Materials Circular Economy (2022) 4:9
https://doi.org/10.1007/s42824-021-00050-2

ORIGINAL PAPER

Brazilian Agro-industrial Wastes as Potential Textile and Other Raw Materials: a Sustainable Approach

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Received: 18 June 2021 / Revised: 8 December 2021 / Accepted: 13 December 2021 / Published online: 26 January 2022

Abstract

The Brazilian agro-industrial chain generates about 291 million/tons/year of wastes, which, if inadequately destinated, could originate social and environmental risks. There is a growing need for the use of alternative raw materials to replace that originated from fossil resources in the Brazilian industry. Renewable materials play an important role on the sustainability of ecosystems and materials' circularity. The issue has acquired importance in light of recent bio-based agro-fiber development potential applications. Considering sustainability guidelines, this study aimed to analyze the main Brazilian agro-industrial waste crops (temporary and permanent) as important sources of natural fibers and other raw materials. A systematic review of the literature (SRL) about Brazilian researches, based on concepts of industrial ecology, and the creation of a bibliometric analysis network were carried out. The agricultural biomass related to the main crops presents characteristics making them suitable to be applied for textiles, as natural fibers and polymers, in biosorbents for industrial effluents, and cellulose obtention and reinforcement material in composites. Thus, scientific investment in researches on materials and technology development are necessary to provide applications that could meet current and future demands and expand the scope of new materials for sustainability.

Keywords Brazilian · Agro-industrial wastes · Textile industry · Natural fibers · Sustainability

Introduction

In Brazil, agribusiness plays an important role in the production, processing, and transformation of food. According to the Brazilian Institute of Geography and Statistics (IBGE 2021), the crop of agricultural production forecasts a record 2.5% in 2021, and to meet food needs in 2050, it requires a 60% increase in the planted area, and in the consumption of water in the region amid water crises (Biase 2017). The abundance is the result of increased activity in the modern agricultural sector, which produces 291.1 million/ton. of residues in its largest crops (Schneider et al. 2012). However, this system presents unexplored economic opportunities, pressuring conservation of resources, polluting and degrading natural ecosystems, causing environmental risks and contamination to society (Biase 2017; Ellen MacArthur Foundation 2017).

The need for renewable manufactured products is a major challenge for the Brazilian industry dependent on petrochemical resources. For Dungani et al. (2015), agricultural waste is the most abundant form of natural fiber. The use, processing, and characterization of agro-industrial wastes are a great opportunity to generate value and develop by-products and co-products (Berté 2009; Dahiya et al. 2020; Embrapa 2018; Shahid-ul-Islam et al. 2013).

Renewable resources are aimed at the sustainability of ecosystems and for maintaining healthy and sustaining the textile industry. There is great interest in sustainability by industry professionals, including in materials with competitive mechanical properties, lightness, and biodegradability of low-cost natural fibers to replace petroleum-based fibers

This article is part of the Topical Collection on *Natural Fibers: Materials of the Future*

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in composites (Alarcon et al. 2021; Atiqah et al. 2020; Hoque et al. 2021; Izwan et al. 2021). Indeed, markets for products based on the agro-fiber present great potential for application in absorbents, technical textiles, geotextiles, filters, biocomposites, and other automotive and construction sectors (Shishoo 2007). Research efforts have been alternatives to different levels of control and management (Chan et al. 2021; Onu & Mbohwa 2021d).

The high volumetric rate of agro-industrial residue in combination with increased environmental awareness makes research into appropriate textile technologies and treatments a priority (Madhav et al. 2018). In this way, this study aimed to analyze the main Brazilian agro-industrial waste crops (temporary and permanent) as important sources of natural fibers and other raw materials.

Research Methods

The methodology was based on a bibliographic survey and analysis by systematic literature review (RSL) followed by bibliometrics. The focus, based on industrial ecology concepts (Giannetti and Almeida 2006; Lifset and Graedel 2015), examined researches on the use of agro-wastes for the development of sustainable textile materials. The results were compared with data from the Brazilian Ministries of Agriculture and Environment and related associations. To index a descriptive exploratory bibliometric analysis of the data with greater precision to the object of study, it was built a network from the grouping of bibliographic sources in the Scopus platform (from December 2020 to January 2021 that encompass the years from 2021 to 2006) and transcribed by Software VOSviewer (*Universiteit Leiden*). To generate the database, the searches performed used the variation of the terms "agro-industrial," "agro," "waste," "fiber," "textile," "fashion," and "bio-based" limited to Brazil. When diagramming the network, 3,296 significant expressions were identified, out of the 305 articles selected, of which 2,496 meet the correlation requirement. The same database was used to develop a diagram focusing on the highest incidence of materials citation by classification and types, crops, formats, conversion technology, and end-of-use researches. Crops were divided following the Food and Agriculture Organization of the United Nations (FAO) food classification (FAO 2021b).

The next items discussed respectively the following: (i) structural analysis of the textile industry from the perspective of the progress of synthetic materials, consumption patterns, and interaction of the value chain with the agricultural industrial segment; (ii) the dynamics of sustainability as a guideline and fundamentals for restructuring cycles of agricultural residues; (iii) the Brazilian scenario of productive insertion (marked by the data analysis network); (iv) materials and related applications in Brazilian development researches.

Results and Discussion

Textile and Agricultural Sector Challenges

The textile and agricultural industries share challenges within the current Brazilian economic system, concerning global demand consumption, land use, greenhouse gas emissions, pollution, effluent generation, generation and disposal of waste, and recycling (Circular Systems 2020).

According to the Brazilian Association of Artificial and Synthetic Fiber Producers (ABRAFAS), the Brazilian petrochemical-textile complex operates on a large scale and is responsible for productivity above 380 thousand tons/year, between synthetic and artificial fibers and multifilaments (ABRAFAS 2020). Brazil is currently the 5th largest textile industry in the world and the 4th in the clothing segment. In 2019, textile production reached an average of 2.04 million tons, which represents a turnover of near US$ 36.5 billion from the entire chain, investments of about US$ 730 million, creating about 1.5 million direct jobs and 8 million indirect jobs, of which 75% are female labor, the 2nd largest employer in the manufacturing industry, the most complete in the West, from fiber production to retail (ABIT 2020; Cavalcanti and Dos Santos 2021; Filleti and Boldrin 2020), with estimated expansion of 11.5% from 2017 to 2022 in apparel retail (Mariano 2018) growth of 10.4% in apparel production in volume, reaching 5.5 billion pieces (IEMI 2021).

The rise in consumption and use of synthetic fibers represents a major change in the country's textile chain, which until then remained largely with the production of cotton and natural fibers (Zeferino 2019), in contrast to the exponential growth of 42.7% synthetic textile fibers over the period 2010–2017, while natural fibers did not show significant growth worldwide (Cavalcanti and Dos Santos 2021) (Fig. 1).

In reason to the expansion of activities in the clothing textile industry to meet the growing demand in the clothing supply chain, there is a significant and abusive increase in the use of inputs such as energy, water, and soil (Barbosa et al. 2016).

In the textile sector, with the growing and large consumption demand of natural textile fibers, the production and market of synthetic fibers found a great space for expansion due to their characteristics of low cost, strength, shine, and, mainly, the absence of large agricultural spaces, a special type of climate and intensive work (Lobo et al. 2014).

Onu and Mbohwa (2021a) support the argument that the continuous application of petroleum derivatives involves

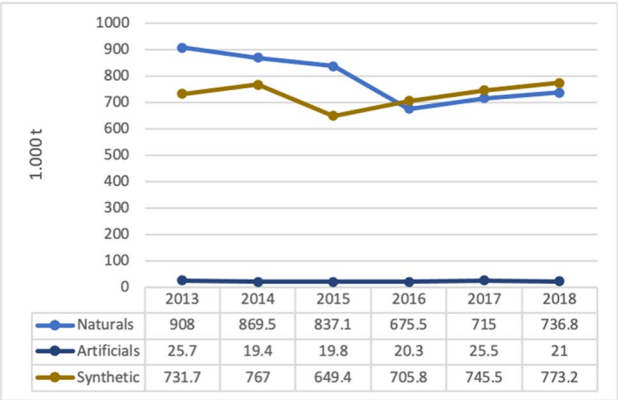

Fig. 1 Consumption of natural, artificial, and synthetic fibers and filaments in Brazil, 2013–2018. Source: adapted from ABIT (2018)

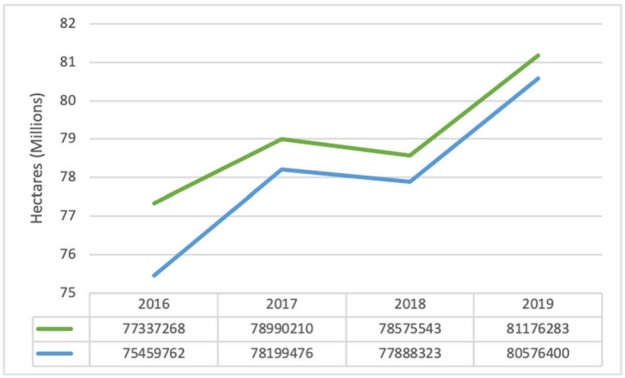

Fig. 2 Planted area or destined for harvesting (green line) and harvested area (blue line) from temporary and permanent crops. Source: adapted from IBGE—Municipal Agricultural Production (PAM 2021)

high cost, intensive use of energy, and insecurity, while the diversity of agricultural residues is the basis for replacing the use of non-biodegradable synthetic materials.

Agriculture and food processing plants represent point and diffuse sources of agricultural waste that are difficult to control (Hanson 2014). The deficiencies of the agricultural system attract the interest of effective management, which consider the inadequate disposal of material in landfills and the distribution of space, facing the challenges of greenhouse gases and the toxic runoff of water in useful fertile land (Gomiero 2018; Onu & Mbohwa 2021a; Warner 1980; Yusuf et al. 2019). In addition to discarded nutritional and economic values, environmental, social, and cultural values are wasted. Soil, water, energy, land, logistics, and labor are heavily used up in the service of wasted food production (Biase 2017; Saath and Fachinello 2018; dos Santos et al. 2020). The deterioration of these systems imposes a time limit, and their regenerative properties are slow and cannot be boosted healthily. For Kapoor et al. (2016), since the generation of waste and by-products are consequences of all industrial sectors, just like their inadequate disposal, the study of recovery and reuse of these by-products must be disseminated.

The current degradation reveals an inadequate technology, as industrial progress must be more concerned with increasing its efficiency more than production, and the consumption scale assumes limitations to the carrying capacity (Goodland 1995). In the case of agro-industrial residues, due to their abundance, renewability, and use, they are economically and environmentally advantageous for their low density, low CO_2 emission, and biodegradability characteristics, when compared to thermoplastic polymer composites. The technology applied for conversion of agricultural biomass in products is not being realized in scale-up due to competitiveness with synthetic products (Dungani et al. 2015; Prithivirajan et al. 2015; Zeferino 2019).

Goodland (1995) emphasizes that human's dependence on agriculture will always exist, so land and other renewable sources are essential. This reflects the concerns of the Malthusian theory, addressed by Lambin (2012), that the finite stock of land and its inadequate distribution are insufficient to meet growing demand, causing a decline in welfare. Based on the work of Malthus, Moran (2011) argues that, since demographic pressure has brought about a rapid agricultural technological innovation, resulting in extensive and harmful agriculture, one should expect from its expansion to increase the level of deforestation as well. In global studies, about 12% of the global surface is used for cultivation; it is estimated that 15% of the global surface of land without ice could be converted to agricultural land, and more than 40% of the available lands were used (Foley 2005; Rockström et al. 2009).

The 2017 Agricultural Census recorded an area of 351.3 million hectares (41.3% of the national territory). The area occupied with crops, 63.5 million hectares, represents 7.5% of the territory with annual, semi-perennial, and perennial agriculture (grains, horticulture, fruit, and forestry) (Embrapa 2018; Ministério da Agricultura 2019a, 2019b). Patterson (2012) highlights that population growth of advanced per capita consumption, rising temperatures, world food, clean water, and fuel supplies are at constant risk, putting pressure on declining amounts of farmland and mineral and mineral reserves and fresh water (Patterson 2012). Salleh et al. (2021) raises the issue that natural fiber production is expected to decline due to the need for more land for food production. Fibrous material is cultivated in agriculture (animals and plants) (Tobler-Rohr 2011).

The search for more land is a threat to afforestation and increases the impacts of the climate crisis (Campbell et al. 2018; Onu and Mbohwa 2021c). Brazil faces a growth curve in planted area and harvested area in all temporary and permanent crops grown in the country (Fig. 2):

Waste from these activities is an example of an expensive and inevitable result of human activity that poses a threat to the environment, while the decrease in the supply of raw materials is also a cause for concern (Dungani et al. 2015; Sundarraj and Ranganathan 2018). The threat linked to agricultural exploration activities and the production of materials attracts the attention of both industries, in an attempt to balance habitats, protect the ecosystem, and dispose of useful land in reversing the loss of biodiversity (Macaulay 2007; Onu and Mbohwa 2021c, e).

Specific analyses reveal that the increase in temperature in Brazil can cause the reduction of suitable regions for cultivation (Bolfe et al. 2018). The protection until then economic extend to biological safety and plant biodiversity (Teixeira et al. 2015). The future of agriculture, therefore, must encompass sustainable agricultural systems, understood as the management and conservation of the natural resource base and the orientation of technological changes to ensure the achievement and satisfaction of the human needs of the present and future generations (do Bezerra and da Veiga 2000; Bolfe et al. 2018; FAO 2021c; Pinazza and Araujo 1993; Soglio and Kubo 2016; Vieira and Vieira 2019).

Recent reports by Laudes Foundations reveal that turning innovations to the responsible use of agro-waste to generate raw materials based on cellulose textiles would not require increasing cultivated land or increasing the volume of crops. Studies show that there is sufficient residue for fiber relocation and emphasize the importance of collaborative interventions in textile and agri-food systems to enable scaling of materials (Laudes Foundation 2021).

The Agro-industrial Wastes Issue

The issue of food loss and waste (FLW) is highlighted in regional, national, and international political agendas, still on the rise in Brazil (FAO 2021a; Henz and Porpino 2017; Teuber and Jensen 2020). The Committee on World Food Security (CFS) highlights the importance of FLW in the search for more sustainable and equitable food systems and societies (FAO 2015).

The dumping of agricultural waste is one of the great eminent challenges that are highly expensive, harmful to soil contamination, greenhouse gas emissions (GHG), toxic to local waters, damage to land, and compromise environmental safety and quality of life and regional food (Onu and Mbohwa 2021c; Wilts et al. 2020). According to the 2021 Food Waste Index, 931 million tons of food was wasted, and 20% of the volume belongs to Latin America, where 55% are fruits and vegetables; however, there is no consistent information on each developing country (FAO 2016; United Nations Environment Programme 2021).

The definitions of food loss and waste take different approaches. The loss of food considers the decrease in the quality or quantity of food resulting from suppliers along the harvest/slaughter/capture supply chain that is not used as feed or seed, whereas food waste is related to a decrease in the quantity or quality of food from service providers and consumers (FAO 2018; SOFA/FAO 2019, 2020).

Waste is liquid or solid materials that are generated from agricultural activities, direct consumption, or industrialization, and are not useful to the process, which assumes concepts such as reduction, reuse, and recycling (Loehr 1974; Nguyen and Schnitzer 2008; Onu and Mbohwa 2021d). Some of the influencing factors are topography, precipitation, cover crop, season, and location, and even the chemicals, cultivation practices, and fertilizers used, which make impact assessments and measurements difficult (Hanson 2014).

In large volumes, the residues are in the form of straw, stems, bark, wood, and forest residues, and commonly occupy land in the form of disposal by burning, which allows the start of fires and the proliferation of diseases. Residues and by-products are rich in lignocellulosic materials that can be recovered through chemical, physical, and biotechnological treatments (Bigdeloo et al. 2021; Dietrich et al. 2016; Scarlat et al. 2010).

Five segments classify the types of FLW, namely the following: (i) agricultural production (mechanical damage and harvesting operations); (ii) post-harvest handling and storage (spill and degradation); (iii) processing (industrial and domestic); (iv) distribution (market and retail systems); and (v) consumption (household) (FAO 2011). Considerations involve FL as unintentional reduction of food available for human consumption as a result of inefficiency in the production and supply chain, and FW to the intentional disposal of food items, particularly by retailers and consumers (CEDES 2018). Groups can also be divided into food losses (during processing); unavoidable (perish during the consumption stage, e.g., husks and pits); and avoidable (suitable for food, but wasted in the period of human consumption) (Ahmad et al. 2021) (Table 1).

About 45% of fruit and vegetable biomass is wasted during agriculture, post-harvest, processing, distribution, and consumption. Residues such as fruits and vegetables can be considered valuable raw materials, as they are produced in large quantities all over the world (Dietrich et al. 2016).

Losses and waste are classified into four categories along the supply chain: (i) primary and post-harvest production; (ii) processing and manufacturing; (iii) wholesale, food retail, service, and distribution; and (iv) consumption or household waste (WRAP 2009). For Six et al. (2016), biomass recovery can be divided into groups of direct use (unchanged), material recovery (biochemical extraction, conversion of biomass and useful products), and energy recovery (biogas/energy content). Developing countries,

Table 1 Definitions for food losses/waste in supply chain

Food loss			Waste of food	
Production	Postharvest and storage	Processing	Distribution, Retail	Consumption
Loss occurs during and shortly after the harvest	Loss occurs during handling, drying, local/regional transport, and storage	The loss occurs during processing and local or industrial treatment and packaging	The waste occurs during the market and retail systems	The waste occurs at household and consumption levels

Source: adapted from Ruviaro et al. (2020)

such as Brazil, face a higher rate of waste in the primary stages (FAO 2020; Henz and Porpino 2017; Júnior 2020).

There is insufficient world data on the edible fraction of food waste (UNEP 2021), although fruit processing residues, as parts of the entire food waste processing sector, such as bagasse (peel, seed, and pulp), bark, seeds, and stems can be considered unavoidable residues (Kavitha et al. 2020; Kosseva 2020b, 2020a). Currently, the methods used in FW organizations are animal feed, mainly composed of organic fertilizer, anaerobic use, carbonization, and landfill; no method has been supported for the ecologically correct use of FW. Therefore, FW can be used in the production of biocomposites using sustainable FW management methods (Blakeney 2019). For Dai et al. (2018), lignocellulosic biomass resources do not affect the food supply chain.

Brazil follows a waste management structure similar to developed countries (Nascimento et al. 2015). The Brazilian Solid Waste Plan (PNRS), law n. 2305/2010, valid since 2010, prioritizes non-generation, reduction, reuse, recycling, waste treatment, and, finally, the final disposal of waste. In theory, all the possibilities of recovering available and economically viable technologies were considered (BRASIL 2010; Henz and Porpino 2017; Nascimento et al. 2015).

Efforts are aimed at reducing the amount of waste according to the stipulated hierarchy, a large amount of unavoidable waste remains being generated. Therefore, agricultural innovation should apply sustainability at different levels and structures. Sustainable agriculture can facilitate technological integration and facilitate the production and processing of food as fiber and green resources, as greater knowledge of processes becomes presuppositions for significant advances (Onu and Mbohwa 2021e, 2021a; Shahid-ul-Islam et al. 2013).

Taking into account the growing scarcity of ecosystem services, the question would be how to reallocate the structure between the raw materials needed for production and survival. Otherwise, allocation strategies must be judged for their sustainability, fairness, and efficiency (Farley 2010).

Agro-industrial Waste and Industrial Ecology for Materials Circularity

Sustainability has multifaceted concepts (Salleh et al. 2021). The Science of Sustainability affirms the need to be able to integrate such a range of temporal scales (Becker 2014). Sustainable development is defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Keeble 1988). The Brundtland report also highlights an interest in three main pillars: (i) environmental preservation; (ii) social equity; and (iii) economic growth (Akiyode et al. 2017). In 2015, the Sustainable Development Goals (SDGs) were re-adopted to address climate change and environmental protection,

divided into 17 goals that address social and economic issues. These are directly linked to sustainable industry, infrastructure, clean energy, and responsible consumption and production, which relate to the efficient use of natural resources and reduction of waste (Ishak et al. 2021). The promoted actions by World Summit on Sustainable Development in 2000 reveal that resource management and distribution are approaches to controlling global depletion in ecosystem conservation (Onu and Mbohwa 2021b). Regarding the 2030 Agenda with a focus on food and agriculture transformation, the 2nd key principle for sustainability is "protecting and enhancing natural resources," which includes "improving soil health and restoring the land; protect water and manage scarcity; conserve biodiversity and protect ecosystem functions; reduce losses and encourage reuse and recycling and promote sustainable consumption" (FAO 2018, p.18). Onu and Mbohwa (2021d) highlight that all Sustainable Development Goals (SDG) centers contribute resources to these biodiversification opportunities.

The life cycle of textile products is one of the shortest due to the logic of the fashion industry (Lopes et al. 2021). The linear model of the textile industry causes restrictions in the supply of products and high costs and environmental risks (Gardetti 2018; Senthil Kumar and Femina Carolin 2018). Industrial systems follow the context of open flow, that is, the use of materials and energy that generate non-usable waste. The current situation does not yet cover the closing of the cycle efficiently (Coste-Maniere et al. 2018). Biofibers are among the most researched and demanded materials in the twenty-first century (Nishino 2017). Studies reveal that mentions of sustainability have increased. For two-thirds of respondents, sustainability has become a priority in combating climate change after COVID-19 (Arici and Lehmann 2020; Lehmann et al. 2019; Wong et al. 2021). For Textile Exchange Institution (2019), the textile industry acts primarily in 14 of the 17 UN SDGs (Textile Exchange 2019).

Industrial ecology definitions comprise similar attributes and different emphases (Clift and Druckman 2015). Among these, El-haggar (2007a, b, c, d) highlights, in short, a systemic and balanced view of the interactions between industrial and ecological systems, based on the study of flows and transformations of materials and energies, as an ideal model for the management of natural resources and waste industrial. Cooperation between industrial processes and environmental sustainability (El-Haggar 2007c, d). Authors talk about industrial ecology integrating the circular economy in search of eco-efficiency.

Ayres (2002) exemplifies the field of Industrial Ecology as an enhancer, which can highlight the importance of efficient biogeochemical cycles through concepts, metaphors, applications, and analyses, comprising technological knowledge and environmentally informed processes for this purpose. The author identifies that the study of material flows as raw materials has a great contribution to the development of types of efficiency and cycling of materials already produced by natural ecosystems (Ayres 2002). Ayres (2002) exemplifies the field of Industrial Ecology as an enhancer, which can highlight the importance of efficient biogeochemical cycles through concepts, metaphors, applications, and analyses, including technological knowledge and environmentally informed processes for this purpose. The author confirmed that the study of material flows as raw materials has a great contribution to the development of types of efficiency and cycling of materials already produced by natural ecosystems (Giannetti and Almeida 2006).

Thus, adding value to agro-waste by converting it into useful products is currently one of the main areas of basic laboratory research, and will soon reach an economic potential that can collaborate with green technologies (Kapoor et al. 2016).

Efforts are aimed at reducing the amount of waste according to the stipulated hierarchy, a large amount of unavoidable waste remains being generated. Therefore, agricultural innovation should apply sustainability at different levels and structures. Sustainable agriculture can facilitate technological integration and facilitate the production and processing of food as fiber and green resources, as greater knowledge of processes becomes presuppositions for significant advances (Barker and McLemore 2005; Onu and Mbohwa 2021e, 2021a; Shahid-ul-Islam et al. 2013).

Taking into account the growing scarcity of ecosystem services, the question would be how to reallocate the structure between the raw materials needed for production and survival. Otherwise, allocation strategies must be judged for their sustainability, fairness, and efficiency (Farley 2010). Regarding the 2030 Agenda with a focus on food and agriculture transformation, the 2nd key principle for sustainability is "protecting and enhancing natural resources", which includes "improving soil health and restoring the land; protect water and manage scarcity; conserve biodiversity and protect ecosystem functions; reduce losses and encourage reuse and recycling and promote sustainable consumption" (FAO 2018, p.18). Onu and Mbohwa (2021d) highlight that all Sustainable Development Goals (SDG) centers contribute resources to these biodiversification opportunities. Target 12.3 addresses the issue of food waste and loss, which contributes not only to SDG 12, but also SDGs SDG 2 ("Zero hunger and sustainable agriculture"), 6 ("Drinking water and sanitation"), 13 ("Action against global climate change"), 14 ("Life in the water"), and 15 ("Terrestrial life") (Filho et al. 2021).

For Barket (2005), the difficulty in finding new sources of raw material while the safe disposal of waste is scarce, makes hierarchy and the total use of waste a necessity. Minimization is a priority in the hierarchy of waste management strategies, rather than treating the end of the tube; however,

there is no economic incentive and technology available, turning the importance of waste recovery as opportunities for sustainability (Herrero et al. 2020; Sillanpää and Ncibi 2019c).

The LCA methodology can define the main impact areas, assess potential environmental threats, make environmental decisions, and ensure the labeling and ecological certification of textiles (Eryuruk 2015). For Laudes Foundation (2021), conscious sourcing decisions contribute to help farmers, agricultural communities, and the textile industry to achieve greater sustainability, ensuring a possible balance of resources and people (Laudes Foundation 2021).

By-products from the food industry can be seen as waste or resources when recovery technologies are implemented (Herrero et al. 2020). However, the reprocessing of organic matter does not include the recovery of energy used in the recycling process (Wiesmeth 2021). For this, the concepts of circularity become restricted when focused only on waste management (Sillanpää and Ncibi 2019b, 2019a, c). Therefore, sustainable development represents a shared commitment to stable economic growth in the satisfactory and available management of resources. The allocation of these resources can be solidly directed to ensure new supplies (El-Haggar 2007a; Vivien 2011).

Brazilian Biomass Scenario

According to the Confederation of Agriculture and Livestock of Brazil (CNA), agribusiness is recognized as a great vector of expansion and Brazilian economic growth (CNA 2020). The agricultural productive harvest forecasts a record increase of 2.5% for Brazil in 2021 (IBGE 2021). Its abundance is the result of increased activity in the modern agricultural sector, which annually wastes 1.3 billion tons of food along the production chain (FAO 2013; Zaro 2018). Agroindustry accounts for approximately 5.9% of the Brazilian gross domestic product (GDP), promoting integration with the economy (EMBRAPA 2020; Torrezan et al. 2017).

The "Panorama of Solid Waste in Brazil 2020" by the Brazilian Association of Public Cleaning and Special Waste Companies (ABRELPE) highlights that organic matter comprises 45.3% of the total solid waste generated in 2020, approximately 170 kg discarded per person/year, and it is estimated that this waste will increase 50% by the year 2050 (ABRELPE 2020). In contrast, this report reveals that the total amount of waste generation and final destination remain inadequate, growing respectively 19% and 16%, even after the implementation of the Brazilian PNRS in 2010, which institutes the plan for integrated management, responsibility, and economic instrumentation applicable to solid waste (ABRELPE 2020; de Campos and Goulart 2017; Freiria 2011).

Table 2 Data about the main Brazilian temporary crops

Temporary crops	Waste, million/ton	Residual factor
Soybeans (grain)	41,862,129	73%
Corn (grain)	29,432,678	58% (straw and cob)
Sugar cane	201,418,487	30%
Beans (grain)	1,847,984	53%
Rice (paddy)	2,530,355	20%
Wheat (grain)	3,033,315	60%
Cassava	23,786,281	-

Sources: adapted from ABIB (2011), Matos (2005), Schneider et al. (2012), and Silva et al. (2007)

Table 3 Data about the main Brazilian permanent crops

Permanent crops	Waste, million/ton	Residual factor
Coffee (beans)	1.220.029	45-55% (husks and straw)
Cocoa (beans)	83.025	38%
Banana (bunches)	99.640	50% (husks and stalks)
Orange	8.825.276	50%
Coconut	405.009	60%
Cashew nuts	80.484	73%
Grapes	300.459	40%

Sources: adapted from ABIB (2011), Mello (2006), RezzadoriI and Benedetti (2009), Silva et al. (2009), and Vale (2007)

Biomass was defined as "any material, excluding fossil fuel, which was a living organism that could be used as fuel directly or after a conversion process" (ASTM 1995). According to EMBRAPA, Brazil is responsible for 140 gigatons of agro-industrial residues, in which there are different types of biomasses of heterogeneous chemical composition from different physical states, such as oily biomass, saccharide biomass, and starchy and lignocellulosic biomass, which is more abundant (Júnior 2020). Worldwide, the main crops responsible for agricultural residues are rice, wheat, cotton, and corn (El-Haggar 2007b).

Therefore, the report by the Institute of Applied Economic Research (IPEA) of Organic Waste (2012) was based on 7 temporary crops (Table 2) and 7 permanent crops (Table 3), which are the greatest representation ones in Brazil. Among the permanent crops, the following were selected: coffee (beans), cocoa (almonds), bananas (bunch), oranges, coconuts, cashew nuts, and grapes. For the temporary crops, in turn, the following were selected: soy (in grain), corn (in grain), sugar cane, beans (in grain), rice (in husk), wheat (in grain), and cassava. It highlights that these 14 largest crops in the country produce a total of 291.1 million tons of waste per year (Schneider et al. 2012).

According Table 2, only soybean crops correspond to 49% of the planted area in Brazil, producing about 2,700

tons of residues for every 1 thousand processed grains; around 73% of residues are generated from processing (MATOS 2005; Schneider et al. 2012). This percentage is visible for each crop in Tables 2 and 3. Sugarcane crops stand out, distinguishing residues in liquid vinasse, filter cake, and bagasse. There is no estimate of percentage of waste generation for cassava crops.

The Systematic Survey of Agricultural Production (LSPA) by period (April 2021) highlights that the average yield per harvest of these main selected crops presents a stable growth variation in the country's agribusiness, which consequently projects a greater number of residues than those currently presented in Tables 2 and 3: according to productive amounts, respectively, sugar cane (654,727,996); cereals, pulses, and oilseeds (264,453,928); soybean (131,927,408); corn (^{1st} crop 25,771,50/2nd crop 76,727,987); cassava (18,708,437); orange (18,708,437); rice (11,081,650); wheat (7,394,918); banana (6,915,259); beans (1st crop 1,281,098/2nd crop 1,111,999/3rd crop 562,935); Arabica coffee and canephora coffee (2,820,596); grapes (1,416,398) and cocoa (280,661). There is no data for "coco-da-baía" (Brazilian coconut varieties) crops (LSPA/IBGE 2021). In network analysis, it is possible to observe the large incidence of these crops (Fig. 3).

Through the network analysis, it is possible to observe the scientific advances in Brazil regarding the main materials used, formats, and applicability. The main agro-waste correlated terms in intensity are as follows: "sugar cane," "fruit," "soy straw," "cassava," and "rice." The main formats indicated are for "bagasse," "biomass," "fiber," "nanocrystals," and "polymer." The main applicability involves "absorption," "enzymes," "wastewater," "textile fibers," and "ethanol." There is a great interest in the study of the physicochemical performance of materials, paying attention to the number of researches involving "crystallinity," "pH," "mechanical properties," "chemical composition," and "thermogravimetry."

The term "cellulose" is the most used term with full link strength of 3098 and 108 co-occurrences, while "lignin" is linked in 1245 and 38 co-occurrences, which demonstrate the interest in biomass supply and possible inclusion of lignin studies for product development, adhering to terms such as "Cellulose derivates," "nanocellulose," "cellulose nanocrystals," and "particle size." The term "Textile Industry" is only presented in 10 co-occurrences, with total link

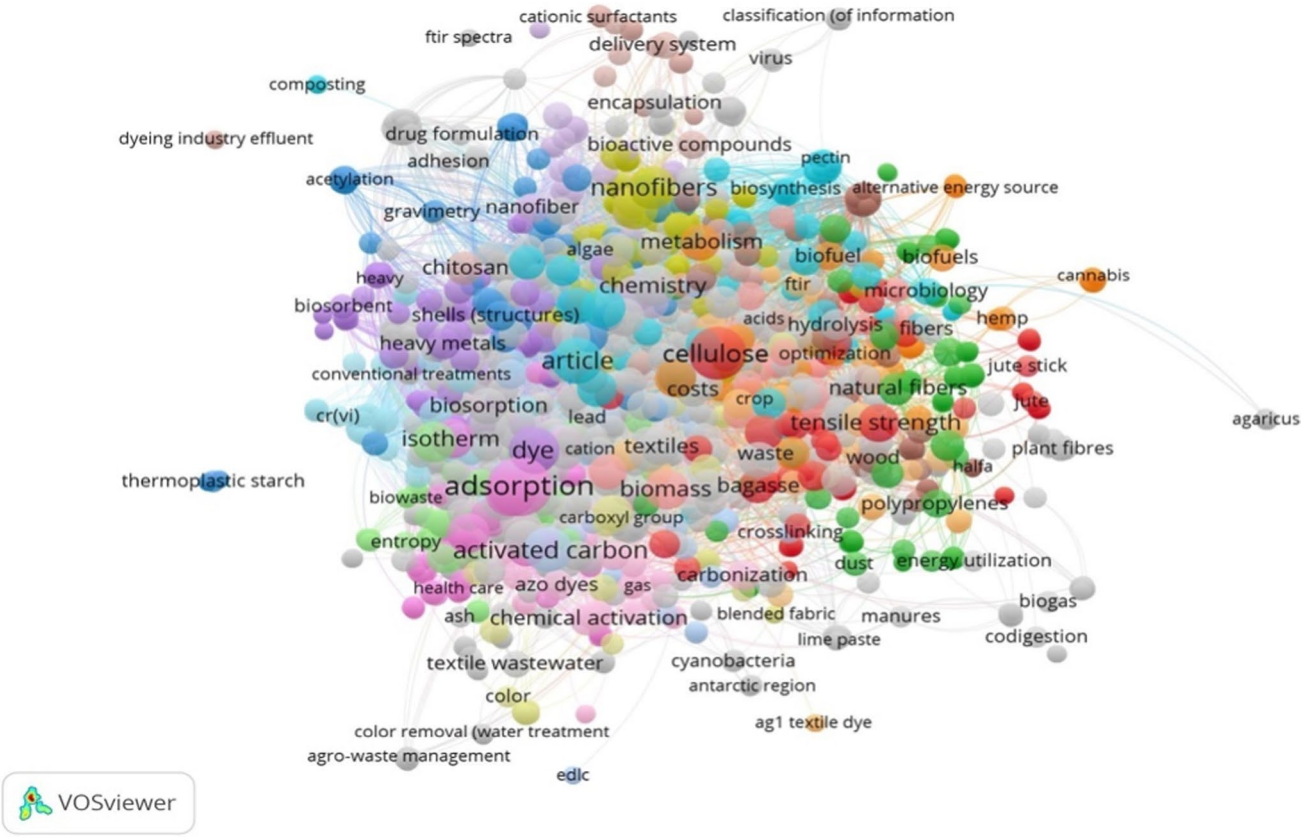

Fig. 3 Scientific literature database network built with VOSviewer software (*Universiteit Leiden*) through the analysis of 305 articles and co-occurrence of 2,496 specific expressions. Source: authors

strength at 425 in the document, while the term "textile fibers" has 12 occurrences and 384 total links, and "textile," has only 273 links to the name, and 8 co-occurrences, showing a small impact on the Brazilian textile industrial scenario in scaling materials.

The Brazilian Agroindustry Profile Report of the Institute for Applied Economic Research (IPEA) states that the inventories of existing products, material flows, and the functioning of circuits are still some of the challenges found in its main structure (IPEA 2013), although, according Organic Waste Report, wastes from the country's main crops present distributive potential and Brazilian legal support for reverse logistics projects (Schneider et al. 2012).

The Application of Agro-industrial Wastes in Textile and Other By-products in Brazil

The water content, pathogenic potential, and biological instability make the disposal of waste difficult to control, directing it generally to animal feed (Dietrich et al. 2016). In the same way, the administration of large residues leads agrarian communities to opt for low-cost and low-effort options, such as burning to clear the scums for the next harvests (Textile Horizons International 1993). The content of organic matter prioritizes its application on 4 main fronts: (i) animal fodder; (ii) briquetting; (iii) biogas; and (iv) composting; moreover, there is a surplus input for exploration in other industrial applications (El-Haggar 2007b). One of the main difficulties in the converting process of biomass into products is the transport and storage protocol, in addition to the knowledge of the operational techniques that should be applied (Onu and Mbohwa 2021b). For Laudes Foundation (2021), the domestic uses such as forage, animal bedding, mulch, and compost use a small part of the waste. Among the benefits of using waste materials are the protection and maintenance of natural resources, protection of human health, and reduction in resource extraction (Ahmad et al. 2021).

The world's largest production crops such as sugarcane, corn, rice, and wheat are in discussion as food and fuel commodities as well as due to their important source of hemicellulose and lignocellulose for industrial manufacture. Waste treatment and disposal are only part of agricultural waste management systems (Loehr 1974). For Shishoo (2007) and Yu (2009), agricultural-based fibers should present special quality criteria as follows: strengthening potential (strength), stiffness, wear resistance, brittleness, moisture-related properties (aging, dimensional stability, swelling), heat stability, purity, resistance to microorganisms, non-odor, resistance to chemicals, etc.

The use of solid potential fibers, lack resilience and have low elasticity and elongation potential, being mixed with other sources of natural fibers can have better performance (Laudes Foundation 2021; Salleh et al. 2021). Some textile innovations such as Orange Fiber, Green Whisper, AltMat (Fig. 4), and Agraloop, in collaboration with Fashion For Good, enable alternatives through bio-based products, processes, and technologies in the production of fibers from pineapple, hemp, banana stem, fruit residues citrus, and food crops for textile and clothing manufacturing (FFG 2021; Laudes Foundation 2021).

Sharma et al. (2016) highlight that fruit and vegetable wastes mainly contain soluble materials and fibers, but they are the most commonly discarded in landfills and rot in industrial and retail establishments. Vegetables, cereals, roots and tubers, and fruits are the most promising resources for value-added production (Galanakis 2012).

The adaptation of fibers to consumption needs, in order to be employed in conventional technologies and applications, has increased tremendously their market potential

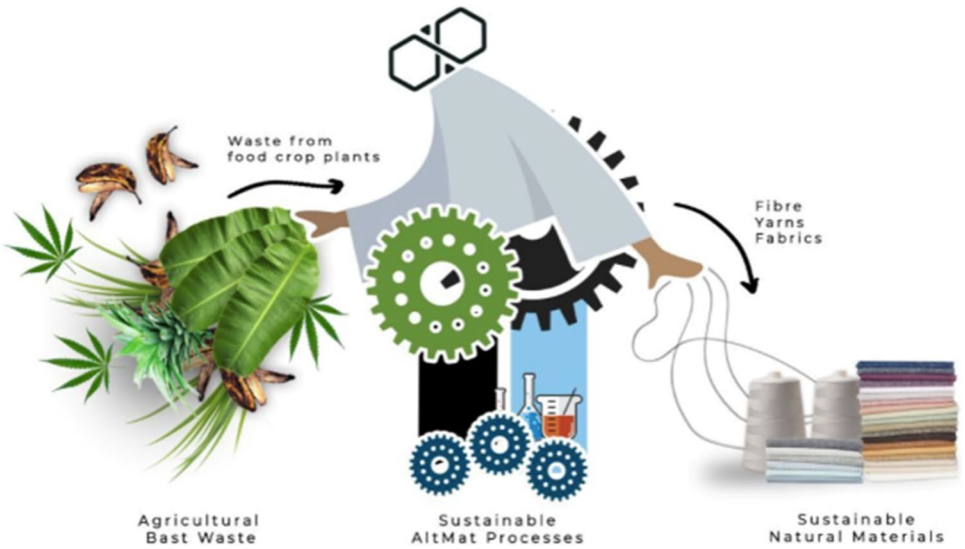

Fig. 4 AltMat representation processes. Source: AltMat (2021)

(Narasimhan et al. 2016). Depending on the extraction methods, fibers can be prepared in various forms, such as long continuous fibers, processed fibers, short-staple fibers, and powdered microfibers or nanometric fibers. The most common source of natural fiber reinforcement extraction is from stems (bast fibers), while leaves are the least reported in previous studies (Izwan et al. 2021). Worldwide, residues such as corn husks, rice, sorghum stalk and leaves, banana leaves, pineapple leaves, and others have been studied to develop new cellulose fibers with similar mechanical properties as those of common textile fibers (Reddy and Yang 2005, 2009). Companies that embrace the concept of circularity of materials claim that banana crops, pineapple leaves, rice straws, and sugarcane husks together can provide more than 250 million tons of fiber per year, meeting 2.5 times the world demand for fibers (Biomimicry 2020).

In Brazilian scenario, agribusiness has gained great notoriety in the context of studies and political-economic-institutional focus (ABRA 2013). There is a movement of research in the country in order to create viable alternatives for the relocation of waste. According the Brazilian Agricultural Research Corporation (EMBRAPA), the industrial processing of agricultural biomass from waste can be distributed in the generation of materials (polymers, resins, and fibers), energy, food and animal feed, chemical inputs (biofertilizers, surfactants, esters, acids organic), and biofuels (ethanol, biodiesel, and biogas) (Júnior 2020).

Soy straw, in particular, is an abundant and renewable form of biomass with enormous potential as a cheap and sustainable source. According to Martelli-Tosi et al. (2017), soy is a very significant agricultural commodity (Martelli-Tosi et al. 2017). However, its application in by-products is mainly used for rural energy, animal feed, and disposal in the field (Liu et al. 2015). Araújo et al. (2019), evaluating parameters, which consider the chemical composition, growth rate, and disposition, state that soy straw is the most suitable residue to be used as raw material for the production of cellulosic-based materials, followed by sugarcane leaf, corn husk, sugarcane straw, and bagasse, revealing that the main crops in the country are the most suitable residually.

Mustafa et al. (2021) highlights that agropolymers from agricultural residues such as starch and cellulose derivatives can be efficiently regulated by natural or chemical mechanisms for the development of green materials, highlighting the use of biofibers in structural performance as a significant reinforcement. Currently, natural fiber reinforcement composites are used in advancing technologies due to their low density, light weight and good mechanical strength, and ecological characteristics (Ahmad et al. 2021; Benyus 1997) (Fig. 5).

For Ahmad et al. (2021), the advantages of using natural fiber in thermoplastic composites are as follows: (i) biodegradability; (ii) lower greenhouse gas emissions; (iii) availability in variety and format; (iv) job creation in rural areas; (v) non-linear economic development; (vi) efficient and (vii) economical energy consumption. The growing interest in technical lignins, by-products of cellulose, as a polymeric material is also due to their large-scale availability and biodegradability. These can play different roles in promoting and regulating adhesives, fillers, and reinforcing agents in engineering, replacing synthetic fixed terms (Lapsa et al. 2000).

The economic and technological advantages of lignocellulosic fibers can increase the durability and also

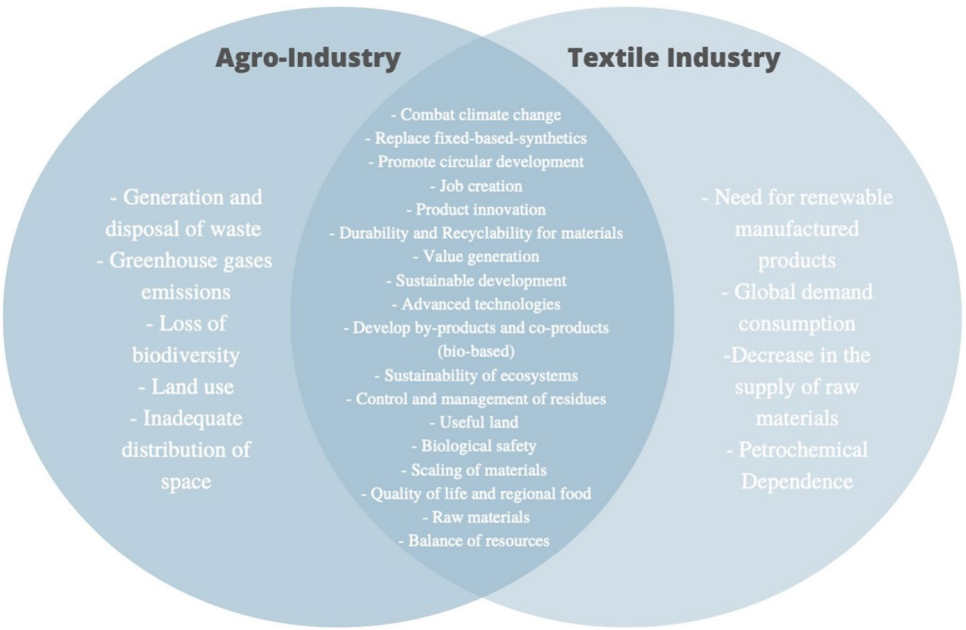

Fig. 5 Economic beneficial factors to the conversion of agro-industrial waste into textile raw material. Source: partially adapted from Circular Systems (2020), Dungani et al. (2015), Gomiero (2018), Laudes Foundation (2021), Onu and Mbohwa (2021a, b), Sundarraj and Ranganathan (2018), Teixeira et al. (2015), Wilts et al. (2020), and Yusuf et al. (2019) and partially authors

recyclability of incorporated products, leading to sustainable development (Mustafa et al. 2021). Fibers based on agricultural residues are promising innovations and can meet dual objectives, in the solution to the search for alternatives in the fashion industry and, in parallel, a path for millions of farmers who burn their agricultural residues and generate dangerous levels of emissions (LOUDES FOUNDATION 2021) (Fig. 5).

Scientific Literature Database Diagram on Agro-industrial Materials' Researches

The same network database was used to develop a diagram focusing on the highest incidence of materials citations by classification and types, crops, formats, conversion technology, and end-of-use researches (Fig. 6).

Sugarcane is the largest incidence term from studies in the analyzed database (Fig. 6). Brazil tightly generates bioenergy and bioethanol from sugarcane. Studies show the growing and improvements in these processes, employing bagasse, straw, and fibers from the residual material (Aguiar et al. 2021; Alarcon et al. 2021; Barbosa et al. 2020; Canilha et al. 2012; Giese et al. 2012; Soares et al. 2020). In bagasse format, sugarcane presents a greater diversity of technology conversions for applicability for final use of cellulose nanocrystals (Fig. 6) (Bilatto et al. 2020; de Oliveira Júnior et al. 2020; Leão et al. 2017, 2020; Oliveira et al. 2016; Pereira and Arantes 2018, 2020). Figure 6 also highlights studies in which the plant works as a matrix for other textile fibers such as sisal for new biodegradable composites (de Castro et al. 2021; Satyanarayana et al. 2009); fibers are commonly used for reinforcement in composites (Cardoso et al. 2017; De Lemos et al. 2017; Dos Santos et al. 2018; Ferreira et al. 2019; Mulinari et al. 2012); production of multifunctional biocatalysts (Bilal et al. 2020; Silveira et al. 2014a, b); enzymes such as peroxidase (Queiroz et al. 2018), amylase (Orlandelli et al. 2017), cellulase (Do Nascimento and Coelho 2011), hemicellulase (Camassola & Dillon 2007), and xylanase (L. A. Oliveira et al. 2006); and dye adsorption (Cunha et al. 2018; B. C. S. Ferreira et al. 2015; Giusto et al. 2017; Meili et al. 2019; Piffer et al. 2020). In addition, Costa et al. (2015) highlight the use of sugarcane as a material suitable for textile application and the development of bioproducts.

Soybean, the main cultivated area in Brazil, presents husks and straw in its main format (Fig. 6): functioning like a chemical adsorbent (de Souza et al. 2021); bioenergy (De Pretto et al. 2018); biomaterials (Rosa et al. 2015); and

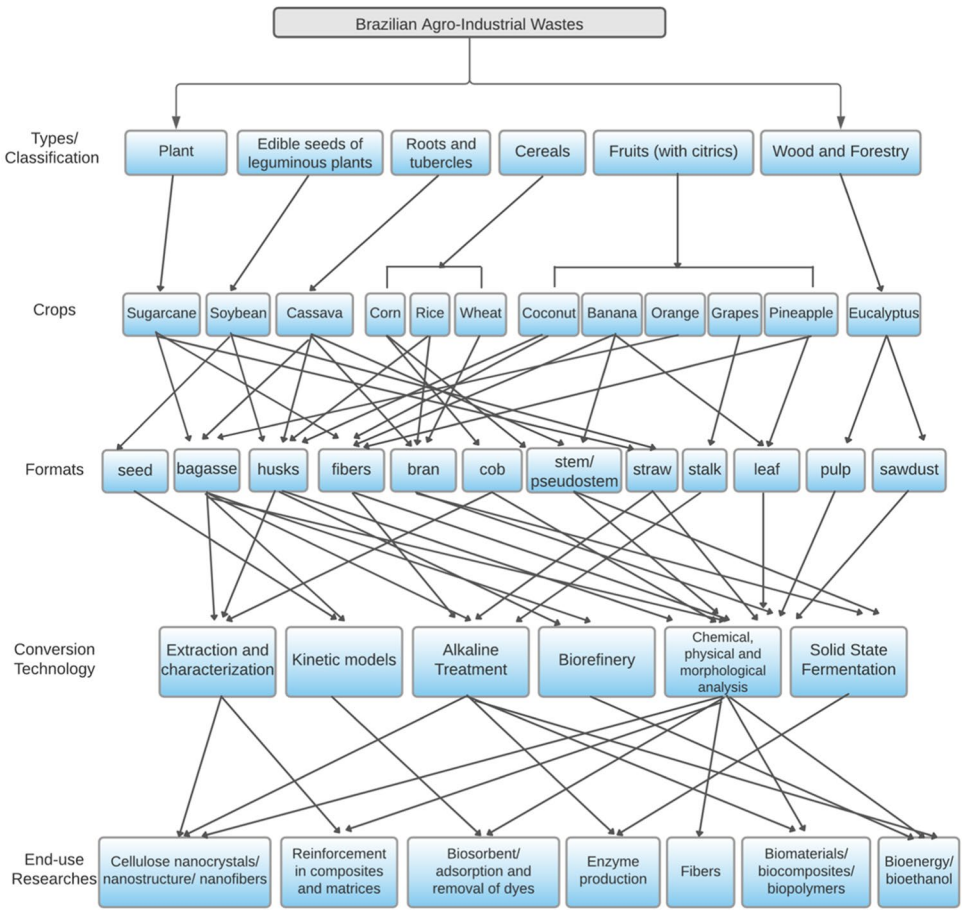

Fig. 6 Scientific literature database diagram focusing on the highest incidence of agro-industrial materials citations by classification and types, crops, formats, conversion technology, and end-of-use researches. Source: partially adapted from Onu and Mbohwa (2021b) and partially authors

cellulose (Souza et al. 2020), in particular, nanofibrillated cellulose (Debiagi et al. 2020; Flauzino Neto et al. 2013; Martelli-Tosi et al. 2016). One of the highlights is its potential for composites and films (Martelli-Tosi et al. 2017).

Cassava presents its main formats in husks, stems, and leaves for the following: the generation of bioenergy (Cruz et al. 2021); a substrate for composites (de Lima et al. 2020); a generator of cellulose nanocrystals (Czaikoski et al. 2020; Travalini et al. 2018); biosorbent (de Oliveira et al. 2019a, b); and enzyme production (Oliveira et al. 2006) (Fig. 6).

In the cereals group, corn presents the main format as a cob and stem. Its main applications are as follows: adsorption material (Campos et al. 2020); to obtain cellulose (Araújo et al. 2020; Ditzel et al. 2017; Longaresi et al. 2019; Souza and Quadri 2014); biocatalysts (Bilal et al. 2020); green composites (Ramos et al. 2019); reinforcement polymers (Coiado et al. 2017; Silvério et al. 2013); and enzyme productor (Grigorevski-Lima et al. 2009; Orlandelli et al. 2017). Rice, on the other hand, is presented in the form of husks and husk bran from the cultivation. Its main applications are the following: to obtain cellulose nanocrystals (Hafemann et al. 2020); enzymes (Gautério et al. 2020); adsorption of violet dyes in textile industry (Ribeiro et al. 2017); and biodegradable composites (Pereira et al. 2015). Wheat term appears less frequently, but it presents unique bran format for applications: in enzyme production (Camassola and Dillon 2007; Do Nascimento and Coelho 2011; Grigorevski-Lima et al. 2009; Orlandelli et al. 2017) and composites (Pereira et al. 2015) (Fig. 6).

The fruit group contains also the citrus fruits. The study by Alarcon et al. (2021) mentions coconut and banana as references to textile fibers and their application to composites and polymeric films. The fermented banana pseudostem and coconut fiber are potential producers of lipase and cellulase (Ferreira da Silva et al. 2019) and nano crystallized cellulose (Pereira et al. 2014). Coconut husk fibers, which represent a large amount of material mass, present applicability as follows: biosorbent for textile dyes (Carvalho Costa et al. 2020; de Oliveira et al. 2018b, a; Merci et al. 2019; Lopes et al. 2020), and bioenergy and cellulosic ethanol (Gonçalves et al. 2014, 2019). The applicability with this fiber involves crafts (Nunes et al. 2020), green composites (Lomelí-Ramírez et al. 2018), and copolymers (Rosa et al. 2009), in particular, for the removal of chromium from tannery effluents (Cunha et al. 2018). Orange term presents the greatest intensity of studies with the pomace, for the generation of nanofibers (Miranda et al. 2019), nanocellulose (Mariño et al. 2018, 2016), and adsorbent of dyes (Nascimento et al. 2014). The grape appears with its research in the stalk, in the development of polymeric composites (Borsoi et al. 2020; Taurino et al. 2020), and removal of blue and brown textile dyes (Benvenuti et al. 2020; Oliveira et al. 2018b, a). Pineapple has great potential for studies in the textile sector. Applications such as cellulose fibers and nanofibers from their residual crowns have been increasingly developed (Pereira et al. 2021; Prado et al. 2020; Prado and Spinacé 2019), and the use of fibers from the sheets for reinforcement mechanics in polymer composites (de Azêvedo et al. 2021; Leão et al. 2015; Sena Neto et al. 2015). Leao et al. (2010) highlighted the textile fibers from their sheets as the future of industrial applications (Fig. 6).

Sawdust from eucalyptus wood provides a biosorbent for removing textile dyes such as methylene blue (Cemin et al. 2021), and its pulp, cellulose nanofibrils (Camani et al. 2020; Demuner et al. 2020; Siqueira et al. 2019) (Fig. 6).

Other fruits, not shown in the diagram, stand out, such as apple, khaki, avocado, and pomegranate for the removal of dyes (Bazzo et al. 2016; Bonetto et al. 2021; Silveira et al. 2014a, b); the seeds of açai in the adsorption and obtaining of fibers and application in composites (de Oliveira et al. 2019a, b; Wataya et al. 2016, 2015; Zavarize 2021); cashew and acerola for bionanocomposites (Duarte et al. 2015; Vieira Amorim et al. 2021); cocoa husks for cellulose nanofiber (Souza et al. 2019); and papaya and mango for the generation of enzymes for the textile industry (Okino-Delgado et al. 2018). The cereal group also presents incidence of moreover materials, such as oat husks for the generation of nanofibrillated cellulose (Debiagi et al. 2021). Tubers such as sweet potato also demonstrate to have composite potential (Pereira et al. 2017). The group of nuts, which are not identified in the diagram, contains pecan nutshells for biosorption of cationic dyes (Georgin et al. 2018; Pang et al. 2019). Peanut husks stand out from the oleaginous grain in dye adsorption research (Nascimento et al. 2014; Villar da Gama et al. 2018). Coffee beans, which are not very evident, act as reinforcing recycled polymers (Coiado et al. 2017).

According to all analyzed studies, the technology conversions are diverse: preliminary analysis of the chemical, physical, and morphological structure is the most used in materials, added to thermal, rheological, and mechanical ones; alkaline treatment in synergy with spectroscopy, ultrasound, bleaching, hydrothermal, and chemical/acid treatment; extraction and characterization, on the other hand, appear as chemical sequential and moderate; kinetic analysis in examples with pseudo-first and second-order models, pyrolysis, and combustion; solid-state fermentation was mentioned the most, but the data includes submerged fermentation with hydrolysis; the biorefinery includes a set of general analyses that are not in-depth in the present study (Fig. 6).

Conclusion

Efficient management, based on sustainable criteria, of agro-industry wastes, requires urgent programs to evaluate methods and new possibilities in the short and long term. The

development of appropriate technologies for these processes reduces the sector's negative impacts and increases its eco-efficiency, generating ecological benefits on several fronts, from land use and waste, as well as greater management of the extraction of non-renewable resources.

All reported results contributed to a preliminary understanding of the potential use of agro-industrial waste in the generation of industrial textile products in agreement with other industries. The employment of fibers from residual agricultural biomass is a cheap, accessible, and widely available alternative, constituting a model for adding economic value to the agro-industrial chains of the Brazilian main crops.

The analysis of the scientific literature database reveals that research on the recovery and relocation of agro-industrial materials in the textile industry still shows incipient advances in Brazil. The main areas identified address materials such as dye biosorbents from industrial effluents and reinforcement material in composites. In general, researches on natural fibers represent further advances in sugarcane, coconut, banana, and pineapple, which are already employed as fibers in these studies. Materials such as açai, rice, wheat, and corn are highlighted for obtaining the raw fiber of the material, especially for reinforcing composites. Furthermore, all other agro-industrial materials are investigated to obtain cellulose nanofibers.

Sugarcane has a higher incidence in the analyzed studies, presenting a greater diversity of formats and implemented technologies compared to other materials. Despite the largest area of productive land being devoted to soy in Brazil, the waste is devoted only to absorbents, biomaterials, and cellulose nanofibers. Fibers are commonly used as reinforcement in composites, biodegradable composites, and film production. Due to preliminary studies and material knowledge, there is little scalability of materials for the market and industry at the moment, but great potential for product development due to analyzed properties. The studies that highlight the transfer of technology to the Brazilian textile industry involve materials such as sugar cane, corn, rice, coconut, banana, pineapple, and acai seeds in the production of fibers and application in green composites. Those fibers stand out due to their intense abundance of residues, and their physicochemical properties of high quality, low cost, and biodegradability The industrial applicability of fibers in Brazil is small, almost null in the textile sector, while availability is growing.

The researches directed to the textile industry present a larger incidence focused on treating effluents than applied to new materials, constituting scientific opportunities. Thus, scientific investment in researches on materials and technology development are necessary to provide applications that could meet current and future demands and expand the scope of new materials for sustainability.

Acknowledgements The authors gratefully acknowledge CAPES (Coordination for the Improvement of Higher Education Personnel of Brazilian Education Ministry).

Author Contribution The authors MUS, BC, PRBF, RRS, PUS, and JBR carried out documentation process and design of the study. Material preparation, data collection and analysis were performed by MUS, BC, PRBF, and RRS. The manuscript was written by MUS, while BC, PRBF, RRS, PUS, and JBR reviewed critically all versions of the manuscript. Supervision was performed by JBR. All authors MUS, BC, PRBF, RRS, PUS, and JBR read and approved the final manuscript.

Availability of Data and Materials All data generated or analyzed during this study are included in this published article, more information is available with the corresponding author on reasonable request.

Declarations

Competing Interests The authors declare no competing interests.

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