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Review

Revolutionizing Sustainable Nonwoven Fabrics: The Potential Use of Agricultural Waste and Natural Fibres for Nonwoven Fabric

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Abstract: There has been a growing interest in recycling and upcycling different waste streams due to concerns for environmental protection. This has prompted the desire to develop circular economies and optimize the utilization of bioresources for different industrial sectors. Turning agricultural and forestry waste streams into high-performance materials is a promising and meaningful strategy for creating value-added materials. Lignocellulose fibres from plants are emerging as a potential candidate for eco-friendly feedstock in the textile industry. Nonwoven fabric is one of the most innovative and promising categories for the textile industry since it currently utilizes about 66% synthetic materials. In the upcoming wave of nonwoven products, we can expect an increased utilization of natural and renewable materials, particularly with a focus on incorporating lignocellulosic materials as both binders and fibre components. The introduction of low-cost fibres from waste residue materials to produce high-performance nonwoven fabrics represents a shift towards more environmentally sustainable paradigms in various applications and they represent ecological and inexpensive alternatives to conventional petroleum-derived materials. Here, we review potential technologies for using agricultural waste fibres in nonwoven products.

Keywords: renewable materials; environmental sustainability; high performance

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1. Introduction

In recent years, nonwoven technology has been considered one of the most modern, innovative, and important textile production methods. The nonwoven sector is experiencing remarkable growth, accounting for approximately one-third of the textile market and serving various purposes, whether it be for disposable or long-lasting applications [1–6]. In 2022, the global nonwoven fabric market boasted a valuation of USD 43 billion, and experts indicate that it will experience growth in the coming years with an estimated value of USD 68 billion by 2030, fueled by a steady compound annual growth rate (CAGR) of 5.6% throughout the forecast period spanning from 2022 to 2030. Many nonwoven fabrics are used in disposable products with 65–70% of the total consumption. By the 2019 coronavirus outbreak (COVID-19) pandemic [7], there was an increased demand for personal protective equipment such as gloves, facial masks, facial covers, and gowns, leading to high demand for nonwoven fabrics throughout the world. These materials are traditionally thermoplastic polymers, such as polypropylene (PP), polyethylene (PET), polyester (PES), polyamide (PAI), and polycarbonate (PC), which are not biodegradable and can lead to environmental problems such as the generation of microplastics [8,9]. Figure 1 shows that polyester is the major raw material used for global nonwovens [8,9]. Wet wipes and feminine hygiene products are major products made by the nonwoven value chain;

they make up the top 10 marine litter items found on beaches [7]. Due to the challenges associated with recovering conventional nonwoven materials consisting of synthetic fibres after their use, biodegradable nonwoven fabrics have been developed and commercialized. These types of nonwoven fabrics are usually made of bio-based materials that can be conveniently buried in the soil, allowing for them to decompose naturally with the assistance of microorganisms [10–12]. Incorporating materials that can naturally break down into the industry is a pivotal step toward handling waste, reducing the amount of space needed for landfills, and making use of sustainable resources. Millions of metric tons of waste fibres are available every year and the amount increases annually due to the increased activity in the modern agricultural sector. Agricultural waste fibres contribute a significant proportion of the total agricultural waste in the developed world [11,13]. Since biomass is available throughout the world in abundant quantity, it is necessary to use alternate resources to fulfil our needs in high-demand industries like textiles. Utilizing biodegradable materials like lignocellulosic waste fibres, including agricultural residues, forestry waste, and energy crops, can be considered a promising feedstock for use in the nonwoven industry. These types of fibres can significantly contribute to material recovery, reduction in landfills, and utilization of renewable resources which would reduce their environmental impact upon disposal [10,11,13]. On the other hand, the emergence of various legislation focused on sustainability across the world has led to finding sustainable alternatives for synthetic materials used in nonwoven industries with sustainable raw materials [7,14]. The effective utilization of agricultural waste fibre is a good option to convert these wastes into valuable products. Moreover, opening new applications for the waste fibres obtained from agriculture can provide farmers with new prospects, possibilities, and opportunities to broaden the spectrum of agricultural activities. Natural fibres have significant comfort advantages over synthetic fibres, which is one of the most important factors in nonwoven fabrics. The comfort of nonwoven fabrics is mainly associated with the aesthetics of the fabric, fabric–skin interaction during wear, thermal comfort, and air permeability. Having moisture absorption properties along with very good electrostatic properties of natural fibres has a benefit for the comfort of nonwoven fabrics. Moisture absorbency of natural fibre facilitates the charge dissipation on the fibre and thus diminishes the high potential electrical discharges during production line [15,16]. Therefore, there has been increasing demand for natural fibre-based nonwoven fabrics in recent decades as they are good substitutes for conventional materials in several products. While natural fibre provides other advantages comparable to those of synthetic materials, including good thermal and acoustical insulation characteristics and reduced dermal and respiratory aspects, most natural fibres like cotton are more expensive than synthetic fibres, and this is due to several factors such as smaller quantities and dependence on resources [6,17–20]. Also, at some point in the future, because of the demand for natural fibres, there could be a debate on whether land should be used for food or fibre production. For example, there is a significant focus in the textile industry to develop bio-based synthetic fibres such as polylactic fibre using corn; therefore, the fibre industry is directly competing with the food supply [21]. While the development of other types of biodegradable synthetic fibres addresses some of the environmental problems that plastics present, some of these solutions are not cost effective yet. Therefore, mixing natural fibres with synthetic fibres is performed to achieve an optimal ratio between the performance and the cost of the fabric, but the environmental problem related to using synthetic fibre still exists. There is a lot of research in progress to explore cost-effective ways of substituting synthetic materials with lignocellulosic materials in the production of nonwoven fabrics [8]. Because of the cost of raw materials for nonwoven production, the use of low-cost cellulosic raw materials, such as agricultural and forest waste fibres, is attractive for industrial production. From the consumer's point of view, these types of fibre are green, and the diversity of these fibres helps to deliver properties similar to those of polyester and polypropylene [22]. If properly managed, this can reduce their ecological footprint and be both technically and economically practicable [23].

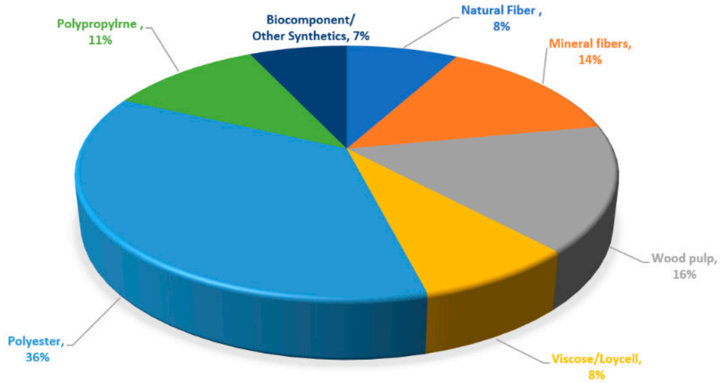

Figure 1. Global nonwoven staple fibre consumption [7].

Most lignocellulosic fibre waste produced from agricultural and forest waste is burned in fields, which releases a variety of pollution in the environment [23–25]. Interest in using these fibres as elements in manufacturing nonwoven fabrics is mainly related to their favourable structural properties and environmental/economic benefits. Natural cellulosic fibres have attracted much attention in relation to the production of nonwoven fibres and nonwoven reinforced composites because of their biodegradability, low density, thermal and acoustic insulation, strength, low adverse health effects, and low cost [23,26]. The most suitable processes for converting natural fibre derived from plant waste to the nonwoven fabric are air-laid and wet-laid techniques [4,27,28]. From a manufacturing point of view, air-laid and wet-laid technologies incorporate large quantities of waste as short fibres (above 90 wt.%) and use biodegradable or water-soluble binders to bond them [28,29]. Recently, spun-laid technologies have also been developed that use thermoplastic cellulose fatty acid esters for melt spinning techniques, which means these fabrics are a renewable and recyclable alternative in several hygienic textiles [30]. This review summarizes the range of agricultural fibres that could be used for nonwovens, their current use, and the breadth of applications in an industrial production environment.

2. Nonwoven Production

Nonwovens are the most rapidly expanding segment in the textile industry with hundreds of end uses and product niches, not only as disposable products but also in more valuable non-disposable products [1,3,31,32]. Nonwovens are an essential part of the fibre industry, competing with conventional textiles such as woven or knitted fabrics, paper, and board products, and they are forecasted to expand to a market value of USD 53 billion by 2030 [5]. Nonwoven fabrics are sophisticated materials created from randomly arranged fibres or cut yarns strengthened through mechanical, chemical, or thermal bonding [1,5,33]. The features of nonwoven fabrics are determined by bonding, type of fibres, and manufacturing parameters [1,5,7]. Figure 2 shows nonwoven fabric manufacturing from raw material preparation, web formation, web bonding and the finishing of the nonwoven fabrics [1,3]. A two-dimensional or a three-dimensional web can be produced through a nonwoven web-forming process, which is used as a precursor for the final fabric production [8,34]. Nonwoven manufacturing systems are either dry-laid, wet-laid, or polymer-laid [1,5]. Dry-laid nonwovens have their origins in textile applications, whereas wet-laid nonwovens are primarily found in the paper industry, and polymer-laid nonwovens are mainly used in manufacturing plastics and polymer extrusion [1,8,11,35]. Early dry-laid systems have existed since medieval times, known as felting systems [1]. Preparation and use of dry-laid nonwoven fabrics are the most extensive categories of the nonwoven industry, with a predicted growth of 5.3% over the next decade.

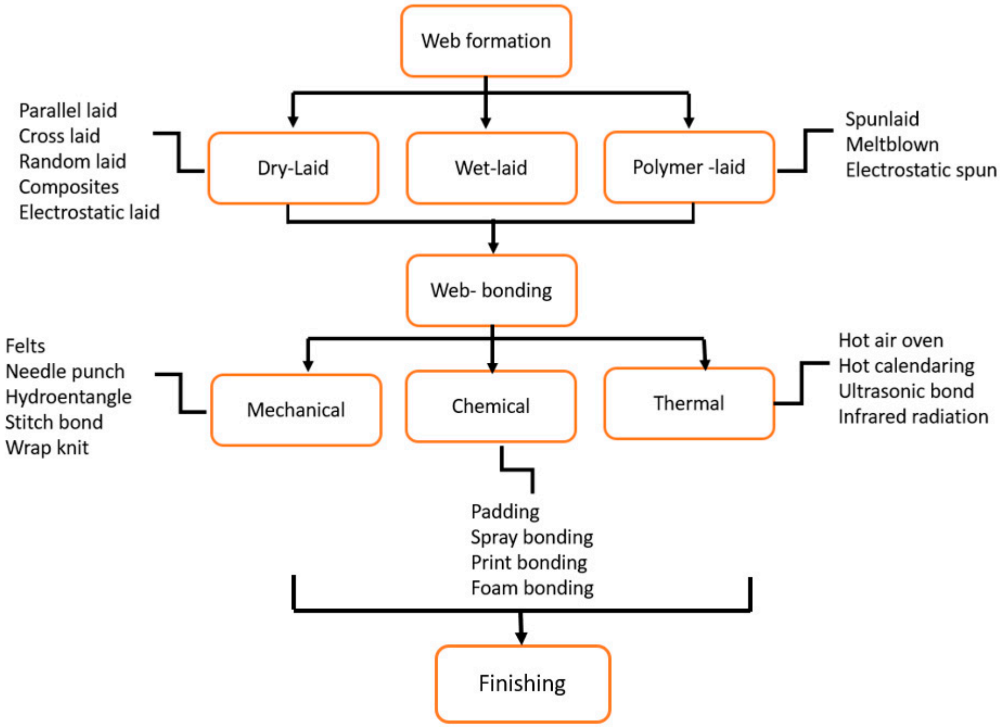

Figure 2. Classification of nonwoven fabrics based on production techniques.

In dry-laid web formation, fibres are manipulated in the dry state by carding and cross-lapping or aerodynamically manipulated (air-laid) and then bonded [1,4]. In wet-laid forming, nonwoven fabrics are manufactured using water: the fibres are suspended in an aqueous solution and spread out on a drying screen where the water is removed [4,28,29]. There are several similarities between the wet-laid process and conventional paper making, but the wet-laid fabric is made with long fibres greater than 3 mm [28,29]. Polymer-laid or spun-melt nonwovens, including spun-bond, melt-blown, flash-spun, apertured films, and layered composites of these materials, are manufactured using polymer extrusion machines [1]. Once the web is formed, nonwovens can be mechanically, thermally, or chemically bonded. These bonding methods include needle-punching, hydroentanglement, stitch-bonding (mechanical), thermal bonding (thermo-bonding) and chemical bonding [1]. Chemical bonding techniques involve the application of adhesive binders to webs along with processes like saturating, spraying, printing, or foaming techniques to join fibres together, improving the final nonwoven fabric's overall stiffness, softness, and waterproofness properties [36,37]. Bonding agents can also be applied to the final product to enhance visual aesthetics, flame-resistant characteristics, and surface roughness [37]. Solvent bonding involves the partial solvation of fibre surfaces using a suitable chemical to provide self-bonded fibres at the intersection points [1]. Thermal bonding involves heating the web to soften the fusible bonding element followed by cooling to bond the fibres to each other. This type of bonding has advantages such as lower water consumption, energy efficiency, lesser environmental impact, and the possibility of recycling both webs and fabric [1]. The main method for consolidating a fibrous web structure is mechanical bonding using hydro-entangling, stitch-bonding, and needle-punching [38]. Needle-punching is among the earliest techniques of bonding nonwoven fabrics, involving the mechanical interconnection of fibres through repetitive punching through the fibre mat with an array of barbed needles. Needle-punching is the most suitable method of producing thick nonwoven fibres [39]. The stitch-bonded fabric is created by interconnecting fibres and yarns through subsequent stitching or knitting [40]. Hydro-entangling takes place within a web using high-velocity water jets. High-pressure water jets increase fibre entanglement, leading to the displacement and reconfiguration of fibre segments within the web [41].

The choice of fibres in different applications depends on the product specifications, the need for composites or laminates, and cost effectiveness. Natural fibres have uneven and inhomogeneous surfaces compared to manufactured fibres [34]. The chemical composition of natural fibre is distinguished from synthetic fibres by containing multiple-phase structures providing hydrophilic or hydrophobic properties. Manufactured fibres make up 60% of all nonwoven production [42]. This has motivated researchers to further reduce costs using agricultural by-products/wastes [22,43]. The European Disposables and Nonwovens Association (EDANA) reported an increase in the use of materials from low-cost biomass wastes in constructing high-performance nonwovens, highlighting a worldwide trend of increased sustainable and renewable production [9].

3. Natural Fibres and Cellulose-Based Fibres

Fibres are generally categorized as natural or man-made fibres. Because they are renewable, biodegradable, compatible and have eco-friendly properties and sustainability benefits, biofibres are replacing synthetic fibres in nonwovens [34,44]. Natural fibres are mainly classified into three categories such as plant-based fibres, animal-based fibres, and mineral-based fibres (Figure 3) [26,34]. Natural plant fibres have countless desirable properties, including low cost and low density, and the added benefit of less skin and respiratory irritation to the human body [26,44,45]. Natural cellulosic fibres come from various parts of the plant (Table 1). Plant fibres can be classified into six types of fibre: bast fibres (flax, hemp, jute, kenaf, and ramie), leaf fibres (abaca, pineapple, and sisal), seed fibres (coir, cotton, and kapok), straw fibres (corn, rice, and wheat), grass fibres (bagasse and bamboo), and wood fibres (softwood and hardwood) (Figure 4) [8,34]. Many of these plants are purpose-grown for fibre (e.g., cotton, flax, hemp, kenaf, etc.) or produce fibres as by-products (coconut (coir), sugarcane, banana, and pineapple) [15,17]. Plant fibres are composed of cellulose, hemicelluloses, and lignin, in addition to several secondary components (pectin, waxes, tannins, ash, and inorganic salts) [20,46]. Cellulose is the strong and stiff component of the fibre; the cellulose content and degree of polymerization determines the properties of the fibres, and increasing non-cellulosic components tends to reduce the strength and modulus of the fibres [20,46]. For example, the high strength of kenaf and ramie fibres compared to the low strength of coir fibre is attributed to high cellulose content and a higher degree of polymerization [47]. Lignin, the second most abundant natural compound in the world following cellulose, is a high-molecular-weight polymer composed of phenolic compounds that provide structural support to plants [45]. Hemicellulose comprises highly branched polysaccharides attached to the cellulose after the removal of pectin. The wax content of the fibre influences the wettability of the fibre and influences interfacial fibre–matrix adhesion in the composite [26].

Table 1. Classification of natural fibres and origin [26].

Fibre Source	Species	Origin
Abaca	*Musa textilis*	Leaf
Bagasse	*Sugar cane*	Grass
Bamboo	(>1250 species)	Grass
Banana	*Musa indica*	Leaf
Cantala	*Agave cantala*	Leaf
Caroa	*Neoglaziovia variegate*	Leaf
China jute	*Abutilon theophrasti*	Stem
Coir	*Cocos nucifera*	Fruit
Cotton	*Gossypium* sp.	Seed
Curaua	*Ananas erectifolius*	Leaf
Date palm	*Phoenix dactylifera*	Leaf

Table 1. *Cont.*

Fibre Source	Species	Origin
Flax	*Linum usitatissimum*	Stem
Hemp	*Cannabis sativa*	Stem
Henequen	*Agave fourcrocydes*	Leaf
Isora	*Helicteres isora*	Stem
Istle	*Samuela carnerosana*	Leaf
Jute	*Corchorus capsularis*	Stem
Kapok	*Ceiba pentranda*	Fruit
Kenaf	*Hibiscus cannabinus*	Stem
Kudzu	*Pueraria thunbergiana*	Stem
Mauritius hemp	*Furcraea gigantean*	Leaf
Nettle	*Urtica dioica*	Stem
Oil palm	*Elaeis guineensis*	Fruit
Piassava	*Attalea funifera*	Leaf
Pinneapple	*Ananus comosus*	Leaf
Phormium	*Phormium tenas*	Leaf
Roselle	*Hibiscus sabdariffa*	Stem
Ramie	*Boehmeria nivea*	Stem
Sansevieria	*Sansevieria*	Leaf
Sisal	*Agave sisilana*	Leaf
Sponge gourd	*Luffa cylinderica*	Fruit
Straw (cereal)	–	Stalk
Sun hemp	*Crorolaria juncea*	Stem
Cadillo/urena	*Urena lobate*	Stem
Wood	(>10,000 species)	Stem

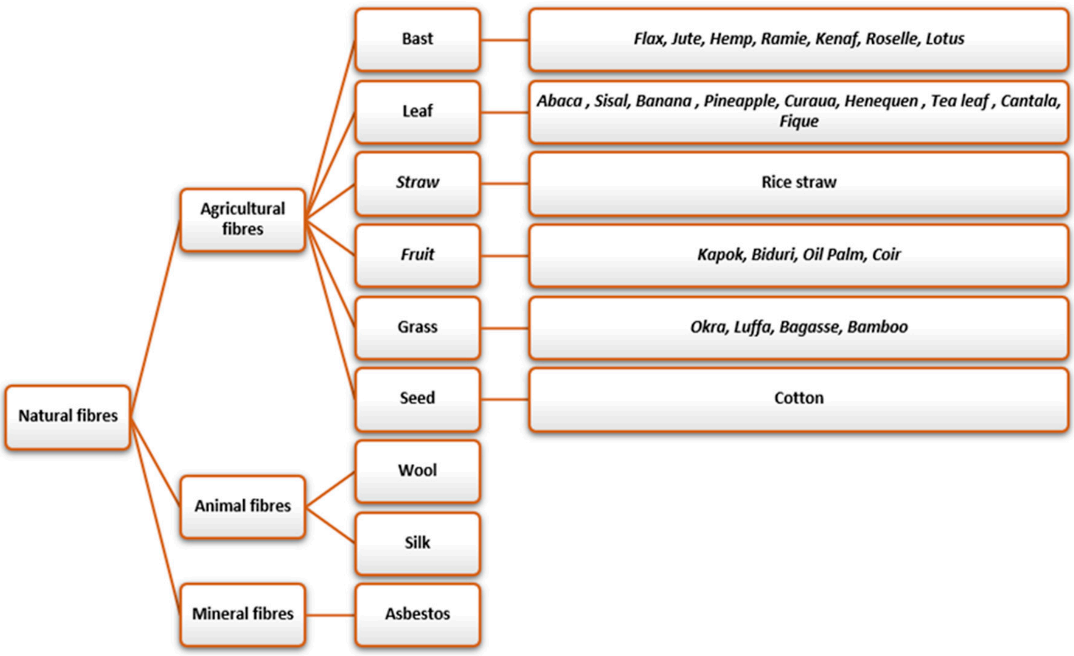

Figure 3. Classification of natural fibres.

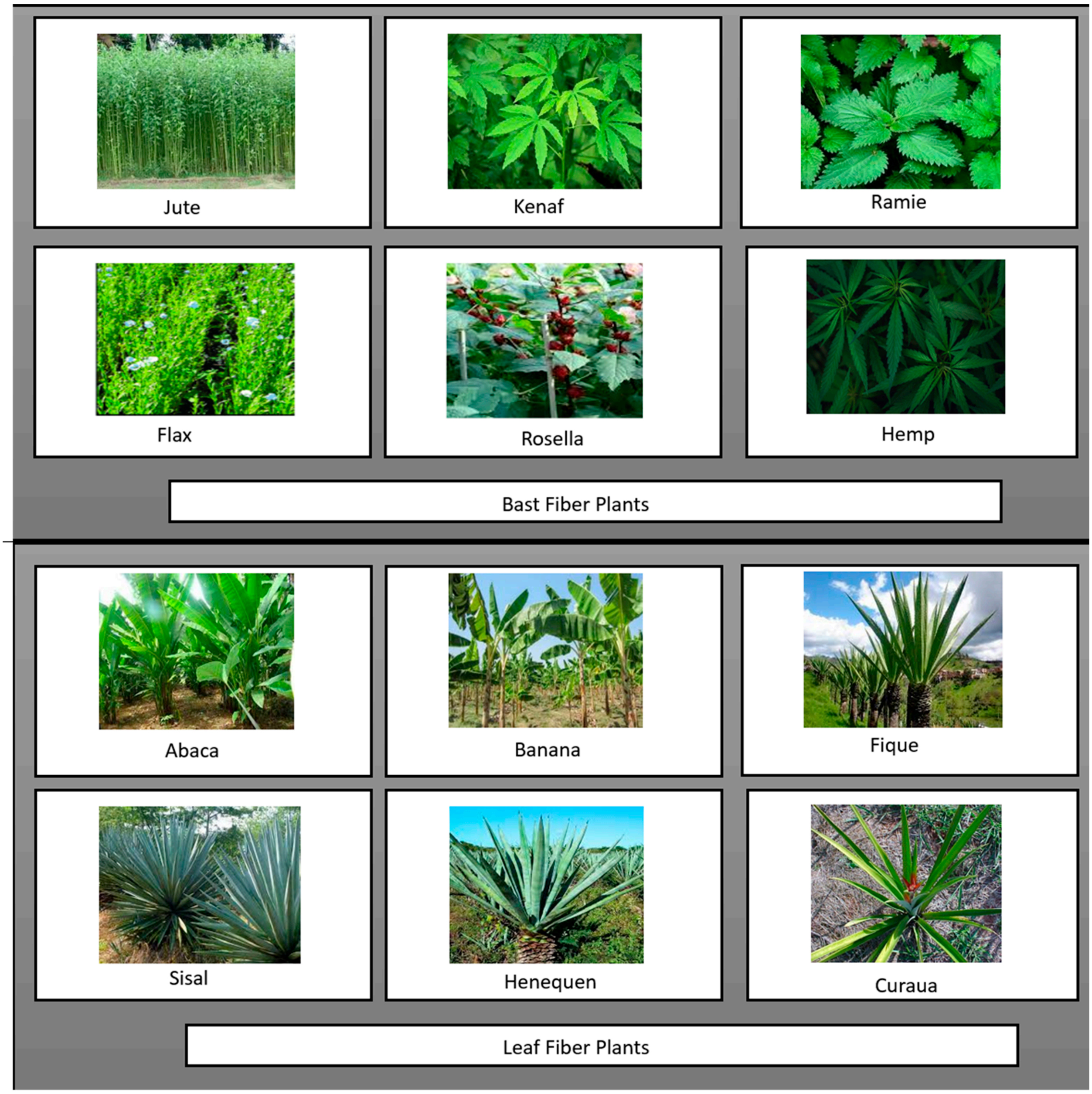

Figure 4. Natural fibre-originated plants of jute, kenaf, ramie, flax, roselle, hemp, abaca, banana, fique, sisal, henequen, curaua, kapok, biduri, luffa, bamboo, grass, cotton.

The quality of the natural fibres depends on factors such as the source of the fibres, growing conditions, plant age, maturity, size, chemical composition, part of the plant from which fibres are extracted, and storage conditions. The method of fibre extraction also has an impact on fibre yield, fibre quality, chemical composition, structure, and properties of the fibre [26].

Table 2 shows the chemical composition and mechanical properties and classification of different types of natural fibres for nonwoven production including the structure of fibres, cellulose content, and moisture content [23,48].

Table 2. Chemical and mechanical properties of some common plant fibres [23,48].

	Physical Properties		Major Chemical Components (%)				Mechanical Properties			
Fibres	**Diameter μm**	**Length mm**	**Cellulose (%)**	**Hemicellulose (%)**	**Lignin (%)**	**Pectin (%)**	**Tensile Strength MPa**	**Elastic Modulus GPa**	**Elongation %**	**Moisture Uptake %**
Jute	18–20	0.8–6	67	16	9	0.2	325	37.5	2.5	10–13
Hemp	16–50	10–15	81	20	4	0.9	530	45	3	6–12
Kenaf	12–36	1.4–11	53.5	21	17	2	743	41	/	16–18
Flax	12–37	15–20	70.5	16.5	2.5	0.9	700	60	2.3	7–12
Ramie	50	60–250	72	14	0.8	1.95	925	23	3.7	7.5–17
Bamboo	25–88	1.5–4.0	34.5	20.5	26	/	575	27	/	10–12
Banana	12–30	0.4–0.9	62.4	12.5	7.5	/	721.5	2–4	2–3	2–3
Alfa	/	/	45.4	38.5	14.9	/	350	22	5.8	7–10
Coir	7–30	0.3–3	46	0.3	45	4	140.5	6	27.5	12–14
Pineapple	8–41	3–8	80.5	17.5	8.3	4	1020	71	0.8	/
Sisal	10–300	600–1500	60	11.5	8	1.2	460	15.5	/	10–12
Henequen	/	/	60	28	8	/	/	/	/	/
Abaca	10–30	4.6–5.2	62.5	21	12	0.8	12	41	3.4	5–10
Bagasse	/	/	37	21	22	10	290	17	/	/
Kapok	20–43	10–35	13.16	/	/	/	93.3	4	1.2	9–11
Cotton	12–35	15–36	89	4	0.75	6	500	8	7	7–20
Curaua	/	/	73.6	5	7.5	/	825	9	7.5	/
Jute	18–20	0.8–6	45–72	12–21	0.2–26	0.2–12	325	37.5	2.5	10–13
Hemp	16–50	10–15	55–80	12–22	3–13	1–3	530	45	3	6–12
Kenaf	12–36	1.4–11	30–55	18–24	8–21	3–9	743	41	/	16–18
Flax	12–37	15–20	43–71	16–21	2–23	1.8–3	700	60	2.3	7–12
Ramie	50	60–250	68–91	5–17	0.5–1	1.5–2.5	925	23	3.7	7.5–17
Bamboo	25–88	1.5–4.0	26–75	13–73	10–31	0.3–1	575	27	/	10–12
Banana	12–30	0.4–0.9	48–60	10–16	14–22	2–4	721.5	29	27.5	2–3
Coir	7–30	0.3–3	40–50	0.2–0.5	43–47	3–5	140.5	6	12–14	12–14
Pineapple	8–41	3–8	55–75	78–85	4–10	0.8–1.5	1020	71	0.8	/
Sisal	10–300	600–1500	45–80	10–25	7–15	0.8–10	460	15.5	/	10–12
Palm	/	/	43–65	17–34	13–25	/	50–400	4–18	/	/
Abaca	10–30	4.6–5.2	56–63	15–17	7–13	0.3–1	90–95	1.2–1.5	5–10	5–10
Kapok	20–43	10–35	13–20	/	/	/	200–800	1–2	9–11	9–11
Cotton	12–35	15–36	83–90	1–6	0.7–29	0–6	/	12–12	7–20	7–20

Bast fibres, originating from hemp, sisal, jute, ramie, and kenaf, are characterized by high stiffness, low elongation, and good tensile properties. These properties enable bast fibre utilization in many industries, such as composite, automobile, building, and textiles. Hemp bast fibres have a cellulose content of about 70% and are identified as one of the strongest members of the bast fibres [49]. The fibres are generally extracted from the plant by retting and degumming processes, which results in breaking bonds between cellulosic fibres and the non-cellulose matrix. The degumming process combines two or three methods, which can be physical, semi-physical, chemical and/or biological to achieve the best bast fibre qualities [49].

Leaf fibres are coarse and rigid fibres isolated from plants that can be extracted by removing the epidermal tissue of the leaf by scratching and then retting. Leaf fibres can be derived from the following plants: sisal, banana, abaca, pineapple, henequen, and agave. These fibres have relatively high strength and are used for producing ropes, handkerchiefs, mats, insulators, and composites [26].

Fruit/seed fibres are extracted from the outer shell of fruits such as the husk of coconuts (coir). The fibrous layers are isolated through manual de-husking mechanical crushing [26]. These fibres are lightweight and tough and are mainly used in the production of ropes, twines, doormats, mattresses, and brushes.

Grass fibres are obtained from bamboo, bagasse, corn, sabai, and canary. Grass fibre extraction methods include either the water retting process, a mechanical process, or a combination of both. The most efficient extraction process for grass fibres uses water retting because the process is straightforward, easy to carry out and inexpensive [26,46].

Straw fibres are derived from cereal plants after grain and chaff are harvested. The straw is obtained from a wide range of cereal crops such as rice, wheat, barley, oats, and rye. It is typically collected and stored in a bale and is used in diverse applications, mainly for animal feed, biofuels, biomass, construction material, paper, and packaging [26].

Wood fibres are produced from various trees and are commonly classified as softwood (gymnosperm) and hardwood (angiosperm) fibres. Both types of wood fibres play a significant role in paper manufacturing. The main difference is that the softwood fibres (2–4 mm) are longer than the hardwood fibres (0.5–1.5 mm) in dimensions [26,46].

In many countries, large amounts of natural fibres from agricultural or industrial processes are discarded. Recycling waste fibres can help to preserve natural resources while also reducing waste and encouraging more environmentally friendly manufacturing.

Numerous recent endeavors have been undertaken to explore novel applications for these residues and wastes. One innovative approach involves using them in a nonwoven material. This review focuses on nonwoven fabrics manufactured from by-product natural fibres and their potential application areas.

4. Agriculture Waste Fibres for Nonwovens

4.1. Bast Fibres

4.1.1. Flax

Flax (*Linum usitatissimum*) is a food and fibre crop cultivated primarily in Canada, France, and Belgium and primarily used for fibre and linseed oil. It is one of the earliest fibre crops that has been spun and woven into textiles [49]. Low-grade fibres are usually used as material to produce nonwovens with different technologies such as needle-punching, hydroentangling, stitch bonding, and adhesive bonding [50]. Martin et al. (2016) compared the reinforcement capacities of polypropylene polymer modified by layers of nonwoven flax fibres made using three different processes: spun-lacing, needle-punching, and paper processing [51]. In the needle-punched nonwoven fabric, fibres were gathered in slightly curved bundles with a random orientation. In the spun-laced nonwoven fabric, greater splitting along with the shortening of fibre bundles was obtained compared to the needle-punched nonwoven fabric. In fibre mats, the fibres were gathered into straight bundles and randomly placed. Tensile tests on raw fibres and fibres extracted from the nonwoven fabrics showed that spun-lace and needle-punch processes resulted in a slight decrease in the mechanical properties of the fibres. The mechanical properties of spun-laced and mat-reinforced composites were higher in the machine direction (MD) than in the cross direction (CD), while the opposite was observed for the needle-punched reinforced composites [51].

Another study by Anandjiwala and Boguslavsky (2008) also presented an investigation of the utilization of flax fibre waste in developing multi-layered needle-punched structures for filtration applications [52]. Flax fibre with desirable fibre fineness and length distributions was obtained during the extraction of line fibre followed by cleaning, opening and separation of fibre with the opening machine and then subjecting it to mechanical cottonization. Multilayered nonwovens were fabricated by combining single-layered fabrics in various combinations and subsequently re-needling. The results showed that pre-cleaning the fibres with adequate cleanliness and uniformity in fibre length distribution is essential to prevent the occurrence of processing issues on a nonwoven machine [52]. Table 3 reports some studies on the utilization of flax fibre in nonwoven fabrics.

Table 3. Reported work on the utilization of flax fibre in nonwoven fabrics.

Type of Material	Nonwoven Process	Type of Fibre	Fibre Ratio	Ref.
Nonwoven	Needle-punch	Flax: PVA [1] Flax: bicomponent [2]	Flax in the 10–30 wt.%	[52]
Bio-composite	Needle-punch, Hot press	Semi-rettedd Flax: PP/PE [3] Retted Flax: PP [4] Flax: T-255 [5]	50:50	[53]
Nonwoven	Air-laid and needle-punch	Flax	100	[54]
Nonwoven	Parallel-laid of carded web Needle-punching Hot rolling	Flax/PP	40:60	[55]
Composite	Carding/overlapping/needle-punching, hot press	Flax/PP Flax/MAPP [6]	50:50	[56]
Nonwoven	Spun-lace, thermal bonding by panel presses and stamp-forming press	Flax/PP	50:50	[57]
Nonwoven	Wet laid, hot press	Flax/PP	90:10 80:20 70/30	[58]
Nonwoven	Layer-by-layer filtration process	Flax Nanofibrillated cellulose	10, 20, 30 wt.%	[59]
Nonwoven	Needle-punch	Flax/Polylactic	40 wt.%	[60]
Nonwoven	Wet-laid	Flax/binder fibre [7]	90:10 80:20 70:30	[61]
Nonwoven	Wet-laid	Flax/PP	90:10 80:20 70:30	[58]
Nonwoven	Needle-punch	Flax/PP	50:50	[62]
Nonwoven	Needle-punch	Flax/wool	50:50	[63]
Nonwoven	Air-laid	Wool/flax/bicomponent	42.5% 42.5% 15%	[63]

[1] Polyvinyl alcohol; [2] Polyamide 6/co polyamide; [3] Polypropylene/Polyethylene (65/35); [4] Poly propylene; [5] Polyester/Co polyethylene (50/50); [6] Maleic Anhydride-grafted PP; [7] Polyvinyl alcohol, Bicomponent polyamide 6/copolyimide.

4.1.2. Jute

Jute (*Corchorus capsularis/Corchorus olitiaus*) is mainly cultivated for its fibre and stands as one of the most significant natural fibres, second only to cotton. Jute is a bast fibre crop and is one of the least expensive sources for fibres grown in tropical regions. Nonwovens from jute fibres are manufactured by stitch bonding, adhesive bonding [64], needle-punching [65–67], thermal bonding [40], and hydroentanglement [64]. They are used in many applications because they possess many desirable features such as high strength, good dimensional stability, and high moister absorption; in addition, they are bleachable, dyeable, and printable [40]. In one study, jute mill waste (jute broadloom caddis), including stapled raw jute, woollenized jute, viscose rayon, and their combinations were used for the fabrication of nonwoven fabrics using an air-laying technique and chemical bonding [68]. Mechanically bonded jute nonwovens made from caddis (waste from the weaving process of jute fibre) are commercially produced regularly and extensively used in industrial applications such as automobile parts and packaging [22].

4.1.3. Hemp

Th hemp (*Cannabis sativa*) plant of the family Cannabaceae is cultivated for its bast fibre or its edible seeds [69]. Liao et al. (2020) investigated the use of hemp nonwoven fibre for the application of sound absorption [70]. In recent work, Gutierrez-Moscardo et al. (2022) developed new sustainable nonwoven materials by utilizing waste material derived from processing hemp fibres in the textile industry using wet-laid technology and a thermal bonding process [25]. Nonwovens with different areal densities were manufactured with a high content of hemp waste (70–90 wt.%) and different binder fibres (polylactic acid and viscose fibres). However, a fungal growth study on the developed nonwovens hemp revealed low antifungal properties of hemp fibre waste nonwovens. Ramaratnam et al. (2016) developed a new method for manufacturing cellulosic structures generated from waste cannabis fibre using a wet-laid technique [71]. Using this method, the absorbent cellulosic structures had low weight, high pectin concentration and equal absorbency, strength, and softness compared to porous cellulosic fabrics of higher weight. Table 4 reports some studies on the utilization of hemp fibre in nonwoven fabrics.

Table 4. Summary of nonwoven fabrics consisting of hemp fibre.

Type of Material	Nonwoven Process	Type of Fibre	Fibre Ratio	Ref.
Nonwoven	Needle-punch	Hemp/PP	30, 40, 50 and 70% hemp by weight	[72]
Nonwoven	-	Hemp/PP	50:50	[73]
Three-layered nonwoven composite	Needle-punch	PP/Hemp/PP	Every layer with 330 gsm ($g \cdot m^{-2}$)	[74]
Three-layered nonwoven composite	Needle-punch	PLA/Hemp/PLA [1]	Every layer with 330 gsm ($g \cdot m^{-2}$)	[75]
Nonwoven	Needle-punch	Hemp/PP	50:50	[76]
Nonwoven reinforced polyester composites	Needle-punch	Hemp	100%	[77]
Nonwoven	Needle-punching hydro-entanglement	Hemp	100%	[78]
Nonwoven	Carding-thermal bonding	Hemp/PP	90:10	[78]
Nonwoven	Carding and needle-punching	Hemp	100%	[79]
Nonwoven	Air-laid and needle-punching	Hemp	100%	[54]

Table 4. *Cont.*

Type of Material	Nonwoven Process	Type of Fibre	Fibre Ratio	Ref.
Nonwoven	Spun-lace	Hemp/cotton Hemp/viscose	60:40 60:40	[80]
Nonwoven composite	carding/overlapping/needle-Punching, Hot-press	Hemp/pp Hemp/MAPP [2] Maleic Anhydride-grafted PP	50:50	[56]
Biocomposite	Needle-punch, Hot-press	Unretted hemp: PE/PP Retted hemp: PP Unretted hemp: PP Retted hemp: PP Flax: T-255	50:50	[53]

[1] Poly lactic acid; [2] Maleic Anhydride-grafted PP.

4.1.4. Ramie

Ramie (*Boehmeria nivea*) is a type of bast fibre with much higher strength and modulus than cotton as well as increased air and moisture permeability and antibacterial properties. It also has undesirable properties such as poor elasticity and wrinkle recovery, as well as a rough handle [16]. Shiga Ramie Industry Co. (Koto, Japan) produces a ramie fibre web made from crimped ramie fibres. The fibre web exhibits good tactility and appropriate extensibility, but its low strength makes it impractical for real applications [81]. Electrospinning polyurethane onto the surface of ramie fibre webs is used to improve the physical properties of ramie fibre webs supplied by Shiga Ramie Industry Co. Significant improvement in the ramie fibre web's physical properties is observed after adding only a small amount of polyurethane nano fibres related to connections between the polyurethane nano fibre membrane and the ramie web [81]. The nonwoven fabrics of ramie/cotton are made for hygienic product applications; for example, female panty liners. The pulping condition is carried out in NaOH mixed with Na_2CO_3, and then ramie/cotton nonwoven fabrics are fabricated by wet-laid techniques. The results demonstrate that increasing ramie content increases the air permeability, compressive strength, and compression recovery rate. In addition, surface roughness, compressional energy, absorption capacity, and tensile strength all decrease [82]. Chen et al. (2008) evaluated the physical properties of hemp/PP (70:30), kenaf/PP (70:30), ramie/PP (70:30), and bagasse/PP (50:50) composites produced by carding and needle-punching techniques and then the thermo-bonding process [83]. The results showed that composites containing kenaf, ramie, and hemp have a similar modulus. The ramie composite showed higher water absorption in comparison to other nonwoven composites. Ramie fibre is finer than other fibres, resulting in a more significant number of ramie fibres in a unit volume that contributes to an increase in water absorption.

4.1.5. Kenaf

Kenaf (*Hibiscus cannabinus*) is cultivated mainly for fibre and seed oil production in tropical regions. A study by Yang et al. (2001) showed the extraction of kenaf fibre by a modified chemical degumming method [84]. Because of the low strength of 100% kenaf fabric, 80% and 50% nonwoven fabrics were produced by blending kenaf with rayon fibre. Chemical degumming of the fibre was performed by alkaline treatment with NaOH and softener to reduce stiffness and coarseness of the fibre for the carding process. It was observed that softener treatment under alkali conditions was effective in removing impurities and producing finer fibres with no negative influence on the strength of the fibre. Kenaf-embedded nonwoven samples containing PP and PET fibres were fabricated employing the needle-punching process. A substantial proportion of low-melt PET fibres resulted in smaller pore sizes, allowing for low air permeability and water absorption [85]. In another study, the empty fruit bunch (EFB) and kenaf PP nonwoven composites were fabricated using the needle-punching technique followed by compression moulding. Increasing the natural fibre content (EFB and kenaf) in nonwoven fabrics decreased the tensile strength linearly while increasing the flexural modulus of nonwoven composites linearly [86]. Another example is kenaf/ramie nonwoven fabrics produced via carding, needle-punching, and wet bonding techniques [87]. These nonwoven fabrics showed excellent strength which is suitable for use in automotive interior parts. Finally, cellulosic-based nonwoven composites were fabricated from kenaf, jute, flax, and waste cotton fibre using recycled polyester and substandard PP [62]. Samples consisting of kenaf and cotton needle-punched composites showed superior thermal insulation properties compared to the sample made of synthetic fibres.

4.1.6. Roselle

Roselle (*Hibiscus sabdariffa*) is the bast fibre that is native to West Africa and India and today is mainly cultivated in China and Thailand. Roselle fibre can be used as a substitute for jute. In a recent study, Kazi and Ramasastry (2022) reported using short roselle fibre mats to produce epoxy composites using the hand lay-up technique [88]. The water absorption capacity of the roselle fibre composites rises as the fibre content increases. The short roselle fibre composites are lightweight, and the densities are considerably lower than those of sisal fibre epoxy composites.

4.1.7. Lotus

Lotus fibre (also called Nelumbo nucifera fibre or lotus root fibre) is extracted from the lotus root [89]. One invention developed by Panpan (2015) introduces the lotus fibre into nonwoven fabric production, which is produced by a wet-laid technique using water as a suspension medium [90]. This lotus fibre nonwoven fabric has the characteristics of being antibacterial, mildew proof, moisture absorbing and deodorizing, fluffy soft, waterproof, and breathable, flexible, non-combustible, non-toxic, non-irritating, inexpensive, easy to decompose, and recyclable.

4.1.8. Bamboo

Bamboo is a perennial evergreen in the family Poaceae, subfamily Bambusoideae, and the tribe Bambuseae. Bamboo has a high growth rate, and bamboo fibres consist of a hollow tube with a micron-scale fibre bundle [91]. Both natural and regenerated bamboo fibres contain a component known as Bamboo Kun, which exhibits exceptional antibacterial and bacteriostatic characteristics. These qualities make bamboo fibre a valuable choice for applications in hygiene products [92]. In one study, surface modification of bamboo spun-lace nonwoven fabric was achieved using glow discharge oxygen plasma which had a profound impact on the surface properties and enhanced the air permeability, water vapour permeability, and wick ability characteristics of the fabric, and also caused a slight reduction in fabric weight, thickness, and breaking force. Plasma treatment increases the hydrophilicity of nonwoven fabric by introducing polar functionality on the surface and increasing the surface roughness and surface energy of the fabric [93].

Another example reported by Devaki and Indumathi (2019) is the production of 100% bamboo nonwoven fabric by the spun-laid technique and a natural antibacterial finish (88). About 1% of extracted herbal material was directly applied on 100% bamboo nonwoven fabric using the pad-dry-cure method. The final product was an eco-friendly wet wipe with properties softness, disinfectant, and anti-allergy properties for baby and adult pimple control. In other research, bamboo and PP fibres were selected to produce needle-punched nonwoven fabrics with three different blend proportions (80:20, 20:80, and 50:50). The results indicated that the 20:80 bamboo/PP nonwoven fabrics exhibited the highest tensile strength and elongation compared to other samples. Recent studies also showed the production of a nonwoven composite made from three renewable materials, bamboo fibre bonded with polylactic acid and dimethyl carbonate. Increasing the content in the bamboo/PLA membrane supports the increase in the tensile strength by 124% while the elongation at break does not change significantly [94].

4.2. Leaf Fibres

4.2.1. Abacae

Abaca (*Musa textilis*) is mainly cultivated in the Philippines, Ecuador, and Costa Rica, predominantly falling under the banana family (Musaceae) [95]. Madrid et al. (2013) produced an amine-type nonwoven fabric from adsorbent abaca/polyester using the grafting of glycidyl methacrylate on the electron beam irradiated abaca/polyester nonwoven fabric [96]. Guzman et al. (1982) studied the possibility of utilizing abaca as raw material for abaca/polyester nonwoven manufacturing. The production of abaca nonwoven fabric was carried out in the following steps: (1) the degumming process, (2) carding, and (3) the production of the nonwoven fabric (using both adhesive bonding and needle-punch processes) [95]. The creation of tea bags is being explored by looking at the wet-laid nonwoven fabric using long fibres such as abaca fibres with fibrillated synthetic polymers. These nonwoven structures offer excellent tea leaf infusion, facilitate the tea-making process, and maintain high tea retention of fine tea particles [97].

4.2.2. Sisal

Sisal (*Agave sisilana*) is a commercial crop cultivated mainly in Tanzania and Brazil. These fibres are categorized into three types based on their extraction source: mechanical, ribbon, and xylem. The mechanical fibres exhibit the highest strength, while xylem fibres possess the lowest strength [98]. In the study conducted by Santos et al. (2009), nonwoven sisal fibres were manufactured by a needle-punch process and then cold-treated with 2 wt.% NaOH solution [98]. Recently, Ouhaibi et al. (2021) developed a needle-punch nonwoven fabric based on pretreated sisal fibre and wool waste fibre [99]. The microstructure analysis showed the anisotropic porous structure which helps in lower thermal conductivity and higher water penetration. A recent work by Indu (2021) explored the fabrication and parametric evaluation of needle-punch nonwoven material prepared from sisal (100%), sisal/coir (70:30), and sisal/coir (30:70) [100]. By introducing coir fibre to the nonwoven structure, the bursting strength was reduced; therefore, pure sisal resulted in higher bursting strength compared to the other nonwovens. Coir has increased fibre thickness and density compared to sisal, leading to greater thickness and air permeability in the nonwoven fabric.

4.2.3. Banana

Banana (*Musa acuminata*), a natural lignocellulosic plant fibre, is harvested from the leaf or the pseudostem of the banana plant, which grows abundantly in tropical areas. The pseudostem can be processed through various methods, resulting in soft or coarse fibres [101].

Banana fibres can be extracted from all the parts from different parts of the bark and leaf of the banana plant, including outer bark (OB), middle bark (MB), inner bark (IB), and midrib (MR), by treating them in alkaline condition at high temperature and then using for fabrication of nonwoven fabrics using the wet-laid process [101]. Alkaline treatment removes impurities like oil and wax from the banana fibre and results in an increase of anchoring points for mechanical interlocking of fibres [101]. Tensile strength and Young's Modulus of nonwoven made of different parts are found in a decreasing order of OB > MB > MR > IB, and elongation at break of nonwovens is seen in a decreasing order of OB > MB > IB > MR [101]. In the study by Kenned et al. (2020), banana fibres extracted from the pseudostem of Nendran banana plants were converted to fibre-reinforced polymer composites using needle-punched nonwoven fabric bonded with an unsaturated polyester matrix [102]. The mechanical properties of the composite improved by uniform area density obtained through the needle-punching technique, which caused a smooth transfer of stress from matrix to fibre. In this context, a superior strength was obtained by the honeycomb structure due to excellent bonding of the fibre with the matrix.

Shroff and Karolia (2015) investigated the method to soften the fibre by removing non-cellulosic gummy-like materials from banana fibre and preparing nonwovens through needle-punching [103]. In this study, three eco-friendly enzymes, hemicellulase, pectinase, and cellulase enzyme, were used for the treatment of grey banana fibres and the best-softened fibre was selected for preparing nonwovens. For preparing 100% banana nonwoven fabric, the fibres were passed through the softener machine, sprayed with oil–water emulsion, processed through the carding machine and then forwarded to the manual needle-punch machine. When fibres were treated with enzymes individually, they removed impurity; for example, the hemicellulase enzyme removes hemicellulose from the fibre, the pectinase enzyme attacks pectins, and the cellulase enzyme removes cellulose from the surface of the softened fibres. On the other hand, when fibres were treated with the combination of the three enzymes, impurities were removed evenly throughout the fibre, suggesting that the enzymes acted synergistically. The best combination of enzymes for fibre processing was as follows: 5% hemicellulase, 2% pectinase, and 5% cellulase. However, treatment with enzymes leads to loss of weight and strength. In another study, natural fibres extracted from *sansevieria stuckyi* leaves, banana and hemp stems were used for fabrication of needle-punched nonwoven fabric [18]. The Dilo nonwoven machine consisting of an opener, a carding, and a needle loom was used for fabrication of needle-punch nonwoven fabric. While banana nonwoven fabric exhibited the highest air permeability, hemp nonwoven fabrics showed lowest air permeability [18].

4.2.4. Pineapple

Commercial pineapple leaf fibres (PALFs) (*Ananas comosus* var. *comosus*) have been progressively studied for use in polymer composites as mechanical reinforcement [104].

PALFs are bioproducts of pineapple plant cultivation. They have a ribbon-like structure and consist of a vascular bundle system with bunches of fibrous cells.

Fibre extraction with alkali treatment was carried out to remove all impurities and to enhance the adhesive nature of the fibre surface by generating a roughened topography. The nonwovens were fabricated from 100% PALF fibres using needle-punching technology [105].

Pinatex leather is a nonwoven textile that is produced from pineapple leaf fibre and a mix of biodegradable and nonbiodegradable compounds. This fabric contains 80% pineapple leaf fibre and 20% polylactic acid fibre. The quality of Pinatex leather is similar to animal derived leather such as being heat-resistant, impermeable, flexible, soft and durable [106].

In the study by Hanifah and Giarto (2019), a nonwoven fabric was produced from pineapple fibre (90%) and low-melt polyester fibre (10%) using the thermal bonding method under high temperature and pressure [107]. The results showed that the greater area density of fabric leads to higher thickness, density, strength, stretch, and filtering efficiency and lower water permeability, porosity, and pore size than other nonwoven fabrics.

4.2.5. Curaua

Curaua (*Ananas erectifolius*) is cultivated in the semi-arid areas of the Amazon (Brazil and Venezuela), mainly for commercial purposes. Spinacé et al. (2009) studied the curaua fibre for mechanical properties, moisture content, water absorption, density, diameter, thermal behaviour, chemical composition, and surface morphology [108]. Novel curaua nonwoven fabric composites were produced for use in ceramic armour systems. The results indicated that these composites can be used as substitutes for synthetic fibre laminates in ceramic backing materials [109].

4.2.6. Henequen

Henequen (*Agave fourcroydes*) is a strong lignocellulosic fibre obtained from the leaves of the tropical American agave [110]. In one study, Cuban henequen fibre web and an epoxy-novolac matrix were used to produce a composite material. Natural fibres were used without any surface treatment. The results revealed that the introduction of Cuban henequen fibres into composites led to higher tensile and impact strength compared with that of a pure matrix [111].

4.2.7. Tea Leaf

Tea (*Camellia sinensis*) leaf fibre is a by-product of tea processing, obtained following drying and chopping of the leaves. Konjac pastes were used on the surface of papers of hemp and wasted tea leaves to prepare nonwoven fabric 'KAMIKO'. The result showed that the paper products containing 10 wt.% of tea-leaf waste exhibited an excellent deodorization effect [112]. Three layers of industrial tea-leaf fibre waste materials with a single layer of woven cotton cloth were used for sound absorption applications [113].

4.2.8. Cantala

Cantala (*Agave cantala*) is mainly grown in dry and rocky climates such as Sumenep and Madura in Indonesia. Fibres derived from finer leaves are more suitable for spinning than sisal. One study reinforced an epoxy resin matrix with unidirectional cantala fibre mats [114]. It was demonstrated that the flexural strength improved by random arrangement of cantala fibres as it helps distribute the applied load longitudinally [114].

4.2.9. Fique

The fique plant (*Furcraea agavaceae*) is an endemic species of agave plant that grows in South America [115]. Fique fibres are derived from the plant leaves by mechanical methods. In one study, fique nonwovens were fabricated using a chemical bonding method by spraying natural rubber latex between fique fibre layers and then compacting with a hydraulic press [115]. Fique nonwovens presented higher density than sisal, glass, and polyester fibres by about 5.1×2.5× and 2.8×, respectively. In another study, fique fibres were extracted from the plant leaves using decortication techniques, and nonwoven fabrics were formed using short fique fibres and polymer covering [116]. A study performed by Hidalgo-Salazar et. al. (2018) investigated the effect of the incorporation of nonwoven industrial fique fibre mats on two polymer matrices (linear low-density polyethylene (LLDPE) and epoxy resin (EP) using compression moulding and resin film infusion processing techniques, respectively [117]. Tensile and flexural mechanical characterization showed that incorporating nonwoven fique in composites leads to higher strength and modulus, but lower deformation capability than LLDPE and EP alone. LLDPE–fique bio composite tensile modulus and tensile strength were enhanced by 166% and 36% compared to LLDPE. On the other hand, EP-fique tensile modulus and tensile strength were improved by 700% and 66% compared to EP.

4.3. Fruit and Seed Fibre

4.3.1. Husk

Betel nut husk (BNH) fibre is a type of agri-waste fibre which consists of approximately 60–80% of betel nut's total volume and weight [118]. The BNH fibre showed tensile properties like the kenaf fibre with higher elongation-at-break values [119]. The random nonwoven BNH fibre nonwoven fabric was prepared by arranging ripe BNH fibres on a flat surface and subsequent cold pressing. The flexural modulus was increased by about 46% after incorporating a 10 wt.% ripe BNH fibre into BNH fibre-reinforced vinyl ester composites. However, the flexural strength of BNH fibre-reinforced vinyl ester composites significantly decreased when using increasing amounts of ripe BNH fibre content. Poor flexural properties were observed with random nonwoven ripe BNH fibre-reinforced vinyl composites. Large and nonuniform ripe BNH fibre led to trapped air during resin penetration in the nonwoven mat, resulting in the formation of voids within the composites and reducing the mechanical properties of the final composites [119].

Coir (*Cocos nucifera*), one of the abundant agricultural wastes, is a natural fibre extracted from coconut husk [26]. Nonwoven fabrics such as sisal, a blend of sisal (70%) and coir (30%), and a blend of coir (70%) and sisal (30%) were fabricated by using the needle-punch technique [100]. Samples with lower thickness showed higher air permeability and higher concentration of interlocking spots and voids in the nonwoven fabric. The presence of a natural convolution or crimp in the coir fibre led to greater water absorbency and a significant elongation percentage compared to that of sisal. However, the sisal fibre has a greater mean breaking strength compared to coir. Better air permeability was observed for the sisal (70%) and coir (30%) blend and lower air permeability was observed for the sisal 30% and coir 70% blend [100].

Corn husk is a by-product of maize. In one recent study, the nonwoven fabric was produced using corn husk and banana stem waste. The fibres from corn husk and banana stem were extracted using baking soda and cleaning vinegar, respectively. The results showed nonwoven fabrics fabricated from baking soda-extracted fibres exhibit a more uniform and smoother [120]. In another study, the corn husk fibre was extracted using the water retting method and alkali and bleaching treatments using NaOH and H_2O_2. The nonwoven composite was produced using the water-laid method and vacuum-assisted resin infusion. The tensile strength and tensile modulus of the different composites decreased in the following order: H_2O_2-treated composites > NaOH-treated composites > untreated composites > neat epoxy. The composite-containing fibres treated with NaOH and H_2O_2 had lower water absorption compared to the untreated fibres. Fibres with a rough surface were obtained with NaOH treatment due to removing part of lignin and hemicellulose from the fibre. In contrast, the H_2O_2 bleaching process led to fibrillation on the fibre due to removing most of the lignin and hemicellulose. Therefore, both rough fibre surface and fibrillated fibre contributed to fibre–matrix interaction adhesion and composite improvement [121].

4.3.2. Kapok

Kapok is a fibre derived from the silk cotton tree's fruits and it has a hollow structure with a central lumen comprising 77% of the total fibre volume with absolute and bulk densities of 1474 kg/m^3 and 384 kg/m^3, respectively [122]. The waxy surface of kapok fibre is essential in determining the hydrophobic oleophilic characteristics. In one study, the air-laid nonwoven technology was used to develop thermally bonded nonwovens from the mix of cotton, kapok, and PP fibre. The fibres were mixed and fabricated through a miniature Trytex air-lay machine to create fibre webs, and then the nonwoven mat was thermally bonded. A small number of PP fibres were used to improve the formation of fibre webs by bonding the fibre and enhancing mechanical stability [123].

The blend of cotton and kapok fibre waste was used to produce needle-punched nonwoven fabric. The kapok fibre was needed to blend with the cellulose fibre in needle-punch processing due to the short fibre length range and decreased cohesiveness. The results showed that the increase in the proportion of kapok in the blend decreased fabric bulk density due to the increase in the thickness of the samples [124].

The nonwoven fabrics made of kapok fibre mixed with hollow polyester, viscose fibre, PP fibre and cotton fibre were fabricated by carding, followed by needle-punching [125]. In another study, needle-punched nonwoven structures were produced using nettle/kapok blends. The microscopic images showed that nettle fibres have properties such as coarseness, strength, continuous and rough surfaces. In contrast, kapok fibres are smooth and fine; with the two fibres combined, the resulting material has a void percentage of more than 50% [126]. The nonwoven fabrics were produced by mixing kapok and PP fibres in a 70:30 blend ratio, processing through a miniature carding machine, and then thermal bonding by applying heat and pressure [127]. The kapok/PP nonwoven fabrics were prepared by opening and mixing, carding, web forming, the web bonding process (needle-punching), and winding. The results showed that the morphologic incompatibility force between PP and kapok fibres led to lower bulk density of 75:25 PP/kapok blend and 25:75 PP/kapok blend samples in comparison to the values predicted by the rule of mixtures [128].

4.3.3. Biduri

Biduri (*Calotropis gigantea*) is a wild shrub plant that is often considered a weed and found worldwide. Biduri fibres resemble kapok in that they are located around the plant seeds rather than the stem or leaves. The biduri seeds' fibre is the staple fibre, lustrous, with a wide lumen and thin walls covered with a waxy coating. The presence of a cavity in the middle of biduri fibres leads to lightweight and sound insulation properties, and the waxy coating provides excellent hydrophobic–oleophilic properties. In another study by Sukmawati (2021), biduri nonwoven fabric was created from either a mixture of biduri fibres with polyester fibres or biduri fibres with PP [129]. The biduri fibres were modified using an alkaline mercerization treatment, resulting in nonwoven fabrics with altered oil absorption properties due to the removal of lignin from the fibres.

4.3.4. Oil Palm

The oil palm tree (*Elaeis guineensis*) belongs to the family of Palmae. The fibres of oil palms can be extracted from the fruits (Empty Fruit Bunch fibre; EFBf), fronds (Oil Palm Frond fibre; OPFf), and trunks (Oil Palm Trunk fibre; OPTf). These fibres are interesting due to their high tensile strength and toughness [130].

Recently, a nonwoven fabric composite was produced with empty fruit bunch/PP and kenaf/PP fibre mixtures by a carding and needle-punching process followed by compression moulding [86]. This finding indicated that the fibre type did not have a substantial impact on the tensile strength of the nonwoven fabric. This is because the tensile strength of the nonwoven fabric is primarily determined by the efficiency of fibre entanglement, rather than the inherent tensile strength of the fibres themselves. The tensile strength of the nonwoven fabric is mostly related to the PP content because the PP fibre provides better fibre entanglement and interaction among fibres and develops more compacted structures and higher frictional forces among fibres, which leads to higher tensile strength of the fabric. Nonwoven fabrics with higher EFB are bulkier, enabling the fibres to slide over each other during the tensile strength test. Furthermore, 60% of natural fibre nonwoven fabrics result in high tensile elongation, poor entanglement between fibres, and a less compact and rigid fabric. The nonwoven tensile strength increases directly with increasing fabric weight [86].

Windmill palm fibres have been extracted from windmill sheath mesh with treatment by H_2O_2 and NaOH and wet-laid techniques [131].

Ventura et al. (2015) investigated the possibility of oil palm frond fibres (OPFf) for producing nonwoven textile-reinforced composite materials [130]. Nonwoven fabrics were made with treated and untreated fibres derived from frond waste using wet mechanical entanglement. The alkaline treatment was effective in increasing the wettability and water retention value of the fibres.

4.3.5. Okra

Okra (*Abelmoschus esculentus*) is grown in tropical, subtropical, and warm temperate regions worldwide; it originated in Africa. The mechanical properties of okra fibres resemble those of traditional bast fibres like flax, kenaf, and hemp [132]. One study used okra stem wastes to produce needle-punch nonwoven fabrics. To hydrophilize and fibrillate the okra stem waste fibres, surface modification of the fibre was performed with an alkaline solution (NaOH). Then, combing and needle-punching processes were applied to the fibres with and without modification of the fibre. Alkali treatment led to a decrease in fibre diameter and weight and an increase in tensile strength, roughness rate on the fibre surface, brightness, and the ability to absorb moisture [133]. In one study, okra fibres were extracted by water retting in different time intervals from 3 to 15 days to optimize the time of the retting process. After the retting process, degumming was carried out with sodium carbonate, and bleaching was performed with hydrogen peroxide. Nonwoven fabrics were prepared from 100% okra fibre and blended with jute fibre in four different ratios, i.e., 80:20, 70:30, 60:40, and 50:50%. The nonwoven fabric of the okra/jute 50:50 ratio showed the highest general appearance, followed by 100% okra nonwoven fabric [43].

4.3.6. Luffa

The sponge gourd (*Luffa cylinderica*) is a subtropical plant abundant in China, Japan, and other Asian countries. The fibre can be separated from the skin, flesh, and seeds [134].

In one study, the stitched luffa fibres were sandwiched between the needle-punch cotton or polyester fibres and used for nonwoven fabric production through a needle-punching machine. Higher thickness and bulk density were obtained because the cell-like structure of luffa fibres prevents compact packing of fibres during needle-punching [135]. In other research, the nonwoven fabrics were produced from luffa cylindrica fibres using a dry laid and bonding agent [136].

4.3.7. Waste Cotton

Cotton can come as bleached, virgin, waste, and reclaimed cotton. Cotton fibres that are removed during ginning and textile manufacturing processes are waste cotton. A study performed by Latifi et al. (2019) showed the production of a cotton waste nonwoven web using the nonwoven needle-punching method [137]. The results showed that processing factors such as fibre feeder speed and number of stacking layers have a notable impact on the mechanical properties of the fabrics. A lower fibre feeder speed leads to the production of stronger nonwoven fabric. This can be attributed to the higher punching density at a specific spot on the web, resulting in enhanced fibre interlocking.

4.4. Straw Fibre

Straw is an agri-residue or a by-product obtained from several cereal crops such as rice, wheat, barley, oats, and rye when grain and chaff are removed. Those fibres could be considered as reinforcement in composite production. For example, Prasad et al. (2007) reported that the incorporation of rice straw fibre of about 40% in polyester resins increased tensile strength to 46 MPa, which is greater than that of plain polyester [138]. Rice straw/cotton (90:10 *w*:*w*) nonwoven fabric is produced by pre-treating the rice straw with NaOH, enzyme, and the wetting agent, blending with cotton in a 9:1 ratio, then carding and needle-punching. The results showed that after surface modifications of the rice straw with alkali and enzyme treatments, non-cellulosic foreign materials were removed, and fibre surface roughness was increased [139]. In another study, cellulose fibre was extracted from the rice straw with NaOH, and nonwovens were prepared by the wet-laid process. The optimal condition for cellulose fibre extraction from the rice straw was obtained at 5% NaOH at 90 °C for 2 h [140].

4.5. Grass Fibre

Bagasse

Bagasse (*Saccharum officinarum*), also known as sugarcane, has short bast fibres that remain after crushing the stalks and sugar extraction. The sugarcane stalk is composed of two central pith regions that contain the majority of the sucrose, along with an outer layer composed of 60–70% lignocellulosic fibres. Many studies were carried out regarding the production of bagasse nonwoven fabric with technological processes involving extraction, cleaning, and carding as the preparation of the fibre web and needle-punching and thermal bonding for the bonding of the fibres in the web [141]. It was concluded through laboratory trials that the manufacturing of nonwoven materials with a composition of over 70% bagasse is challenging due to the short length and rigidity of the bagasse fibres [141]. The Louisiana State University (LSU) Human Ecology Textile Processing Laboratory has developed a method to produce bagasse fibre nonwoven fabric and composites [142]. Recent patented work aimed at producing beverage infusion bags consisting of a plurality of mono-component polylactic acid for forming a nonwoven web through dry thermal bonding. This polylactic acid fibres is sourced from sugarcane [143].

Chen et al. (2008) produced hemp/PP (70:30), kenaf/PP (70:30), ramie/PP (70:30), and bagasse/PP (50:50) composites using a carding and needle-punching technique followed by thermo-bonding. The results demonstrated that bagasse/PP composites have a tensile strength close to that of hemp/PP, the lowest wet absorption amongst the other composites, and no ability to resist termite attack [83]. Research at LSU used alkaline extracted bagasse fibres as the main component of bagasse/cotton (70:30) nonwoven fabric. Nonwoven composites were produced by fibre web formation by carding, needle-punching, and the bonding of the nonwoven webs with biodegradable adhesives to form the nonwoven composites [144].

4.6. Noncommon Fibre

Cotton grass, a by-product of peat excavation, is a member of the sedge family. It is common in bogs in the United Kingdom and Ireland. The cotton grass nonwoven fabric was fabricated by hot pressing with or without a binding agent [145].

A nonwoven composite was prepared applying wet-laid technology and a hot-press molding process with a high content of tiger nut waste (*Cyperus esculentus* L.), binder fibres and thermo-bonding fibres. The best mechanical responses were obtained with the additions of binder fibres and thermo-bonding fibres. The polyamide bicomponent used for thermo-bonding had the most significant impact on energy absorption. The bonding between fibres through an entangling effect occurred because of the difference between the melting point of the outer (135 °C) and inner (220 °C) parts during the thermo-binding forming process [146].

The fibre extracted from the leaf of the Harakeke (*Phormium tenax*/New Zealand Flax) plant using traditional methods, the muka fibre, was also used to produce needle-punch Harakeke nonwovens [147].

In a recent study, yucca and kenaf waste fibres were blended with a mass ratio of 70:30, 50:50, and 30:70 to generate a 3D structure of fibrous media [148]. The results show that flow resistivity decreased by increasing the yucca component content in the composite samples with 100% yucca fibres having the lowest flow resistivity values.

In another study, a multifunctional wet-laid nonwoven fabric with a 3D structure was prepared from a *Posidonia oceanica* waste marine plant and carboxymethylcellulose binder. Increasing the number of fibres and binders increased tensile strength due to inter-fibre friction and binding properties [149].

Kudzu (*Pueraria thunbergiana*) is a fibre crop native to southern Japan and southeast China. The tensile strength of kudzu is compared to that of other natural fibres like Henequen. The kudzu fibre was used for reinforcing PP composites [150].

A recent work by Raj et al. (2020) investigated the potential of converting areca nut leaf sheath into a needle-punch nonwoven form [151]. Areca catechu is a type of palm species that comes under the family of Arecaceae and is grown mainly for its fruit. SEM images demonstrated the kidney bean-shaped cross-section of the fibres and wax-like impurities on the surface of the fibres. The physical characterization of fibre was determined to be coarse, strong, rough, and thermally stable; undergoing a nonwoven process, it becomes finer.

Olive pomace wastes are generated by cold-pressing olives. In a recent study, Gutierrez et al. (2020) assessed the potential of upgrading olive pomace wastes into a nonwoven composite using wet-laid technology combined with different thermoplastic binder fibres from both natural and synthetic origins [152]. Composite materials were manufactured using hot-press molding or continuous lamination. The results showed that the wet-laid technique could successfully prepare high-olive-pomace-content materials (up to 80 wt.%) with 10 wt.% of Lyocell fibres and 10 wt.% thermo-bonding fibres.

In one study, with fibre extracted from stems and barks of these three plants (Sesbania grandiflora, Mutingia calabura, Bauhinia purpurea) by a decorticator and blended with other natural fibres like jute and flax in a 45:10 ratio and after the carding process, nonwoven fabrics were prepared using the needle-punching method [39]. Dhaincha (Sesbania aculeata) is a leguminous plant that is cultivated or found in the wasteland, and it is the source of organic matter and a nitrogen fixer. Extraction of fibres from the stem of *S. aculeata* by retting and treating with KOH and H_2O_2 and then converting into a needle-punch nonwoven was explored [153]. The results showed that the nonwoven fabric of *S. aculeata* fibres had properties like medium weight, dense structure, strong air permeability, good bursting strength, low tensile and tearing strength, and poor abrasion resistance.

The nonwoven fabric was made from natural Pennisetum grass using the air-blowing spinning process. The results showed a mild pre-treatment process with a low concentration of NaOH solution, and a mild temperature had an optimal effect on grass fibre regarding practically destroying the biomass recalcitrance, improving the dissolution of the Pennisetum grass and retaining most of the components of the grass [154].

5. Application of Agriculture Waste for Nonwoven Applications

5.1. Thermal Insulation

Reducing energy consumption in the building and introducing building materials with improved thermal insulation capacity is a significant economic and environmental challenge. Furthermore, the new buildings must meet optimized heating and cooling criteria while providing thermal comfort. The reduction in heat flow can then diminish energy consumption for heating and cooling. Nonwoven textiles represent an important class of materials able to fulfil these needs, providing thermal insulation, mechanical robustness, and lightness for specific applications in automotive and aerospace areas, for example [1]. Heat transfer through porous media consists of conduction through solid material, convection through the gas phase, and radiation through pores [155]. The presence of stationary air within the porous structure results in efficient thermal insulation of materials because the thermal conductivity of static air coefficient is approximately 0.024 W/mK at room temperature, making static air an exceptional medium for thermal insulation [156]. Therefore, the total air trapped within a nonwoven structure and the thickness of air spaces within the fibrous material is essential for heat transfer [157].

Heat transfer through materials of fibrous insulations is attributed to the function of the fibres' thermal conductivity and mechanical properties. Thermal conductivity in nonwoven fabric depends on factors such as the interaction at each fibre contact point, fibre content, stuffing geometry, the temperature difference per unit thickness, and nonwoven structures such as thickness, areal density, bulk density, and porosity [158]. Thermal insulation can be improved by increasing the thickness of fibrous nonwoven material due to reduction in the conduction and radiation of heat transfer. The reduction in heat transfer can be obtained by increasing the total amount of entrapped air within the thicker fibre webs and reduction in radiation can be obtained by a tortuous path or smaller mean free path created by the fibres of the thicker webs [158]. The 'tortuous path' reduces the conduction path between the fibres and then reduces radiation by increasing absorption, thus scattering the radiation within the batting. The narrow and tortuous air passages are more likely to obstruct the airflow, which reduces heat convection resulting from the obstructed airflow and leads to better thermal insulation performance [156]. Thermal conductivity and density of nonwoven fabric are inversely related to its porosity; as porosity increases, both thermal conductivity and density decrease. However, the extent of this decrease is not constant with pore size variation; with almost the same apparent density, the material's thermal conductivity increases gradually with pore size increase [159]. Numerous research findings have established that fibres with lumens offer effective thermal insulation, as the presence of lumens reduces fibre density [160]. Therefore, plant fibres are potential raw materials for use in thermal insulation applications. Incorporating cellulosic fibres as sustainable materials in nonwoven structures forms a natural fibre nonwoven fabric with a capillary-linked, tortuous porous network, which causes good mechanical properties and high porosity required for thermal insulation properties (Table 5). Some published studies have reported using natural fibre waste such as coir, hemp, date palm, sisal, bamboo, and jute in thermal insulation nonwovens.

Table 5. Comparison of thermal conductivity properties for various natural vegetable fibrous nonwoven fabrics.

No.	Materials	Thickness, mm	Bulk Density, kg/m^3	Key Findings	Thermal Conductivity, W/mK	Ref.
1	Bassage	5.69	83.025	Thermal insulation of nonwoven fabric is 0.726 clo.	0.0505	[161]
2	Cotton/milkweed	13.50	67.000	The thermal conductivity of samples decreases with increase in the thickness of nonwoven fabric.	0.0310	[124]
3	Cotton/kapok	8.90	78.000		0.0040	
4	Coconut/2D-PET	10.00	20.000	The thermal conductivity coefficient of the composite increases with the increased amount of coconut fibres of less than 15 wt.%.	0.0279	[156]
5	Betel Nut Husk (BNH)	10.00	-	The incorporation of BNH random nonwoven fabric decreased the thermal conductivity and thermal diffusivity of the composite.	0.1800	[119]
6	Fique	1.50	66.67	Fique nonwoven fabric has good thermal insulator material with the reference of mineral wool.	0.0360	[116]
7	Fique	3.50	197	Thermal conductivity increases by increasing the weight of nonwoven fabrics.	0.0434	[115]
8	Fique	-	-	Fique fibre incorporation affects the thermal stability of the composites.	-	[117]
9	Pineapple	1.03, 3.48	194, 201	By increasing the thickness of the nonwoven fabric, thermal conductivity decreased.	0.0039, 0.0021	[105]
10	Pineapple/PET	0.83	241	The addition of low-melt PET decreased the thermal conductivity of the nonwovens.	0.0197	[105]
11	Bamboo/PP	4.93	194	Banana/PP nonwoven fabric has better thermal insulation properties than the other two nonwovens.	0.2660	[162]
	Banana/PP	6.43	151		0.0178	
	Jute/pp	4.28	154		0.0360	
12	Sesbania Grandiflora	6.40	108	Areal density, thickness, and bulk density influence thermal conductivity.	0.0472	[39]
	Mutingia Calabura	5.49	107	-	0.0353	
	Bauhinia Purpurea	5.40	110	-	0.0129	

Table 5. *Cont.*

No.	Materials	Thickness, mm	Bulk Density, kg/m^3	Key Findings	Thermal Conductivity, W/mK	Ref.
13	Kapok/cotton	2–12	75–130	The thermal conductivity of fabric decreased with an increase in the blend proportion of kapok and milkweed.	0.0310	[124]
	Milkweed/cotton	3–13.5	60–100		0.0040	
14	Cotton/Luffa	0.73	98	The thermal conductivity decreased with an increase in luffa blend proportion.	0.0430	[135]
	Polyester/Luffa	0.72	91		0.0800	
15	Banana fibre	6	105	Composites showed thermal stability up to 260 °C.	-	[102]
16	Okra fibre	3.5	197	The nonwoven fabric produced from alkaline-treated fibres showed better heat transfer coefficient.	0.4500	[133]
17	Kenaf/PP	6	-	Nonwoven composites containing kenaf were more thermally stable than raw PP plastics.	-	[163]
18	Kenaf/Ramie Binder: PVA	0.791	150	There is an insignificant difference of the thermal conductivity between the acrylic copolymer-bonded composite and the PVA-bonded composite.	0.0210	[87]
	Kenaf/Ramie Binder: Acrylic copolymer	0.689	172		0.0230	
19	FR flax	5	100	Air-laid nonwoven fabric showed excellent insulation performance.	-	[63]
	FR flax/wool	5.5	93		-	
	FR flax/wool/Bicomponent	35	20		0.0430	
20	Flax: PVA	1.5–2	263	PVA in flax: PVA nonwoven fabric does not melt; the nonwoven fabric has high porosity and poor matrix continuity and lower thermal conductivity.	0.0200	[58]
21	Jute/epoxy Hemp/epoxy Flax/epoxy Jute/Hemp/epoxy Hemp/Flax/epoxy Jute/Hemp/Flax/epoxy	-	-	Reinforcement of natural fibres improved the thermal stability of neat epoxy under dynamic loading conditions.	-	[164]

Table 5. *Cont.*

No.	Materials	Thickness, mm	Bulk Density, kg/m^3	Key Findings	Thermal Conductivity, W/mK	Ref.
22	Posidonia oceanica	-	-	Posidonia fibre nonwovens have good insulation properties due to porosity and the amorphous structure.	0.0240	[149]
23	Kenaf, jute, flax, and waste cotton: recycled polyester: PP	0.5–2	50–100	The cotton-based composite showed the highest specific thermal conductivity while the jute-based composite was the least conductive to heat.	0.0300–0.0400	[62]
24	Olive Pomace/Lyocell/PES/PE	0.5–1	300	The thermo-bonding fibre has very low effect on thermal insulation properties of the obtained composites.	0.0870	[152]
25	Olive/Lyocell/PLA	0.5–1.5	300	Hemp fibre content or binding fibre content and areal density of the nonwoven fabric do not affect nonwoven thermal insulating properties.	0.0880	[25]
	Waste hemp/PLA/V	3.5–4.5	100–300		0.0270	
	Waste Hemp/PLA	3–4	100–300		0.0280	
26	Sisal	10	-	There were no significant differences between natural and treated nonwoven fabrics in terms on thermal conductivity.	0.0420	[98]
27	Sisal: wool	7.9	134	Nonwoven sisal fibre material provides 76% reduction in annual heating needs.	0.0380	[99]
28	Sansevieria stuckyi	6.19	89	The thermal conductivity of the nonwoven fabrics showed that the fabric is suitable for insulation materials.	0.044	[18]
29	Banana	6.22	88	-	0.0410	[79]
	Hemp	6.14	91	-	0.0490	
	Hemp (Purini)	6–45	25	Thermal conductivity depends on the fabric thickness for both nonwovens, but the trends are not consistent.	0.0280	
	Hemp (Bialobrzeskie)	31–30	25		0.0280	
	Nettle	2–3	75	From the Box–Behnken experimental design, minimum thermal conductivity was achieved at needle-punch density of 75 punches/cm^2, 8 mm needle penetration depth and fabric areal weight of 150 g/m^2.	0.0251	[165]

5.2. Acoustic Insulation

With the development of urbanization and transportation, excessive levels of noise pollution levels have been present all over the world. Based on information released by the World Health Organization (WHO), exposure to higher noise levels is a global issue that causes multiple auditory and non-auditory health issues [166]. As a result, the implementation of efficient engineering strategies for noise control becomes necessary.

Sound-absorbing materials (either porous or fibrous) are classic examples of passive noise reduction technology. Recently, the use of fibres in manufacturing sound-absorbing materials has attracted much attention. Plant fibre as a porous material contains various pores, canals, cracks, or cavities that allow for penetration of sound waves within the structure [167]. The dissipation of sound energy in the sound absorption of fibrous materials occurs due to viscous effects and thermal transfer within the flexible porous structure. When sound propagates through fibrous material, the air molecules at the material's surface and within the material's pores are forced to vibrate, resulting in the loss of original energy. This is because a portion of the energy of the air molecules is transformed into heat because of thermal conduction between the air and the absorptive material [156]. At lower frequencies, these variations remain isothermal, whereas at higher frequencies, they become adiabatic. Within fibrous materials, a significant portion of the energy can also be absorbed through scattering from the fibres and the resulting vibrations within the individual fibres. However, absorption mainly occurs through the interconnected pores of the fibres which rub together under the influence of sound waves.

The usage of nonwoven materials for noise control in the construction, building and transportation industries is attractive because of inbuilt advantages such as porous fibrous structure, lightweight, bulky nature, and economically low price. The key factors that determine the sound absorption properties of nonwoven structures are fibre type, fibre size, material thickness, density, porosity, and airflow resistance. In a recent study, Gomez investigated the effect of fibre cross-sectional shape, denier, and fabric density on the acoustic performance of nonwovens [166]. It was shown that fibres with round cross-sections show greater air permeability, improving sound absorption and insulation. In recent years, many studies (Table 6) have analyzed the applicability of lignocellulosic fibres as a replacement for synthetic materials in the production of acoustic absorbers. Thesound absorbers nonwoven mainly are made from hemp, coir, bamboo, oil palm, sugarcane, yucca gloriosa, kenaf, date palm, Jute, flax, broom, and other various vegetable fibres. This natural fibre from agricultural by-products is categorized as a genuinely sustainable and environmentally friendly sound absorber. Many studies have already proposed various mathematical models to interpret the acoustic behaviour of absorbing materials. So far, several analytically based models, such as the Delany–Bazley empirical model and the phenomenological model developed by Johnson-Champoux-Allard, have been used to achieve optimal alignment between the observed experimental data and optimization refinement of acoustic prediction. Theoretical models presented for analytical studies usually aim to derive the expected propagation constant. The acoustical behaviour of porous absorbing materials is the function of properties such as open porosity, airflow resistance, and tortuosity [167].

Overall, sound-absorbent materials derived from plant fibres, like bast fibres, are readily recyclable, and their production boasts a low carbon footprint. Consequently, they can be categorized as environmentally friendly building materials as sustainable substitutes for chemical building materials, polymers, and other non-sustainable alternatives.

Table 6. Comparison of acoustic properties for various natural vegetable fibrous nonwovens.

No.	Materials	Thickness, mm	Bulk Density, (kg/m^3)	Key Findings	Frequency Range (Hz)	Ref.
1	Kenaf	33.00	150	Bulk density, thickness, and airgap behind samples affect acoustic absorption.	100–6000	[167]
2	Kenaf/PP/low melting PET fibres	0.60	500	Nonwovens with high thickness, high weight and low pore size have high sound absorption coefficient.	500–6300	[85]
3	Coconut fibre/polyester	10.00	20	The acoustic absorption coefficient of composite board dramatically increases when the amount of CF is 25 wt.%	128–4000	[156]
4	Bamboo/PP	4.93	194	Bamboo/polypropylene nonwoven has the highest absorption coefficient in all frequency levels.	100–3200	[162]
	Banana/PP	6.43	151			
	Jute/pp	4.28	154			
5	Pineapple	1.30 3.48	194 201	Blending of the low-melt PET with PALF shows a slight increase in the Noise Reduction Coefficient value.	100–6300	[105]
	Pineapple/PET	0.83	241		100–6300	
6	Kapok/PP	6.34–9.36	185.02	Maximum absorption of sound is obtained from the uncompressed kapok/PP nonwoven composite of a 30:70 blend ratio.	250–2000	[106]
7	Areca nut leaf sheath	6.00	105	Increasing thickness has good effect on sound absorption coefficients, especially at higher frequencies (3000–5000 Hz).	100–5000	[151]
8	Fique	3.50	197	Fique fibre's acoustic performance could improve when reducing its fibre diameter.	60–6300	[115]
9	Fique	15.00	80	Acoustical properties are comparable to mineral wools, and also thickness and grammage are effective for nonwoven fabric acoustic performance.	100–5000	[116]
10	Jute	14.00	45	Area density, number of layers, and distance of fabric from sound have effects on sound absorption.	-	[168]
11	Arenga pinnata	50.00	300–900	Sound absorption coefficients of Arenga piñata samples mixed with natural rubber are better than those of the sample without natural rubber as a binder.	90–7000	[169]
12	Windmill fibres	4.00–12.00	200	The addition of PVA significantly improves the sound absorption ability.	60–6300	[131]
13	Kenaf/PP	6.00	-	Nonwoven composites with panel-felt-panel sandwich structures are good noise absorbers in the high-frequency range.	100–6400	[163]

Table 6. *Cont.*

No.	Materials	Thickness, mm	Bulk Density, (kg/m^3)	Key Findings	Frequency Range (Hz)	Ref.
14	Sesbania grandiflora	6.40	108	Increasing the fibre layer in the fabric leads to increase in sound absorption.	100–2000	[39]
	Mutingia calabura	5.49	107			
	Bauhinia purpurea	5.40	110			
15	Kenaf/yucca	3.00	200	100% kenaf and 100% yucca samples have the highest and lowest NRC [1], respectively.	80–6300	[148]
16	Kapok/cotton	2.00–12.00	75–130	The otton/milkweed nonwoven fabric has better sound reduction than cotton/kapok.	-	[124]
	Milkweed/cotton	3.00–13.50	60–100			
17	Cotton/Luffa	0.73	98	The cotton/luffa and polyester/luffa 50/50 fabric showed higher sound reduction.	-	[135]
	Polyester/Luffa	0.72	91		-	
18	Kapok/hollow polyester	10	-	Sound absorption coefficients rise with the increase in thickness for all kapok-based fibre nonwoven fabric samples.	100–6300	[125]
	Kapok/viscose	10.00	-			
	Kapok/cotton	10.00	-			
	Kapok/PP	9.00	-			
19	Corn husk	0.65–2.91		The acoustic absorption peak gradually moves to lower frequency range with the increase in back cavity distance.	100–6000	[170]
20	Flax	5.00	100	The airlaid flax/wool/bicomponent nonwoven fabric showed lower sound absorption in comparison to two needle-punch flax and flax/wool nonwovens.	-	[63]
	Flax/wool	5.50	93			
	Flax/wool/Bicomponent	35.00	20			
21	Flax: PVA	1.50–2.00	263	Both flax: PVA and flax: PA6/CoPA nonwovens showed good acoustic insulation properties in the medium frequency range (500–600 Hz).	50–2000	[58]
	Flax: PA6/CoPA	1.50–2.00	210			
22	Olive/Lyocell/PES/PE	0.5–1	300	High olive pomace content offers a low acoustic absorption coefficient at low frequencies (below 600 Hz). Composites with PLA improve acoustic absorption coefficient compared to those derived from PES/PE fibres.	100–6000	[152]
	Olive/Lyocell/PLA	0.5–1.5	300			
23	Waste hemp/PLA/V	2–4.5	100–300	The highest values of acoustic absorption coefficient are obtained using three-layered nonwovens with high areal density and high content of hemp waste.	100–6000	[25]
	Waste hemp/PLA	3–4	100–300			

[1] Noise reduction coefficient.

5.3. Oil–Water Separation

The separation of oil residues in wastewater is a global concern due to the substantial volume of oil residues discharged by industries such as steel, aluminium, food, textile, leather, petrochemical, and metal finishing, as well as a result of accidental oil spills. Therefore, the development of functional solid surfaces designed for separating oil-based contaminants from oil–water mixtures has become of great importance in reducing industrial pollution. With this goal in mind, over the past decade, researchers have developed different types of solid surfaces including metallic meshes, porous ceramic materials, carbon-based sponges, and fabric. Amongst these types of solid surfaces, nonwoven fabrics stand out as some of the most promising substrates because of their unique properties such as being ready-made for large-scale applications, low cost, porous structure, easy penetration of the liquids, flexibility, and absorption capacity for oil–water separation [171]. With the right choice of fibre and nonwoven process, the nonwoven fabrics usually show excellent tensile strength, large surface area, and interconnected porous structure that make oil–water separation more efficient. In a recent study, Yuan et al. (2020) found that rewetting the PP-wood pulp fibre composite nonwoven fabric had superior underwater oleophobic properties and oil–water separation performance even after repeated separation and long-term soaking cycles [172]. In a study by Choi et al. (1993), needle-punched nonwovens were prepared using cotton/PP blends [173]. It was demonstrated that higher oil absorption capacity is attributed to higher cotton content because of the lumen as well as the wax coating on the cotton fibre surface. Nevertheless, some lignocellulosic fibres were found to be efficient in separating oil because of their oleophilic and hydrophobic nature. Am environmentally friendly oil–water separation substrate can be fabricated using inexpensive, flexible, and lightweight biomass generated from agriculture waste as raw material. Leaves and residues of palm and sisal, sponge guard, sugarcane bagasse, rice husk, peat moss, sawdust, barley straw, kenaf, flax, and natural fibres such as cotton, kapok, milkweed fibres, etc., were tested for their oil sorption capacity [174]. Rengasamy et al. (2011) investigated the thermal-bonded nonwovens for oil spill separation [127]. In this work, nonwoven samples were prepared by a series of filled fibre assemblies from 100% PP, kapok, and milkweed fibres and by blending milkweed and PP fibres and kapok and PP fibres nonwoven, followed by thermal bonding. The results showed that oil sorption capacity porosity depends on the porosity of fibre assembly, and the nonwoven samples showed higher oil sorption capacity than the filled fibrous assembly. Also, for all the fibre assemblies, oil sorption capacity was higher for high-density oil rather than diesel oil. In a recent study, kapok fibre nonwovens were produced by blending with PP fibres or hollow conjugated polyester fibres at several weight ratios for oil absorbent and fuel/water separation filters. The prepared kapok nonwovens demonstrated high-performance oil absorbent functions with absorption properties over 30 times their weight in comparison with net PP nonwovens. Also, the hydrophobic–oleophilic characteristics of the kapok fibre led to high water-in-fuel separation efficiency [175]. The work by Lee et al. (2013) focused on the effect of the blend ratio of PP/kapok nonwoven fabrics on oil sorption capacities [128]. Therefore, nonwoven PP/kapok blends with different ratios were prepared by a needle-punching process at optimized conditions. An increase in oil sorption capacity was observed with the rise in kapok content up to 50%, but it subsequently declined with further increases in kapok content. The researchers ascribed this to the low bulk density of fabric at that proportion, which might be due to the highest morphological incompatibility between PP fibre and kapok. Another example reported by Ventura et al. (2015) investigated the oil sorption capacity of needle-punched nonwoven structures of 100% nettle and nettle/kapok blends with 50:50 and 75:25 ratios [126]. The nettle/kapok blended structure with a 50:50 ratio showed the highest oil sorption capacity of 28.5 g/g and 22.5 g/g for high-density and diesel oil, respectively, which is a higher oil absorption capacity than that of commercial PP-based nonwoven fabric. Kapok fibres are inherently hydrophobic and increase the oil sorption capacity by 13–18%; they also reduce water absorption properties in the nettle/kapok blended nonwoven structure. In another study, Thilagavathi et al. (2018)

produced excellent and selective oil absorption in nonwoven milkweed fibres blended with cotton and PP [123]. The highest oil absorption capability of the thermally bonded nonwoven fabric reached 40.16 g/g for high-density oil and 23.00 g/g for diesel oil. The oil absorption capacities of three natural fibres, milkweed, cotton, and kenaf, were examined. Maximum oil sorption capacity was obtained in milkweed fibre followed by cotton fibre due to a large amount of wax on the fibre surface and the larger and non-collapsing lumen. The introduction of milkweed in the mat led to an increase in the oil absorption capacity of the PP pad between the values obtained by milkweed floss and PP web [176].

The biduri fibre has excellent hydrophobic and oleophilic properties that can be used for oil and water absorption. In a recent study, a nonwoven structure made from a 90/10 mixture of biduri and polyester showed high oil absorption of about 42.86 g/g [129]. In one study, the oil absorption efficacy of needle-punched cotton grass nonwovens was investigated. Higher oil sorption was obtained for cotton sorbents compared to those made of 100% PP fibres. Cotton grass mats, a by-product of peat excavation, absorbed oil approximately two to three times better and faster than the synthetic sorbent mat. Cotton grass is appropriate for oil separation from the surface of the water because it has low density, which enables it to remain on water even after seven days without sinking [145]. A recent work looks at the production of a high-absorbent web for coconut, castor, and ground nut oil using Calotropis gigantea fibre. Calotropis gigantea fibres have large free spaces, which are used for the absorption of oils even though oil absorption depends on the density of both the oil and the web fibre [177]. In recent work published by Xia et al. (2022), the authors presented an environmentally friendly and economically efficient approach for producing high-performance oil–water separation nonwoven fabric using Hybrid Pennisetum grass as raw material [154]. This nonwoven fabric showed high efficiency around 100% for oil–water separation and the capability of oil sorption in high-salt and -acid/alkaline solutions. To test the effects of fabric weight, needling density, and blend proportion of nettle and PP fibres, the oil absorption of needle-punched nonwovens was studied for diesel engine oil and crude by Brindha et al. (2019). The nettle/PP (30:70) nonwoven fabric with lower needling density and lower fabric weight showed maximum oil sorption. It was observed that these nonwovens with excellent sorption capacity after the eighth cycle for oils could be used efficiently for oil spill cleanup applications [174]. In another work, Renuka et al. (2016) investigated the oil absorption behaviour of needle-punched nonwoven fabrics fabricated from milkweed, kapok, cotton, and PP fibres using air-lay and carding technologies [178]. Milkweed and kapok nonwovens exhibited superior oil absorption and retention capacities in comparison to cotton and PP nonwovens. The results indicated that web-forming technology had no influence on the oil absorption and retention capacities, as well as the absorption rate.

Moreover, the separation capacity of cellulosic fibre nonwoven fabric can be enhanced by treating the surface of the nonwoven fabric with finishing materials and methods. In one study, the surface of four types of knitted, woven, and nonwoven fabrics was treated with a small aliphatic molecule to produce hydrophobic cellulose-based fabrics. The modified fabrics exhibited hydrophobic and super-oleophilic properties and high separation efficiencies above 93% for various oil mixtures along with stability under acidic conditions and elevated temperatures and durability after 30 separation cycles [179]. In a study performed by Doh and coworkers (2012), polyvinylidene fluoride (PVDF) was fabricated using electrospinning technology onto kapok nonwoven fabric for use in filtration/separation media [180]. PVDF polymers possess high mechanical properties, good chemical resistance, good piezoelectric and pyroelectric properties, and resistance to severe environmental stress. Composite nonwovens showed good oil–water separation performance.

5.4. Ballistic

Recently, the application of less expensive, abundant, renewable, degradable, and recyclable fibres such as sisal, curaua, giant bamboo, malva, mallow, jute, bagasse, rami, and coir fibres and their flexible fibre mats was used for body armour application. Benzait and Levent (2018) reported that composites containing natural fibres can be used as a second layer in a multilayered armour system while the tensile strength and modulus of the natural fibres are considerably smaller than that of Kevlar [160]. Curaua fibres as light, low cost and sustainable materials are promising alternatives to Kevlar, replacing fibre laminates as ceramic backing materials [109]. Braga et al. (2017) studied the possibility of using curaua nonwoven fabrics as reinforcement for epoxy polymer [109]. The results showed that those composites had an impact toughness of about ten times more than the high-impact neat epoxy resin [181]. Kenaf–Kevlar hybrid composites consisted of nonwoven kenaf, and Kevlar fabric was fabricated. This composite was produced in three different layering sequences based on the locations of the kenaf layers to evaluate the effect of the layering sequence of kenaf–Kevlar in an epoxy matrix, as well as the hybridization effects. The result demonstrated that hybrid composites with Kevlar as the outer layers showed stronger penetration force and energy absorption. Kenaf–Kevlar hybrid composite samples showed lower ballistic limit and energy absorption compared to Kevlar–epoxy composites [182]. In addition, Yahaya et al. (2015) also conducted experiments on the effect of kenaf volume contents and fibre orientation (woven, 0°/90° cross-ply unidirectional, and nonwoven mat) with different kenaf fibre content on tensile and flexural properties of kenaf–Kevlar hybrid reinforced epoxy composites [183]. Increasing the volume fraction of kenaf fibre in hybrid composites reduces tensile and flexural properties because of weak kenaf–matrix bonding. It was observed that composites with kenaf mats decrease tensile strength as a result of the high void content within the kenaf mats in the laminates and suboptimal interfacial bonding.

5.5. Agri-Textile Applications

Nonwoven agri-textiles are used effectively to enhance the productivity of crops, gardens, and greenhouses [184]. The most used natural plant fibres for agri-textile products are jute, coconut, sisal, flax, and hemp. The research studied the effect of jute fibre content in PP/jute needle-punch agri-textile nonwoven fabric blend and needle density. The findings indicated that water absorption capacity decreased as fabric weight and needling density increased. The water absorption capacity initially increased when increasing the fibre content to 55%, and then the absorbency decreased with a further increase in jute fibre content. The highest water absorbency of the fabric can be obtained at a 60% jute content level with lower needling density and fabric weight. There is a lot of work seeking the effect of agri-textiles on soil related to weed control and thus on the effect on plant growth yield. In a recent study, a field experiment of different thicknesses of nonwoven jute agri-textile mulches and other mulches on soil health, growth, and productivity of broccoli was conducted [184]. The results showed that mulching with jute nonwovens increases moisture content, organic carbon, available nitrogen, phosphorus, and potassium along with the microbial population of soil.

One study addressed the use of bast fibres (flax and hemp) nonwoven biopolymers as biodegradable mulch fabrics. Nonwovens were obtained by a mechanical method based on pre-needling and hydroentanglement. The results showed that the hydroentanglement process led to micro and nano fibre formation with a continuous fibrous network and eventually fabrics with higher tensile properties. Research has demonstrated that spraying carbon black-based pigment on hemp nonwoven fabric led to obtaining fabrics as effective at suppressing weeds as black polyethene woven mulch fabrics [185]. Degradation and decomposition of nonwoven fabrics are of particular significance when considering the extensive use of fabrics in agricultural machinery, with the intention of material decomposition. In research conducted by Mankowski et al., the sanitary nonwoven fabrics composed of three layers were prepared [186]. The nonwoven fabric was made from the top layer of 80% hemp and 20% flax fibres joined by the middle layer of jute fabric and the bottom layer of latex. The tensile strength of a nonwoven sanitary mat, with a mass per unit area of 900 g·m^{-2}, decreased from 140.7 N to 78.3 N after four months, further decreasing to 14.3 N after eight months, and eventually decreasing to 90% after 12 months of exposure. The research performed by Zhou et al. (2018) reported the production of ramie fibre/starch nonwoven film prepared from air-laid nonwoven fabric consisting of 86% ramie and cotton waste fibres from the textile industry bonded by 14% aqueous solution of modified corn starch in a drying chamber [187]. The biodegradation process began rapidly within four days with an average degradation rate of 4.08% per day compared to control reference cellulosic material with an average degradation rate of 4.73% per day. The results showed that ramie fibre/starch nonwoven film could be used during the early stage of cultivating rice seedlings.

5.6. Hygiene Applications

The use of nonwoven materials in medical applications offers numerous advantages regarding the meeting of user demands and material properties. Shorter production cycles, higher flexibility, versatility, and lower production costs are reasons for the popularity of nonwovens in medical applications. Air-laid and wet-laid nonwoven structures made of flax fibres and their blends can be used for disposables in the medical space [188]. The use of bamboo in hygiene products is widely recognized, and many products are available in the market. One example is utilizing nonwoven bamboo in sanitary wipes and baby diapers [189]. Another example by Manjula and Shanmugasundaram (2017) investigated the influence of surface treatment with glow discharge oxygen plasma in purchased bamboo spun-laced nonwoven fabrics to improve hydrophilic properties for medical textile applications [190]. A study performed by Kathirvel and Ramachandranused (2014) demonstrated the usage of aloe vera and regenerated bamboo fibre for producing anti-microbial nonwoven sanitary napkins [191]. The results showed that bamboo fibre has good antimicrobial resistance against both *E. coli* and *S. aureus*. The bamboo sample showed better liquid strike-through properties and absorption tests when compared with the aloe vera sample. In another study, bamboo fibre was used to produce a nonwoven fabric with a spun-laid technique and antibacterial treatment by incorporating herbal extracts used in wet wipe applications [92].

5.7. Apparel Textile

Due to advancements in nonwoven technology and materials, innovative nonwoven fabrics have been developed with acceptable aesthetical properties for fashion garments. The fashion industry's shift toward natural materials derived from plants makes the system more sustainable and eco-friendlier. Therefore, there has been a tremendous increase in the use of agri-derived fibres and acceptance of the production of sustainable and eco-friendly fashion products such as footwear, textiles, and other apparel. For example, the Spanish company Pinatex produces nonwoven material from waste pineapple leaf fibre which is the by-product of the existing agriculture in the Philippines for footwear and other materials in the fashion industry [192].

In a recent study, an effort was made to develop nettle nonwoven fabrics for apparel applications. The results showed comfort characteristics acceptable for apparel use of needle-punched nonwoven fabrics such as water absorbency and air permeability, and minimum thermal conductivity was obtained for needle-punch nonwoven with the density of 75 punches/cm^2 and fabric areal weight of 150 g/m^2 [165]. Bamboo fibres were used to manufacture nonwoven fabric specifically for making insoles for both working and special shoes [193].

5.8. Filtration

In contrast to woven filters, nonwoven filters offer several advantages, including greater permeability, overall improved filtration efficiency, enhanced temperature resistance, and reduced pressure drops at equivalent efficiencies [194]. A study by Hanifah and Giarto (2019) used pineapple nonwoven fibres for producing air filters [107]. The results showed the nonwovens were particularly useful if the desired characteristics included thickness, density, tensile strength, elongation, and filtering efficiency of the nonwoven fabric and were less reliant on air permeability, porosity, and pore size.

6. Conclusions

In recent years, managing agricultural waste and finding innovative approaches for repurposing agricultural byproducts and residues have been highlighted as some of the most significant environmental challenges. Concerns over landfill space and greenhouse gas emissions are driving the search for alternative waste management methods. Agricultural waste fibres, combined with nonwoven technology, now enable the production of fully biodegradable materials. Recently, the wide availability of agriculture waste fibres, with the development of nonwoven technology, allows for the production of fully biodegradable nonwoven materials. Research on nonwoven fabrics made from agricultural waste fibres is mostly related to dry-laid or wet-laid nonwoven which have similar characteristics to conventional nonwoven synthetic fibres. The surging demand for sustainable materials derived from renewable sources suggests a probable rapid increase in research activity within this field. Growth of potential applications for this new generation of nonwoven has been observed in various fields of geotextiles, dry filtration, automotive applications, household goods, agriculture and horticulture, acoustic and thermal insulation, fashion and apparel and hygiene products.

We are convinced that the development of nonwovens utilizing the abundantly available agricultural waste fibre through modifications and functionalization of fibre and using a few selected different production methods is expected to create a significant breakthrough soon to compete in the current trend of the nonwoven industry.

7. Future Work

In spite of the large amount of waste fibres globally, there has been little or no effort to utilize their biomass fibres efficiently. The scarcity of landfill capacity, the rise in greenhouse gas emissions, and the issue of runoff residues have prompted a search for alternative waste management solutions. Extensive studies have been concentrated on elucidating the profile of the lignocellulosic components of agricultural fibres and exploiting their physical and chemical properties for the engineering and preparation of novel biobased materials. Therefore, the fabrication of high-demand materials such as nonwoven fabrics has developed via utilizing waste and residual fibres from agricultural waste. Numerous investigations indicated that nonwoven fabrics consisting of waste or residue materials exhibit comparable properties to conventional nonwoven fabrics. It appears probable that research activity in this field will increase dramatically due to advances in science and technology coupled with higher demand for sustainability; in addition, industries have been focusing more on the utilization of natural fibres from renewable agricultural and forestry resources. Considering the numerous varieties of natural waste fibres characterized by highly complex structures, there will also be need for many different methods to produce nonwoven fabrics, resulting in different properties of nonwoven fabrics. As it is feasible to enhance the characteristics of nonwoven fabrics with a proper combination of waste fibres materials from a variety of sources, there is enormous potential to develop new unique nonwovens with specialized properties.

Nonwoven fabrics produced from waste fibres offer multiple advantages over nonwoven fabrics from synthetic fibre materials such as inherent hydrophilicity and thermal isolation which contribute to the comfort of fabrics. However, the low tensile strength of this type of nonwoven fabric is a drawback associated with waste fibres. Nonetheless, we can safely predict that the modification of waste fibres or reinforcement with other materials can be considered for the development of nonwoven fabrics from natural waste fibres.

Reducing reliance on petroleum-based materials and shifting toward more sustainable natural fibres to leverage product performance is the current trend in the modern nonwoven fabric industry.

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