. Composting will not only reduce toxicity but also convert the resistant lignocellulose material into a more digestible substrate. Preparing compost from wastes offers many advantages. It provides incentive for communities to recover locked nutrients in the wastes, eliminate the problem of waste disposal and increase the manurial values of the materials [32].

Compost can be prepared throughout the year. Three common methods of preparing composts include on the earth/flat surfaces, the use of compost pits and preparation in boxes. Methods adopted are dependent on availability and access to space (**Figure 3**).

Compost manure will regulate soil structure, softens hard soil and improves the water holding capacity of the sandy soil, thus increasing soil aeration and the soil's ability to withstand erosion by wind or water [25]. It requires little or no technical

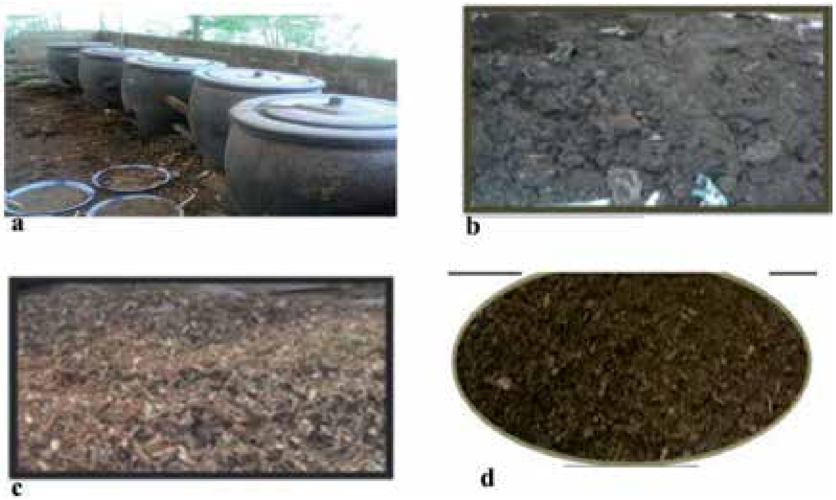

Figure 3.
Composting materials and matured compost; a, b, c and d are composting using bins, poultry manure, cassava peels and finished compost, respectively.

know-how. It is cheap and can be made on-site where wastes are deposited, thus reducing cost of transport. As an organic fertilizer, it has the ability to release nutrient slowly into the soil, thereby making the effect to last longer, even to the succeeding crops. It creates a good environment for soil microbes, by providing carbon compounds which serve as nutrients for soil micro-organisms and other soil habitats. Compost manure due to its composition is the storehouse of all essential macro- and micronutrients required by plants. When composts are fortified with other amendments, it can be used to control plant diseases and reduce crop losses on the field. [30]'s report indicated that this type of product significantly reduced the need for pesticide, fungicide and nematode application, which could cause environmental pollution. Matured compost should conform to at least one of the four tests outlined below: (i) The carbon to nitrogen ratio (C: N) must be less than 25:1, and seed germination using radish in the compost is at least 90% of control. (ii) The compost is cured and does not reheat to 20°C above ambient temperature. (iii) The compost is cured and there is a 60% weight reduction of organic material. (iv) The material is cured under aerobic conditions without reheating.

4. Biochar production

Biochar is known as "biological charcoal" which is produced from large biomass of organic materials in the presence of little or no oxygen "at relatively low temperature (<700°C)" [33]. It is the carbon-rich product obtained when biomass, such as wood, manure or leaves, is heated in a closed container with little or no available air. It is also known to be of tremendous benefits to soil microbial population, improve growth of crops and soil functions. It is very helpful in environmental protection. Biochar, when used as a soil amendment, has been reported to boost soil fertility and improve soil quality by raising soil pH, increasing water holding capacity, attracting beneficial organisms like fungi and microbes, improving cation exchange capacity (CEC) and retaining nutrients in soil [34–36]. Another major benefit associated with the use of biochar as a soil amendment is its ability to sequester carbon from the atmosphere-biosphere pool and transfer it to soil [37, 38]. It may also decrease emissions of other more potent greenhouse gases (GHG) such as N_2O

and CH_4. It may persist in soil for a long period of time because it is very resistant to microbial decomposition and mineralization.

One of the challenges in characterizing biochar as a class of materials is that it is new and unique [33]. Nevertheless, the defining property is that the organic portion of biochar has a high carbon (C) content which comprises the so-called aromatic compounds characterized by rings of six C atoms linked together without oxygen (O) or hydrogen (H).

Some essential nutrients can be depleted in biochar due to the pyrolysis method used in its production. Some materials are heat labile, especially at the surface of the material, while other nutrients become concentrated in the remaining biochar. Individual elements are potentially lost to the atmosphere, fixed into unavailable forms or released as soluble oxides during pyrolysis. For wood-based biochar, carbon (C) volatizes around 100°C, N above 200°C, S above 375°C and K and P between 700 and 800°C, while volatilization of magnesium (Mg), calcium (Ca) and manganese (Mn) occurs at a temperature above 1000°C. Biochar additions to soil do provide a modest contribution of nutrients depending, in part, upon the nature of the feedstock (wood versus manure) and the temperature under which the material is formed.

Much of the current understanding of the properties of biochar is derived from studies centred on the phenomenon known as "Terra Preta". Terra Preta (meaning black in Portuguese) refers to the expanse of very dark, fertile soils mostly found in the Amazon Basin of Brazil. The majority of the biochar applied and incorporated within the soil in this region of the Amazon over countries underwent various changes and became microscopically unrecognizable while enriching the soil with nutrients and changing soil properties. This implies that biochar, when added to soil, undergoes changes slowly but surely over the years. Change in soil properties has been recorded in different soils to which biochar was added. Increase in cation exchange capacity and pH of soil as a result of biochar addition has been documented.

Biochar can be produced from a variety of biomass materials, otherwise known as feedstock. These include biological, decomposable materials like wood and wood-based waste materials, municipal waste, domestic wastes, agricultural/industry wastes, etc., depending on its availability and abundance. The production of biochar from materials with high economic benefits and other competing uses will however not be sustainable. Biochar can be produced at almost any pH between 4 and 12 [32, 33] and can decrease to a pH value of 2.5 after short-term incubation of 4 months at 70°C. The pyrolysis temperature of biochar production and its pH are directly proportional. The burning and natural decomposition of biomass and particular agricultural waste adds large amounts of CO_2 to the atmosphere. Biochar that is stable, fixed and recalcitrant carbon are known to be capable of storing large amount of greenhouse gases; hence, it has the potential of reducing or stalling the increase in atmospheric greenhouse gas levels. It can also be used to improve water quality, increase soil fertility and raise agricultural productivity. Biochar, like coal, can sequester carbon in the soils for hundreds to thousands of years; hence, it has the potential of helping the withdrawal of CO_2 from the atmosphere while producing and consuming energy. It is estimated that the sustainable use of biochar could reduce the global net emissions of carbon dioxide (CO_2), methane and nitrous oxide by up to 1.8 pg. $CO_{2\text{-}}C$ equivalent (CO_2—C_C) per year. Biochar is a high-carbon, fine-grain residue which can be produced through modern pyrolysis processes. Pyrolysis is the direct thermal decomposition of biomass in the absence of oxygen to obtain an array of solid (biochar), liquid (bio-oil) and gas (syngas) products. The specific yield from the pyrolysis is dependent on the type of process, temperature, feedstock and other conditions that it is subjected to.

Figure 4.
Biochar made from sawdust; a and b represent milled biochar and biochar in granular form respectively.

Biochar application to soil has the potential to positively improve the soil health and increase availability of both macro- and micronutrient elements in the soil. The application of biochar can decrease the Al saturation of acid soils which often is a major constraint for productive cropping in highly weathered soils of the humid tropics. Biomass production to obtain biofuels and biochar for carbon sequestration in the sol is a carbon-negative process, i.e. more CO_2 is moved from the atmosphere than released, thus enabling long-term sequestration. A recent study indicated that appropriate combinations of these feed stalks will produce good fertilizer blends with optimum nutrient availability. For example, a feed stalk with plantain peels/wastes contains high content of potassium [39], while citrus waste-based biochar has higher N and P content. Biochar made from sawdust is presented in **Figure 4**.

5. Biogas production

In recent years, interest in anaerobic digestion as a management option for the disposal of organic wastes has grown considerably because of its major role in an effort to reduce greenhouse gas emission and protect the environment. The continuing use of fossil fuels is universally regarded as the principal contributor to global anthropogenic emission of GHG. It also anticipated that the fossil fuel reserves, which provide the bulk of world energy need, will be depleted in foreseeable future. In addition, the challenge of unstable fuel prices and security of the energy supply makes the call for alternative source of energy imperative. Anaerobic digestion, a proven technology for conversion of various organic wastes to biogas, is widely regarded as a source of renewable energy and technology for achieving pollution reduction.

For any nation to be self-sufficient in food production, there is the need to encourage the stakeholders to go from subsistence level where they are to intensive farming. This however has the challenge of high waste generation, particularly organic waste. The farmer/processor, etc. are therefore faced with the challenge of proper disposal of waste. However, proper management of these wastes through anaerobic digestion process could serve as an income generation venture for the stakeholders as well as cheap source of methane gas for cooking and biofertilizer from the slurry. This will save the women long hours previously spent in search of fire wood, hence, more time for their husbands and to breastfeed their children. With appropriate biogas digester for household use, agricultural and other wastes could be channeled towards generating biogas and other by-products that could be used for other purposes.

Properly designed biogas digester will accept highly digestible organic materials such as kitchen waste and other starchy/sugary feedstock (waste/spoilt grain, over-ripe/rotten fruits and vegetables, nonedible seeds, fruits and rhizomes, etc.). Biogas digester takes organic material (feedstock), with animal waste as an inoculant, into an air-tight tank carefully designed container where bacteria break down the material and release biogas—a mixture of mainly methane (CH_4) (50–70%) and carbon dioxide (CO_2) (30–40%) with low amount of hydrogen sulphide (H_2S). The biogas can be burned as a fuel, for cooking or other purposes (the calorific value of biogas has been estimated to be about 6 kWh/m^3 (20 mega joule), which corresponds to about half a liter of diesel oil), and the solid residue (effluent) can be used as organic compost. The impurities (CO_2 and H_2S) should be eliminated so as to get good quality methane gas for cooking.

Biogas yields from substrates largely depend on the substrates' composition and biodigester conditions. For biodigestion of horticultural wastes on individual farm, the available designs of biodigesters that have been widely disseminated in developing countries could be employed. The available designs of biodigester unit include fixed-domed digester, floating-drum digester and low-cost bag/balloon biodigester. A fixed dome biodigester consists of a closed, dome-shaped digesting unit with a non-movable, rigid gasholder and a "compensation tank" which serves as a reservoir for displaced slurry (**Figure 5**). The gas is stored in the upper part of the digester, and the gas pressure is determined by the difference between the levels of the slurry in the digester and compensating tank. Given the high rates of biogas production from some horticultural wastes, fixed dome digesters could be an ideal option for internal storage of large volume of biogas (estimated to store up to 20 m^3). It also requires less space for construction and less maintenance, offers self-agitation of slurry and is durable. Some of its demerits include special skills required for its construction and challenge of maintaining a stable gas pressures.

Floating-drum digester consists of an underground digester and a moving gasholder. The gasholder floats either directly on the fermentation slurry or in a water jacket of its own. The gas is collected in the gas drum, which rises or moves down, according to the amount of gas stored. Though it is durable, easy to maintain and offers steady gas pressure, floating-drum digester may not be an ideal option for large farms where the rate of waste generation may inappropriately be higher than the handling capacity of floating dome digester (the digester volume is generally accepted not to exceed 20 m^3 as compared with the volume of fixed dome digester which could be between 6 and 124 m^3) [41] (**Figure 6**).

A balloon biodigester consists of a digester bag with the upper part of the bag serving as gas holder. The inlet and outlet are attached to the skin of the balloon. The desired gas pressure is achieved by the elasticity of the bag or by placing a

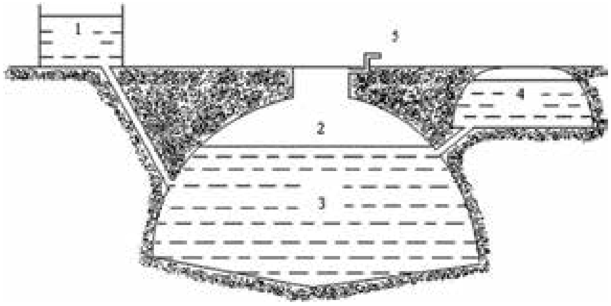

Figure 5.
Fixed dome digester. (1) Mixing tank with inlet pipe. (2) Gasholder. (3) Digester. (4) Compensation tank. (5) Gas pipe. Source: Arthur et al. [40].

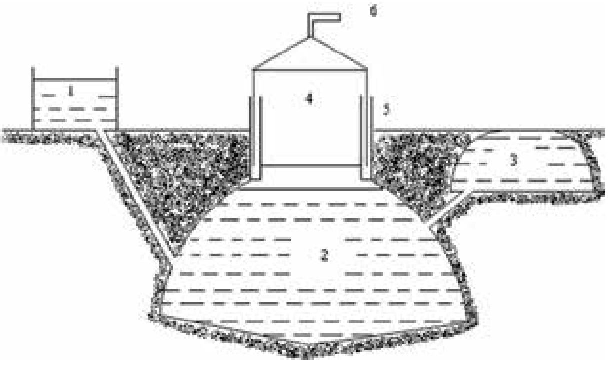

Figure 6.
Floating-drum digester. (1) Mixing tank with inlet pipe. (2) Digester. (3) Compensation tank. (4) Gasholder. (5) Water jacket. (6) Gas pipe. Source: Arthur et al. [40].

weight on the balloon. The useful life span of balloon digester is usually between 2 and 5 years. This type of digester seems to be ideal for farm-based management of horticultural wastes due to its low installation and operational costs, low construction sophistication and versatility in treating different waste materials.

Biogas digesters described above are simple and easy to construct from locally available materials, and their operations do not require special skills. Therefore, these reasons provide technical justification for adoption of anaerobic digestion for farm-based management of horticultural wastes. The construction of biogas digesters can also help to create new jobs and help stimulate the rural economy. Biogas technology in developing countries has been based on animal dung as the only viable biogas digester feedstock. Given the higher biogas potentials of various horticultural wastes, animal dung could be co-digested with horticultural wastes, thereby promoting the paradigm shift from mono-feedstock digestion to multi-feedstock digestion. This will also improve the economics of biodigester operation.

The biodigester could be operated as a batch-fed or continually fed system. For batch-fed digesters, the digesters are usually filled with substrate and left to digest over a period of time (which can be considered to be their retention) until gas production ceased. Thereafter, the digesters are emptied and fresh substrate added. Though simple in operation, the major drawback is that the process of emptying and filling is laborious. Alternatively, the digesters could be operated as continually fed system. Effluent from an existing biogas plant mixed with carefully prepared substrate can be used. The feeding of the biogas digester should be built up over a few weeks until it provides a steady supply of gas, and thereafter fresh substrate is added and digested slurry added at interval. For greater efficiency, feedstock with large lumps (more than 20 mm) should be broken up or cut to pieces to produce large surface area for bacteria to act on.

A common challenge with biogas digester that uses highly digestible organic materials is that it can become acidic and fail if it is overfed. This however can be recovered by causing feeding to cease and then start building up the feed rate slowly. An important design parameter for biogas digester is the overall loading rate. These are commonly expressed as the number of days of retention time or the quantity of organic matter applied to a given tank volume. This largely depends on the type of feedstock and digester system. Common detention times for farm-based manure digesters are roughly 20–30 days. More complex wastes that include fats and proteins will usually have retention times higher than 30 days.

The digestion process is commonly designed at one of the three different temperature zones, i.e. phsychrophilic (15–20°C), mesophilic (30–40°C) and thermophilic (50–60°C). Each of these temperature zones relies on a different species of bacteria that thrives at their given temperatures. The choice of appropriate temperature zone to operate is a function of the available feedstock, project site logistics, costs for heating and intended use of the digestate. Although, higher temperature systems will achieve additional pathogen destruction, more energy will be required to provide the required temperature. Lower-temperature, mesophilic systems, on the other hand, can provide the benefit of a faster-growing, more robust bacteria population than thermophilic which have slower-growing bacteria. Nigeria annual temperature is forecast to be in the range of 16–25°C in Jos Plateau area and can be as high as 44°C in the far north [42]; this indicates that most biogas digesters in Nigeria will operate well within mesophilic temperature conditions.

Methane, the major constituent of biogas, is an environmentally friendly cooking system that burns with a blue flame, without producing any smoke or soot. Hence, the introduction of simple, efficient and low-cost biogas system would not only help households in finding alternative use for agricultural and other wastes but also help in preventing the hazards caused due to indoor air pollution as a result of smoke and soot from burning fuelwood in traditional cooking methods (firewood, kerosene stove, etc.), especially by women and children in rural households. The replacement of fossil fuels with environmentally friendly alternative presented by promoting biogas use will reduce the emission of greenhouse gases. The adoption of biogas production from horticultural waste will also help to promote sanitation by turning wastes that are potential public nuisances and threats to public health into useful organic fertilizer and feed material.

6. Local soap production

Plantain/banana is a major staple food in sub-Saharan Africa [43]. It is majorly planted in the southern part of Nigeria due to the favorable growing condition of the area. It has numerous economic values. It can be eaten raw, cooked/fried/baked or processed into other secondary products such as plantain/banana flour. It is reported to have several health benefits. Hence, there is the need to encourage its production in large quantity.

In order to maximize the potential of plantain/banana in meeting the need of farmers and also take them beyond subsistence to commercial level of production, cultivation of large hectarage is required. In the alternative, farmers could be encouraged to form clusters (growers and processors). One of the “disadvantages” of mass production of plantain/banana is the enormous waste generation (the peels, stalk and the pseudo stem). Plantain/banana peels could be fed to livestock. However, in places where it is produced in large quantities, the “supply” is usually greater than the “demand”. Hence, they are usually piled up at dumpsites where they serve as menace to the society. Apart from odor generation, it could also serve as breeding ground for vectors. These “wastes” are also very rich in potash; hence they could be used in local soap production.

Soap is a new substance produced by the interaction of oils and alkali solution through a process known as saponification. Care must be taken to ensure that no free alkali or excessive, free oil remains in the finished product. Virtually, all wastes that are rich in potash can be used for local bath soap production. In cocoa-producing area (e.g. south-western part of Nigeria) where cocoa pods are generated in large quantities, they constitute nuisance to the environment. These can also be used for local soap production.

Waste from different cultivars of plantain/banana, viz. peels and stalks, as well as cocoa pods could be collected, shredded and dried. Potassium hydroxide can be

Figure 7.
Stages in local soap production from agricultural waste. (a)–(d) represent ashing of dried cocoa pods/plantain waste in a carefully constructed metal drum, the soap production process, finished product in solid form and finished product in liquid form, respectively.

extracted from the dried waste via ashing, i.e. burning in a partially closed environment (e.g. in a drum) so as to minimize oxygen (**Figure 7**). Clean water is used to extract potassium hydroxide from the ash. It is then concentrated and used for local soap production.

Most people prefer to make single oil soaps. Due to its relatively cheaper cost, palm kernel oil is commonly used. However, it is possible to mix two or more oils, e.g. blending 80% palm oil and 20% palm kernel oil or using 75% palm oil, 20% palm kernel oil and 5% vegetable oil so as to improve the soap quality. It is believed that the higher the ratio of palm oil and vegetable oil to that of palm kernel oil, the better the quality of the soap. The oil is poured into a steel drum and placed on a gentle fire, starting towards a slow boil. Potassium hydroxide solution is to be added gradually while keeping the heat steady for about 2–6 hours (depending on the quantity and the intensity of the applied heat). The mixture is to be stirred continually in a predetermined direction (depending on the convenience of the one doing the stirring), until it begins to solidify. At this point, the intensity of the heat should be reduced and the content removed from the fire to finish off slowly. Essential oils and/or colorant could be added as desired once the soap is finished cooking. The soap could be "picked" to release the air trapped in it from stirring. It can then be taken out and spread on a flat wooden board to dry in a cool, well-ventilated place for up to 8 hours.

The process of local soap making is very simple, straightforward and easy to understand by stakeholders (unemployed youths, women, etc.). It does not require technical details, and the method could be mastered by people who do not have formal education. More so, it could serve as a means of enhancing their livelihood and improving household income. It is generally believed to be eco-friendly, being a natural product and also friendly to the skin. Hence, the demand for the product is very high.

7. Conclusion

In this chapter, we present the possibilities of using simple waste management techniques in farms and rural set-ups, especially in developing countries.

Agricultural wastes, rather than constituting menace to the society via serving as breeding ground for vectors as well as contamination of water sources, can be turned into wealth, thereby empowering stakeholders through specialized trainings. The use of agricultural wastes for the production of mushrooms, composting, biochar, biogas and soap production was discussed in this chapter. Procedures for turning these wastes into wealth were presented. They were simplified such that anyone, irrespective of their background, can easily learn and adopt these methodologies. These will not only serve as a means of purifying our environment but will also serve as a means of household empowerment. It is concluded that if any of these methods is used, agricultural wastes could also be an avenue for sustainable income generation as well as the preservation of the environment. The methods proffered are not only simple but are also easy to adopt and transfer.

Conflict of interest

The authors declare that they have no conflict of interest.

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Chapter 6

Gold Recovery Process from Primary and Secondary Resources Using Bioadsorbents

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and Hidetaka Kawakita

Abstract

Bioadsorbents were prepared in a simple manner only by treating in boiling concentrated sulfuric acid from various biomass materials such as various polysaccharides, persimmon tannin, cotton, paper and biomass wastes such as orange juice residue and microalgae residue after extracting biofuel. These bioadsorbents exhibited high selectivity only to gold over other metals and extraordinary high loading capacity for gold(III), which were elucidated to be attributable to the selective reduction of gold(III) ion to elemental gold due to its highest oxidation-reduction potential of gold(III) of metal ions, catalyzed by the surface of bioadsorbents prepared in boiling sulfuric acid. By using these biosorbents, recovery of gold from actual samples of printed circuit boards of spent mobile phones and Mongolian gold ore was investigated. Recovery of trace concentration of gold(I) from simulated spent alkaline cyanide solution was also investigated using the bioadsorbent. Application of bioadsorbents to some recovery processes of gold from cyanide solutions was proposed.

Keywords: gold recovery, biomass materials

1. Introduction

In recent years, accompanied by huge consumption of various metals, metal contents or grade of metal ores have become poor and complex. Under such situation, not only poor and complex natural resources but also secondary resources, i.e., various wastes containing valuable metals in low contents, have to be employed as feed materials to recover valuable metals. The typical wastes containing valuable metals are those of spent electric and electronic appliances, i.e., e-wastes.

For the recovery of valuable metals from such poor and complex feed materials, hydrometallurgical processes are more suitable than pyrometallurgical processes. Hydrometallurgical processes consist of leaching of metals from solid feed materials into aqueous solutions, separation and concentration of the targeted metals from other metals, and final recovery as solid metals of high purity such as ingot metals. For the separation and concentration of the targeted metals, various processes such as precipitation, solvent extraction, ion-exchange including chelating ion-exchange and adsorption have been employed. Of these processes, precipitation and solvent extraction are suitable for the recovery from solutions of high concentration, while adsorption and ion-exchange are suitable from those of low or trace concentration.

During long operation, solvent extraction reagents, adsorbents, and ion-exchangers gradually deteriorate and finally they are discarded. For example, in the cases of ion-exchange resins, they deteriorate through the formation of many cracks and clogging of micropores of the resins by fine particles present in actual solutions, both of which impede smooth operation using packed columns.

For the effective separation and concentration in hydrometallurgical processes, high selectivity and high loading capacity for targeted metals are strongly required for solvent extraction reagents and adsorbents. However, the selectivity exhibited by a majority of commercially available ion-exchange resins including chelating resins has not been always satisfactory.

Ion-exchange resins are plastic beads produced from petroleum. In recent years, environmental pollutions by microplastics have been deeply worried all over the world and big expectations are placed on biodegradable plastics. However, their high production costs prevent their actual employments in various fields.

In our recent studies, we found that adsorption gels prepared from various kinds of biomass materials including various biomass wastes, i.e., bioadsorbents, exhibit high selectivity and high loading capacity for targeted metals such as hazardous heavy metals and valuable metals. These are prepared from waste wood [1–4] and straws of rice and wheat [5], spent papers [6–10], cotton [11], waste seaweeds [12, 13], persimmon tannin [14–16] or wastes of persimmon [17, 18] and grape [19, 20] rich in tannin compounds, wastes of citrus such as orange [21] and lemon [22], and residue of microalgae after extracting biofuel [23, 24].

In the present chapter, we introduce the adsorptive recovery of gold from printed circuit boards (PCBs) of spent mobile phones, a typical e-waste, and actual gold ore, a primary resource of gold, as well as that of trace concentration of gold from simulated spent cyanide solutions using some of these bioadsorbents.

2. Preparation of bioadsorbents for gold recovery

The bioadsorbents for gold recovery can be easily prepared in a simple manner as schematically shown in **Figure 1**. Pieces of feed materials of biomass are stirred in

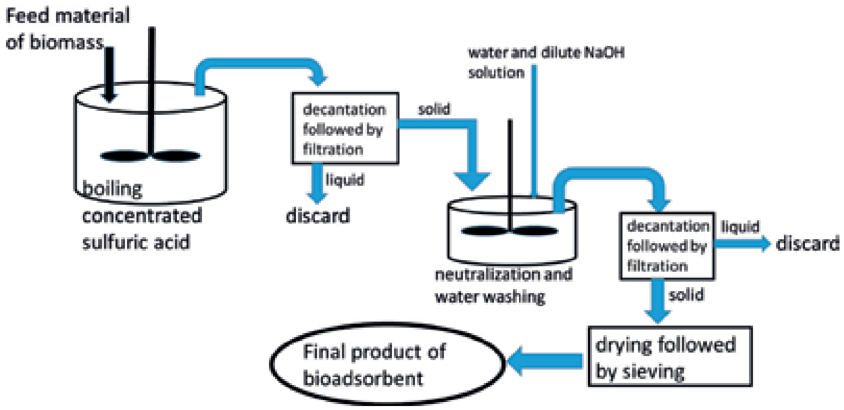

Figure 1.
Flow sheet of the preparation of bioadsorbents.

boiling concentrated sulfuric acid for about 24 h, where hydroxyl groups contained in the biomass undergo dehydration condensation reactions and polymer chains of the biomass are cross-linked via ether bonds. The solid materials are neutralized using dilute alkali solution and water-washed and then, they are dried in a convection oven and pulverized. Finally, they are sieved to uniform the particle size. The final products are black powder, the particle size of which are less than 0.1 mm.

3. Adsorption behaviors of bioadsorbents for metal ions

All of the bioadsorbents prepared by the method mentioned above exhibited extraordinary high selectivity only to gold(III) in the adsorption from hydrochloric acid solutions. For example, **Figure 2** shows the % adsorption of some metal ions onto bioadsorbent prepared from orange waste (orange juice residue) from various concentrations of hydrochloric acid solution [21], where the % adsorption denotes the percentage of metal ion adsorbed on the adsorbent from aqueous solution and defined by the following equation.

$$\begin{aligned}&\%Adsorption = (Mass\ of\ \ metal\ \text{ion}\ adsorbed\ \text{on}\ the\ \ adsorbent/\\ &Mass\ of\ \ metal\ \text{ion}\ initially\ \ present\ \ in\ \ the\ \ aqueous\ \ solution)\times 100\\ &=\{(initial\ \ concentration\ \ of\ \ the\ \ metal\ \text{ion} - concentration\ \ of\ \ the\ \ metal\ \text{ion}\\ &after\ \ adsorption)/initial\ \ concentration\ \ of\ \ the\ \ metal\ \text{ion}\}\times 100\end{aligned}\tag{1}$$

As seen in this figure, only gold(III) is quantitatively adsorbed over the whole concentration range of hydrochloric acid tested, while other metal ions, not only precious metals such as palladium(II) and platinum(IV) but also base metals such as

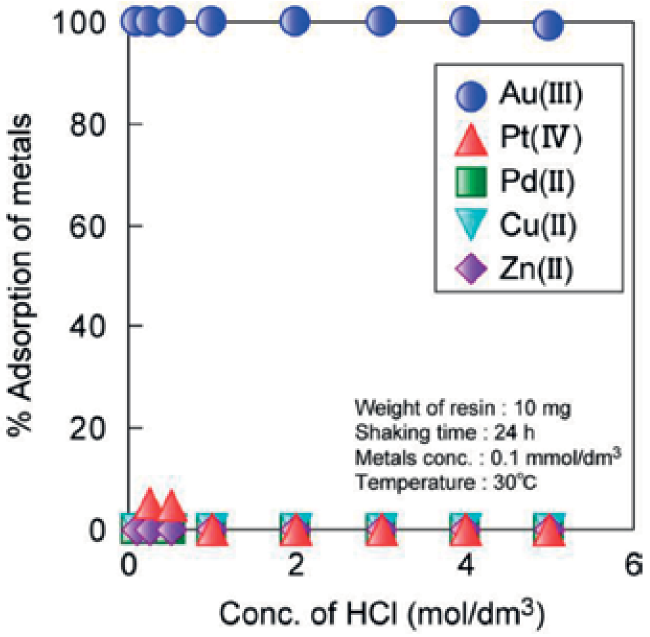

Figure 2.
Percentage adsorptions of some metal ions on bioadsorbent prepared from orange waste by treating in boiling concentrated sulfuric acid [21].

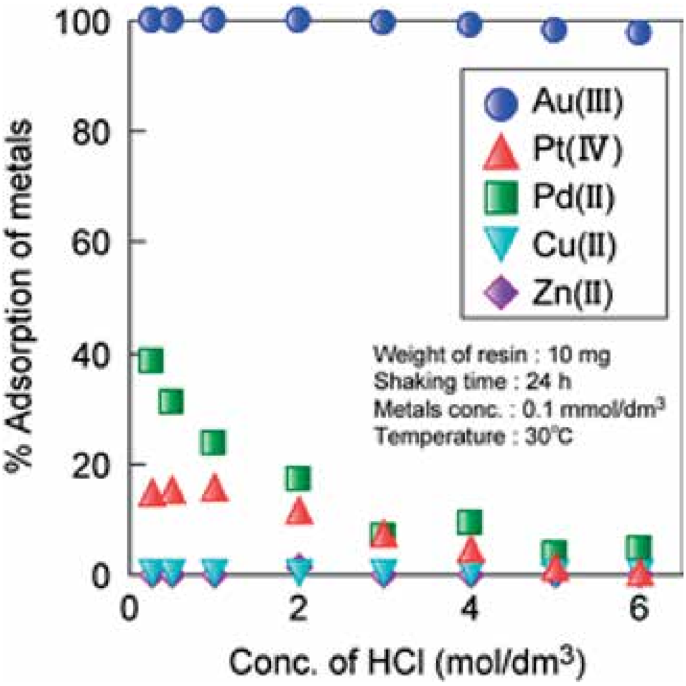

Figure 3.
Percentage adsorptions of some metal ions on bioadsorbent prepared from orange waste by means of carbonization at 800°C.

copper(II) and zinc(II), are not practically adsorbed. Similar phenomena were also observed also for all bioadsorbents prepared by the method using boiling concentrated sulfuric acid.

Figure 3 shows the similar plots in the case of the adsorption on the bioadsorbent of orange waste prepared by means of carbonization at 800°C, for comparison. Although gold(III) is quantitatively adsorbed over the whole concentration range of hydrochloric acid also on this bioadsorbent, considerable amount of platinum(IV) and palladium(II) is also adsorbed at low concentration range in particular; i.e., the selectivity of the carbonized bioadsorbent to gold(III) is inferior to that prepared by using boiling concentrated sulfuric acid.

Figure 4 shows the adsorption isotherm of gold(III), i.e., the relationship between the amount of adsorption of gold(III) and its concentration present in the aqueous solution (0.1 mol/L hydrochloric acid solution) at equilibrium at 30°C, on the adsorbent prepared from orange waste. The amount of adsorption increases with increasing concentration of gold(III) at low concentration range, while it tends to approach a constant value at high concentration range, suggesting the typical Langmuir-type adsorption isotherm. From the constant value, the maximum adsorption capacity for gold(III) on this adsorbent was evaluated as 10.5 mol/kg (= 2.07 kg gold(III)/kg adsorbent), which is an extraordinarily high value, greater than the weight of the adsorbent. Similarly, very high values of adsorption capacity for gold(III) were observed also for other adsorbent prepared from different kinds of biomass materials. **Table 1** shows the maximum adsorption capacities for gold (III) on the adsorbent prepared from various biomass materials and those on other adsorbents reported in some literatures, for comparison.

As seen in this table, some of bioadsorbents exhibit much higher adsorption capacity for gold(III) than commercially available adsorbents such as activated carbon and chelating resins.

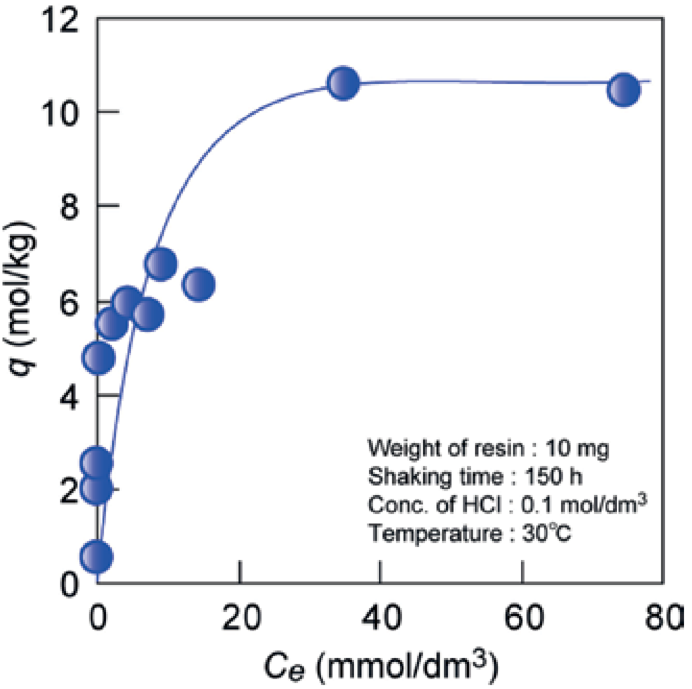

Figure 4.
Adsorption isotherm of gold(III) on bioadsorbent prepared from orange waste [21], where q and Ce denote the amount of adsorbed gold(III) and concentration gold(III) present in the aqueous solution at equilibrium, respectively.

Figure 5 shows the image of optical microscope of the bioadsorbent prepared from residue of microalgae after biofuel extraction after adsorption of gold(III). In this photograph, aggregates of elemental gold particles are observed as brilliant yellow lumps, while black particles are bioadsorbents of microalgae. The formation of elemental gold was confirmed also from the observation by X-ray diffraction (XRD) analysis. Similar phenomena were observed also for other bioadsorbents we prepared. From these results, it can be concluded that the adsorbed gold(III) was reduced into elemental gold on the surface of the bioadsorbent and that the extraordinary high adsorption capacity for gold(III) is attributable to the formation of elemental gold particles on these bioadsorbents. Furthermore, it can be concluded that the high selectivity for gold(III) over other metal ions is attributed to the higher oxidation-reduction potential (ORP) for gold(III) than other metal ions; e.g., those of some metal ions are as follows. Au(III): 1.52 V, Pd(II): 0.915 V, Cu(II): 0.340V, Ni(II): −0.257 V, Zn(II): −0.763 V.

The mechanism of adsorptive reduction of gold(III) is shown in **Figure 6**. Gold (III) present in aqueous solution is adsorbed on the surface of the bioadsorbents and reduced into elemental gold as follows.

1. Interaction of positively charged gold(III) ion with oxygen atoms of hydroxyl groups and ether oxygen atoms of polysaccharide molecules or tannin compounds contained in bioadsorbents followed by adsorption forming stable five-membered chelate rings. Here, by the cross-linking reactions using boiling concentrated sulfuric acid, structures of polymer chains of polysaccharide and tannin molecules are transformed into those suitable for forming stable five-membered metal chelates.

Adsorbent	**Maximum adsorption capacity (g/kg)**	**Reference**
Cross-linked lignophenol prepared from sawdust of cedar	374	[3]
Cross-linked lignocatechol prepared from sawdust of cedar	472	[3]
Cross-linked lignopyrogallol prepared from sawdust of cedar	374	[3]
Cross-linked lignophenol prepared from rice straw	552	[5]
Cross-linked lignophenol prepared from wheat straw	217	[5]
Cross-linked cellulose	1491	[25]
Cross-linked dextran	1418	[25]
Cross-linked alginic acid	1111	[25]
Cross-linked pectic acid	946	[25]
Cross-linked paper	1005	[10]
Cross-linked cotton	1221	[11]
Persimmon extract powder (PT powder, feed material of CPT)	1162	[14]
Cross-linked persimmon tannin (CPT)	1517	[14]
Cross-linked persimmon peel waste (PP)	985	[17]
Cross-linked orange juice residue (OJR)	1970	[21]
Cross-linked lemon peel	1300	[22]
Cross-linked chestnut pellicle	2100	[26]
Cross-linked grape waste	1962	[19]
Cross-linked microalgal residue (CMA)	650	[23]
Microalgal residue, feed material of CMA	79	[23]
Commercially available wood-based activated carbon	493	[3]
Rice husk carbon	150	[27]
Barley straw carbon	290	[27]
Wattle tannin cross-linked using formaldehyde	8000	[28]
Chitosan cross-linked using glutaraldehyde	566	[29]
Commercially available chelating resin containing thiol functional groups (Duolite GT-73)	114	[30]

Table 1.
Maximum adsorption capacities for gold(III) on bioadsorbents we prepared and those reported in some literatures.

2. Reduction of the adsorbed gold(III) ions into elemental or metallic gold particles by the aid of hydroxyl groups that take part in the interaction with the gold(III) ions, releasing hydrogen ions, where the hydroxyl groups are oxidized into carbonyl groups.

3. Protonation of the carbonyl groups followed by returning back to hydroxyl groups which function again as the adsorption sites.

4. Aggregation of elemental gold particles into bigger lumps followed by isolation from surface of the bioadsorbents.

Figure 5.
Image of optical microscope of the bioadsorbent prepared from residue of microalgae after biofuel extraction after adsorption of gold(III).

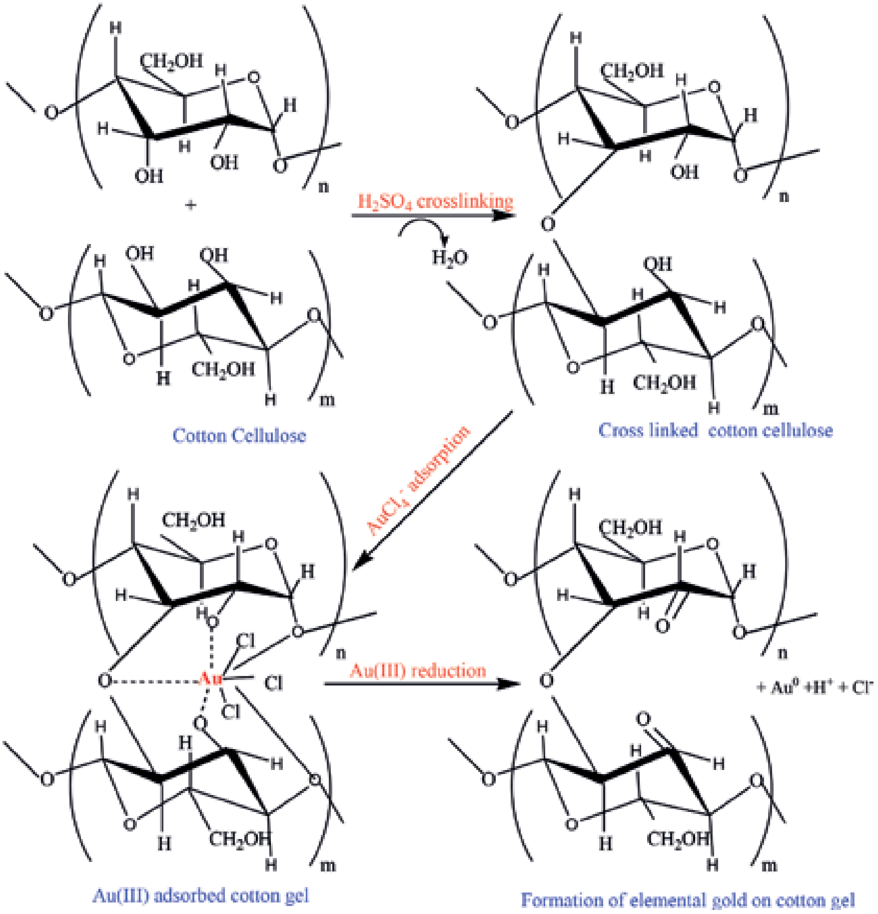

Figure 6.
Mechanism of the cross-linking between polymer chains of cellulose molecules by the aid of concentrated sulfuric acid and that of reductive adsorption of gold(III) on the cross-linked cellulose [25].

The surface of polysaccharides and tannin compounds cross-linked by the aid of boiling concentrated sulfuric acid functions as catalysts for the reduction reaction of gold(III) ions into elemental gold(0) under acidic conditions.

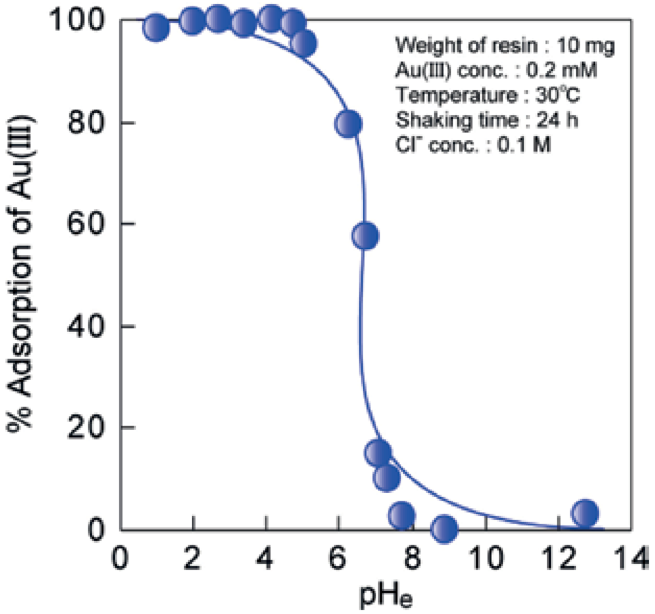

Figure 7.
Effect of equilibrium pH (pHe) on the % adsorption of gold(III) on the bioadsorbent prepared from orange waste by treating in boiling concentrated sulfuric acid where chloride concentration was maintained constant at 0.1 mol/L.

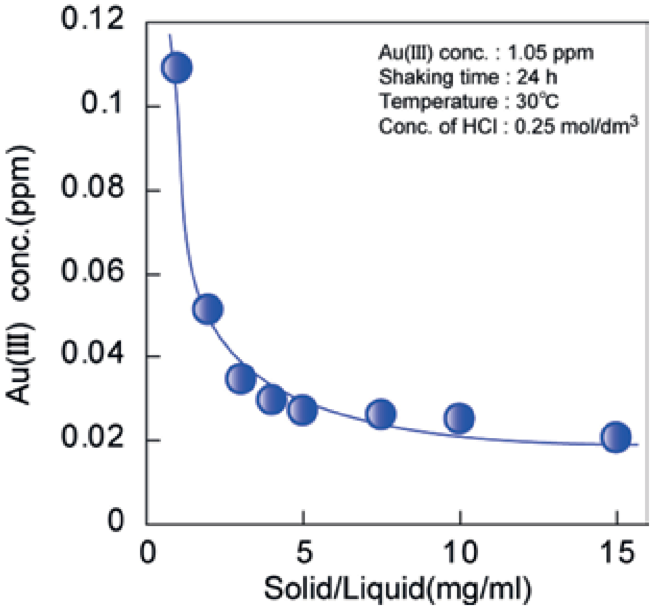

Figure 8.
Relationship between concentration of gold(III) remained in the aqueous solution after the adsorption on bioadsorbent prepared from orange waste by treating in boiling concentrated sulfuric acid and solid/liquid ratio, the ratio of dry weight of the added adsorbent to volume of aqueous solution.

Figure 7 shows the effect of pH on the adsorption of gold(III) on the bioadsorbent prepared from orange waste by treating in boiling concentrated sulfuric acid. As seen from this figure, although gold(III) is quantitatively adsorbed at pH less than 6 (acidic condition), no adsorption of gold(III) takes place at pH higher than 8 (basic condition) in accordance with the mechanism mentioned above.

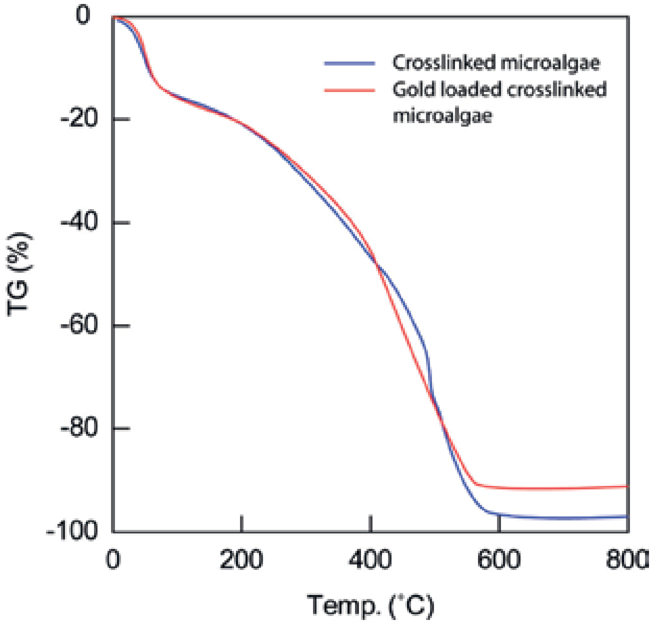

Figure 9.
Thermogravimetric curves of the bioadsorbents prepared from microalgae residue after biofuel extraction before (blue line) and after (red line) the adsorption of gold(III) [23].

Figure 8 shows the effect of solid/liquid ratio, the ratio of dry weight of the added adsorbent to volume of aqueous solution, on the concentration of gold(III) remained in the aqueous solution after the adsorption from 0.25 mol/L hydrochloric acid solution containing 1.05 mg/L gold(IIII) on bioadsorbent prepared from orange waste by treating in boiling concentrated sulfuric acid. As seen in this figure, the concentration of gold(III) is lowered down to as low as 0.02 mg/L (20 ppb) by this bioadsorbent; i.e., about 98% recovery was achieved from such trace concentration of gold(III) solution.

The elution or desorption of the adsorbed gold(III) is difficult or nearly impossible using usual elution agents. In such cases, as will be mentioned in the latter section, gold-loaded adsorbents are incinerated leaving solid gold particles in the incineration residues. The bioadsorbents prepared from biomass materials are easy to be incinerated at relatively low temperature compared with commercially available ion-exchange resins, plastic beads produced from petroleum, which is another advantage of bioadsorbents.

Figure 9 shows the thermogravimetric curves (relationship between percentage decrease in the weight of materials and temperature) of bioadsorbent of microalgae residue after extracting biofuel before and after gold adsorption. As seen from this figure, both samples are completely decomposed at the temperature between 500 and 600°C. In this figure, the difference between red and blue lines at the temperature higher than 600°C corresponds the weight of gold loaded on this bioadsorbent sample.

4. Recovery of gold from printed circuit boards of spent mobile phones

As an example of the use of bioadsorbents we prepared, recovery of gold from printed circuit boards (PCBs) of spent mobile phones is introduced in this section.

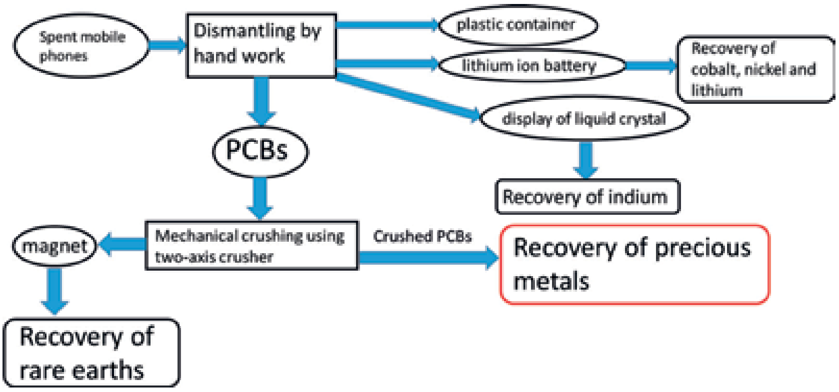

Figure 10.
Flow sheet of the dismantling of spent mobile phones.

Spent home appliances such as mobile phones are dismantled by hand work into various parts to recover various valuables for their reuses as shown in **Figure 10**.

Of these dismantled parts, gold and other precious metals such as palladium and platinum are contained in PCBs; i.e., PCBs of spent electronics are typical secondary resources of precious metals. According to the conventional recovery process of precious metals from complex feed materials such as anode slimes of copper and nickel generated in electrorefining processes of these metals which contain many kinds of metals such as gold, silver, palladium, platinum and base metals, they are recovered by repeating dissolution using aqua regia followed by precipitation for many times, which needs tedious long-time operations and high labor costs. In early 1970s, new recovery process was developed and commercialized by INCO [31]. In this process, the feed materials are totally dissolved in hydrochloric acid into that chlorine gas had been blown, abbreviated as chlorine-containing HCl, hereafter. Here, the chlorine gas dissolved in hydrochloric acid solution is converted into hypochlorous acid (HClO) according to the following reaction:

$$Cl_2 + H_2O \rightleftharpoons HClO + HCl \tag{2}$$

Thus, formed hypochlorous acid functions as a strong oxidation agent, converting solid metals into metal ions, dissolving into hydrochloric acid solution, where the metal ions give rise to stable chloro-complexes interacting with chloride ions; e.g., gold(III) is present as $AuCl_4^-$, anionic species. However, because the hypochlorous acid formed by the abovementioned reaction is unstable and is easily converted into hydrochloric acid, the metal recovery from such solutions is actually the same with that from hydrochloric acid solutions.

In the present work, the sample of spent PCBs was treated in the similar manner using chlorine-containing HCl as schematically shown in **Figure 11**.

They are incinerated at first at 750°C to extinguish epoxy resin boards on which various parts are placed. Then, the residues are leached using nitric acid solution to remove silver, which impedes the recovery of gold and other precious metals in the latter steps, together with some base metals. The residue of the nitric acid leaching was calcined at 750°C again and leached using chlorine-containing HCl to recover gold and other precious metals. In the present work, the sample of such metal-loaded leach liquor was kindly donated by Shonan Factory of TANAKA

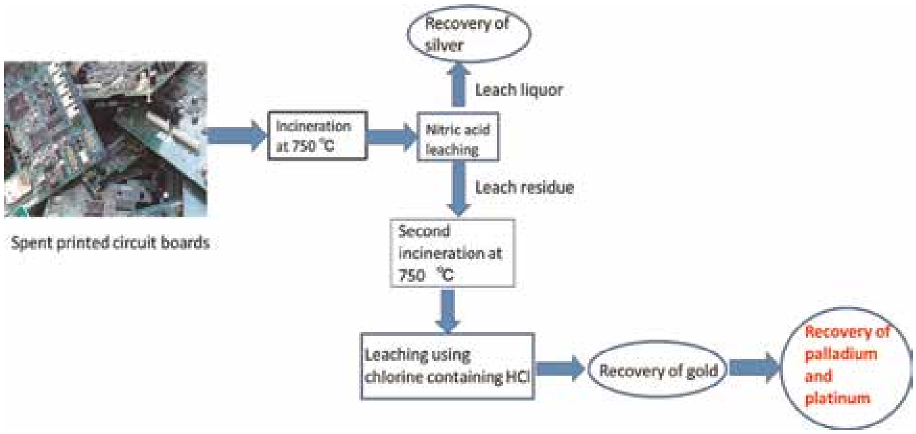

Figure 11.
Flow sheet for the treatment of spent PCBs in the present work.

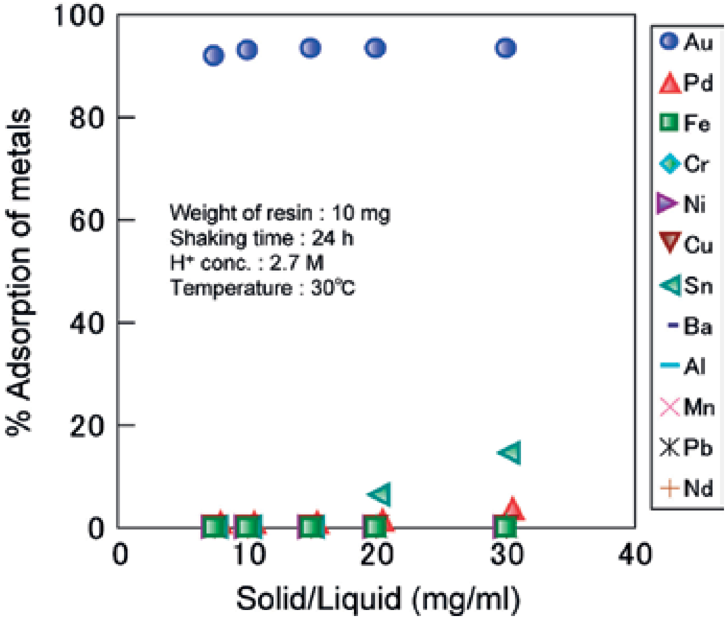

Figure 12.
Effect of solid/liquid ratio on the % adsorption of various metals from leach liquor of chlorine-containing HCl using the bioadsorbent prepared from orange waste by treating in boiling concentrated sulfuric acid.

KIKINZOKU KOGYO Co. Ltd., Hiratsuka, Japan. The metal concentrations of this sample solution measured by ICP-AES were as follows (mg/L): Au(100), Pd(8), Pb (342), Fe(314), Cu(250), Ni(411), and Zn(41). The total acid concentration measured by acid-base titration was around 3.0 mol/L.

Figures 12 and **13** show the effect of solid/liquid ratio, the ratio of amount (dry weight) of added bioadsorbent to unit volume of sample leach liquor, on % adsorption of each metal in the case of adsorptive recovery using bioadsorbents of orange waste and cotton prepared by treating in boiling concentrated sulfuric acid, respectively. As seen from these figures, although gold is nearly quantitatively adsorbed, other metals are not practically adsorbed on these bioadsorbents.

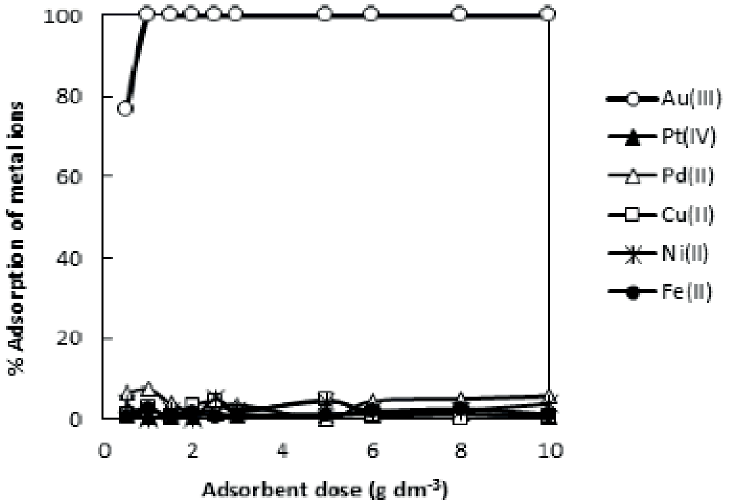

Figure 13.
Effect of solid/liquid ratio on the % adsorption of various metals from leach liquor of chlorine-containing HCl using the bioadsorbent of cotton prepared by treating in boiling concentrated sulfuric acid.

5. Recovery of gold from Mongolian gold ore

At present, majority of gold has been recovered from gold and silver ores by means of cyanide process developed at the beginning of twentieth century as schematically shown in **Figure 14**. In this process, pulverized ores are leached using alkaline cyanide solution to extract gold as gold(I)-cyanide complexes according to the following reaction:

$$4\mathrm{Au} + 8\mathrm{CN}^- + \mathrm{O}_2 + 2\mathrm{H}_2\mathrm{O} = 4\mathrm{AuCN}_2{}^- + 4\mathrm{OH}^- \quad (3)$$

The extracted gold(I) as anionic species, $\mathrm{AuCN}_2{}^-$, is adsorbed onto activated carbon or strongly basic anion exchange resins, which are termed as CIP and RIP

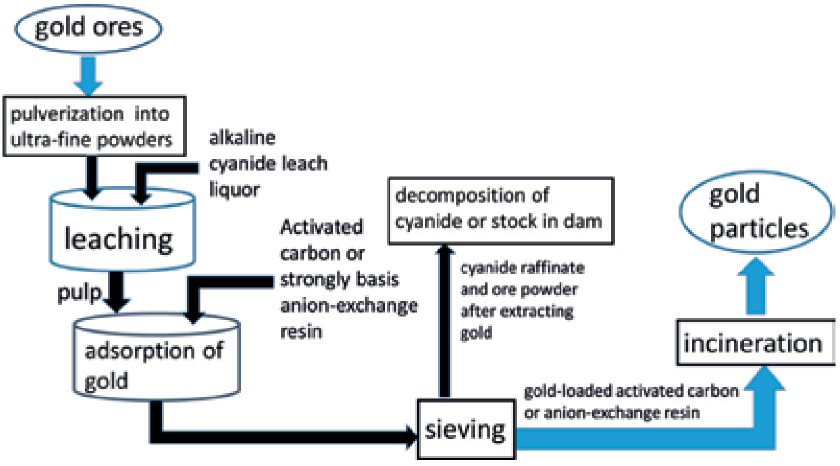

Figure 14.
Flow sheet of conventional gold recovery process from gold ores using alkaline cyanide solutions.

processes, respectively. Because it is difficult to desorb the gold adsorbed onto these adsorbents, these are incinerated at high temperature to recover metallic gold.

This cyanide process has suffered from some problems as follows:

1. Strong toxicity of cyanide, which causes serious environmental problems and, consequently, needs some costs for safe operation and environmental protection.

2. Interference by other coexisting metals or low selectivity over other metals.

3. Slow dissolution of gold as shown in **Table 2** that shows the comparison of dissolution rate of gold by some lixiviants.

As alternatives to cyanide leaching, some noncyanide leaching processes such as those using hypochlorous acid, bromine, thiosulfate, and thiourea have been proposed. However, these new processes also suffer from their own drawbacks as follows. Thiourea is known as carcinogen and, additionally, it is expensive and chemically unstable compared to cyanide, while it has a big advantage of much faster dissolution rate of gold than cyanide; that is, it was reported that the dissolution rate of gold using the mixture of 1% thiourea in 0.5% sulfuric acid containing 0.1% ferric ion is over 10-folds faster than that using the mixture of 0.5% sodium cyanide and 0.05% calcium oxide [33].

Following the recovery of gold from spent PCBs, a typical secondary resource, we attempted to apply the bioadsorbents we prepared to noncyanide leach liquor of actual gold ore (one example of typical primary resources). The sample of the ore was kindly donated by Western Mongolian Metals Co. Ltd., Ulaanbaatar, Mongolia. It was fine powder, the particle size of which was around 75–150 μm and the metal contents (mg/g) were as follows: gold 0.046, platinum 0.018, aluminum 0.694, iron 64.75, cobalt 0.008, nickel 0.040, copper 0.779, and zinc 0.069.

In the present work, the recovery of gold from the abovementioned gold ore was investigated by means of leaching using acidothiourea solution consisting of 0.1 mol/L thiourea and 0.05 mol/L sulfuric acid followed by adsorption using bioadsorbent of cotton. **Figure 15** shows the effect of liquid/solid ratio (ratio of volume of the leach liquor to unit dry weight of the sample of ore powder) on the leached amount of gold and platinum from the ore sample. From this result, 30 mL/g appears to be the most suitable liquid/solid ratio for extracting gold and platinum from the ore sample; i.e., addition of about 0.23 g of thiourea and 0.15 g of sulfuric

Reagents or mixtures	**Operating condition**	**Dissolution rate (g/cm^2 h)**
32 wt.% HCl + MnO_2(s)	100°C, atm	0.137
32 wt.% HCl + MnO_2(s)	90°C, 639 kPa	0.25
6 mmol/dm^3 NaCN + 4 mmol/dm^3 $Ca(OH)_2$ + air	30°C, atm	0.7
0.45 mol/dm^3 NaCN + 0.2 mol/dm^3 NaOH + air	30°C, atm	1.5
6 mol/dm^3 HCl + 0.22 mol/dm^3 H_2O_2	50°C	4
6 mol/dm^3 HCl + saturated Cl_2 (typical chlorine-containing HCl)	40°C, atm	180
3 HCl + HNO_3 (6 mol/dm^3) (aqua regia)	80°C, atm	1800

Table 2.
Comparison of dissolution rates of gold using some lixiviants [32].

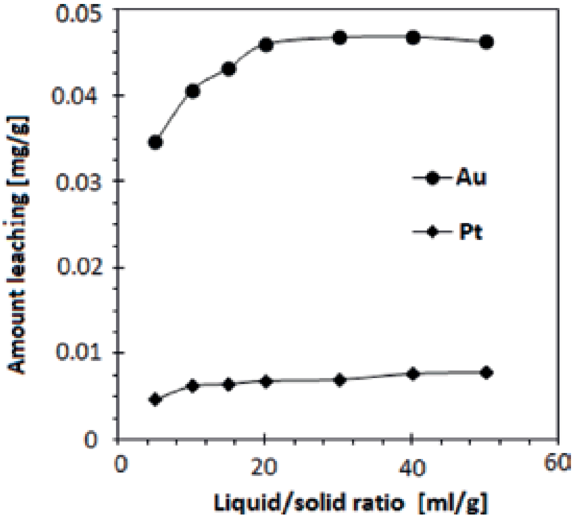

Figure 15.
Effect of liquid/solid ratio on the leaching amount of gold and platinum from the Mongolian gold ore sample using acidothiourea consisting of 0.1 mol/L thiourea and 0.05 mol/L sulfuric acid.

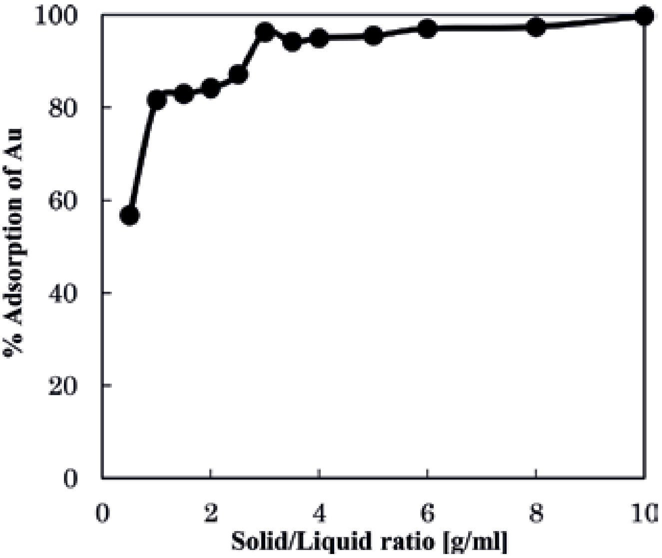

Figure 16.
Effect of solid/liquid ratio on the adsorption of gold using cotton adsorbent from the leach liquor of the Mongolian gold ore.

acid is necessary for complete extraction of gold and platinum from unit gram of the ore sample.

Figure 16 shows effect of solid/liquid ratio (ratio of dry weight of the added adsorbent to unit volume of the leach liquor containing gold(III)) on the adsorption of gold using bioadsorbent of cotton prepared by treating in boiling concentrated sulfuric acid from the leach liquor of Mongolian gold ore. This figure indicates that addition of at least 3 g of bioadsorbent of cotton is necessary for quantitative adsorption of gold(III) from this leach liquor.

Figure 17 shows the XRD pattern of the bioadsorbent of cotton after adsorption of gold(III). Four sharp peaks in this figure obviously evidence the presence of solid

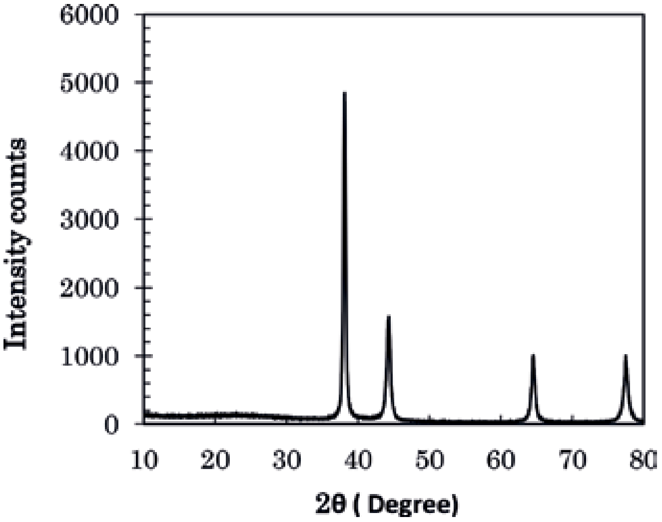

Figure 17.
XRD pattern of the cotton adsorbent after adsorption of gold(III).

elemental gold, suggesting that gold was recovered as elemental gold particles also in this system.

6. Recovery of gold from simulated spent cyanide solutions using bioadsorbents

As mentioned earlier, cyanide solution has been extensively employed for a long time in gold mining and also in plating applications because of its special complexing capabilities in aqueous solutions, creating the soluble $Au(CN)_2^-$ complex. Also as mentioned in the preceding section, such $Au(CN)_2^-$ complex is recovered by means of adsorption on activated carbon or strongly basic anion-exchange resin. However, such adsorptive recovery of gold is not always quantitative and trace concentrations of gold still remain in the cyanide solution. Spent cyanide solutions generated after the recovery of gold are treated for cyanide decomposition before discharging in environments according to the following processes [34]:

1. Oxidative decomposition using sulfur dioxide (INCO process)

In this process, cyanide ion is decomposed by the aid of sulfur dioxide and oxygen gasses blown into the cyanide solution catalyzed by cupric sulfate according to the following reaction:

$$CN^- + SO_2 + O_2 + H_2O = OCN^- + SO_4^{2-} + 2H^+ \tag{4}$$

where OCN^- ion is unstable and easily hydrolyzed into ammonium bicarbonate. The sulfur dioxide gas can be replaced by sulfurous acid or sodium pyrosulfite ($Na_2S_2O_5$).

2. Oxidative decomposition using hydrogen peroxide

Cyanide ion is decomposed by the aid of hydrogen peroxide also catalyzed by cupric sulfate according to the following reaction:

$$CN^- + H_2O_2 = OCN^- + SO_4^{2-} + 2H^+ \tag{5}$$

3. Decomposition using Caro's acid

Cyanide is decomposed using Caro's acid, which is formed by interacting hydrogen peroxide with sulfuric acid according to the following reaction:

$$CN^- + H_2SO_5 = OCN^- + SO_4^{2-} + 2H^+ \tag{6}$$

4. Decomposition by the aid of microorganisms

Cyanide is decomposed by microorganisms according to the following reaction:

$$CN^- + 2H_2O + 1/2\,O_2 + Bac = HCO_3^- + NH_3 \tag{7}$$

5. Decomposition by the aid of sodium hypochlorite

Cyanide is decomposed by the aid of sodium hypochlorite in alkaline media according to the following reaction [15]:

$$2NaCN + 5NaClO + H_2O = 2NaHCO_3 + N_2 + 5NaCl \tag{8}$$

The recovery of trace concentrations of gold remaining in spent cyanide solutions has been difficult due to relatively high processing costs as well as other various technical problems. However, the recovery of such trace concentration of gold has become highly attractive from an economical point of view due to the high price of gold in recent years. Consequently, we attempted to recover such trace concentration of gold(I) from waste cyanide solutions.

However, since gold(I) cyanide solutions are very toxic and its use is prohibited in our laboratory, a sodium salt of gold(I) sulfite, i.e., sodium gold(I) sulfite, $Na_3[Au(I)(SO_3)_2]$, was employed for the adsorptive recovery test of gold(I) in the present work as a simulated solution of cyanide solutions to obtain the fundamental information for exploring the feasibility for the recovery of gold(I) [35]. The use of the gold(I) sulfite complex for gold plating had been known since 1842 [36] and has

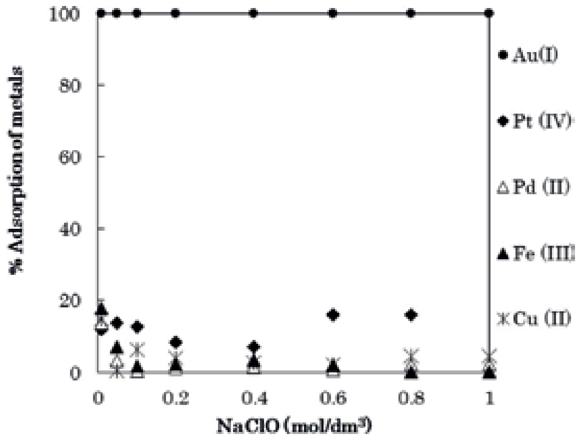

Figure 18.
Effect of sodium hypochlorite concentration on the adsorption of some metal ions on bioadsorbent of pure cellulose prepared by treating in boiling concentrated sulfuric acid [35].

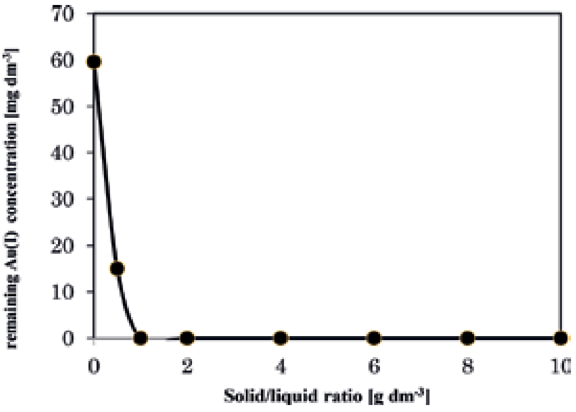

Figure 19.
Effect of adsorbent dose on the concentration of gold(I) remained in the aqueous solution after the adsorption on bioadsorbent of cellulose at pH = 3 where the test aqueous solution initially contained 0.3 mmol/L gold(I) in 0.1 mol/L sodium hypochlorite [35].

been currently employed in noncyanide gold plating. The trace amount of Au(I) is also exhausted from such gold sulfite-based plating baths.

In the adsorption of gold(I) in the absence of hypochlorite, only negligible adsorption of gold(I) was observed regardless of pH values. However, by adding sodium hypochlorite to the gold(I) solution in hydrochloric acidic media, the adsorption was drastically improved as shown in **Figure 18**, suggesting that the addition of sodium hypochlorite provides suitable chemical changes for gold(I). Additionally, a high selectivity to gold(I) was also observed over other metals similar to the case of the adsorption of gold(III) from hydrochloric acid solution as shown in **Figure 2**, for example.

It is considered that gold(I) was oxidized into gold(III) by the aid of sodium hypochlorite according to the following reaction and adsorbed onto the bioadsorbent of pure cellulose.

$$\mathrm{NaClO + HCl \rightarrow HOCl + NaCl} \tag{9}$$

$$\mathrm{2Au^+ + 3HOCl + 3H^+ + 5Cl^- \rightarrow 2AuCl_4^- + 3H_2O} \tag{10}$$

Here, the sample solution of sodium gold(I) sulfite, $Na_3[Au(SO_3)_2]$, was colorless. But, after the addition of excess amount of sodium hypochlorite in the presence of hydrochloric acid, the color was changed to pale yellow, the color of $AuCl_4^-$, i.e., Au(III) solution, which visually evidence the oxidation reaction.

Figure 19 shows the effect of solid/liquid ratio, the ratio of added amount (dry weight) of bioadsorbent of cellulose prepared by treating in boiling concentrated sulfuric acid to unit volume of the test solution, on the concentration of gold(I) remained in the aqueous solution after the adsorption from the aqueous solution initially contained 60 mg/L gold(I). As seen from this figure, gold(I) can be quantitatively recovered from the solution at the solid/liquid ratio = around 1 g/dm^3.

7. Prospects for the application of bioadsorbents to actual cyanide processes

As mentioned in the preceding section, gold(I) can be quantitatively recovered by means of adsorption using bioadsorbents under acidic conditions similar to gold

(III) after oxidizing gold(I) into gold(III) by the oxidation treatment using sodium hypochlorite, for example.

Also as mentioned earlier, the main hydrometallurgical process for gold and silver ores is cyanide leaching followed by gold recovery by means of adsorption on strongly basic anion exchange resins and activated carbon or by means of cementation using zinc powder. In the adsorption process, the adsorbed gold is recovered by incinerating these loaded adsorbents because the elution of gold adsorbed on these adsorbents is difficult. On the other hand, the cementation using zinc powder also suffers from some problems, one of which is severe control of oxygen or air, except for which it would consume too much amount of zinc powder and cause redisolution of the resulted elemental gold powders. The major gold plating process is also that using cyanide plating solution, in which gold is recovered by the same processes. In these processes, after the recovery of gold, spent cyanide solutions are discharged into environment after the decomposition of cyanide using sodium hypochlorite, for example, as mentioned in the preceding section.

However, by means of the adsorption using bioadsorbents as mentioned above, more economical and more environmental benign process can be proposed as schematically depicted in **Figure 20**.

In the new process shown in **Figure 20**, trace concentration of gold(I) contained in cyanide solution will be able to be quantitatively recovered using bioadsorbents, which are easy to be incinerated at comparatively low temperature consuming less amount of energy leaving only gold powder as shown in **Figure 9**, for example.

A number of processes for recovering cyanide from gold plant barren solutions or pulps also have been developed [32]. For example, the acidification, volatilization and reneutralization (AVR) process as schematically depicted in **Figure 21** was practiced at Pachuca silver mine in Mexico and at Flin Flon mine in Canada more than 60 years ago and still now is under operation. Further, it has been recently installed at several other mines around the world.

In this process, by adding acid to the barren solution after recovering gold, cyanide is converted into HCN gas, which is scrubbed using caustic solution, returning into cyanide for reuse again. For this process, more economical and more

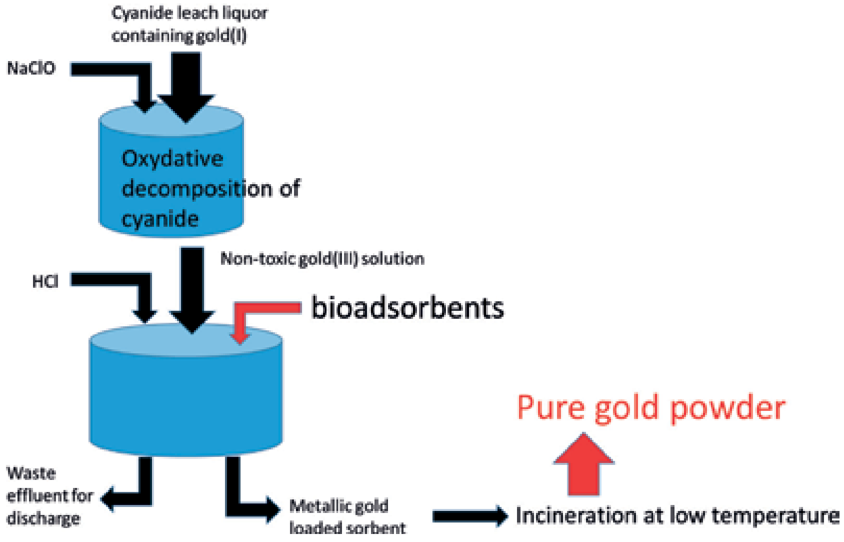

Figure 20.
New recovery process of gold from cyanide solutions using bioadsorbents.

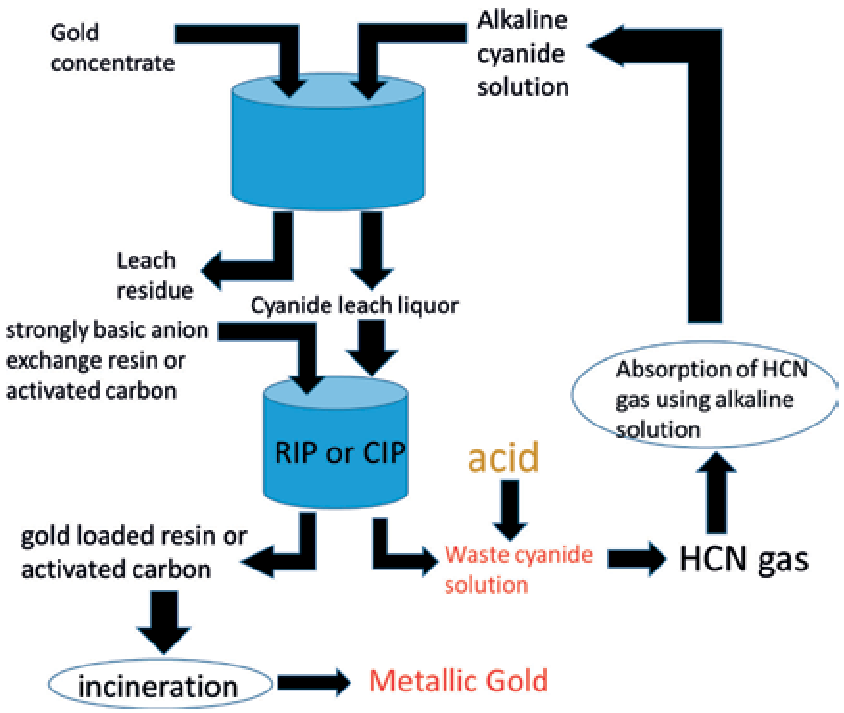

Figure 21.
Flow sheet of AVR process for the recovery of gold by cyanide leaching followed by recycling of cyanide.

environmentally benign process using bioadsorbents can be proposed as shown in **Figure 22** only by changing the order of the step of acidification.

Further, a more recent advancement is the sulfidization, acidification, recycling, and thickening of precipitate (SART) process schematically shown in **Figure 23** developed for ores containing high content of copper, which consumes large

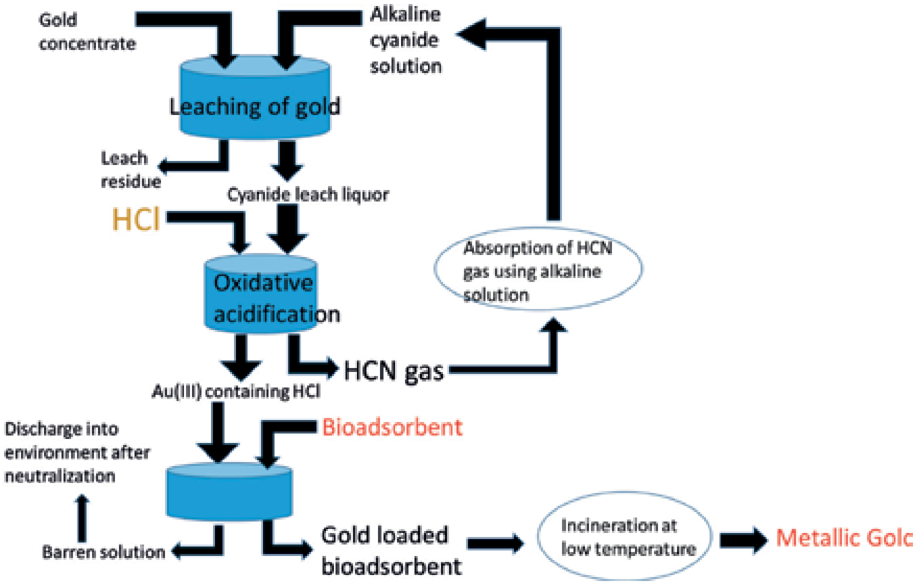

Figure 22.
Modification of AVR process using bioadsorbents.

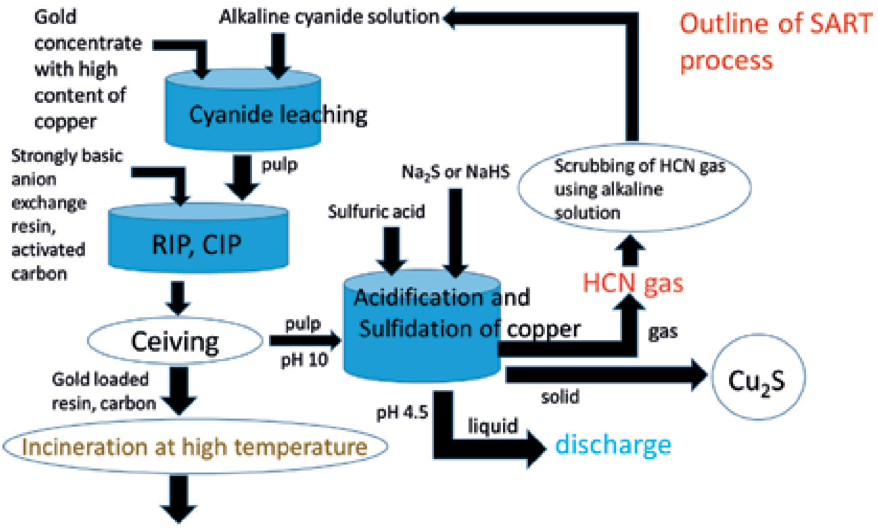

Figure 23.
Flow sheet for the recovery of gold by means of cyanide leaching followed by recycling of cyanide by means of SART process.

amount of cyanide, making worse of the economy of gold recovery. In this process, sulfides are added during the acidification by which pH is lowered from about 10 to 4.5. Under such conditions, the copper present as cyanide complex, $Cu(CN)_4^{3-}$, is completely converted into the mineral chalcocite, Cu_2S, releasing hydrogen cyanide, HCN gas. However, because selectivity of both strongly basic anion exchange resins and activated carbon to gold(I) cyanide are inferior, large amount of copper (I) cyanide are also adsorbed onto these adsorbents together with gold(I) cyanide, which results in tedious posttreatments.

Also for this process, more economical and more environmentally benign new process using biomass adsorbents can be proposed as schematically depicted in **Figure 24**. In this proposed process, cyanide leach liquor is acidified by adding

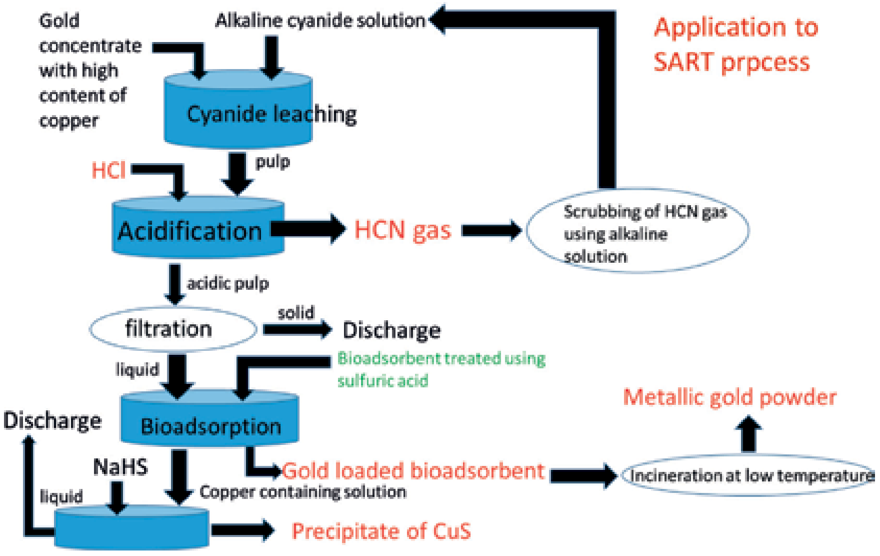

Figure 24.
Modification of SART process using bioadsorbents.

hydrochloric acid, not after the recovery of gold but before the gold recovery step. During the acidification, gold(I) and copper(I) are spontaneously oxidized into gold (III) and copper(II) by oxygen in air. From such acidified liquor containing gold (III) and copper(II), gold(III) can be quantitatively and highly selectively recovered over copper(II) using the bioadsorbents as metallic gold in a simple manner, leaving copper(II) in the raffinate, which can be easily recovered by means of solvent extraction using hydroxime reagents or, more simply, by means of precipitation using sodium sulfide as the precipitates of copper sulfide.

8. Conclusion

Bioadsorbents for gold recovery were prepared from various biomaterials including biomass wastes such as orange juice residue in a simple manner only by treating in boiling concentrated sulfuric acid. These bioadsorbents exhibited extraordinary high loading capacity and high selectivity for gold in the adsorption from acidic chloride media, which were elucidated to be attributable to the reduction reaction of gold(III) into gold(0), elemental gold, due to the highest oxidation-reduction potential of gold(III), catalyzed by the surface of the bioadsorbents prepared by condensation reaction using concentrated sulfuric acid.

It was confirmed in the recovery tests of gold from printed circuit boards of spent mobile phones, Mongolian gold ore, and simulated spent cyanide solutions containing trace concentration of gold(I) that satisfactory gold recovery was achieved by using these bioadsorbents. Some new gold recovery processes using bioadsorbents were proposed for actual cyanide processes.

By using other types of bioadsorbents, it is possible to recover other precious metals such as palladium and platinum and hazardous materials such as heavy metals.

Acknowledgements

The authors are deeply indebted to Shonan Factory of Tanaka Kikinzoku Kogyo Co. Ltd. and Western Mongolian Metals Co. Ltd. for the kind donation of the samples of printed circuit boards of spent mobile phones and Mongolian gold ore, respectively. We also indebted to Miss Kumiko Kajiyama, Miss Miyuki Matsueda, Miss Sayaka Yamada, Mr. Minoru Abe, Jun-ichi Inoue for their assistance in adsorption and recovery tests.

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Chapter 7

Digital Solutions in the Forest-Based Bioeconomy

Chihiro Watanabe and Nasir Naveed

Abstract

This chapter aims to illustrate the potential and significance of forest-based industry to take the lead in the sustainable development of the bio-based economy under digitalization. The digital solutions are transforming the forest-based industry by enabling the real-time end-to-end supply chain visibility, stock level optimization, demand planning, and real-time order status tracking and transparent, speedy, and hassle-free order fulfillment. In addition, increasing diversification corresponds to eco-consciousness, and shift in people's preferences induces the transformation of forest-based bioeconomy into a digital platform industry. Further, this chapter will highlight the circular economy way of thinking that offers the possibility for the use of material to a more efficient level along with creating new, sustainable business models for many industries. The future of many industries lies in cross-industrial collaboration and creation of new value network based on circular economy as in the industrial ecosystems; the side streams generated in the production of one firm may be the input raw material for others. Based on all of these developments, transformation of forest-based bioeconomy into a digital platform industry can be expected.

Keywords: forest-based bioeconomy, transformation, digital solutions, creative disruption platform, circular economy

1. Introduction

The human activities are depleting available resources that mainly come from the processes such as mining and petrochemicals. At the same time, dependence on the fossil-based resources is increasing the concerns related to the climate change. In future, societies need to manage the resources much more efficiently and increase the dependence on renewable resource. The consequences of this will lead to more sustainable bioeconomy from a traditional fossil economy.

The bioeconomy is considered as the economy relying on the production of renewable biological resources and their use for food, feed, bio-based products, and bioenergy [1]. The major contribution of biomass comes from the forest; therefore it is viewed as important sub-sector of the bioeconomy [2, 3] that can take a lead in the sustainable development of bio-based economy [4]. The transition to a sustainable bioeconomy will not immediately replace the traditional facilities, but the new technologies will be integrated to the existing one. Many leading forest firms have taken major steps in developing the sustainable bio-based innovations and understanding the consumer behavior by linking these efforts to digitalization. For example, Metsä Group invested 1.2 billion euros to develop the next-generation bioproduct mill in Äänekoski, Finland.

The new industrial revolution based on new digital developments will enable the integration of dynamic supply chains, end-to-end supply chain visibility, stock level optimization, elimination of distance between upstream and downstream of the chain, and interaction among different industries and sectors. All these developments will lead forest-based bioeconomy to a consolidated platform ecosystem [5].

The transformation of forest-based bioeconomy can be extended from technological and material processes to cultural, ethical, and wider socioeconomic perspectives [6, 7]. Watanabe et al. [5] propose the following thinking for devising a new business model under digitalization:

1. Recognizing complexity, phenomena-driven policy, and new social dynamics

2. Understanding global interdependencies that require multilevel thinking and knowledge about the significance of the coevolution of technologies, economy, and society

3. Re-understanding traditional regimes and regions as the convergence of several fields in potential industries can possibly emerge in future

The system nature of forest-based bioeconomy has been studied by the different authors. Wolfslehner et al. [4] highlighted the potential use of forest-based indicators in Europe and their development in future. They argue that forest-based industry can take lead in the sustainable development of bioeconomy. Hetemäki et al. [2] and Hetemäki [8] are of the view that European forest-based sector has undergone creative destruction as the production of some of the traditional forest products has declined in recent years. However, at the same time, strong growth is observed in many value-added engineering wood products. Thus, creative destruction emerged as described by the Schumpeter. Further, they discussed that knowledge on economics, politics, markets, and marketing is vital to realize the challenges, barriers, and opportunities as well as to support business and policy strategies. The mega forces such as climate change and resource scarcity are perceived more as opportunities than threats in European pulp and paper industry because pulp and paper industry is diversifying their product portfolio [9] by fostering digital solutions.

This chapter explains the transformative direction of forest-based bioeconomy into a digital platform industry; therefore all stakeholders from different sectors engaged in various roles must be considered [10]. However, consequences of transformation are not yet known.

2. Perspectives on the forest-based bioeconomy

As described earlier, forest-based bioeconomy is the important sub-sector of bioeconomy that holds significant share in this economy. The forest-based products include raw materials (e.g., wood chips) and intermediate products (e.g., pulp) that can be converted to different products to fulfill the customer needs. Forest-based services (e.g., recreation and tourism) are also valuable for local economies [11, 12]. The scope of forest-based bioeconomy is demonstrated in **Figure 1**.

Mubareka et al. [14] argue that resource efficient and sustainable development of products such as biochemical, bioenergy, and biocomposites will not achieve the economic gains only but benefit the environment also by reducing the carbon footprints. The development of green energy, green transport, and other breakthrough

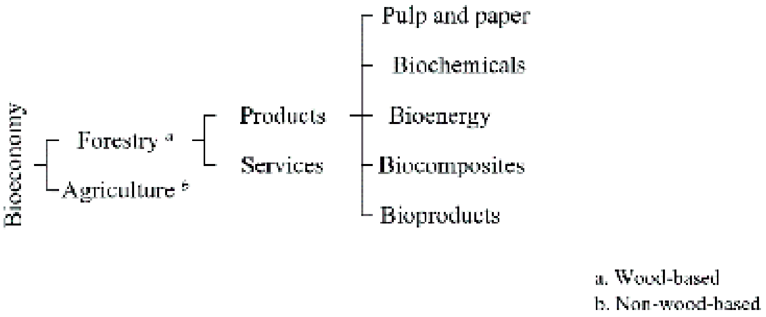


Figure 1.
Scope of the forest-based bioeconomy. Source: Adapted from Watanabe et al. [13].

technologies is on top priority to achieve a goal of sustainable decarbonized society worldwide [15]. Thus, forest-based bioeconomy is gaining popularity as a real global asset for both industrialized and growing economies as forest industry offers sustainable and recyclable products, reduces dependency on fossil-based nonrenewable materials, and ultimately contributes to the development of decarbonized society.

2.1 Structural change in the supply chain

Pulp and paper industry (PPI) is the backbone of forest-based bioeconomy in Europe as big chunk of gross domestic product (GDP) of European Union (EU) comes from PPI. In recent years, the demand for printing and graphic paper in industrialized countries has declined; therefore the forest-based industry is prone to major structural changes, especially in forest-dependent countries. The industry needs to be more dynamic in developing new products, research-related ecosystems, and innovative business models [13].

Figure 2 demonstrates the geographical structure of production and consumption of paper and paperboard in 2015. Asia is on top in both production and consumption while they are lagging behind in adopting the digital solutions. Conversely, the USA and Europe (particularly Finland) are leading in developing digital solution [16].

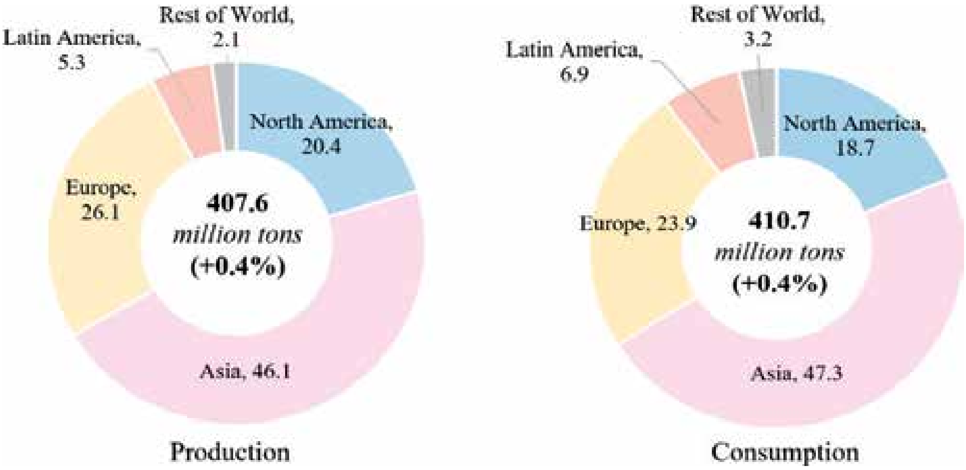


Figure 2.
Worldwide production and consumption of paper and paperboard (2015). Original source: Watanabe et al. [13].

World pulp and paper industry leaders and their digital ability (2015).

Production (Wood pulp)	Export (Paper and paperboard)	Consumption (Paper and Paperboard)
USA (7)	Germany (13)	China (62)
Canada (11)	USA (7)	USA (7)
Brazil (84)	Finland (2)	Japan (10)
Sweden (3)	Sweden (3)	Germany (13)
Finland (2)	Canada (11)	India (89)

The figures in parenthesis indicate World ICT ranking (WEF, 2015).

Ojala et al. [17] discussed that forest-based industry was not facing fierce competition until the 1990s and was running under low degree of internationalization with prime focus on business-to-business products while maintaining the long-term business relationships. The forest-based industry is reshaping over time due to new business dynamics, customer needs, global competition, and strategic orientation [18].

Nowadays, the increasing role of Latin America, Southeast Asia, and China has intensified global competition in pulp and paper industry by lowering the production cost for pulp and paper. Thus, many firms in pulp and paper industry need to innovate their business model, product portfolio, services, and processes. Therefore, forest-based companies are introducing the performance improvement programs to cope with the challenges in their value chain ranging from equipment reliability to analytics in commercial operations. The incorporation of digital solutions and internet of things (IoT) potentially delivers significant gains to the industry by focusing on the following areas:

1. Optimization of tree plantation and forestry operations for improved yield and quality

2. Constraints free supply to the downstream processing activities and reduce the supply chain costs.

3. Support skills development and technology transfer across the firm operating in global settings

4. Enable customer retention by improving the customer value and experience

The implementation of digital solutions in the forest-based industry is subject to the formation of a sophisticated global value chain comprising upstream and downstream players interacting each other and having the capacity of embracing digital innovations. **Figure 3** demonstrates the value chain of forest-based bioeconomy focusing on the PPI wherein digital solutions are incorporated in both upstream and downstream of the value chain.

The framework that facilitates the transformation of forest-based bioeconomy through digital innovation is illustrated in **Figure 4**.

2.2 Consumer preferences and role of prosumers

While learning about the transformative direction of forest-based bioeconomy, people's preferences cannot be ignored as both demand and supply sides are equally important in forest-based bioeconomy value chain. Wesseler and Von Braun [20] are of the view that customer's preferences are shifting toward eco-friendly products

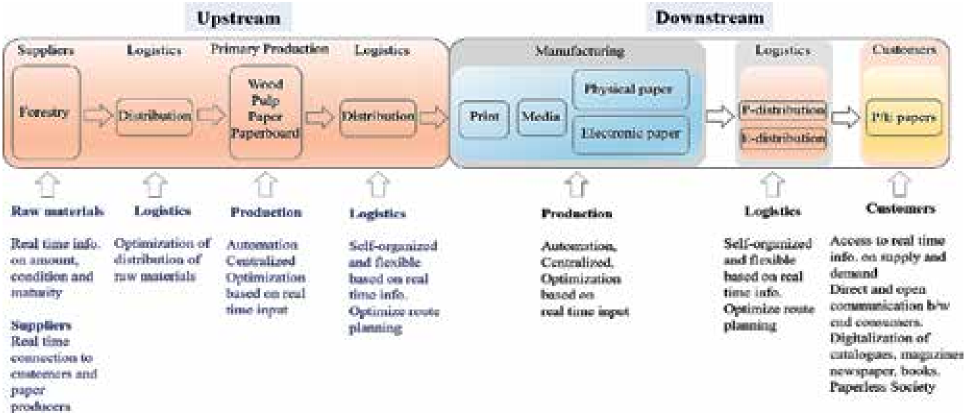


Figure 3.
Value chain structure of the forest-based bioeconomy focusing on pulp and paper industry. Original source: Watanabe et al. [13].

(bioproducts: food, textiles, composites materials) in both industrialized and developing countries. According to the Ministry of Economic Affairs and Employment of Finland [21], the demand of organic food is steadily increasing in supermarkets. The promotion of bioproducts, tax policies, and regulations are the drivers of shift in customer's preferences. Further, virtual communities are playing their role by sharing their views on what is ethical, sustainable, and eco-friendly by using the power of social media. People follow and take advices online; thus the role of digital technologies has increased in setting the people's preferences, and role of consumers has been changed to the prosumers.

The increased consciousness toward sustainability and environmental issues has made prosumers to appreciate those companies who deliver great customer experience and are more responsible in using the natural resources in their operations. Therefore, companies are trying to find ways to waste less; for example, in 2013, Hennes and Mauritz (H&M) launched a global program for collecting used garments for recycling and transforming those to the new products. Similarly, Amazon is supporting individuals in multiple ways by letting them to offer their services (e.g., book publishing on kindle, cleaning, assembly, and electrician) to Amazon customers by using Amazon's digital platform.

The abovementioned trends indicate that the upstream of the value chain of forest-based bioeconomy is largely driven by the downstream of the economy; therefore all stakeholders in the value chain need to focus on consumer-driven business models and appreciate consumer's involvement in the innovation process to increase the acceptance of newly developed products.

Amazon with its disruptive business strategy triggers the demand worldwide in the retail sector, which in turn stimulates the upstream industries in the bioeconomy chain. Amazon analyzes customer buying behavior by using big data

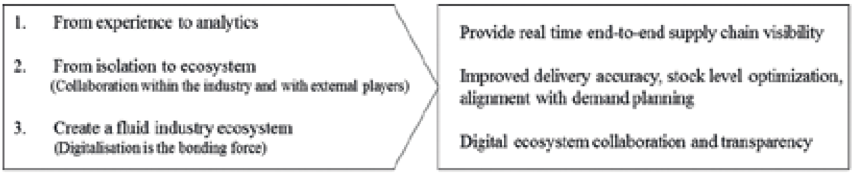


Figure 4.
Transformation of forest-based bioeconomy under digitalization. Original source: Tieto [19].

UPM	Versatile use of renewable wood biomass, combined with innovation, resource efficiency, and sustainability aimed at replacing nonrenewable materials with renewable and low-impact alternatives
Stora Enso	Transforming from a traditional paper and board producer to a renewable material growth company by the means of a strong customer focus and new innovation approaches
Metsä	Involved in various joint and development and innovation projects focused on enhancing the sustainability of forest operations. In addition, they are continuously developing digital services to help forest owners manage their forests sustainably
KaiCell Fibers	Versatile and competitive biorefinery with novel bioproduct applications, optimized capacity based on a local fiber approach, cultivated bioproducts out of chemical softwood pulp, and the bioecosystem of circular economy meeting economical requirements
Finnpulp	Digital ecosystem provides advantages related to raw material and delivery chain management, improving the efficiency of the mill's support functions and optimizing production quality and quantity. This concept further improves the facility's occupational safety and environmental performance

Sources: UPM [22], Stora Enso [23], Metsä [24], KaiCell Fibers [25], and Finnpulp [26].

Table 1.
Finnish forest-based firms' initiatives under digitalization.

analytics and offers recommendations to the customers for future buying based on their browsing history. Amazon's business strategy adheres to the shift in customers' preferences and response time to those changes by leveraging digital technologies as source of competence.

Similarly, leading forest firms are putting their efforts in understanding the consumer behavior and developing new products accordingly by using digital technologies and circular economy way of thinking. Examples of such trends are demonstrated in **Table 1**.

3. Transformation toward a creative disruption platform

The digital solutions enable the consolidation of upstream and downstream, producers and consumers among the diversified industrial sectors in the forest-based bioeconomy value chain [27]. Consequently, we can expect creative disruption platform as illustrated in **Figure 5**. Digitalization challenges the traditional practices in forest-based industry encompassing low performance production, traditional business models, rules and regulations applicable to non-digital

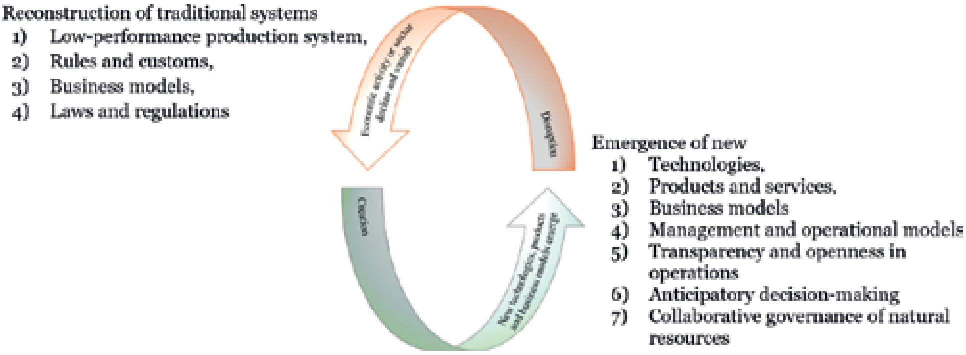
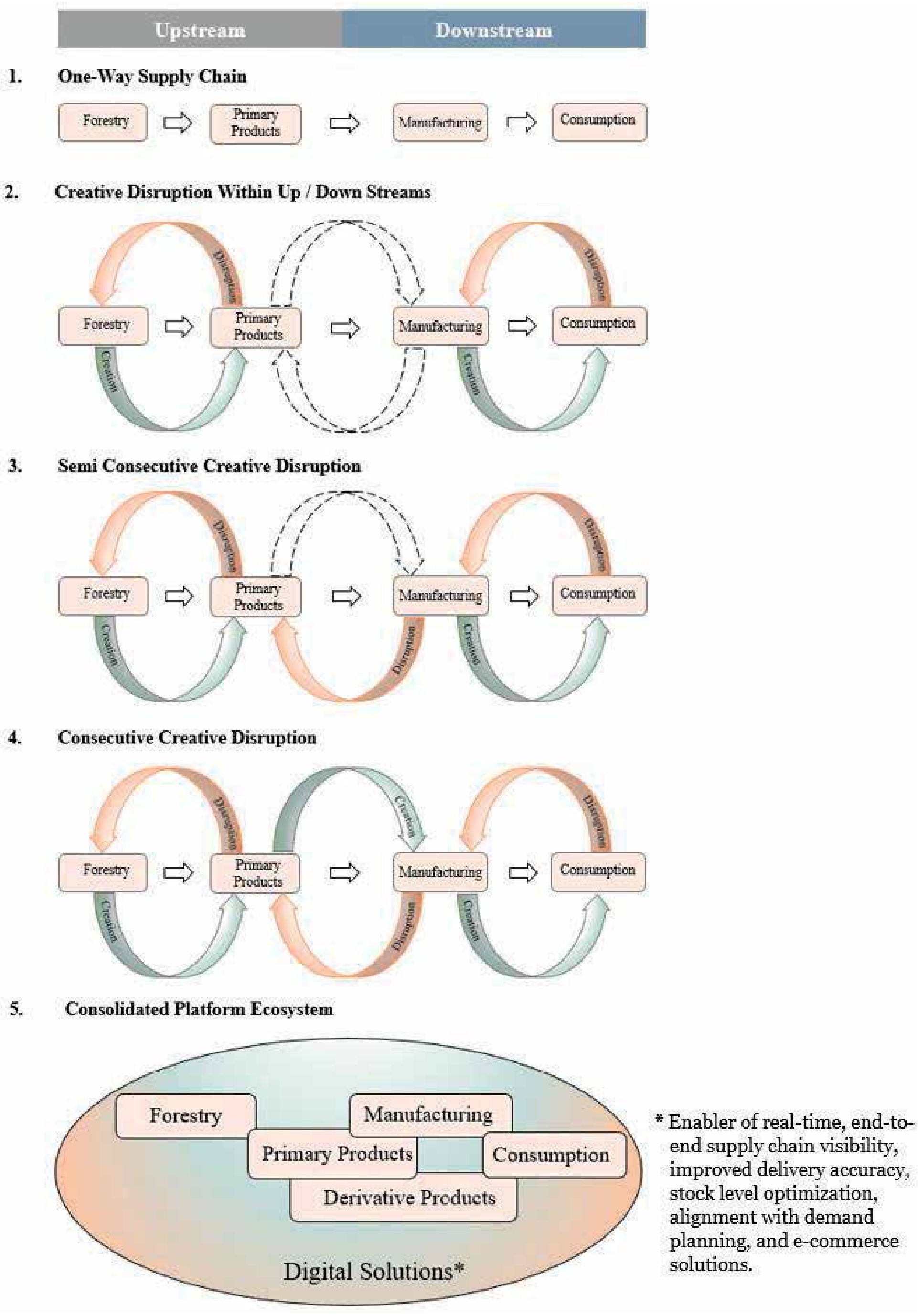


Figure 5.
Creative disruption platform embracing digital solutions. Original source: Watanabe et al. [13].

economies, and set platform for new business models, technologies, products, and services, collaborative governance of natural resources, visibility and transparency in operations and so on.

With such understanding, Watanabe et al. [13] described the stepwise concept of creative disruption platform as illustrated in **Figure 6**. In the forest-based bioeconomy, the linear value chain from forestry (upstream) to consumption



* Enabler of real-time, end-to-end supply chain visibility, improved delivery accuracy, stock level optimization, alignment with demand planning, and e-commerce solutions.

Figure 6.
Steps in constructing a creative disruption platform. Original source: Watanabe et al. [13].

(downstream) transforms into creative disruption platform. First, the disruption and creation are observed within the upstream and downstream. Further development of digital solutions in the downstream instigates disruption in upstream with the prospect of new developments and consequent creation of new business system in the downstream. Thus, all stakeholders involved in the value chain of forest-based bioeconomy will play different roles and interact each other to accelerate the consolidation of upstream and downstream which will in turn lead to the emergence of creative disruption platform as expected.

4. Summary

In the bioeconomy context, the consumer-centric and circular economy way of thinking combined with digitalization leads to a digitalized bioeconomy that satisfies the concerns for eco-consciousness and increases competitiveness across the value chain as illustrated in **Figure 7**.

Digitalized bioeconomy enables (1) bioeconomy monitoring system based on big data analytics, (2) smart design and manufacturing to meet downstream needs across the value chain, (4) collaborative governance of natural resources, (5) decentralized production, (6) efficient management of raw material streams, (7) data-based business models and decision-making tools, and (8) consumer-centric innovations and so on.

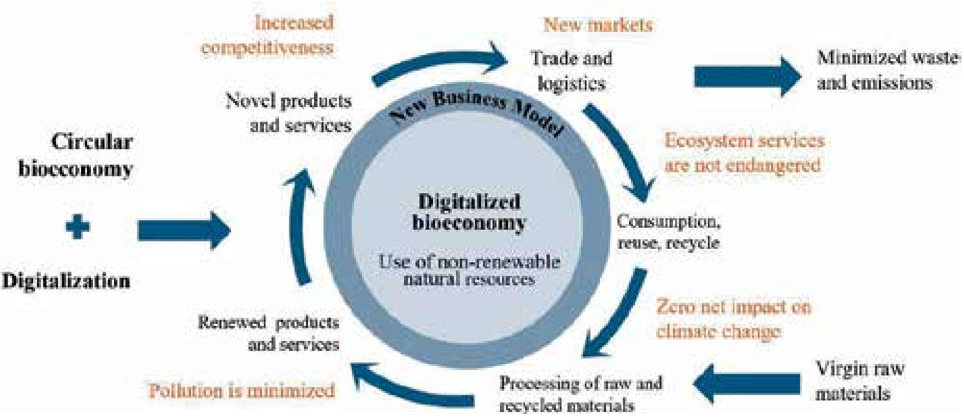


Figure 7.
Concept of digitalized bioeconomy Source: Authors' elaboration based on Watanabe et al. [28] and Mistra [29].

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Chapter 8

The Bioeconomy: An Opportunity for the Spanish Economy

Manuel Laínez and María Jesús Periago

Abstract

The objective of this chapter will be to show the possibilities of the bioeconomy in Spain and how it can help to create new productive models that favor the sustainable economic development, taking into consideration the circular economy framework that the EU Commission has launched. For this, we will collect the current socioeconomic weight of the sectors that integrate the bioeconomy in Spain. We will then review the current policies and those that are predictably a short and medium term, at European level, and are going to affect the use of biological resources, as well as the evolution of the behavior of European Consumers. This will give us the chance to demonstrate the need and the opportunity to move forward different economic activities through the interaction between science, society, and companies, in order to increase efficiency and sustainability in the traditional value chains and, at the same time, to create new ones. Then we will briefly describe the Spanish strategy of bioeconomy: the process of elaboration, its essential elements, and observatory of bioeconomy, as the instrument that promotes its development. We will describe the Spanish Bioeconomy Observatory as a tool to move forward towards an ecosystem where science and technology, society, and the economy work together to overcome the challenges of our society.

Keywords: sustainability, resource efficiency, rural development

1. Introduction

The bioeconomy can be defined as being the result of all the economic activities related to the direct or indirect production, transformation, and utilization of resources of biological origin. However, technological advances mean that—in addition to the production of food, forest products, textiles, and energy—such resources can now be exploited to obtain extracts or active compounds for use in nutrition and pharmacology as well as diverse biocompounds, such as bioplastics and biofuels.

The European Union (EU) approved its bioeconomy Strategy in 2012, driven by the General Research Directorate of the European Commission. One of its objectives was to stimulate the development of a national strategy in each member state, adapting the objectives and lines of work to the particular conditions, singularities, and specifications of each country. In Spain, the Bioeconomy Strategy was launched at the start of 2016. This considers the use of science and knowledge as an essential element, while attempting to meet the challenges presented in each of the socioeconomic sectors related to the production and utilization of resources with a biological origin.

The Spanish Bioeconomy Strategy defines the bioeconomy as the whole of the economic activities that provide goods and services, and thus generate economic value, through the use, as fundamental elements, of resources of biological origin in an efficient and sustainable manner. As recognized in this Strategy, and in our context, the objective is the production and commercialization of foodstuffs, forest products, bioproducts, and bioenergy, obtained by means of physical, chemical, biochemical, or biological transformations of the organic materials not destined for human or animal consumption. It is implicit that this should involve processes that are respectful of both the environment and the development of rural communities.

In this chapter, we analyze the possibilities for the bioeconomy in Spain. We describe the sectors that currently form part of it and the challenges that, from our perspective, it must meet, as well as stressing the need to incorporate technology based on the generation of knowledge and innovation. Then, we focus on the Spanish Bioeconomy Strategy, describing its genesis and the elements essential to it, before finishing with an explanation of the activity of the Spanish Observatory of the Bioeconomy, an instrument vital to the development of the bioeconomy in Spain.

2. The bioeconomy in Spain

The development of the Spanish Bioeconomy Strategy involved the economic characterization of the sectors that constitute the bioeconomy. It was not an easy task due to the absence of the necessary series of statistical data. This led to the accumulation of data from diverse sources; in some cases, they were obtained directly from the different sectorial administrations and in others from the different economic sectors themselves. Based on this, the bioeconomy in Spain represented 6.5% of the gross domestic product (GDP) in 2015, employing around 9% of the economically active population [1].

The report on the bioeconomy in the EU presented by the Joint Research Center for the year 2016 [2] mentions the difficulty faced in collecting the statistics for the economic and employment data related to this activity in Europe. However, it includes information from the official statistics of the relevant sectors: agriculture, forestry, fishing and fish farming, food processing, drinks, tobacco, the production of textiles of biological origin, the production of wood products and furniture, the production and processing of paper and paper-derived materials, the synthesis of chemical compounds, pharmaceuticals, plastics and gums from biological resources, the production of liquid biofuels, and the generation of electricity.

Taken together, in 2015, these activities employ 18.6 million people in the EU and have an economic value of 2200 M€, which represents around 9% of the total economy of the EU. The agri-food sector accounts for around three-quarters of this employment and two-thirds of the economic value [3, 4]. Using the data from the report, in 2016, the Spanish bioeconomy represented 8.6% of the total economic value of this sector in the EU, and 7.1% of the jobs. Based on the statistical analyses of the Bioeconomy Knowledge Center [3], in 2017, the bioeconomy in Spain generated around 192 M€ and more than 1.3 M jobs. The data are presented in **Table 1**.

According to this same source, the agri-food sector is the most important sector of the Spanish bioeconomy. The agricultural sector comprises around 900,000 farms, representing 2.5% of the GDP; fishing involves more than 5000 companies and almost 9900 boats, representing 0.2% of the GDP, and the food and drink sector comprises almost 28,000 companies, representing 2.7% of the GDP. Forestry (wood, cork, and paper) represents 0.56% of the GDP. In addition, there are 540 companies involved in biotechnology (excluding healthcare) and 170 in the transformation of biomass into energy.

Sector	Value (M€)	%	Employment (no of people)	%
Agriculture	43.8	22.7	678,700	50.9
Fishing and fish farming	2.5	1.3	53,035	4
Foods, drinks, and tobacco	104.9	54.5	351,315	26.4
Biotextiles	8.2	4.2	70,153	5.2
Bioproducts	9.1	4.7	28,921	2.2
Bioelectricity	0	0	0	0
Biofuels	1.88	0.9	3781	0.2
Forestry	0.95	0.5	26,100	1.9
Paper and derivatives	12.5	6.5	40,826	3
Wood and furniture	8.5	4.4	78,778	6
Total	**192.4**		**1,331,609**	

Table 1.
The importance of the bioeconomy in Spain in 2015, by sector [3].

The Joint Research Center has recently published data concerning the biorefineries in the EU, distinguishing them according to their products and the raw materials used [5]. The same authors (Parisi y M'Barek, personal communication) have informed us that their database includes 29 such plants in Spain; of these, 25 produce "bio-based chemicals," 19 produce "liquid biofuels," and four produce "bio-based composites and/or fibers." In relation to the raw materials processed, most of these Spanish biorefineries use resources of agricultural origin. Thus, 10 use the organic fraction of residues, five use biological materials from forests, five use materials of marine origin, and one uses material from short-term pastures and catch-crops.

3. The challenges faced by the bioeconomy

The resources of biological origin have varied uses and are subject to changeable conditions of production and transformation, due to fluctuations in the agro-climatic, market, and political circumstances. In consequence, the bioeconomy faces a set of challenges, summarized in **Figure 1**. All of these were taken into account during the development of the Spanish strategy, as described below.

The most important usage of biological resources is the feeding of human beings. In the coming decades, the human population of the Earth will reach 9100 million. To feed this population, around 68% more food will be required [6]. In addition to the population rise, it must be borne in mind that economic growth will modify the demand of foodstuffs, with a particular rise in the consumption of products of animal origin [7]. Another factor to consider is the concentration of the population in cities and the consolidation of large conurbations [8].

In an ever more globalized world, the total worldwide demand will condition the production of foodstuffs, as well as the type of use of agricultural zones, the production systems, and their technologies. For this reason, the *first challenge* that the bioeconomy faces is to produce more food, in a more efficient manner since the availability of resources is limited. On a global scale, the soil available for agricultural purposes is limited. Before, the solution would have been to expand agricultural activities into land occupied by forests or jungles; but, this is no longer an option due to the effect that deforestation would have on the atmospheric concentrations of greenhouse gases. Another limiting resource is the availability

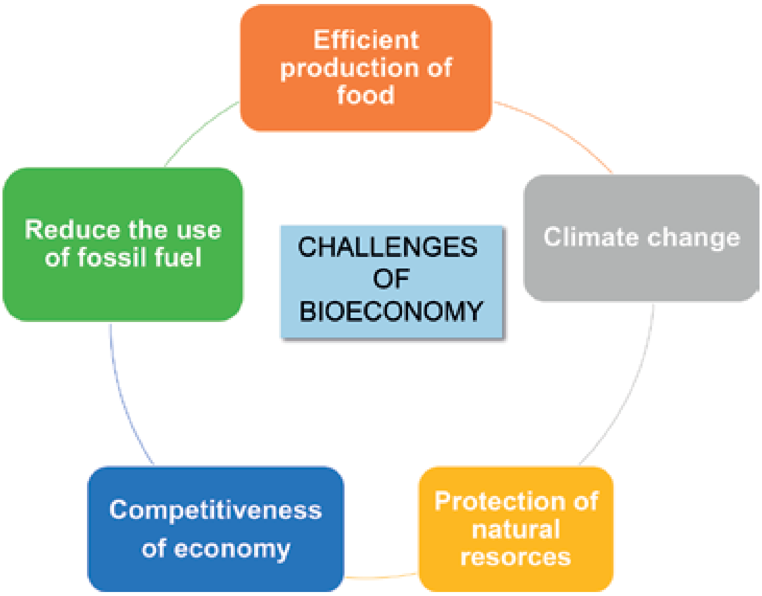

Figure 1.
The five challenges of bioeconomy (own elaboration).

of high-quality fresh water, for both agriculture and other human uses, especially in zones that currently have a water deficit. However, the efficiency of water use should increase—for instance, due to technological advances in irrigation and plant breeding.

The different groups of the Intergovernmental Panel on Climate Change (IPCC) concluded that there is increasing evidence showing the form and magnitude of the impact of climate change on agricultural production. The majority of the models that have been used to simulate the consequences of increases in the concentrations of greenhouse gases indicate the advancement of a process that combines an increase in mean temperatures, a decline in precipitation, and a greater frequency of extreme meteorological events, such as droughts and floods. These projections have started to become a fact in the Mediterranean Basin, where the mean temperatures have risen, on average, to 1.4°C since the pre-industrial era; this is 0.4°C more than the global mean [9]. According to these authors, under the most favorable scenario, a decrease around 10–30% in the precipitation means that irrigation requirements will rise by 4–22%.

The climate change is the *second major challenge* facing the bioeconomy. Its consequences, with respect to the resources of biological origin, are both physical and legal. The former are that climatic and agricultural systems will need to be adapted through the use of new varieties, modifications in soil and water management, monitoring and control of diseases and infestations, etc. The legal aspects are related to the obligation, enforced by governments, to reduce the emission of greenhouse gases: CO_2, CH_4, and N_2O. Thus far, the production of biological resources, especially in fish-farming, has been considered a diffuse source of these gases and has not been subjected to concrete and individualized regulation in order to reduce emissions. However, the policies being developed, particularly in the EU, may alter this situation, with concrete measures tailored to the individual activities.

The bioeconomy should allow the production systems within it to maintain their output levels under changing agro-climatic conditions, while reducing their emissions. The achievement of these two objectives will be possible only with the development and implementation of the necessary technology.

The *third challenge* is to protect the natural resources. For the systems that produce resources of biological origin, soil and water are essential elements. Also, their activities take place in natural surroundings, often in picturesque locations, that society and governing administrations insist should be protected, to maintain the biodiversity and ecosystems. The new and developing concepts governing the bioeconomy imply that it is necessary to go beyond protection and advance towards a circular economy and an integrated use of all resources.

Different authors have focused on these aspects. For example, [10] the need to reduce the environmental impact and, regarding human beings, the need to maintain global levels of food production and the types of diet that can sustain both, mankind and the planet were pointed out. Others [11] modeled the environmental consequences of a reduction of between 25 and 50% in the consumption of products of animal origin in Europe. Other authors [12] discussed a nutritional transition in developed countries, and among the middle class in developing countries, in which the trends in consumption are determined not only by income but also by considerations of health, the environment, and ethics (in relation to animal welfare). The loss of biodiversity is another important aspect pointed out by others [13], who put forward ideas of how to advance economically in parallel with an increase in biodiversity, while also raising food production.

This point of view has become widespread in society, especially in Europe, as it was demonstrated in a survey of 2783 consumers in Germany, the United Kingdom, Belgium, and the Netherlands [14]. Of the replies, in 62% of cases, the consumption of foodstuffs was influenced by sustainability; of these, in 31% of cases, the consumption was influenced also by health concerns. Currently, more than 22% of the food consumption is determined by health aspects.

To overcome this third challenge, it is vital to redesign the systems of production and the chain in which value is added to products. First and foremost, the inputs must be minimized, and the wastes converted into secondary products, so that the whole production and utilization process is sustainable and renewable. Again, this is dependent on the development of the necessary technology.

The *fourth challenge* for the bioeconomy is to guarantee the competitiveness of the economic activities related to biological resources. In free-market economies, companies must maintain their presence in the markets, both internal and external, in a continuous fashion. As a function of the demand, directly from the consumers or mediated by the distribution chains, the producers must control the arrival of their products in the market so that they are able to compete on price and/or novelty. In the case of the bioeconomy in general, in particular for foodstuffs, they must consider the nutritional and health-related properties of their products as well as the environmental sustainability. The completion of this task depends, once again, on technological advances in the systems of production, in relation to the efficient use and conservation of the resources.

The *fifth challenge* facing the bioeconomy is to facilitate the transition from a fossil fuel-based economy to one based on the use of renewable resources. The use of petroleum derivatives in economic activities leaves an important environmental footprint, in terms of CO_2. Resources of biological origin could form the basis for the synthesis of any of these derivatives. Currently, petroleum derivatives are more competitive in terms of price, due to differences in production costs. Notwithstanding, the development of the appropriate technology and the fragmentation of the market could allow bioproducts—biofuels or bioenergy—to compete with "nonrenewable" materials.

The Organization for Economic Cooperation and Development [15, 16] has, on numerous occasions, underlined the potential of the bioeconomy to overcome the challenges described here and to stimulate the development of new economic activities in the countries where it is promoted. For this, it is imperative to strengthen the traditional series of activities that add value to biological resources, the most important being agri-food, followed by forest products. The appearance of new series of this kind would permit the commercialization of bioplastics, biocomposites, cosmetics, biofuels, bioenergy, and bioproducts related to nutrition and pharmacology.

The growth of all these areas requires, as described by the Standing Committee of Agricultural Research [17], the application of a series of principals essential to the development of the bioeconomy. These are described below:

1. Prioritize the use of biological resources for the production of foods, guaranteeing their worldwide availability for human consumption.

2. Include sustainability in the development of the bioeconomy, such that the amounts of the resources harvested or extracted, in any system or setting, never exceed the capacity for regeneration. This principle should be applied equally to the inputs.

3. Utilization in a cascade, guaranteeing that the biomass is used to obtain the product with the highest added value, while achieving its integral utilization.

4. Move towards a circular economy, by designing productive processes that minimize the output of wastes and maximize reutilization and recycling.

5. Diversification of the use of resources and the accompanying activities.

In the case of the member states of the EU, the challenges described above are reflected in the strategies that define the European policies related to the production and use of resources of biological origin. Below, their most important aspects are described:

- *Climate change policy.* This has been establishing objectives in the medium and long term. By 2020, the aim was to reduce greenhouse gases by 20% compared to 1990, increase renewable energies to 20%, increase the use of renewable biofuels to 10%, and increase energy efficiency by 20%. The successive summits since the United Nations Conferences on Climate Change (COP21 and COP24) have seen greater commitments of the European Commission in this area. For the year 2030, the objectives for these same indicators are 40, 27, and 27%, respectively, while for the year 2050, an 80–95% reduction of greenhouse gases is the aim. To achieve these objectives, reduction requirements are imposed on the emission sectors and neutral or negative technologies are promoted in their CO_2 balance. The diffuse sectors, such as agriculture, will have to assume a reduction of their emissions of 10% by 2020 and an additional 30% by 2030.

- *Environmental policy.* The objectives set at the European level are to achieve a “greener” economy through green growth in a framework of environmental sustainability, to protect nature, and to safeguard the health and quality of life of people, with special attention to water quality, air quality, and hazardous chemicals. In this context, the sustainable use of soil, land, biodiversity, and ecosystems is considered essential, as are ammonia emissions or the generation of dust that has recently become something to consider.

- *Circular economy policy.* This has also been defined recently, in a package that includes as objectives the recycling of 65% of urban solid waste and a reduction of the burial of waste by up to 10% by the year 2030. The action plan recognizes the potential of the bioeconomy to improve the use of waste in current chains that add value and in the creation of new and innovative chains. As a specific example, the European Plastics Strategy states that by 2030, all plastic packaging marketed in the EU must be reusable or recycled cost-effectively [18].

- *Common agricultural policy* (CAP). The communication "The future of food and agriculture," written by the European Commission, was made public in November 2017. In this document, farmers are considered as the managers of the natural environment (responsible for the care of soil, water, air, and biodiversity) and the suppliers of food and other renewable products, while at the same time, agriculture is credited with the function of retaining carbon in the system as a whole. The aforementioned communication considers that the future CAP must lead the transition towards more sustainable European agriculture. In addition to its traditional objectives, this policy must take advantage of the potential of the circular economy and the bioeconomy to support the care of the environment and the fight against and adaptation to climate change [19].

- *Energy and biofuel policy.* This policy has promoted first generation biorefineries, although its objectives for the coming years have been modified, since the European Commission proposes to reduce the production of first generation biofuels by 7% by the year 2021, and by 3.8% by 2030. Individual countries can even set lower limits. Further, it states that the incorporation of 1.5% of renewable energy in transport in the year 2021 should be obligatory, reaching 6.8% in 2030. In addition, the generation of biofuels from further generation biorefineries must rise from 0.5% in 2021 to 3.6% in 2030.

4. The importance of science and technology in the bioeconomy

Overcoming the challenges we have described for the bioeconomy will be possible with the accumulation of knowledge in different scientific areas, and its transformation into innovations applied to each of the areas that comprise the bioeconomy.

The improvement in the efficiency of the processes that make up agri-food production will be one of the essential elements. Implementation of the eco-blueprint—rethinking all the productive, organizational, and logistic processes to reduce the quantity of inputs, which is proposed for the application of the circular economy [20], thereby achieving a balance between productivity and sustainability—will require the integration of knowledge from different areas:

- The areas of biology and biotechnology are essential for the development of new genetic materials for use in arable and livestock farming. The selection and crossing of materials will become much more precise and faster with the sequencing of complete genomes, the use of bioinformatics tools, or the editing of genes. This will allow responses to the joint challenges of productivity, resistance to drought, diseases, and pests, improved efficiency in the use of nutrients, and enrichment of food in certain components of interest. Knowledge of the microbiomes of the soil or the digestive tract of animals will improve the efficiency of the use of fertilizers, water, and feed ingredients, or improve the immune response of plants or animals. These same technologies, as well as nanotechnology, will also be applied to agri-food processing. The European Court of Justice issued a ruling in which it equates, for the EU, the techniques of gene editing with those of genetic modification. A decision of this type, if it is not modified, could inhibit the scientific development in Europe in the coming years, making it difficult to advance in this field.

- The areas of engineering (mechanization, automation, robotization, avionics, and artificial intelligence) will revolutionize both the work itself and, above all, the precision in the handling and application of inputs, allowing progress in arable and livestock farming in the coming years. The use of the means of production at the correct moment and in the exact quantity that is extracted by plants or used by animals improves efficiency and, at the same time, reduces the use of natural resources, the impacts on the environment, and the final waste output of the productive processes. Some of the current objectives, such as reducing the use of fertilizers, phytosanitary products, or antimicrobials, will become a reality.

- The application of information and communication technologies in agri-food production processes will facilitate precision in the use of inputs. Decision support tools will be developed based on the capture and storage of data, or images, for both the productive systems and external ones. The sensors and cameras placed in/on plants, animals, buildings, production chains, vehicles, drones, or satellites will continuously inform about the real productive situation. The processing of this information, and its combination with other external information from consumers or markets, will allow us to leave behind the descriptive analysis of the events that have happened, and instead to predict what may happen and even to prescribe a certain decision.

The aforementioned technological development is fully applicable to the sector of the production and transformation of forest resources. In Spain, there is a tendency to consider that the exploitation of forest resources entails a loss of natural capital and associated environmental services. This vision of the conservation of the environment has manifested itself in the preparation of the Spanish Bioeconomy Strategy [21]. As a result of this, the Juntos por los bosques initiative has arisen [22] that tries to install in Spanish society the concept that where there is forest management with sustainability criteria, the biomass, and therefore the sequestration of carbon, increases, thereby maintaining an economic activity and the preservation of the forests. This group defends the use of forest-based biomass as a unique opportunity to reduce the fire risk, create jobs, mitigate climate change, and reduce the dependence on external energy.

Spain has almost 6000 km of coasts. If we leave tourism aside, the traditional use of the marine environment has focused on the extractive fishing industry. Aquaculture has developed slowly, and the extraction of algae for different purposes (to obtain active ingredients, animal feed, or human food) is incipient. The Blue Growth initiative [6, 23] identified other opportunities linked to marine biotechnology (understood as the exploration and exploitation of marine organisms in order to create new products), as well as other areas far from the bioeconomy such as ocean energy or the mineral exploitation of the seabed.

Paredes [24] grouped biomass conversion technologies into: biological (based on techniques of anaerobic digestion, fermentation, and enzymatic hydrolysis), mechanical (such as densification, extraction, and pressing), chemical (transesterification), and thermochemical (carbonization, combustion, gasification, and pyrolysis). However, this author pointed out that the main technological pathways for biomass research include: combustion, gasification, cogeneration, pyrolysis, transesterification, fermentation-hydrolysis, and anaerobic digestion. The foresight document of SCAR [17] also explored these issues.

5. The Spanish bioeconomy strategy

In 2014, the process of drafting the Spanish Bioeconomy Strategy began. It ended at the end of 2015, the strategy becoming public in early 2016. The essential milestones of this process, as it has been reported [1], were the following:

- Analysis of the opportunity to develop the Bioeconomy Strategy, within the framework of the National Ministry of Research, Development, and Innovation.

- Agreement to initiate the work by the ministries involved (economy and competitiveness; agriculture, food, and environment; and energy, industry, and tourism), and the start-up of a working group with representatives from the three ministries, the scientific and business worlds, and technological platforms.

- Preparation of a first draft of documents, and their distribution and discussion among economic sectors and representatives of society, research, and local, regional, and national administrations.

- Preparation and adoption of the final document, after submitting it to public consultation.

The definition of bioeconomy included in the document appears in the introduction to this chapter, as do its objectives. It is important to refer to some specificities of this strategy, which were widely discussed throughout the elaboration process, such as the scope, the bases, the particularities of Spain, and the essential elements.

The scope of the strategy is included in the definition: agri-food, forest production and marine resources, residual biomass, and bioproducts. The importance given to each of these areas is proportional to the specific weight that each currently has in the Spanish economy, with the proviso that the transformation of biomass into bioproducts and bioenergy should be an important objective since it was a field of activity that was still under development. From certain points of view, it was considered that agri-food should be excluded from both the concept and the scope, in the same way as in other European strategies that were being worked on. Subsequently, the same decision was made in some of the Spanish regional strategies. However, the agreement that it was necessary to address the production and transformation of all biological resources in an integral manner, from a rural and coastal development perspective, led to its integration.

The basis of this integration determined that foods were considered first, using productive methods based on efficiency and sustainability. Therefore, from the very beginning, the need to prioritize the use of agricultural and marine resources to provide food was considered, suggesting that the raw material for biorefineries should be the residual biomass of the agricultural industries. It was understood that the use of natural and biological resources is an economic decision of their owners. However, it was considered also that, as a principle, priority should be given to the alimentary use of agricultural products, as against the current European policy that promotes first-generation biofuels. Today, this policy has been changed, as a consequence of public opinion.

Another founding principle was the requirement to give efficiency and sustainability—economic, social, and environmental—the same level of importance. There were two reasons for this: the first was related to the social perception in Europe of the bioeconomy, meaning that the European strategy had been launched thinking especially about the efficiency of the use of biological resources. This had provoked a reaction of rejection in certain groups that believed that behind the strategy, there was an interest in depleting forest resources. The second was the assurance that the future of the agri-food and forestry sector would be based on the guarantee of both its viability in a globalized market and the maintenance and recovery of the natural capital that sustains it, due to the use of more efficient and sustainable production processes.

The triangle of science, economy, and society must be present throughout the process of creating the bioeconomy, and it has been demonstrated that the basis for the development of the bioeconomy is the availability of technologies. The emergence of new technologies is only possible if it is supported by new scientific knowledge of the existing environment. The generation of basic knowledge comes from different areas, such as fundamental biology, genomics, biotechnology, ecology, physics, chemistry, physics, nanotechnology, transformation technologies, biochemistry, and thermochemistry, as well as information and communication, without forgetting the social sciences associated with the social economy and its organization. This knowledge should be aimed at solving specific problems of the different processes or areas. For this reason, it is necessary to invest in research that is both cutting-edge and oriented to face the challenges that, progressively, arise in our society, thereby achieving technological development.

In our opinion, society must be aware of the bioeconomy, its justification, its challenges, its objectives and interests, and the tools to make it possible. Only in this way will it be possible for the population to support public financing of research activities, accept the extension of knowledge in certain controversial areas, and have a broader vision when voicing its opinion in relation to the derived technologies, such as gene editing or genetic modification. In addition, when new bioproducts reach the market, competing with those derived from fossil resources, the members of the public will be able to make sound purchasing decisions based on their knowledge. For these reasons, from the first moment, we have had representatives of consumers, NGOs, and other collectives in our working groups.

The last component of the bioeconomy is the companies capable of interpreting the current and potential demand for these new products and of integrating emerging technologies in a productive process, obtaining an economic benefit. Basically, this refers to innovative companies, which require these technologies that are controversial or, at least, different from the conventional ones present in the market. The source of knowledge for these activities is in research centers and consortiums, where new information or processes can be produced to remove old limitations or make previous transformations more efficient. These entities must be in a close relationship with research projects, technological platforms, and places where scientific results are presented, and they must participate in projects aimed at the assimilation of knowledge. In short, they have to maintain a close collaboration with research as the only possible way to innovate in a pioneering way in these areas.

Spain has a great diversity of agro-climatic areas, but in 80% of its territory, the availability of water is limited. Here, the water supply is a primary constraint on agricultural yields and, therefore, on the production of resources of biological origin or on the processes that require a large input of water.

The approaches of the Spanish Bioeconomy Strategy are aimed at promoting the development of the bioeconomy through the following routes:

- Public and private research and the investment of companies in innovation in the areas of the bioeconomy. Here, one can highlight the promotion and facilitation of multidisciplinary alliances between researchers and companies that can participate in all calls for the funding of projects, from European to national or regional levels. Another aim is to publicize the European models of public-private collaboration for the development of the bioeconomy, the search for financing of pilot-scale installations (both public and private), and the interaction between technology platforms and campuses of excellence.

- The reinforcement of the social, political, and administrative environment of the bioeconomy, based on the creation of an observatory, the launching of a program of dissemination and social dialog, and the generation and training of a group of stakeholders focused on this discipline.

- The improvement of competitiveness and the development of the bioeconomy market, which could be achieved by developing the concept of sustainability (by means of precise indicators), identification of the limitations for its development (both technical and legal or administrative), the identification and promotion of new chains of value, or the standardization and certification of new bioproducts.

- The development of the demand for new products, through the identification of new products and the difficulties for their entry into the market, the development of innovative public sale campaigns applied to bioproducts, and the labeling of such products.

- Support for the expansion of the bioeconomy through the collection and presentation of success stories and cooperation and collaboration among stakeholders, so that specific strategies can be implemented at the regional level and connections can be made with international projects.

The strategy is promoted through annual action plans focused on developing the activities described in the five strategic areas. The promoter of this plan is the Observatory of the Spanish Bioeconomy Strategy, which we will describe in a specific section.

In the first 3 years of operation of the strategy, progress has been made in different areas, as discussed below:

- The bioeconomy has been included, in a comprehensive fashion, among the Spanish research and innovation objectives, within the framework of the revision of the State R & D Plan for the period 2017–2020. It is considered globally, integrating all the economic and social challenges associated with the agri-food, marine, and maritime sector and bioproducts, clearly establishing that the bioeconomy is a tool to advance towards the circular economy. In this context, the EU is moving in the same direction, in research and innovation, both in its work package within H2020 and in the ideas that are emerging for the 9th research program. In addition, the connection and interaction between the bioeconomy and the circular economy are considered, considering the former as a tool to develop the latter in the field of biological resources.

- A project has been carried out to determine the social perception of the bioeconomy in Spain, based on discussions with 20 focus groups, throughout the country, representing different age groups, professions, and levels of study. Particular emphasis was placed on knowing the opinion of the people active in social networks and environmental NGOs. The conclusions were varied; among them, one can highlight the scarce knowledge of what underpins the bioeconomy, the interest it provokes for the sectors linked to the production of biological resources, the doubts that its implementation raises in certain groups actively involved in the defense of the environment, and the need to improve information and communication, identifying the administrations related to science, technology, agriculture and food as the only ones that will have sufficient credibility to address the process.

- A coordinated strategy of training and communication has been developed, which has enabled 21 dissemination and training courses to be organized: eight by the central administration and the autonomous regional communities, in seven cases by universities, especially through their summer courses, and on six occasions by private entities. The scheme followed has always been based on a general presentation, explaining the concepts, objectives, elements, and strategic lines. From there, modules have been developed for different areas, with examples of bioeconomic activities in operation in the market. It has been quite common to explain the ways in which financing can be obtained for projects, both research and innovation.

- Two public-private collaboration forums have been organized—with the participation of researchers, administrations, and companies—to discuss the sustainability indicators applied in arable and livestock farming and forestry production. These agreed on the need to continue developing proposals and collaborating at the European level.

- At the international level, the Spanish bioeconomy has been represented in the SCAR working groups, in the stakeholder panel of the European Commission, and in the events organized by the Commission. It has also participated in the two Global Bioeconomy Summits, organized in Germany, and has established collaborations with the Latin American bioeconomy group through contacts within the framework of FONTAGRO and CEPAL.

- Several autonomous communities have started to develop their own initiatives in the area of the bioeconomy. Sixteen of the 17 Spanish regions featured the bioeconomy in their “smart” specialization strategies at the beginning of the current programming period; today, they all have it. In addition, eight communities have been working on their own strategies. At present, Andalusia has finalized and adopted the document of its regional strategy. Extremadura has included it in its green growth strategy. Aragón has included it in its circular economy strategy, but trying to promote rural development as an element of differentiation. Other Communities where work is being done, in different stages of progress, are Asturias, the Balearic Islands, Castilla León, the Region of Murcia, and the Valencian Community.

- There is an online platform available to the participants in which different documents can be presented, as well as showing examples of successful cases, for both the central administration and the Autonomous Communities that are working in this area. Training sessions have been organized to raise awareness of what constitutes the bioeconomy and the possibilities of financing its activities.

In 2018, work began to develop a Circular Economy Strategy in Spain. Since its implementation, the Bioeconomy Strategy has been present as such. The activities of the observatory, with its annual action plans, have become one of the measures of the Circular Economy Strategy itself, which shows the complementarity between the two strategies with regard to promotion of economic development and sustainability.

6. The Spanish observatory of the bioeconomy

An essential element for boosting the bioeconomy in Spain is the Spanish Observatory of the Bioeconomy. It is an instrument of support and cooperation for the development of the Spanish Strategy of Bioeconomy, dealing with both administrations, central and regional, and with the different stakeholders of science, economy, and society as a whole.

Its functions are the following:

- Promotion of the Spanish Strategy of Bioeconomy and the measures stipulated therein.
- Adoption and promotion of the action plans.
- Collaboration in the analysis, diagnosis, evaluation, and monitoring of the activities defined within the framework of the Spanish Strategy of Bioeconomy.
- Monitoring of the development of the activities included in the action plans.
- Encouraging a strategy of public communication, education, sensitization, and participation of Spanish society in relation to the bioeconomy.
- Promote the inclusion of the bioeconomy in policies at the national level.

The Spanish Observatory of the Bioeconomy is made up of 38 members belonging to different administrations (central, regional, and local), to research facilities and companies within the structure of the bioeconomy, to universities, public research organizations, and technological platforms related to those same areas, and to social organizations that include sectoral representatives, trade unions, nongovernmental organizations, credit entities, etc.

Its structure, as shown in **Figure 2**, is as follows:

- *Monitoring group*: with representatives of the different administrations.

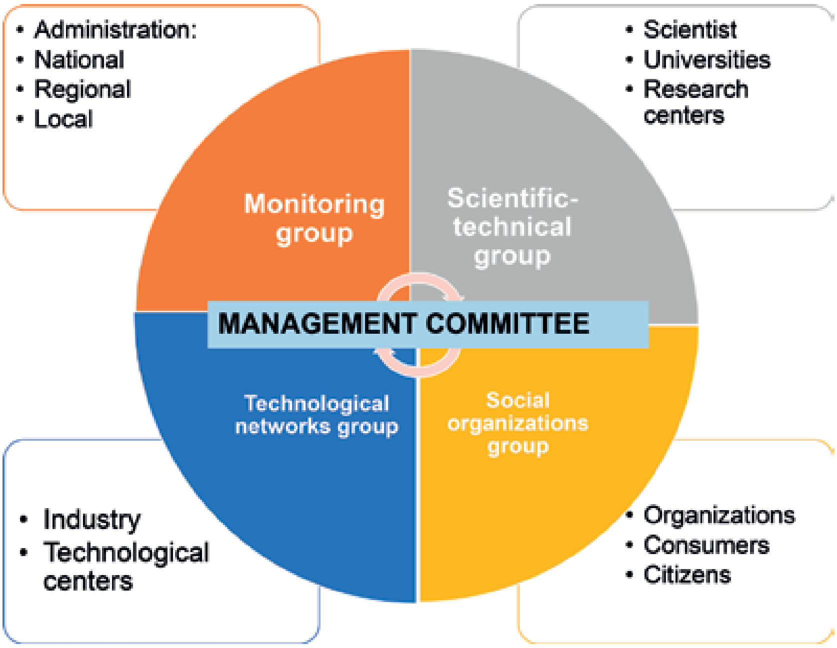

Figure 2.
Structure of the Spanish observatory of bioeconomy (own elaboration).

- *Scientific-technical group*: with a clear leadership role across the full gamut of possibilities in the bioeconomy and promoting innovation.
- *Technological network group*: this facilitates collaboration among the spheres of science, business, and innovation.
- *Social organization group*: this articulates the opinions within society as a whole.
- *Management committee*: this is formed by the two people who coordinate the work of each of the previous groups, together with a general coordinator. The coordinators mobilize and energize each of the previous groups, follow up on the general work, convene meetings, and summarize what was discussed in them.

7. Concluding remarks

The planet is facing a number of challenges that must be addressed in the coming decades, in relation to the use of natural resources to feed, in the medium and long term, all of humanity. Society has become aware of this reality and, at the international level, an agreement is being reached that obliges countries to modify their production and consumption practices in relation to goods and services. The sustainable bioeconomy, as a tool to develop the circular economy, can be an adequate instrument to overcome these challenges.

The bioeconomy groups together all activities related to the use of biological resources, providing a global and integrated view of their use in which the generation of knowledge and its application by companies, taking into consideration the opinion of society, will provide a response to political and social challenges with tools that guarantee the sustainable and efficient use of these resources.

In a country like Spain, in which biological resources represent 6.5% of GDP and provide employment for 9% of the active population, and which will be subject in the medium term to the pressure of changing agro-climatic conditions, the development of the bioeconomy—from the rural to the coastal environment and from the production of food to the commercialization of bioproducts—is a strategic area with a promising future.

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Chapter 9

Biotechnology in Agricultural Policies of Sub-Saharan Africa

Joel W. Ochieng and Anthony Ananga

Abstract

The agricultural policy environment in sub-Saharan Africa in the last 15 years has been erratic, especially with regard to adoption of biotechnology. While many biotech products such as tissue culture (TC) banana, hybrid maize, and others are now frequent at farm level, the adoption of some of the technologies remains relatively low, partly due to political and regulatory bottlenecks that have hampered farm deployment and entry into market systems of genetically engineered crops and products. This chapter reviews the political landscape of biotech crops across sub-Saharan Africa; analyses the state of enabling policy environment in key countries; discusses the impact of push-pull factors on food security, research, and training; and identifies the opportunities for investment in biotechnology and agribusiness in sub-Saharan Africa.

Keywords: biotechnology, policy environment, Africa, agriculture, GMO, adoption, regulation

1. Introduction

Sub-Saharan Africa (SSA) is one of the regions that depend mainly on agriculture but have largely remained food insecure. In fact, food insecurity in SSA has progressively worsened since 1970 with the proportion of malnourished population reaching 30% in 2017 [1]. Farming in SSA relies on rudimentary methods, which, among others, are characterized by continuous tilling of land, which depletes soil nutrients, leading to poor soil quality. Many countries in the region are making efforts at rehabilitation and expansion of irrigable land, in addition to subsidy on fertilizer and seeds. However, intensive use of inputs depletes agriculture's natural resource base, jeopardizing current and future productivity. More than three-quarters of food is produced in this manner on smallholder farms despite serious production challenges including degradation and nutrient-deficient soils, soil-borne and plant pathogens and pests, unreliable rain-fed farming, high postharvest losses, especially of milk, grains, and tubers, resulting from poor processing and storage, poor farming skills, and limited access to and utilization of appropriate agricultural technologies. In SSA, studies have shown that majority of smallholder farmers lack awareness of improved agricultural practices and technical know-how, partly because of weak linkages between researchers, extension staff, and farmers [2]. The food production-consumption gap for SSA is projected to widen, allowing food insecurity to reach catastrophic levels in the coming years as majority of smallholder farmers continue aging, while the youth remain less attracted to farming. This will be exacerbated by the projected increase in population in the region, with a higher increase than rest of the world (**Figure 1**).

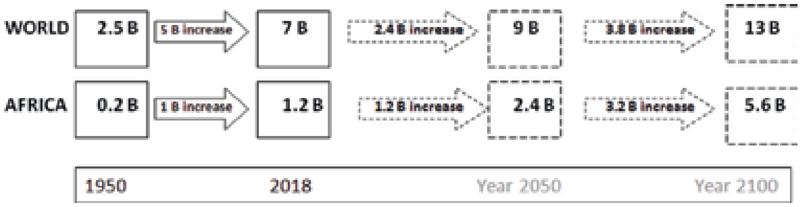

Figure 1.
World human population compared to Africa, across major timescales. Population in Africa has been and is projected to increase more rapidly than rest of the world.

The region's agricultural development is in a race against time to eliminate this deficit as climate change is expected to lead to significant reductions in crop yields, threatening the livelihoods of millions of poor subsistence farmers and agricultural workers [3]. On the other hand, closing the development deficit and providing farmers with access to the investment, technologies, and knowledge they need to adapt to climate change could transform their development prospects. Increasing farm productivity is therefore a priority as yields have stagnated at levels well below global averages. It is quite clear that scientific and technological advances could be used to mitigate the factors that have continued to keep African agricultural productivity at very low levels. Prospects do exist for significant productivity improvement through a combination of technological and policy measures. Improving farmers' access to technology is central to meeting the double challenge of closing the development deficit and adapting to climate change. The African Union (AU)'s comprehensive approach that envisions a 6% annual growth in agricultural productivity requires the deployment of advanced technologies coupled with strong policy support. It has been observed that realizing a 6% agricultural productivity growth rate will need unprecedented policy support from African governments and international development partners [4]. Such policy shifts should aim for sustained investment in the generation of agricultural technologies and most particularly for the deployment of advanced biotechnologies. "Biotechnology" as a term has evolved since it was coined in the early twentieth century and is today defined differently by different organizations, groups, and individuals. For example, the US National Science Foundation defines it as "The controlled use of biological agents, such as microorganisms or cellular components," while the Food and Agriculture Organization of the United Nations (FAO) and the Convention on Biological Diversity (CBD) define biotechnology as "any technological application that uses biological systems, living organisms or derivatives thereof, to make or modify products or processes for specific use." Generally, therefore, biotechnology is *any use of organisms or its components in industrial, medical, agricultural and environmental engineering or processes.* The growing human population, coupled with climate change, has triggered the need to explore complementary biotechnological innovations for improving food production, better healthcare, and cleaner environment.

Many challenges faced in agriculture can be minimized through the application of various biotechnologies. Low production associated with degraded soils, drought episodes, emergent plant pathogens and pests, and postharvest losses can now be mitigated using suitable biotechnologies that enrich soils, target production traits for improved yields, selective breeding, and genetic engineering for insect resistance and drought tolerance. Further, biotechnologies now exist for overcoming accumulation of aflatoxin, usually produced by certain fungal species under moist and dump conditions. Generally, biotechnologies have revolutionized farming in industrialized economies, and have the potential to reduce food deficits, make farming more remunerative, and attract the youth to agriculture in both middle- and low-income economies. In healthcare, various biotechnologies have been developed in the last few decades to manage both infectious and non-infectious diseases. Diabetes, for example, is now managed using insulin produced in bacteria through genetic engineering. To reduce malnutrition, biofortification for micronutrients and selective breeding for nutritional improvements have been used. In environmental conservation, biotechnologies are applied in removal of contaminants such as heavy metals, and waste decomposition. In industrial biotechnology, biological agents such as microorganisms, tissues, cells, or enzymes isolated from living systems have been used, either in the natural state or genetically engineered to reduce or remove waste materials from the environment. Others involve the use of genetically improved trees for phytoremediation (plant-based cleanup of contaminated soils), use of microorganisms to decompose effluent (sewage), and the use of biofertilizers and biopesticides instead of chemical sprays. Although biotechnology is applied in many fields beyond agriculture, this chapter focuses on its integration into agricultural policies of African countries.

2. Regulation and management of biotechnology

Application of biotechnology requires, among others, at least the following to be in place: systems that ensure there is adequate capacity to develop and apply the technologies; systems that promote research, extension, and wider adoption; and systems that regulate the sector to assure sustainable use of resources, environmental and human safety. With growing urbanization and the supply crisis from food production deficits, and as more and more people gain interest in agribusiness, there is urgent need to develop guidelines and policies that create a conducive climate for agricultural investment while providing safeguards against environmental and social risks. Although biosafety relates to all biotechnology applications, and genetic engineering is just one of the many biotechnologies in use today, most discussions about biosafety in many countries worldwide revolve around whether a country has projects involving genetic modification (GMO), and hence some internationally agreed way of treating safety and associated assessments. The GMO-centered handling of biosafety emanates from the erroneous interpretation among non-experts that biotechnology = GMO. Biotechnologies (whether low- or high-tech) may introduce certain risks. Both modern biotechnology such as genetic engineering and traditional techniques commonly used such as crossbreeding (with wild counterparts) may confer the same kind of risks but which many people generally do not know about. From a scientific perspective, therefore, the controls should be the same if the risks (real or perceived) are the same, or nearly same. Practically across the world, however, this is not the practice. The level of protection required for a product should necessarily relate to its intrinsic characteristics rather than to the method of obtaining it, a position taken both by world toxicologists in their valuable position paper on genetically modified foods [5].

As a country determines an appropriate level of protection for any product, social and political considerations have to be built-in within the scientific decision framework in order to calibrate the balance between controls and safety, against accessibility/benefits. Agricultural wisdom dictates striking a balance between economic development and human as well as environmental health. Thus, an enabling policy environment comprises deliberate actions intended to promote technology development (such as trained personnel, research and development (R&D) infrastructure and R&D funding, efficient extension or advisory services that link labs to farms, policies, laws, and regulations for development and application of biotechnologies in the sector, among others). Consequently, all products of biotechnology are regulated and undergo risk assessment. For example, seeds developed through selective breeding are managed through phytosanitary regulations as well as seed varieties legislations. Risk assessment is a process used every day when choices and decisions have to be made, and is the most critical component of biosafety implementation. Although risk assessment is necessary for all biotechnologies applied in agriculture, health, and environmental work, the attention appears concentrated on genetic engineering and its products (GMO). The risk assessment process used for GMOs closely resembles the assessments made for environmental impact. Before a GM crop is released to the market, regulators worldwide require these products to undergo rigorous risk assessments to ensure an adequate level of safety to humans, animals, and environment. As such, all GMO products available in the market today have undergone a risk assessment. Products of genetic engineering (GMO) are managed through a more stringent regulatory system, often referred to as National Biosafety Frameworks (NBFs). As such, biotechnology policies for most countries are all about GMO and similar products developed through "modern biotechnology"—a term used to refer to more advanced biotechnologies that include tissue culture, molecular marker technology, and genetic engineering, which generally require laboratories and significant level of skills to perform.

2.1 Global management of biotechnology

One of the decisions of the United Nations Conference on Environment and Development (UNCED) in 1992 was the adoption of the Convention on Biological Diversity (CBD), to regulate biotechnology (Articles 8 (g) and 19). In response to Article 19 (3), a decision was made during the Conference of Parties (COP5) in 1995 to develop a protocol on biosafety. The Cartagena Protocol on Biosafety (CPB) was a direct international legal response to the CBD contributing toward the conservation and sustainable use of biological resources. The entry into force of the protocol (2003) obligated signatories to the protocol to localize it within their national laws. Current intergovernmental mechanisms governing the application of modern biotechnology in which African countries actively participate include: (1) The *Codex Alimentarius* Commission, (2) Cartagena Protocol on Biosafety (CPB) to the Convention on Biological Diversity (CBD), and (3) Plant Protection Convention (IPPC). Signatories to the CPB obligated themselves to localize the protocol within their national laws. So far, nearly all SSA countries have ratified or complied with accession requirements of the CBD, except for Equatorial Guinea, Liberia, Sierra Leone, and South Sudan.

Within regional trading blocks of SSA, frameworks of action for biotechnology require a collective understanding among member states, and a regional framework on biosafety. Many regions have made attempts to foster a united framework, but none of these have progressed beyond mere intentions. For example, the East African Cooperation (EAC) Protocol on Environment and Natural Resources (2006) urges partner states to "develop and adopt common policies, laws and take measures to ensure that the development, handling, transport, use, transfer and release of any living modified organisms are undertaken in a manner that prevents or reduces the risks to environment, natural resources and human health" (C 3, A 27(1)). However, implementing such a recommendation would first require a regional discussion to enable member states to understand current issues, trends, challenges, and opportunities for agricultural biotechnology, and to have a collective understanding that will catalyze common policies and biosafety regulations, in line with the goals of regional integration, and to eliminate some of the non-tariff trade barriers associated with transboundary movements of GMOs. At the national level, the National Biosafety Frameworks (NBFs) provide the overall policy, legal and institutional mechanisms for development, deployment and use of biotechnology.

2.2 National biosafety framework

A National Biosafety Framework (NBF) is a combination of legal, administrative, and technical instruments put in place to build a country's competence to handle biotechnology research, development, and commercialization. Specific components of these instruments are the national biosafety policies, statutes passed by parliament and specific regulations linked to the statutes, administrative and technical systems for risk assessment, public awareness and participation, decision-making, enforcement and monitoring. An NBF is also a tool to be used in the implementation of the CBP. These frameworks often focus on GMOs, and have been generally driven by the crop sector, although they are meant to cover broad biotechnology research and applications. Although varying from country to country, NBFs usually contain a number of common elements, such as policy on biosafety, regulatory regime for biosafety, a system to handle notifications or requests for authorizations for certain activities, field releases of GMOs into the environment, among others. All these involve public participation and risk assessment, a mechanism for monitoring and inspections, and a system for public awareness and public information.

The next section appraises the state of enabling policy environment within the SSA in the broad sense, examining specific indicators such as: evidence that a country has an agency that promotes the application of biotechnologies, support for biotechnology development through research funding, support to adoption through extension services, existence of policies, laws and regulations, and specific agency that regulates the use of biotechnology—how efficiently these systems function.

3. State of biotechnology policy environment in SSA

As stated earlier, application of biotechnology requires systems that ensure there is adequate capacity to develop and apply the technologies safely; promote research, extension, and wider adoption; and regulate the sector to assure sustainable use of resources, environmental and human safety. These components together include the national biosafety policies, statutes passed by parliament and specific regulations linked to the statutes, administrative and technical systems for risk assessment, public awareness and participation, decision-making, enforcement and monitoring. This section audits the policy environment by assessing indicators and evidence for promotion and support for biotechnology development through research funds, support to adoption through extension services, existence of policies, laws and regulations, and specific agency that regulates the use of biotechnology within each sector (crops, forestry, livestock, and aquaculture) and overall across sectors. Scores—ranging from very low or very weak to very high or very strong—are assigned to each country based on information (qualitative and quantitative) gathered from various sources, which then forms the basis of the classification.

3.1 Policy and biosafety frameworks

Countries in SSA are at different levels of development and implementation of NBFs. The levels and extents of development of the frameworks largely depend on their adherence to, and domestication of, key international agreements, the political good will as well as human and financial capacities. SSA countries started putting in place biosafety legislation in the 1990s; today, only 18 countries have biosafety

Country	Biosafety framework *(policy, law, regulations, guidelines, and institutions)*	GE crops
Burkina Faso	Has NBF; Act 2006 (revised 2013); Biosafety Decree 2004; Biosafety Law 2011; Policy on Biotech; National Biosafety Authority	Cowpea; CR of cotton suspended in 2016—discussions underway to restore with new variety
Cameroon	Has NBF; Biosafety Act 2003 (revised 2007); Biosafety guidelines 1995	Cotton; no ER of any product
Egypt	Legislation under review; robust R&D; past commercial release	Wheat, potato; CR of maize suspended due to regulatory changes in 2012, with all GM
Ethiopia	Has framework and R&D; product approved for commercial release	Enset, maize, cotton; CR of cotton approved in June 2018; maize, enset in CFTs
Ghana	Act 2011 (Enacted into law 2012); Regulatory Communication Strategy 2014; Regulatory framework yet to be finalized; Policy on Biotech; NBC	Cotton, cowpea, rice; but no ER
Kenya	Has NBF; National Biotechnology Policy 2006; Biosafety Act 2009; 4 biosafety Regulation 2011, 2012; National Biosafety Authority	Cotton, maize, cassava, banana, sweet potato, gypsophila flower, sorghum; NPT for cotton underway, for maize pending; Import ban on GM since 2012
Lesotho	Has some elements of NBF; National Biosafety bill 2005; amended 2014; National biosafety policy; National biosafety awareness strategy 2013; National Biosafety Council; no research	—
Malawi	Has NBF; Act 2002; Biosafety guidelines 1995; Biosafety regulatory framework 2007; National Biotech policy 2008; draft legislation	Banana, cowpea, cotton; NPT for cotton advanced; no ER
Mali	Has NBF; Biosafety law 2008; Biosafety decree 2010; National Biosafety Committee; GMO research prohibited	—
Mauritius	Has elements of NBF; GMO Act 2004; Plant Protection Bill 2006; Ministry of Agro Industry and Food Security	Sugarcane
Mozambique	Has NBF; Biosafety law 2007 (revised 2012); draft biosafety regulations; GIIBS; NBC	Maize, cotton; no ER; *Bt* maize ready for ER; Bt/DT stack in CFT
Namibia	Has elements of NBF; Biotechnology and biosafety policy 1999; Biosafety Act 2006; Draft legislation; Biosafety Council of the NCRST; no research	—
Nigeria	Has NBF; Biosafety bill 2011 (bill still in Senate); Biosafety guidelines 2001; National Biosafety Management Agency (NBMA)	Cotton, cassava, cowpea, sorghum, soybean; CR of cotton approved in July 2018
Republic of South Africa	Has robust NBF; GMO Act 1997; Biosafety guidelines; National Biotechnology Policy and Strategy 2001; Directorate of Biosafety	Maize, soybean, cotton, wheat, potato, sugarcane; CR for cotton in 1997, maize in 1998, and soybean in 2001
Sudan	Has NBF; Law of Biosafety 2010; National Biosafety framework 2008; Sudan National Biosafety Council	Cotton; CR of cotton approved in 2012
Swaziland	Has elements of NBF; Biosafety Act 2012; legislation under review	Cotton; CR of cotton approved in May 2018

Country	Biosafety framework *(policy, law, regulations, guidelines, and institutions)*	GE crops
Tanzania	Has NBF; Biotech policy 2010; Environment Management Act 2004; Biosafety regulation 2009; National Biosafety Committee; strict liability regulations revised in 2015 to allow CFTs; strict liability remains if product is commercialized	Maize; no ER
Uganda	Has NBF; National biosafety bill 2012, (Passed 2017; referred back to Parliament); Biosafety guidelines 1995; Draft Biotech and Biosafety Policy 2013; National Biotechnology Policy 2008; Uganda NCST; National Biosafety Committee	Banana, maize, cassava, rice, cotton, potato, soybean; no ER
Zambia	Has elements of NBF; Biosafety Act 2007 (revised 2013); National Biosafety Policy 2013; National Biosafety Authority 2013; no research allowed	—
Zimbabwe	Has elements of NBF; National Biotech Authority Act 2000; Biosafety guidelines 1998; National Biotechnology Authority; no research allowed; cultivation and imports of GMO banned	—

GE, genetically engineered; ER, environmental release; CR, commercial release; NPT, national performance trial; CFT, confined field trial

Table 1.
Status of policy environment for biotechnology in some notable SSA countries.

legislation in place (**Table 1**). The majority of these (9) were passed in the period 2006–2010. The extent to which biotechnology has contributed to agricultural productivity in various countries is closely linked with, and has been dictated by, the policy/political landscape and the nature of legislation enacted to govern the technology. The lack of biosafety legislation, biotechnology policies, and absence of biosafety procedures in several countries continues to be a major gap and a significant impediment and discouragement to research institutions that are willing to undertake high-end biotech R&D. This is because the institutions are not able to obtain approvals from regulatory authorities, or because processes for application are opaque and tedious, and generally the institutional landscape does not encourage R&D with significant biotech content.

In terms of ranking for policy environment for development, application, and adoption of biotechnology across sectors, Republic of South Africa is comparatively very strong in all sectors except fisheries and aquaculture. Five (5) other countries (Ethiopia, Ghana, Kenya, Nigeria, and Sudan) are "strong" across sectors in enabling environment for application of agricultural biotechnologies. Eight (8) are medium, while the rest are either weak (8) or very weak (22), as summarized in **Table 2**. In comparison, more than half of the countries in SSA have a weak enabling environment in all the sectors. When looked at in terms of two categories, as either weak or strong, three-quarters (75%) of the countries cluster in the weak category, with only 10 countries appearing as above average or strong. This category comprises Botswana, Ghana, Kenya, Malawi, Namibia, Nigeria, South Africa, Tanzania, Uganda, and Zimbabwe. Three countries (Ethiopia, Sudan, and Zambia) cannot confidently be assigned to either of these two groupings because they classify with a wide variation across sectors.

Enabling environment	Countries
Very weak	Angola, Benin, Burundi, Chad, CAR, Congo, Djibouti, DRC, Eritrea, Gambia, Equatorial Guinea, Gabon, Guinea, Guinea Bissau, Lesotho, Liberia, Niger, Togo, Sierra Leone, Somalia, South Sudan, Swaziland
Weak	Burkina Faso, Cameroon, Cote d'Ivoire, Madagascar, Mauritius, Mozambique, Rwanda, Senegal
Medium	Botswana, Malawi, Mali, Namibia, Tanzania, Uganda, Zambia, Zimbabwe
Strong	Ethiopia, Ghana, Kenya, Nigeria, Sudan
Very strong	Republic of South Africa

Table 2.
Classification of countries on basis of enabling policy environment for biotechnology.

3.2 Public and private investments

While the formulation of policy and establishment of biosafety frameworks are principally a function of the political will of the country, and not necessarily resource-endowment, a major aspect of the enabling environment that seems to challenge the majority of SSA countries is "resourcing" of biotechnology programs. This includes investments in capital items (labs, equipment, etc.), human resources, and operations. Although precise value of agricultural biotechnology spending is difficult to obtain, estimates (focusing only on crops and livestock) obtained from IFPRI's Agricultural Science and Technology Indicators (ASTI) database (www.asti.cgiar.org) show that SSA countries invest very limited amounts on agricultural R&D generally, and agricultural biotechnology in particular. Staffing levels (FTEs) from ASTI data indicate low levels of staffing in the majority of countries. Although FTEs (which is only one of the aspects of investment) cannot be used to fairly interpret the level of public or private sector investment (because a section of the experts may have been trained outside their countries, either through incoming scholarships or self-sponsored programs), the low numbers point to a low level of public investment. The total agricultural research for development (ARD) spending takes a similar pattern to policy frameworks, that is, South Africa, Kenya, and Nigeria are consistently among the top in terms of ARD spending. As expected, private investments in ARD in SSA are mainly directed toward high-value crops and non-traditional products such as cut flowers. A recent development is the proliferation of private agribusiness investment funds targeting African agriculture. In addition, although progress is slow since Maputo Declaration (in 2003), the position as at 2015 (lead up to Malabo Declaration) indicated that some countries have taken steps to honor their commitments to increasing investments in agriculture and a number of countries have taken a proactive role in attracting private sector agribusiness investments by offering various incentives such as tax holidays within the first few years of an agribusiness establishment
(e.g., Nigeria) and zero duty on agricultural machinery (e.g., Ghana, Nigeria).

Other than Republic of South Africa, the other top countries in total ARD and biotech spending are Nigeria (96.4 million USD total ARD spending), Kenya (50.8 m), Ghana (42.9 m), and Uganda (25.2 m). The figures show that even these leading countries spend only modest amounts on biotech (**Figure 2**). Among the other countries spending more than 10 million USD on crop and livestock biotech are Burkina Faso, Cote d'Ivoire, Ethiopia, and Zimbabwe, with the rest of the countries spending less than 10 million USD (**Figure 1**). Although many countries signed the Maputo Declaration, committing at least 10% of agricultural

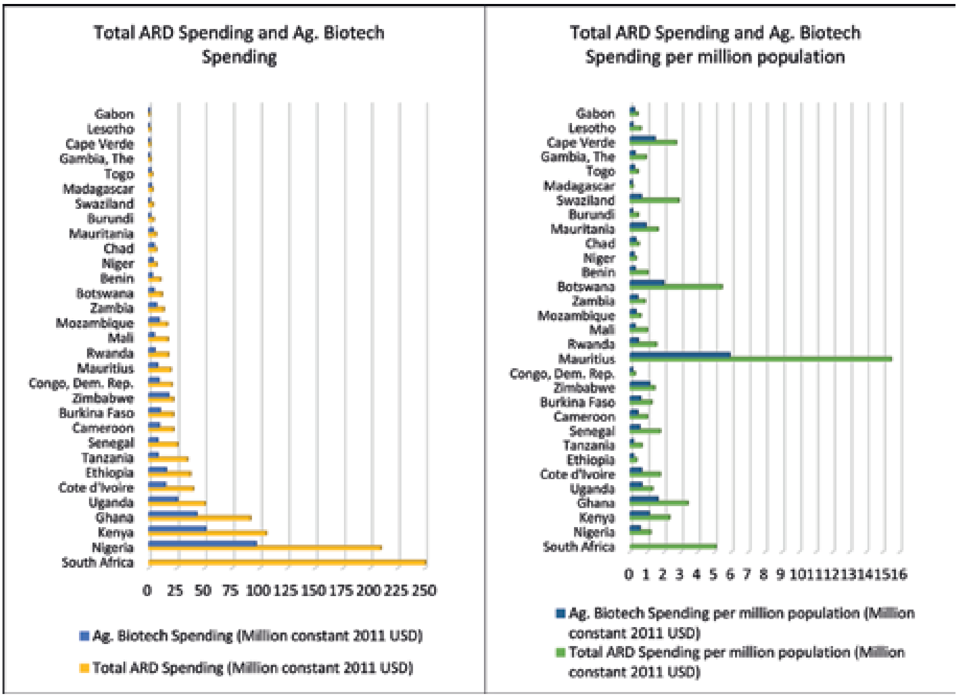

Figure 2.
Total ARD versus biotech spending (in USD) in SSA—absolute, and per million inhabitants (Data obtained from ASTI, 2014) *Comparable biotech spending data for Republic of South Africa was unavailable.*

GDP to R&D, rough estimates suggest that the gross expenditure on R&D for SSA is less than 0.3%. In most of the countries, government contribution to National Agricultural Research Institutes (NARIs) is inadequate, irregular, and often late [6] whereas international donors provide 75% of NARI's budgets. Overall, an estimated 40% of SSA countries spend less than 5 million USD on crop and livestock biotech a year. It appears that the level of spending on agricultural biotechnology largely corresponds to country classifications (**Figure 2**; **Table 2**)—where top 10 spenders are also the countries predominantly classified in the "Strong" and vice versa even though other indices for enabling environment were also used in the classification.

3.3 Collaboration and networking

African countries' entry into biotechnology has been stimulated by many interrelated factors, particularly the cumulative nature of the advancement in biotechnology. In addition, the pace at which SSA biotechnological advancement has benefited from regional and subregional organizations and networks credited with the development of ARD *capacity* in SSA have also contributed in significant ways to many aspects of *enabling environment*. These include the biotechnology support programs and initiatives driven by the Consultative Group on International Agricultural Research (CGIAR) whose centers have, for over three decades, worked collaboratively with many SSA countries on biotechnology research and application in different sectors [7]—with the countries hosting the centers accounting for a relatively larger share of this. In the livestock sector, the International Livestock Research Institute (ILRI) working in partnership with national and other international partners has made strides in developing genetically engineered vaccines while in forestry, the World Agroforestry Centre (ICRAF) has provided support in capacity development as well as research and application of low to medium level forestry biotechnology. It is perhaps in the crops sector that the CGIAR centers have made the greatest contribution, with several centers including ICRISAT, CIMMYT, the International Potato Centre (CIP), and IITA contributing substantially in the research and application of medium- to high-level biotechnology for maize, potato, cassava, and sorghum, among other crops. Further, African regional research organizations such as AGRA and AATF, among others, have played a part in research and development as well as application of biotechnology especially in the crop sector [7].

There is a close relationship among existing capacities, level of application, and enabling policy environment for biotechnology. Higher capacities correspond with higher levels of application and enabling policy environment. A relationship cycle can explain this observation—a stronger enabling policy environment promotes higher capacity and hence enables technology development and application. On the other hand, a country cannot regulate "nothing"—a robust biotechnology research and application would require and hence catalyze the development of regulation, policy, and laws, for example. Policies and legislations on biotechnology in a country with no research on, or application of, biotechnology is meaningless unless it is part of a plan. However, overall, having a critical mass of requisite human capacity is the critical starting point.

3.4 Public awareness and political support

Political support for anything, including biotechnology application, is difficult to gauge, and has to be inferred, for example, from specific deliberate actions. Based on such inferences, therefore, political support for biotechnology application in SSA is varied across countries. The presence of a policy and law on biotechnology and biosafety can be interpreted as evidence of political support, except cases where these laws are enacted to prohibit the use of biotechnology. Due to controversy surrounding GMO in agriculture across SSA, there is more public scrutiny of the application of this technology. This can explain why the media is awash with articles and stories demonstrating, on the one hand, the usefulness of biotechnology to farmers, and on the other, skepticisms and outright opposition, specifically to GMO [3]. Unfortunately, the perceptions and misrepresentations on GMO are often extended to any conversation about agricultural biotechnology as a whole. With the exception of South Africa, there are no calibrated national surveys assessing the public understanding, perception, and acceptance of biotechnology in Africa. The Agricultural Biotechnology Programme of the University of Nairobi has data from an opinion survey on awareness and willingness to use genetically engineered products, and another on actual use of these products in the manufacturing sector. The survey showed more than 90% of raw materials for millers and manufacturers in Kenya to be sourced both from East Africa and countries such as Southern Africa, USA, Europe, and others known to predominantly grow genetically engineered crops such as corn. The South African study [8] reveals a very high level of ignorance about biotechnology among the general population, and favorable support for biotechnology among the informed respondents. Thus, public awareness remains a gap even in countries that rank high in the policy environment for agricultural biotechnology. Thus, despite the perception that the public is aware about biotechnology and what it can do or not do, much of the paranoia can be attributed to lack of understanding, political and business contests.

As explained earlier, development and adoption of agricultural biotechnology require both regulatory and promotional systems. Political will and support can drive agricultural biotechnology even in the absence of NBFs. One of the latest examples where strong political support has been demonstrated is Uganda. In Uganda, a Biotechnology and Biosafety Bill, which has been awaiting enactment since 2012, was passed in Parliament in October 2017 but referred back by the President for some amendments. It was passed again in 2018, but this time with strict liability clauses that will definitely retard biotechnology development in the country. However, the country has a presidential order allowing GMO R&D, awaiting enactment of a biosafety law. Somalia (which has had frequent civil strife since 1991) has also shown a strong political will—as seen in many laws in draft stage but is operational (such as the Veterinary Code—Law No. 34/2006 & 2008 implemented in draft form since 1997). Perhaps the presence of fewer experts (many have fled the country) and a less secure environment for foreign experts to operate have contributed to the slower pace of policy development to support agricultural biotechnology. It is obvious that if a technology is not being applied, then enactment of laws is never urgent. In the neighboring Djibouti, there are some laws and regulations, including those aimed at positioning her for adoption of modern biotechnologies including genetic engineering. However, there lacks specific roadmaps for achieving some of the goals envisioned in the legislation.

The Water Efficient Maize for Africa (WEMA) *Bt* maize adoption in Kenya provides a context to understand the complex political environments that can impede biotech adoption. Kenya is one of the countries with many genetically engineered products at various stages of development: Insect-protected *Bt* maize and *Bt* cotton have both undergone confined field trials (CFTs), and are awaiting the last stages before commercialization—National Performance Trials (NPTs). To prepare the ground for agricultural technology uptake, the government of Kenya put in place legal, structural, and other regulatory frameworks including human capacity to manage GMOs by 2009. This heavy investment in legal, human, and infrastructural capacity for GM research was expected to improve capacity to develop and manage processes for detecting, testing, and assessing the safety of GM foods and products. Four regulations that implement the Biosafety Act have been gazetted (2011–2013) to ensure compliance with all activities undertaken within a field, introduction into the environment, labeling, and import, export, and transit of GMOs. Despite this preparedness, the adoption of GM crops and products has been hampered by political and regulatory bottlenecks that have delayed farm deployment and entry into market systems. In disregard of the provisions of the act and implementing regulations, together with existing infrastructure to manage GMO, the country imposed a ban on GMO in 2012. This ban has undermined efforts to even conduct NPT, a pathway to commercialization of *Bt* maize.

Apart from its effect on high-tech biotechnologies (genetic engineering—GMO), lack of political support can hamper even low-end biotechnologies such as biopesticides. For example, synthetic chemical pesticide (lindane) was first introduced in Nigeria in the early 1950s. Adverse effects resulting from excessive utilization of synthetic chemicals have become widely reported (e.g. [9]). Several studies have identified plant-based sources of pesticide in Nigeria, including *Cannabis sativa*, *Eucalyptus globules*, *Balanites aegyptiaca*, *Khaya senegalensis, Nicotiana tabacum* [10] and neem leaf water extract, and aqueous tobacco extract [11], and demonstrated that tissues from these plants contain bioactive pesticide agents. The broad anthology of living and non-living entities present in biopesticides vary considerably in their properties, mode of action, fate, composition, and behavior within their surroundings. As a result, the government needs to set strict health, safety, and environmental monitoring regulations before granting approval for the production and handling of biopesticides. However, the lack of governmental interest, support, and advocacy, and clear policies on biopesticide development, regulation, and implementation in Nigeria has hampered progress, investments, development, and accessibility to biopesticides, and has deterred farmers from patronizing biopesticides [12].

4. Gaps and opportunities for biotechnology advancement

This section examines areas or issues constituting either challenges which if addressed, or opportunities which if harnessed, will enhance research and commercial applications of agricultural biotechnologies in SSA. Besides selective breeding as well as germplasm characterization based on phenotypes, tissue culture in crops, clonal propagation in trees, sex reversal in aquaculture, and artificial insemination (AI) in livestock, use of modern advanced technologies remains limited in SSA, mostly confined to research projects. However, use of molecular and genomic technologies, while still low, is increasing rapidly especially in research. A major constraint to the application of most of these technologies in SSA relates to capacities (human resources and facilities) and several dimensions of enabling environment—especially political will, low public awareness, and associated effect on acceptance, lack of financial investments, and limited organizational capacities. Five key gaps can be identified for SSA, corresponding to opportunity areas for action: (1) policies and biosafety frameworks, (2) awareness and public participation, (3) utilization of research products and public-private partnerships (PPPs), (4) human capacity and research infrastructure, and (5) financial resources for R&D.

4.1 Biotechnology policies and biosafety frameworks

There is a close relationship between the extents to which biotechnology is being deployed in countries and the policy and political environment for biotechnology. As stated earlier, the relationship among application, capacity, and enabling environment is complex, each somehow acting as driver for the others—with mutually re-enforcing effects. Specifically, countries that are consistently ranked high in applications of biotechnology have also made progress in developing biotech-specific biosafety policies. For high-tech technologies such as genetic modification, the lack of biosafety legislation, policies, and biosafety procedures in several countries continues to be a significant impediment and discouragement to institutions, including private sector institutions that are willing to undertake high-end biotech R&D because processes for application are opaque and tedious, and generally the institutional landscape does not encourage R&D with significant biotech content. Tanzania, for example, has shown a strong political will to promote agricultural biotechnology, as evidenced by the National Biotechnology Development Policy, Biosafety Regulations 2009, Environmental Management Act, and other policies and laws. However, the country's legal framework is prohibitive. Strict liability and redress provisions in the law and regulations are currently a hindrance to advancing biotechnology research and development in the country. Djibouti has some laws and regulations, including those aimed at positioning her for adoption of modern biotechnologies including genetic engineering. However, there lacks specific roadmaps for achieving some of the goals envisioned in the legislation. Djibouti should focus on creating a favorable policy environment to attract private sector working on agricultural biotechnology. Mozambique, on the other hand, has enacted several laws, a large majority of which are focused on protecting natural resources. A few plans have been prepared, such as the National Agriculture Investment Plan 2014–2018. However, these lack clear roadmaps and time-bound actions. While Madagascar has clearly paid attention to policy and legislation side, other enablers that can enhance research and applications are still relatively absent.

4.2 Public awareness and participation

There are major gaps in public awareness and understanding of the science, and the potential promise and usefulness of biotechnology in African agriculture. There are also knowledge gaps, with misinformation on risks and perceptions of risks remaining one of the key factors that have hindered the adoption of biotechnology in Africa. Consequently, there are misconceptions and lack of knowledge about biotechnology in general, and about GMOs in agriculture in particular. Although there have been successes in public awareness creation, there are still gaps in policy support, political commitment, and acceptance of genetic engineering technologies, and this continues to hinder the adoption of certain biotechnologies in agriculture.

4.3 Utilization of research products and public-private partnerships

The process by which biotech research translates to (commercial) applications in the field requires early engagement of industry (private sector players). On the other hand, agricultural biotech research in almost all SSA countries is still primarily driven by NARI and university scientists who either have limited knowledge on or drive to commercialize research products. Indeed, the incentive of the majority scientists seems to be more about the science and the academic products of science (in form of publications and patents). There is limited or no incentive to invest efforts in commercialization, and the research funding mechanisms do not normally include the commercialization phase and modalities for it. At the same time public extension services are generally weak. Although public-private partnerships (PPPs) have been recognized as one of the ways to drive the conversion of biotech research into practical use, and despite the fact that there are a number of PPPs operating in some countries, there remain major gaps in operationalizing the concept and developing functional partnerships at scale. Simple PPP models have been used in delivery of animal health and AI services in some countries—for example, where semen and vaccine production is done by public sector and field delivery done by private sector, including farmers' organizations and cooperatives. Where new technologies and innovations are involved, a major gap in PPPs is the issue of proprietary rights, especially patents, intellectual property rights, and sharing of benefits accruing from joint biotechnology research and development activities.

4.4 Human capacity and research infrastructure

In most SSA countries, there is a clear lack of a critical mass of scientists in areas relevant for agricultural biotechnology. Even countries that rank as relatively "high" in capacities do not necessarily have critical mass in the more "advanced" areas of modern biotechnology such as genomics, and genetic engineering, for example. The majority of SSA national agricultural research systems (NARS) have research programs that are often limited in scope and dependent on a handful of scientists. Due also to the financial and infrastructural constraints, many such programs often have limited national capacities to implement initiatives beyond pilot scales. This calls for innovative ways of forming critical mass of research teams across sectors—working around issues that allow sharing of staff (and facilities). The acquisition and maintenance of the expensive infrastructure needed for high-tech applications remain a challenge for most countries. Facilities in several countries (the low-capacity countries) are too basic to support modern biotech research. In other cases, equipment acquired through projects only function during the life of these projects and thereafter cannot be maintained—due to budget constraints. The lack of engineers and technicians trained to service these fast-evolving and sophisticated equipments presents another challenge, as do inadequate power supplies and frequent power outages, which also affect reliable cold chains—such as for AI and vaccine field delivery. These challenges have informed the establishment of regional shared biotechnology platforms such as the BecA-ILRI Hub; the concept of shared facilities is, in the short- to medium term, seen as a means of gradually supporting the strengthening of capacities in the biotechnology fields in SSA. In SSA, the four agricultural sectors—crops, forestry, livestock, and fisheries/aquaculture—are not necessarily under the same ministry. Indeed, in some countries all of these sectors are in different government ministries—although finding livestock and crops under the same ministry is increasingly more common. The administrative separation of these sectors, combined with poor cross-sectoral coordination is inimical to efficiency in the development of technologies. It limits consolidation and exploitation of synergies across sectors owing to bureaucratic procedure required to share physical and human resources—such as labs and personnel. For most countries, sharing of these resources across ministries is just not practiced at all. Even mobilization of resources is done separately by sector, and the amounts allocated to the "hosting ministry" do not always reflect the needs. The countries also need to establish and/or strengthen biotechnology R&D multisectoral networks at national levels and explore mechanisms for linking these to subregional and continental initiatives in order to leverage resources, create synergies, and avoid duplication (hence, enhance efficiency), facilitate learning, horizontal and transboundary transfer of technologies, and upscale best practices and technologies.

4.5 Financial resources for R&D

The main challenge for public agricultural biotechnology R&D in SSA remains how to mobilize investment capital (beyond what is needed for personnel and infrastructure) to initiate or sustain research (and facilitate the process of taking findings to commercial use). Although there has been some growth in the level of funding to ARD in some countries, the level of financing is still extremely low, especially for biotechnology, and not allowing countries to engage effectively in cutting-edge biotech research. Most of the current biotechnology R&D programs are donor funded—with very limited domestic investments; in most countries the allocation is only for salaries (for the limited number of biotech personnel). Although precise value of agricultural biotechnology spending is difficult to obtain, estimates made on the basis of 2014 sector figures (focusing only on crops and livestock) obtained from ASTI database show that most countries invest very limited amounts on agricultural biotechnology. Mobilization of resources (from domestic and other sources) for agricultural biotech is clearly a major area that governments need to look at. In the meantime, given the high cost of biotech R&D, available investments need to be used in a much more coordinated manner to achieve efficiencies from scale and complementarity—and hence the need for cross-sector coordination in biotech R&D. Despite the clear dominance of the public sector both in the financing and implementation of agricultural research, the unstable funding of ARD to date suggests that other avenues should be explored. Universities in SSA, for example, are an underutilized resource that could greatly increase research output with just slight increases in targeted funding to them.

5. Conclusions

Application of biotechnology in agriculture has increased in recent years due to unrelenting effect of climate change exacerbated by a rapidly growing population. Countries that have adopted biotechnology in their agricultural systems, for example, have significantly improved yields and other farm-level benefits. Safety of biotechnology and particularly products of genetic engineering is assured through rigorous safety assessments conducted within national and international biosafety frameworks. However, lack of awareness on these processes has slowed the adoption of GMO in some countries, especially those with a weak policy environment for biotechnology. It appeared that the enabling policy and regulatory environment is, in early phases, principally driven and shaped by the demand (applications)—and not just the existence of capacity. That is, it starts and evolves at a pace that reflects the level of vibrancy on the "applications." In other words, governments could develop the required frameworks but they will serve very little purpose and will not "evolve" if they are not being subjected to real tests through active applications. Although it is envisaged that existence of biosafety framework would catalyze biotech adoption, the Kenya *Bt* maize situation and similar examples have shown that legal frameworks alone are insufficient to guarantee an enabling policy environment for investment in remunerative agriculture through biotech crops. Countries in SSA adopting biotechnology may require a comprehensive approach that includes anchoring biosafety laws in their constitutions and a strong political will to drive the agenda. Other focus areas are summarized under Section 4. It is emphasized that countries have to deliberately promote public understanding and awareness on modern biotechnology, vigorously improve resourcing for biotechnology development and adoption, including greater private sector engagement, and improve the available research infrastructure and human resources.

Acknowledgements

Values of agricultural biotechnology spending in SSA countries were obtained from IFPRI's Agricultural Science and Technology Indicators (ASTI) database (www.asti.cgiar.org) and were analyzed with the assistance of staff at PICO Eastern Africa.

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Edited by Krzysztof Biernat

This book is a review of the basic problems associated with the implementation of bioeconomic processes. The book contains chapters developed by teams from different countries of the world and therefore the chapters correspond to the degree of advancement of the areas within the bioeconomy in these countries. In selected areas, basic concepts and selected technological processes that create this area of the economy to ensure sustainable development have been characterized.

Published in London, UK

IntechOpen

ISBN 978-1-83962-355-4