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Seiko Jose, Sabu Thomas, Lata Samant, and
Sneha Sabu Mathew

Plant Biomass Derived Materials

Sources, Extractions, and Applications

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Editors

Dr. Seiko Jose
ICAR-Central Sheep & Wool
Research Inst.
Malpura (Tehsil)
Tonk (Dist) Via-Jaipur
Rajasthan
India, 304501

Prof. Dr. Sabu Thomas
Mahatma Gandhi University
Priyadarhsini Hills P.O.
Kottayam, Kerala
India, 686 560

Dr. Lata Samant
Govind Ballabh Pant University
Udham Singh Nagar, Uttarakhand
Pantnagar
India, 263145

Sneha Sabu Mathew
Mahatma Gandhi University
Priyadarhsini Hills P.O.
Kottayam, Kerala
India, 686 560

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Preface

The ceaseless surge in the global population has exerted unprecedented pressure on agricultural systems, consequently resulting in a substantial boom in the generation of agricultural residues. As the population continues to grow, the demand for food, feed, and fiber increases, requiring intensified agricultural production. This intensification often involves practices such as increased cultivation, higher yields, and the use of chemical inputs, which can result in larger quantities of agricultural residues being generated. Agricultural residues encompass various organic materials left over after crop harvesting or processing. To meet the escalating food demand, modern agricultural practices tend to focus on high-yielding varieties and mechanized farming, which in turn contributes to increased residue production. The accumulation of agricultural residues poses challenges for waste management and disposal. If not managed properly, these residues may lead to environmental problems such as air and water pollution and soil degradation. They also contribute to greenhouse gas emissions, as their decomposition can release methane, a potent greenhouse gas. However, it is essential to recognize that agricultural residues also hold significant potential and value. Instead of perceiving them solely as waste, they can be viewed as valuable resources that can be effectively utilized. To address the challenges associated with the substantial generation of agricultural residues, it is crucial to promote the efficient use, valorization, and recycling of agricultural residues.

Our book, *Plant Biomass Derived Materials: Sources, Extractions, and Applications*, is dedicated to exploring the remarkable potential and versatility of plant biomass as a renewable resource. In the initial chapters, readers are provided with a comprehensive overview of biomass, covering its chemistry, extraction methods, and applications. These chapters explore the extraction and synthesis of valuable compounds such as lignin, starch, bio-resin, and plant mucilage. Moving forward, the second section focuses on colorants obtained from plants, fungi, and algae, showing their unique properties and applications. The third part of the book presents a comprehensive exploration of composites developed from polymers and lignin derived from plant residues, offering valuable knowledge in this field. It further provides an extensive examination of the advanced applications of plant biomass in bioplastics, energy production, automotive and aerospace industries, food packaging, water purification, and beyond. In the final sections, the book addresses the vital aspects of recycling plant biomass, as well as the proper handling, storage, and preservation of these valuable resources. These considerations contribute to a holistic understanding of the subject matter and equip readers with practical insights.

This book provides a comprehensive understanding of plant biomass and showcases its immense potential in diverse industries. By highlighting emerging trends and recent advancements in the field, the book offers valuable insights into the future prospects of plant biomass-derived materials. We believe scholars, researchers, and academicians can leverage this book as a roadmap to explore new avenues of research, discover innovative applications, and contribute to the development of sustainable and eco-friendly technologies. The book serves as a platform for interdisciplinary collaborations, stimulating discussions, and knowledge exchange among experts from different fields. It empowers readers to envision a greener future by harnessing the power of plant biomass, making it an indispensable resource for anyone seeking to contribute to the advancement of sustainable materials and technologies.

Editors
Seiko Jose, Sabu Thomas, Lata Samant,
and Sneha Sabu Mathew

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Biomass – An Environmental Concern

Deepak S. Khobragade

Datta Meghe College of Pharmacy, Datta Meghe Institute of Higher Education and Research, Sawangi (M), Wardha, India

1.1 Introduction

Any biological organic matter derived from living or dead organisms can be called "biomass." Every type of biomass is directly or indirectly obtained from the photosynthesis process [1]. Thus, biomass is a natural material with an organic matrix obtained from plants and animals [2]. It encompasses various materials, like wood, agricultural and industrial remains, and animal and human waste. Due to its range, there are substantial differences in biomass composition, whether of industrial or domestic origin [3]. With this vast heterogeneity in the usage and origin of materials, the definition of "biomass" varies. There is a wide range of biomass materials that can be broadly grouped as raw or derived. Cellulose, hemicelluloses, lignin, starch, and proteins are some of the main elements of biomass [4–7]. Various biomass sources of diverse origins, like agricultural, forestry, industrial, and other sources, are presented in Table 1.1 and depicted in Figure 1.1.

Biomass is now primarily used for feed, followed by food, and finally for the production of energy, fuels, and chemical feedstock. It accounts for 13% of global final energy consumption (other renewables contribute another 5%). The industrial organic chemical sector produces 550 million tonnes of chemicals and 275 million tonnes of nitrogen fertilizer, but the chemicals contain only 500 million tonnes of carbon. Furthermore, organic compounds used in organic chemistry contain approximately 100 million tonnes of carbon [8]. Currently, sugar, starch, and vegetable oil are the primary sources of biofuels and biochemicals [9]. Consumers interest and the need for replacement of fossil fuels with renewable energy sources are driving up demand for bio-products. The price level of feedstocks, such as lignocellulose, sugars, starch, and oils, is another factor influencing the competitiveness of biochemical products [9]. Price comparisons of bio-based carbon to fossil-based carbon, as well as cost comparisons of processing bio-based materials with the corresponding fossil-based materials, are difficult to specify because they are dependent on raw materials and the molecular economy of the processes into the final products. The various advantages and disadvantages of biomass are depicted in Table 1.2.

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Table 1.1 Sources of biomass.

Woody biomass (WB)	Nonwoody biomass (NWB)	Animal biomass (AB)	Processed waste (PW)	Processed fuels (PF)
Shrubs	Energy crops	Animal waste	Sawmill wastes	Charcoal
Trees	Cereal straws	Animal residues	Plant oil cake	Briquette and densified biomass
Bushes	Plant fibers, leaves and roots	Animal remains	Fruit waste and nutshells	Biogas
Forest floor sweepings	Grasses	Decomposed animals	Flesh	Vegetable oil
Palms	Banana		Bagasse Producer gas	
Bamboo	Soft plant stems		Cereal husk	Methanol and ethanol
Forest residues	Water plants		Industrial wood, bark and logs	Industrial residues
	Agricultural residues		sewage and other municipal waste	

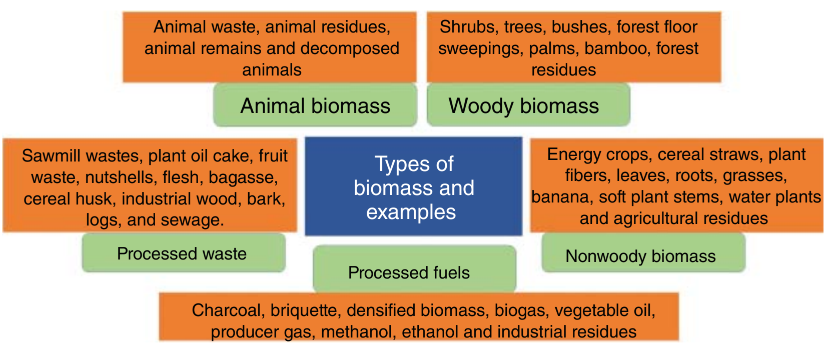


Figure 1.1 Types of biomass and examples.

Mineral oil is refined to produce fossil fuels and basic chemicals with very high carbon efficiency and low labor intensity. In contrast, biomass necessitates more processing steps, which increase the cost and labor requirements (see bioethanol production). Renewable energy sources such as solar, wind, hydro, and geothermal energy, as well as nuclear energy, are carbon-free in the energy industry. The transportation sector accounts for one-third of total final energy demand and 23% of global energy-related CO_2 emissions. Oil products meet approximately 96% of global transportation energy needs, with the remainder being met by electricity and biogas; thus increased use of renewables in the transportation sector is a high priority in the decarbonization of this sector.

The use of biofuels and other renewable energy sources, such as solar and wind, can help decarbonize the transportation sector [10]. The EU and the US have set limits on food-based biofuels. Although only 2% of global land is used for

Table 1.2 Advantages and limitations of biomass use.

Advantages	Limitations
Biomass is a renewable energy source	Biomass plants necessitate a large amount of space
It is available consistently and extensively	It could lead to deforestation
It is considered as carbon neutral.	It is not entirely clean
It helps to reduce our reliance on fossil fuels.	Biomass energy is inefficient compared to fossil fuels.
Is less costly than fossil fuels.	Biomass plants require a lot of space
It results in less garbage in landfills.	Huge requirement of resources like water
Biomass production generates revenue for manufacturers.	

Table 1.3 Biomass classification.

Type of biomass	Content	Utility	References
Wood and woody biomass	Logs, stems and branches Roots Foliage Bark Chips, pellets, and lumps Briquettes Sawdust	• Fuel in itself • Heat and electricity generation • Biogas generation • Fermentation for producing chemical products like alcohol and biodiesel • Manure as by-product	[3]
Herbaceous biomass	Grasses Straws Leaves Other residues like fruits, shells, and husks.		
Aquatic biomass	Algae Seaweed Lakeweed Kelp Water hyacinth, etc.		
Animal and human waste biomass	Excreta Dead and decaying animals Skin and bones, etc.		
Miscellaneous biomass	Food waste Food processing factory waste		

biofuel feedstock production, the "fuel versus food" debate shows that biomass used for industrial purposes is a sensitive issue in society. Some feedstocks (e.g. maize, oilseeds, sugarcane, and vegetable oil) have relatively high demand: biofuels consume 20% of global sugarcane, 12% of global vegetable oil, and 10% of global coarse grain production. Because biofuel accounts for a very small proportion of overall land use changes, crop competition may be reduced (as a percentage of total final energy consumption). Renewable energy sources play a critical role in the economy's "decarbonization," or the process of reducing the amount of greenhouse gas (GHG) emissions produced by the combustion of fossil fuels. These sources are called biomass only if they cannot be reused for subsequent processing [11]. The classification of biomass is presented in Table 1.3.

1.2 Biomass as an Energy Source

Factors that determine the usage of fuel are (i) cost, (ii) accessibility, (iii) stove type and technical features, (iv) cooking practices, (v) cultural preferences, and (vi) awareness about the potential health impacts [12]. Biomass is available on earth in many places, like agriculture, domestic farms, forests, and oceans. The total biomass reserves on land are estimated to be around 1.8 trillion tons, with an additional 4 billion tonnes in the ocean. Biomass is an enormously significant energy source, available everywhere, and bioenergy is the energy generated from biomass. About 33 000 EJ of energy can be produced by the total biomass present in the world. It is more than 80 times the total annual energy requirement of the world. Currently, biomass provides about 14% of the basic energy requirements of the world, i.e., 56.9 million exajoule per year globally (1230 million tonnes of oil equivalent per year) [8, 9]. About 159 billion liters of biofuel are produced each year globally from various biomass sources.

Solid biomass (wood, shrubs, herbs, wood chips, wood pellets, and other biomass sources) provides the majority of household biomass supply (85%). Biomass-based liquid biofuels contribute 8%, municipal and industrial waste contribute 5%, and biogas makes up a meager 2% of the total biomass supply. The utilization of biomass is not equal around the world. In some underdeveloped and developing countries, as much as 50% of the total energy needs are generated by wood combustion. In 2020, 1.93 billion m^3 of wood was produced globally as fuel. Africa and Asia had 36% and 37% of annual wood production, respectively. With 40.5 million tonnes produced globally, wood pellets are the most sought-after source. About 53.6 million metric tonnes of wood charcoal were produced in Africa, i.e. 65% of the total wood charcoal production globally.

In 2019, 2.59 EJ of energy was generated from municipal (56%, i.e. 1.45 EJ) and industrial waste (44%, i.e. 1.14 EJ). Globally, biomass was used to generate 655 terawatt-hours (TWh) of electricity. Of the total bioelectricity generated, 68% was from solid biomass sources, about 17% from municipal and industrial waste, and the remaining from other sources. Asia produced 39% (255 TWh), Europe produced 35% (230 TWh), and the rest of the world produced 35% (230 TWh). About 1.17 EJ of heat was produced from biomass-based sources in 2019. About 53% of the heat energy was produced from solid biomass sources, 25% from municipal solid waste, and the remainder from other biomass sources [10]. According to the 2018

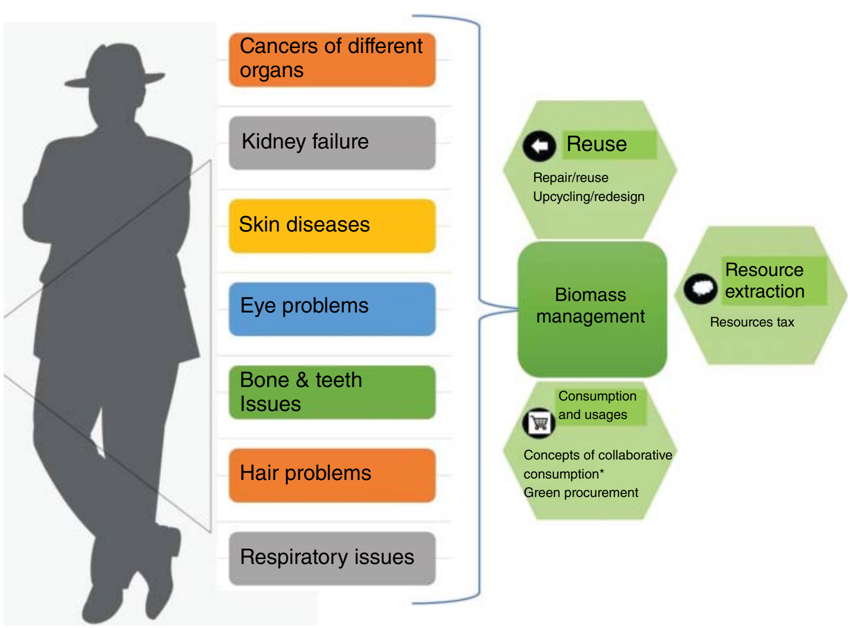
Table 1.4 Main conversion technologies and their corresponding products.

Process	Method	Biomass	Product	Concerns	References
Thermochemical conversion	Combustion	• Agricultural residues • Woody residues • Animal wastes	• Heat • Electricity	Air pollution by releasing gases such as CO_2, CO, nitrogen oxides, and volatile organic compounds	[3]
	Pyrolysis	• Agricultural residues • Woody residues	• Pyrolysis oil • Producer gas • Char	Pollution by synthetic gases and oils, ash, char, and heavy metals	
	Gasification	• Agricultural residues • Woody residues	• Producer gas • Liquid fuels • Char	Pollution by tars, heavy metals, halogens, and alkaline compounds	
	Liquefaction	• Agricultural residues • Algal biomass	• Fertilizer/biofuel • Syngas • Liquid fuels	Release of corrosive materials and salts	
Biochemical conversion	Anaerobic digestion	• Animal wastes • Sewage sludge	• Liquid fuels • Biogas • Electricity	Toxic and asphyxiant spills and gases. High COD liquids	
	Fermentation	• Agricultural residues • Sugars • Starch	• Liquid fuels (bioethanol)	Release of a high amount of CO_2	
Physicochemical conversion	Esterification/ Transesterification	• Vegetable oils • Animal fats • Waste oils	• Liquid fuels • Glycerol	Air water and soil pollution with the release of toxic chemicals	

World Biogas Association (WBA) report, biomass energy production in developed countries stands at 11% of the total energy produced [13]. In the USA, about 3% of energy demands (about 70 Mtoe yr^{-1}) are met by biomass. In Europe, 3.5% of its energy is derived from biomass (around 40 Mtoe yr^{-1}). European countries like Finland, Sweden, and Austria, with approximately 18%, 17%, and 13% of total energy generation from biomass, respectively, have a relatively high use of biomass energy in Europe [14]. Various methods of bioenergy generation and their concerns are presented in Table 1.4. [3, 15–17]

1.3 The Environmental Concern of Biomass

Burning fuels, fossils, or biomass releases carbon dioxide (CO_2). Apart from CO_2 emissions, burning any kind of biomass also emits other pollutants and particulate matter into the air, like CO, volatile organic compounds, and oxides of nitrogen. Sometimes, biomass can emit more pollutants than fossil fuels, and many of these pollutants cannot be sequestered by plants. Pollutants from biomass consumption can create environmental and human health problems if not properly controlled. During biomass processing, waste products like heavy metals, tar, alkaline compounds, and halogens are released, which cause environmental and health hazards. Because of the release of toxic exudates, gases, dust, and ash (both fly and bottom), biomass power generation has serious environmental consequences. It can also produce fire, explosions, high noise levels, odors, and other environmental hazards [18, 19]. Biomass, particularly biomass-based energy, is referred to as a carbon-neutral and nonpolluting energy source. This is not true; depending on the method of use and processing, biomass poses its own environmental risks. Although advanced processing can reduce emissions and subsequent pollution compared to fossil fuels, it cannot be considered environmentally safe [20–22]. Some of the environmental and health hazards of WB are discussed below.



1.4 Air Pollution

During the processing and burning of biomass, pollutants like gases, dust, biomass ash, fly ash, and char are released into the air, adversely affecting the environment by polluting the air and subsequently human health.

1.4.1 Gaseous Emissions

Gaseous emission is the main drawback of biomass utilization when used directly for energy, i.e. burning or processing to obtain a somewhat more efficient biofuel or energy source. Biomass utilization is one of the major sources of GHGemissions. The most common gases emitted are CO_2, NO_2, CO, and other nitric oxides. Though CO_2 is considered the main GHG responsible for global warming and other environmental problems, NO_2, which is produced during biomass generation, processing, and usage, is more harmful to the cause of global warming, i.e. 298 times that of CO_2. The point here is that relatively less NO_2 is released by fossil fuels as compared to biomass-based energy sources [23, 24]. It is reported that if we use NWB for processing, then relatively high levels of sulfur, chlorine, and ash are generated compared to processing WB [25]. It is well established that sulfur and chlorine have many hazardous effects on health and the environment. Sulfur as well as nitrogen are present in the majority of biomass, and their oxides (NO_x and SO_x) produced as by-products of processing have a huge negative impact on the environment [26].

1.4.2 Dust

Dust is generally generated during most of the stages of biomass production, handling, and processing [27]. The handling of dry and friable solid biomass is a major source of airborne particles. When viewed in isolation, biomass appears to be a minor source of dust particles that pollute the environment. But collective dust production by total biomass production, processing, and utilization is very high. Limits for particulate emission are (i) $0.60\,g\,kg^{-1}$ of air for rural areas or urban areas with a population of 50 000 and (ii) 0.20 g particulates kg^{-1} of air for urban areas with a population of 50 000 [28]. Common agricultural biomass produces approximately 8% (ranging from 6% to14%) of the world's dust [29]. Persons dealing with biomass, in general, are exposed to and inhale $>10\,mg\,m^{-3}$ of dust, which is much higher than the limits of $1.5\,mg\,m^{-3}$, said to be acceptable by environmental groups [30]. Inhalation of dust can cause lung damage, interstitial lung disease, COPD (chronic obstructive pulmonary disease), asthma, pneumonitis, cancer, and irritation of the skin and eyes [31]. The size range of 0.2–5 m of dust is considered the most dangerous, causing serious health problems for humans and other living organisms.

1.4.3 Biomass Ash (Bottom Ash)

Ash is the residue left after the combustion of biomass. Materials like ash pose great risks to our health and the environment. But most of the attention is paid to gaseous emissions and other pollutants. Ash content can reach up to 20% in mass for some biomasses. Deposition and uncontrolled release of ash can result in extensive pollution of water sources, air, and soil. The ash can contain toxic elements like arsenic, chromium, lead, barium, cadmium, nickel, and others. These elements have been linked to cancer, neurological disorders, and lung and heart diseases. When exposed in large quantities, they can cause serious health problems and even death. The problem with ash is that it is not classified as hazardous waste, so there are no guidelines for its safe disposal. Even though there are no standards for the leaching of chemicals from it into the environment, ashes are fouling and slagging [32].

1.4.4 Fly Ash

Apart from residue ash, biomass can generate fly ash. It is called fly ash because it is released from gases, especially during combustion. It is a fine powder consisting of noncombustible matter that remains after incomplete combustion. Fly ash comprises spherical and irregular particles with diameters less than 10 μm. The fly ash has a higher concentration of heavy metals and other harmful elemental contaminants than the bottom ash. Based on the variety and source of biomass, the composition of biomass varies. The fly ash not only contaminates the air by releasing hazardous pollutants but also gets deposited in or mixed with water bodies, making them unsafe for drinking. Compared to bottom ash, the potential for health hazards with fly ash is multiplied. [33–35]

1.4.5 Carbon Monoxide Poisoning

It has been known since long that the leading product of biomass burning is carbon monoxide (CO), a colorless and odorless gas. CO is the most common cause of gas poisoning and has very hazardous effects [36]. CO enters the bloodstream after inhalation and binds with hemoglobin to form carboxyhemoglobin (COHb). CO has a great affinity for hemoglobin, and as much as 80–90% of absorbed CO binds with hemoglobin, thus declining the oxygen-carrying capacity of the blood and causing severe hypoxia. Compared to oxygen, hemoglobin has 200–250 times more affinity for CO than for oxygen [37, 38].

1.5 Water Use and Water Pollution

The commercial production of biomass uses a huge quantity of water. [39] Biomass cultivation needs a continuous water supply, and irrigating biomass fields for commercial purposes uses groundwater and surface water. Evan plants, which generate energy from biomass, consume a great deal of water. For example, ethanol production facilities require approximately 3–4 gallons of water per liter. Another critical point is that these processes require pure water, which is pumped from a very deep source [40]. These all have a significant impact not only on surface water but also on groundwater levels. Thus, increased biomass production can produce drought-like