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Review

Residual Biomass: A Comprehensive Review on the Importance, Uses and Potential in a Circular Bioeconomy Approach

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Abstract: The paradigm shift towards sustainable growth is urgent, and biomass, which is the oldest energy source that humans have used since the discovery of fire, might play an important role. Biomass waste from forestry and agriculture is expected to fuel part of the increasing demand for biomass, and its valorization allows for more the efficient use of nutrients and resources. In this study, we carried out an extensive literature review on the valorization of residual agroforestry biomass since the 1970s to understand the leading research focuses on the subject over the last few decades, identify the most recent trends, and establish a possible solution path for the future of biomass. It was observed that most studies focused on biomass as being capable of replacing fossil energy sources. According to the literature, biomass has the most significant potential to meet requirements and ensure fuel supplies in the future. The developments of the last decades have significantly improved the conversion processes, leading to greener solutions, but there is still much to be studied and put into practice. Closing the loop into biomass waste recovery will be essential for a genuinely circular bioeconomy.

Keywords: biomass energy; biomass recovery; circular bioeconomy; sustainability

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1. Introduction

The increasing environmental challenges that humans are facing are propelling research and innovations towards a more sustainable future [1]. The continuous economic and energy consumption growth that was seen in the last few decades have a cost in terms of environmental pollution [2]. It is possible to see a rapid increase in greenhouse gas emissions. CO_2 emissions related to energy production increased from 32.3 billion metric tons in 2012 to 35.6 billion metric tons in 2020, and will reach 43.2 billion metric tons in 2040 [3]. The increasing concern of global warming raises the urgency for solutions in different fields, where the energy sector can be highlighted, focusing on the development of renewable sources, to control CO_2 emissions and energy efficiency, to achieve a low-carbon society [4].

International institutions are committed to the transition to more sustainable production and consumption systems [5]. In this transition, innovation promoting sustainability will be fundamental [6,7]. The European Union is committed to its bioeconomy policy [8]. Current research and innovation in bioeconomy will help Europe to properly manage renewable resources, creating new opportunities in a circular bioeconomy perspective [9,10].

Sustainability, to be effective, must be based on environmental, economic, and social pillars [11]. The creation of new economically affordable, environmentally respectful, and socially responsible business models are bases by which to achieve a truly circular bioeconomy [7]. The concept of the circular bioeconomy is recent and emerged among academic, political and industrial circles conjugating the concepts of a circular economy, bioeconomy and green economy [12,13]. The definition of bioeconomy can be presented as being the production of renewable biological resources and their conversion into new value added products or energy recovery [14,15]. Green economy is an umbrella covering all concepts, such as circular economy and bioeconomy, and adding now new concepts such as nature-based solutions [12,16]. Circular bioeconomy incentivizes the sustainable use of biomass and promotes residue recovery in a circular perspective [17–20].

The definition of biomass refers to all material that was or is a part of a living organism [21]. Although, when considering its use as feedstock, biomass refers to all organic material that is plant-derived [22]. Through the photosynthetic process, green plants convert sunlight into carbohydrates, storing the energy of the sun as chemical energy [23]. This energy can be converted using several processes [24].

Within this literature review, the term agroforestry biomass refers to biomass that can be produced as a result of forestry and agriculture activities, but not exclusively, as suggested by Proto and Zimbalatti, who claim that integrated systems simultaneously growing and breeding crops and stock can be included as well [25]. Agroforestry biomass represents one of the most important sources of biomass worldwide, and should not be discounted when approaching mitigation and adaptation measures facing climate change, because it can also generate benefits for ecosystems [26].

Biomass waste from forestry and agriculture is expected to fuel part of the increasing demand for biomass [27]. Biomass residues stand out as potential raw materials to produce renewable fuels, chemicals and energy [28]. In fact, forestry waste can be considered an important energy source and as an alternative to traditional on-site disposal or burning leftovers. The interest in the use for energy production is increasing, promoting rural development as well as promoting environmentally friendly forest practices [29].

Biomass waste recovery allows the closure of the biomass supply chain loop [17]. When comparing this option with the use of energy crops, residual biomass energy recovery can be considered a much more sustainable approach in all points of view [30]. Each process in the wood industry generates waste; however, only 40% to 60% of the total volume harvested is used. The same is valid for agriculture, which also generates large amounts of waste [31].

According to McKendry, in a biomass energy recovery process, the cost of energy can very often be as competitive as generation from fossil fuels [32]. This leads to the expectation of a very promising future in relation to the exploitation of biomass residues [23]. However, it must be kept in mind that the logistic costs related to biomass handling and transportation for energy recovery are challenging [33].

According to Balat, it is expected that in the medium term, biomass waste will dominate the biomass supply for energy generation [34]. Therefore, the current review focuses on the importance, potential uses and availability of waste from agriculture and forestry activities, which may be essential in accomplishing the environmental goals for this century. This article is organized as follows: materials and methods, literature review, discussion, and conclusion. An extensive literature review on the valorization of residual agroforestry biomass since the 1970s was carried out, in order to understand the main research focuses on the subject over the last few decades, also identifying the most recent trends to establish a potential path for the future use of biomass.

2. Materials and Methods

To understand how this topic has evolved within scientific research, the methodology chosen for this paper was the literature review, which is one of the most appropriate methodologies to identify the contemporary state of the art [35]. The steps performed were as follows: firstly, the area of study was defined, focusing on residual biomass; this step was followed by the selection of the bibliographic databases underlying the research, selecting the platform SciVerse Scopus (SCOPUS); and the third step involved the selection of the keywords, which are presented in Table 1.

Table 1. Keywords used in the review process.

Keywords	Results
1. Residual + biomass + valorization	225
2. Waste + biomass + valorization	1465
3. Residual + biomass + recovery	630
4. Waste + biomass + recovery	3685
5. Residual + Biomass + socio-economic + impact	6
Total	6011

In order to assess the accuracy of the choice of keywords, particularly the terms "residual"/"waste" and "valorization"/"recovery", were compared due to the number of results in the Scopus database. As can be observed in Table 1, the terms "residual" and "valorization" had significantly fewer results when compared with the terms "waste" and "recovery", respectively. This led to the hypothesis that the first two terms are probably more commonly used by non-native English speakers. The only restriction that was applied to the search was in the document type. Only articles and reviews were included in the search for papers to be peer-reviewed [36].

Table 2 presents the results per decade since the 1970s (the first document was published in 1971). As can be concluded, this is not a new research topic, but it has gained considerable momentum since the 2000s, which points to the increasing importance given to biomass waste. This trend reflects the search for new alternatives to fight climate change and to find new ways towards sustainability and circular economy.

Table 2. Number of search results in SCOPUS per decade, including only articles and reviews.

Year	Results
1970–1979	12
1980–1989	93
1990–1999	209
2000–2009	633
2010–2019	3309
2020–present (2021)	1755
Total	6011

After this quantitative analysis to understand research trends, which included the chronological analysis of the literature, the review proceeded to a content analysis, aiming to identify the most important topics within each decade. For this, a few articles that were most aligned with the selected research topic were selected. In the next section, the literature review is presented, starting with some basic concepts related to biomass, energy conversion processes, and agroforestry biomass waste.

3. Literature Review

3.1. Biomass Energy Production

Biomass is considered the oldest energy source that humans use, since the discovery of fire [37]. In fact, in 1850, biomass represented 85% of the energy consumption worldwide, and before that, it was practically the only source of energy used by humans, besides wind (for sailing), domesticated animals (in agriculture) and small amounts of coal for heating [38]. There are many sources of biomass energy, with wood being the most important, but agriculture materials, urban waste, animal waste, and agroindustry waste are among the others [39–42].

There is a well-known direct connection between energy consumption and economic development [43–45]. Generalized access to energy is becoming more important than ever, due to economic development and population expansion, but the concerns regarding climate change and sustainable development have also gained much attention [46,47]. Worldwide, new types of sustainable and clean energy are being implemented and developed to replace fossil fuels [48,49]. According to Wu et al., the current energy matrix is 20% composed of renewable sources and 80% composed of fossil sources [50]. Searching for substitutes to fossil fuels capable of decarbonizing the economy and supplying large amounts of energy are, currently, one of the main objectives of science and technology [51,52].

Biomass is gaining increasing attention because it is a renewable source that can be used directly or in a processed form [24]. Biomass energy (bioenergy) is already essential in the energy supply worldwide, widely recognized as an alternative to fossil fuels, but with more importance in developing countries, where it is mostly used through direct combustion for cooking and heating, representing approximately 35% of the energy demand [50,53]. According to the IRENA renewable energy statistics (https://irena.org/publications/2021/Aug/Renewable-energy-statistics-2021, accessed on 5 January 2022), in 2019, the total amount of electricity generated from renewables was 6963 TWh. Renewable hydro power accounted for about 61% (4207 TWh), followed by wind energy (1412 TWh), solar energy (693 TWh), bioenergy (558 TWh), geothermal energy (92 TWh) and marine energy (1 TWh). Bioenergy generation was divided as follows: 389 TWh (69%) from solid biofuels; 92 TWh (20%) from biogas; 69 TWh (10%) from urban waste; and 8 TWh (1%) from liquid biofuels.

In 2020, the International Energy Agency (IEA) report stated that biofuel production was strongly impacted by the COVID-19 crisis, with an estimated decline of 12% from the record which occurred in 2019 [54]. The report emphasizes that it is the first time in two decades that a reduction in annual production was verified.

In the European Union, biomass for energy is the most important renewable source in terms of gross final consumption, with a share of almost 60% [55]. Despite the pandemic crisis, the demand trend for biomass in the EU and worldwide is increasing [56]. However, the use of agriculture soils for energy crops results in new conflicts with food production and, therefore, it cannot be considered sustainable [57]. In Europe, forests are a biomass source that is not competing with food supply [58]. The demand for forest materials has caused competition between industries; thus, there is a need to increase circularity and resource use efficiency [19]. In this regard, European forests are essential for supplying biomass to a growing bioeconomy [59].

3.2. Biomass Conversion Technologies

3.2.1. Framework

There are numerous technologies of biomass conversion to produce different energy forms, but also to produce fertilizers, value-added chemicals and functional materials [23,60]. Selecting a product for conversion depends on several factors, such as the objective to fulfil, available technologies and its maturity state, and associated environmental impacts [61]. In this section, these modern conversion technologies will be approached succinctly.

3.2.2. Physicochemical Conversion

Physicochemical conversion, which includes size reduction and conformity, drying, densification, or solvent fractionalization, is often used as a pretreatment before other conversion steps [62]. This allows density increase, reduction in feedstock homogeneity, and makes transportation and storage more manageable [63,64].

The pretreatment of lignocellulosic biomass with organic solvents has been performed for more than 100 years, and several solvents have been studied in order to isolate different components from biomass such as cellulose, lignin and hemicellulose [65]. The densification processing allows the homogenization of lignocellulosic biomass, which is important to obtain uniform physical properties, e.g., size, shape, density, and durability [66]. Through the achievement of this consistency, transportation logistics, storability and combustion properties are improved compared with raw biomass [67]. Diverse densification systems (e.g., pellet mill, briquette press, etc.) are used to produce a homogenized solid commodity for energy conversion [66].

3.2.3. Thermochemical Conversion

Thermochemical conversion processes present higher efficiencies in terms of reaction time and capacity to fragment the majority of compounds that can be found in biomass [68]. Thermochemical conversion technologies applied to biomass have been extensively studied and include combustion, torrefaction, pyrolysis, liquefaction, and gasification [69]. As stated above, combustion is the most commonly used conversion method, but gasification and pyrolysis are also frequently used, because higher energy grade products can be obtained [24]. The oldest method for using biomass energy is direct combustion [70]. Combustion methods can be listed in three paths, concerning the evolution of a technological point of view as follows: stove combustion, when the objective is air heating; boiler combustion, when the objective is water heating; and densified biomass combustion, which can be used in both types of equipment, replacing common firewood [71–73].

Pyrolysis is a process where the thermal destruction of organic materials occurs in an atmosphere poor in oxygen where biomass is converted into a fuel, which can be in the form of charcoal, bio-oil, and gas [74]. Another biomass conversion technology is torrefaction. This process only differs from pyrolysis in terms of the operation temperature (much lower); thus, torrefaction allows the homogenization of different biomasses, improves bulk and energy density, and improves hydrophobicity and grindability [75]. The torrefaction process can be described as the slow heating of biomass for a certain period of time, depending of the technology used, in a range of temperatures from 200 to 320 °C in an atmosphere poor in oxygen [76].

Direct liquefaction or hydrothermal liquefaction is a thermochemical conversion process that can be used to convert biomass into liquid fuels. This transformation occurs in a hot, pressurized water environment during a chosen residence time, in which the polymeric structure will break down, forming a liquid output [77].

Gasification is the thermochemical conversion of a solid or liquid carbon-based feedstock into gaseous products, e.g., CO_2, water, CO, hydrogen, gaseous hydrocarbons, and condensable compounds, such as tars and oils, small quantities of solid products (char), and ashes [78]. This conversion occurs in equipment called gasifiers, which can be categorized into three main types: fixed bed, fluidized bed and indirect gasifier [79]. Gasification can be considered an upgrade of the pyrolysis process, although it occurs at higher temperatures, optimizing the gas yield [80].

3.2.4. Biological Conversion

The low efficiency usually associated with the biological conversion of biomass is challenging [81]. Many different biological processes have been studied for biofuel productions, value-added products, and other green chemicals [82]. These processes are mainly fermentative, although some special conditions might be needed, such as an anaerobic environment, specific illumination, and different microorganisms (such as bacteria, yeasts, cyanobacteria, and algae) [83]. Bioethanol, for example, can be produced from different sources, such as agroforestry residues, paper mill waste, urban waste and several energy crops, but, currently, the majority is produced by the fermentation of corn glucose in the United States or sucrose in Brazil [84]. This process comprises the following key steps: the hydrolysis of cellulose and hemicellulose, the fermentation of sugars to ethanol, the separation of lignin residues, and finally, the recovery and purification of ethanol [85]. Hydrolysis is usually performed with enzymes, and the fermentation is performed using yeasts or bacteria [86].

Anaerobic digestion is the biological treatment of organic substrates occurring in the absence, or scarcity, of oxygen, using microbial communities [87]. This process, applied to biomass, enables the recovery of biogas, methane being the most studied, and provides a clean fuel from renewable feedstocks [88]. Lignocellulosic biomass represents an opportunity for conversion into renewable energy, but its structure is complex due to the lignin content, which inhibits the anaerobic digestion process [87]. To overcome this problem, several pretreatment methods are available. The hydrothermal (HT) pretreatment of lignocellulosic biomass is a promising approach to increase biogas production in anaerobic digestion [89]. Using organic waste to produce methane through anaerobic digestion would benefit society due to the replacement of fossil-fuel-derived energy [88].

4. Agroforestry Biomass Wastes

4.1. Framework

Agroforestry biomass waste has been converted to energy for centuries through combustion, and more recently, through other technologies such as gasification, liquification and pyrolysis [90]. Bioenergy produced from forestry and agriculture residues has gained renewed attention concerning reductions in greenhouse gas emissions and climate change mitigation strategies, through sustainable and short-distance supply chains of agroforestry residual biomass [91]. In addition to the reduction in pollution and improvement in the ecological environment, using agroforestry waste in a reasonable and effective manner can have a huge regional impact in terms of the development of rural regions and reduction in forest fires [92]. In fact, most of the available biomass waste products are not valorized and may potentially be useful as energy sources [93]. This means that there is a viable resource that can be valorized for energy production or other products, such as chemicals [94]. The use of agroforestry waste biomass is of particular importance, especially when there is a large quantity available, because it contributes to the circular economy and to decarbonization [95,96]. Recovering and transforming agroforestry waste biomass presents many benefits [52]. As referenced above, some of these benefits include rural development and wildfire risk reduction [97,98].

The estimation of biomass waste generated yearly across different economic activities are in the order of 140 Gt, with more than 120 Gt corresponding to agriculture residues, and approximately 40 Gt originating from forestry activities, with these two sectors corresponding to 30% of the total waste produced in Europe [99,100]. Currently, there is a huge potential for using agroforestry waste, while at the same time solving waste management problems, because discarded biomass may cause negative environmental impacts. In terms of agriculture biomass sources worldwide, it is estimated that 66% of the residual biomass comes from cereal straw (stem, leaves, and sheath material), and the majority (60%) is produced in low-income countries. The second largest source of biomass is sugarcane stems and leaves, and other important waste comes from oil crops, roots and tubers, nuts, fruits, and vegetables. Regarding the forestry sector, most biomass waste comes from timber logging. This can be differentiated from forestry residues as primary and secondary. The first classification includes logging residues, stumps, and early thinning (e.g., branches), whereas the second includes residues from wood processing [99]. According to Gaspar et al., forestry residues have adequate heating value to produce thermal energy. Hemicellulose and lignin contents make this type of materials suitable for obtaining second-generation biofuels, such as biogas and bioethanol [101].

4.2. The Decade 1970–1979

As shown in Table 2, between 1970 and 1979, the number of publications in this field was very small.

Saeman discussed the use of wood residue energy recovery and the production of wood-derived compounds such as ethanol, furfural, methanol, formaldehyde, and phenol [102]. Indirect savings from using forest products instead of other more energy-intensive alternatives are presented. The author stated that the handling and the burning of wood residues can be considered irrelevant. However, at this time, chemical and biochemical recovery of wood residues seemed to not be feasible, involving high investment and no expectable return.

Gopalakrishnan et al. reviewed liquid and gaseous fuel production using fermentation, enzymatic hydrolysis, and hybrid processes, and discussed the suitability of these fuels for internal combustion engines [103].

In another study, different forms of biomass waste produced in Canadian agriculture were estimated. At the time, the authors worried about an energy-conscious society, and demanded an urgent investigation regarding anaerobic digestion, pyrolysis, and hydrolysis for using biomass waste from agriculture [104].

Hileman et al. argued that there was not any technology available at that time that would allow economic recovery from biomass, despite the possibility of energy recovery [105]. Despite the problems related to agricultural residues listed by the authors, regarding moisture content, handling and availability, the authors described a method to achieve a potential economic benefit through the low-cost production of medium-energy-content gas in smaller sized plants.

A study conducted by Harper et al. describes different biomass energy systems, using different conversion processes, such as hydrolysis, pyrolysis and combustion applied to agroforestry residues, estimating mass and energy flows, capital and operation costs (CAPEX and OPEX), and environmental impacts [106].

4.3. The Decade 1980–1989

Wilke et al. designed a process for biomass conversion into sugars and ethanol and conducted an economic assessment of this production using corn stover as a representative raw material, showing that ethanol production costs are mostly dependent on the cost of the raw material, on the glucose conversion efficiency rate, on production costs and enzyme recovery, and on potential uses for xylose as a valuable by-product [107]. In another study from the same year, the authors analyzed the production of ethanol as a liquid fuel by microbial processes from different types of waste, concluding that pretreatment processes influence the competitiveness of the industrial production of this fuel [108].

In 1986, a deep techno-economic study was presented, approaching the production of sugars and alcohols from cellulosic materials, focusing on developing countries [109]. The authors argued that species such as sugarcane, sweet sorghum, and nipa palm are the best candidates for the high-yield production of ethanol, emphasizing that biomass containing cellulose implies a pretreatment to produce glucose and alcohols.

Radhika et al. carried out a study focusing on the United States [110]. According to the authors, the United States planned to achieve a 4.2–5.2% biomass and waste energy consumption within the first decade of the 2000s. The authors discussed technologies such as anaerobic digestion, thermochemical gasification, mass-burning of urban waste and the combustion or co-firing of refuse-derived fuel, landfill gas recovery, and biomass-derived ethanol. Nevertheless, they argued that small-scale plants would predominate in the future because of the limitations of biomass, mostly related to the logistics problem. The article from Radhika et al. is specific o agriculture waste, and the authors classify the processes for energy recovery from these wastes as follows: aqueous or biological processes and dry chemical or thermochemical processes, stating that within the biological processes, the one with most potential is anaerobic digestion.

4.4. The Decade 1990–1999

The bioconversion of biomass to ethanol kept being studied in the 1990s. In a technological and economical study carried out by Duff and Murray, the authors examined the conversion of wood cellulosic waste into ethanol [111]. The authors concluded that waste from the forest industry could reduce the costs of ethanol production which, together with the advantages of a pretreated cellulose-enriched substrate and pre-existing material handling equipment, would make this an ideal industry for integrated ethanol production.

In another article from 1996, biomass and waste power production was addressed [112]. This article initially characterized the important physical characteristics of biomass and waste fuel, classifying biomass into four categories: wood residues, agriculture waste, energy crops, and urban waste. The authors emphasize the importance of biomass waste, given the large volumes that are generated by the wood product industry, as well as by the forestry and agricultural sectors. The authors propose that these residues could be gathered in regional biomass power plants. Wood residues were the main source for power production, and the authors expected an increase over the following 5–10 years, but a stagnation from 2000, because they expected a substitution for energy crops. Importance was given to the stimulation of rural areas through job creation, but also to the fact that it would be an environmentally friendly renewable energy source. A comparison between biomass with conventional fossil fuels, especially coal, was also performed.

Obernberger reviewed combustion as a mature biomass conversion technology and analyzed different technologies and different biomass fuels [113]. Developments regarding reductions in NO_x and higher plant efficiencies were already ongoing, and the problems related to the reactions that occur in hot flue gas that cause corrosion, fouling and slagging problems in thermal conversion equipment needed further research.

In a review article from 1997, the importance of managing the carbon cycle in order to mitigate the emissions of greenhouse gas was addressed [114]. The authors stated that power generation is responsible for one-third of the CO_2 emissions from fossil fuel origins, which implies the need for reducing CO_2 with the use of different technologies and the cofiring of biomass. The authors also suggested the use of indirect biological processes such as growing trees, and argued that biofuels could potentially be an alternative to a large proportion of fossil fuels, and biomass cofiring with coal is one of the options to reduce fossil CO_2 emissions, concluding that biomass waste could have a major positive impact.

4.5. The 21st Century

4.5.1. Framework

Within the first decade of the new millennium, the research trends focused on biomass thermochemical conversion technologies, such as torrefaction, pyrolysis, and gasification, instead of devoting attention to improving combustion; it is the oldest technique for converting biomass to energy and, according to Demirbas, is responsible for 97% of the bioenergy generated in the world [72]. As seen in previous decades, several processes have been used for biomass energy recovery, as well as cofiring biomass with coal. However, in the early 2000s, these modern conversion technologies were further researched. The environmental concerns regarding biomass, namely, its availability and sustainability, have been a major focus in scientific studies since the new millennium, because the prospects for replacing fossil fuels are more real than ever.

4.5.2. The Decade 2000–2009

Demirbas et al. advocated that for the replacement of fossil fuels, the best immediate alternative is biomass [53]. The authors concluded that biomass resources will highly contribute to environmental protection in the 21st century, because it will mitigate CO_2 emissions, reducing the greenhouse effect. The net production of CO_2, the major greenhouse gas, from wood combustion roughly corresponds to 5%, and for that is considered neutral [34].

Belgiorno et al. (2003) present an overview of the gasification conversion technology applied to solid biomass waste [80]. Gasification needs a homogeneous carbon-based material, excluding, this way, many types of wastes, although this is not the case for agroforestry residues. The authors argued that gasification is a good alternative to the incineration of homogeneous carbon-based waste and for pretreated heterogeneous waste.

Gómez-Barea et al. [72] analyzed the gasification of two forms of waste (olive pomace and animal waste) in a fluidized bed pilot plant [115]. The authors wanted to optimize the industrial process, obtaining better ash quality and higher energy efficiency, as well as finding ways of recycling the ash produced. The ash produced contained compounds harmful to the environment; therefore, pretreatment would be necessary in order to use them in agriculture and construction, but it is not necessary if using it for cement kilns. The authors researched other uses that would not require pretreatment, such as the manufacture of lightweight board and bricks, stating that this is a low-cost process generating highly valuable products.

Sadhukhan et al. searched for an economically viable combined heat and power (CHP) plant, using biomass waste, utilizing a cost-effective and cleaner industrial process [116]. The authors chose agricultural waste as a low-cost feedstock, respectively it has been used extensively as standard fuel for power production. The maximization of heat recovery and the increase in the sustainability of the process were explored. The authors predicted the cost of the energy produced, as well as the cost of carbon capture, concluding that using biomass for CHP generation can be economically viable if low-carbon initiatives are in place, and that agriculture waste would be the ideal feedstock.

Skodras et al. studied the behavior of 10 biomass and waste materials in pyrolysis and combustion processes from a perspective of reducing greenhouse gas emissions, concluding that all the materials tested presented good fuel properties, as a reflection of their higher volatiles contents and lower ash contents, respectively [117].

4.5.3. From 2010 to the Present

Regarding the use of biomass, according to Guilhermino et al., the main challenge is its viability and resource sustainability, and not the availability itself [118]. However, academics are not unanimous regarding the sustainability of biomass for energy, with some authors pointing mostly to its benefits, whereas others conclude that this is not such a green source of energy as it may seem at first view. Besides its abundance, biomass has low sulfur and nitrogen (relatively to coal) contents and is considered carbon neutral [119].

Proto et al. presented biomass as an alternative to fossil fuels, but also as a potential driver for the sustainable development of marginal areas [25]. However, these authors point out some environmental risks regarding the intensification of its use, which justifies the importance of a sustainable biomass supply chain. The low environmental impact of biomass and its contribution to improve competitiveness, employment and regional development were outlined by Torreiro et al. [120]. Kang et al. stated that biomass energy recovery reduces greenhouse gas (GHG) emissions, mitigating climate change, and, at same time, promotes environmental and human health and wealth conditions [121].

The logistics problems represent one of the main drawbacks for biomass use. The uncertainties of supply-side externalities represent key challenges in biomass supply chains, leading to reductions in some sustainability benefits [122,123]. Kang et al. identified some disadvantages regarding bioenergy that have not yet been solved, such as the lower fuel quality when compared with fossil fuels [121]. The same authors also emphasized that despite biomass being carbon neutral, the majority of the supply chain is not, and is directly dependent on fossil fuel energy. The sustainability-related aspects of a biomass-based supply chain must be considered to truly understand the sustainability performance of biomass as a bioenergy resource [122]. Despite some disagreements in the literature, one thing is mostly agreed: using biomass waste for energy generation or other valuable products, in a perspective of the bioeconomy, is sustainable and should be further studied and implemented [124]. Using biomass waste solves problems related to competition with other land uses [125].

As a land management system, agroforestry biomass presents a high potential for carbon sequestration, coupled with the production of biomass energy recovery [126]. Soil organic carbon (SOC) sequestration is one of the options available to mitigate climate change by reducing atmospheric CO_2, and this can be deliberately enhanced by agroforestry practices [127]. Obviously, there are some inherent characteristics from agroforestry biomass that need to be overcome in order to fully exploit its potential, such as the grindability of the materials, its moisture content, poor energy density, perishability, and limited logistic properties [128]. Fortunately, there are different biomass pretreatment technologies that already solve the majority of these problems [129].

Tuck et al. reviewed the potential of biomass waste to produce chemicals, fuels, and solvents [33]. According to these authors, the amount of lignocellulosic waste is estimated to exceed 2×10^{11} t·year^{-1}, classified into two groups: one related to leftover residues, and another related to product processing. The authors focused on agricultural and food waste, describing some uses beyond energy valorization, especially large-volume chemicals such as lubricants, surfactants, monomers for plastics and fibers, and industrial solvents. Sheldon also reviewed the use of biomass waste as a feedstock for chemical production, focusing on green chemistry [130].

Cho et al. reviewed the application of biochemical processes to various types of biomass waste from agricultural and forestry activities that exist in high quantities, but also from the food processing industry [131]. The authors demonstrated that enzymatic technology enables a more efficient process of biomass waste conversion into valuable products, that can be used in several industries, such as the chemical, pharmaceutical, cosmetic and food sectors. However, they point out that this valorization is not yet competitive against petroleum-based products.

The production of biofuels was extensively reviewed by Limayem and Ricke, who pointed out that the interest in biomass-derived fuels increases every time there is a price peak in petroleum-derived fuels [132]. The authors stated that industrial research efforts became focused on low-cost large-scale processes for lignocellulosic feedstocks, originating from agroforest waste along with herbaceous and urban waste. This is in line with another article that advocates the use of agriculture residues for bioethanol production, because they are renewable, lignocellulose-rich and available in large amounts [133]. Upgrading techniques to produce gas and/or diesel and chemicals from biomass and waste biomass was reviewed by Jacobson et al., who stated that there is great potential for its conversion to transportation fuels [134].

Foong et al. argued that biomass waste is a promising substitute for fossil fuels, not only for energy purposes, but also for value-added products [135]. According to the authors, pyrolysis seems to be the best thermochemical conversion process applied to biomass, thanks to low pollutant emissions and limited residue formation. The different pyrolysis processes were reviewed, namely, fast, slow, and flash pyrolysis, which produce bio-oil, solid char, and syngas as the main products, respectively. Different types of pyrolysis are also explained: solar pyrolysis, which uses solar energy as the heating source; vacuum pyrolysis, conducted under vacuum conditions to replicate an inert atmosphere; and conventional pyrolysis, which is the most commonly used technology.

Donner et al. focused their research on business models creating value from agriculture waste through a perspective of the circular economy [136]. Through the analysis of case studies and interviews, six types of business models were identified: environmental biorefinery, biogas plant, agricultural cooperative, upcycling entrepreneurship, agropark and support structure. The differences between these business models were discussed, as well as their similarities, the most important of all being the fact that these businesses are completely depending on the partnerships established and the capacity to adapt to new external conditions. It was concluded that there is a great potential for the creation of biomass added-value chains, and that cascading biomass valorization at a smaller-scale will gain importance for local circular bioeconomy stakeholders.

5. Discussion

Until the Industrial Revolution, practically all the energy consumed by humans was from renewable sources. However, industrialization started a process of the exploration of non-renewable fossil resources for energy production, which has been growing exponentially in recent decades. Economic development had obvious positive improvements in the living conditions and general well-being of populations, although the consequent increases in population and standard of living have generated increased pressure on ecosystems and greater emissions of greenhouse gases, which are already causing climate changes.

The energy crisis in the 1970s, due to excess demand over supply with consequently increasing prices which was coupled with the possible depletion of fossil fuels, led to a rapid search for alternative renewable energy sources such as biomass. The discoveries of new reserves of fossil fuels allied to conservation policies relieved the problem, and the oil crises disappeared in the late 1980s. Nowadays, humanity is facing an urgent need for decarbonized energy sources, given the increment of greenhouse gases from anthropogenic origins, potentiating climate change.

The great interest of the scientific community in terms of the research for environmentally sustainable alternatives to respond to a society that increasingly generates more pollution became evident. Renewable energies are taking a central role in environmental preservation, but also in economic and social development.

From the literature review carried out in this study, it can be seen that the interest in biomass and, more particularly, in agroforestry waste biomass, has been growing. Even though biomass is the oldest energy source managed by humanity, the technologies related to its valorization are still developing. Most studies focused on sustainable biomass energy production to replace fossil fuels, because biomass presents several advantages. Biomass meets the requirements to be an alternative to traditional fuel supplies in the future. Different biomass forms can be used to produce fuels, chemicals and energy, and it is this diversity of sources, coupled with the driving forces of market demand and industrial competition, that has led to the development of different technologies in recent decades.

In the 1970s, combustion was the main conversion system, but other modern technologies were already under study, and biomass waste was already seen as a possible viable solution for use as an energy source. In the 1980s, studies focused more on the optimization of industrial processes. The conversion from biomass to ethanol has been widely studied, as well as the large-scale use of bioenergy from residual biomass. In the 1990s different forms of biomass were studied and characterized, and the change from coal to biomass led to the study of equipment corrosion processes. In the new millennium, this period was characterized by an exponential increase in the scientific literature expanding in most areas, and this was also seen in residual biomass, with an increased focus on the new conversion technologies within the first decade, as well as its industrial development, aiming for the end of the fossil fuel era. The perspective of carbon sequestration emerged, and the literature has focused more on sustainability rather than profitability. More recently, the concepts related to the circular economy and bioeconomy are more explored than ever, and new business models will be very important to recover and valorize residual biomass either for energy or chemical production.

6. Conclusions

Climate change is probably the biggest challenge that humanity will have to face within this century. The need for clean energy is as important as the need for effective methods for the treatment and disposal of large quantities of waste, which is a threat to the quality of the environment, although also represent a significant renewable energy resource. The conversion of agroforestry waste biomass is not yet finished. The developments of the last decades have significantly improved the conversion processes, leading to greener solutions, but there is still much to be studied and put into practice. Closing the loop of biomass waste recovery will be essential to achieve a truly circular bioeconomy. From the work carried out in this review, future research directions should include the study of local/regional solutions to recover the potential economic valorization of residual biomass, simplifying the logistics problems, as well as performing cost–benefit analyses of this recovery. This study presents an extensive literature review of studies regarding residual biomass published since the 1970s. The existing review articles address more specific topics, especially those related to energy valorization technologies, not providing a comprehensive view of the subject, as it has been carried out in this article. However, there are some limitations, mostly related to the difficulty of having access to older articles, especially from the 1970s and 1980s, but also related to the difficulty of defining the inclusion criteria because there was a huge number of publications to be analyzed, and this can be pointed out as a drawback due to the personal biases of the authors.

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