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REVIEW PAPER

Bio-based materials for nonwovens

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Abstract The nonwoven industry is one of the most innovative and important branches of the global fiber products industry. However, the use of petrochemical-based materials in many nonwoven products leads to severe environmental issues such as generation of microplastics. Synthetic material use in nonwovens is currently around 66%. This review covers potential technologies for the use of bio-based materials in nonwoven products. The current generation of nonwoven products relies heavily on the use of synthetic binders and fibers. These materials allow for products with high functional properties, such as permanence, strength, bulk, and haptic properties. The next generation of nonwoven products will have a higher fraction of natural and renewable materials as both binders and fiber elements. There are a wide range of materials under investigation in various nonwoven product categories. Especially, lignocellulosic materials are of interest. This includes traditional pulp fibers, regenerated cellulose fibers, lignin binders and nanomaterials derived from wood. The development of water stable, strong interfiber bonding concepts is one of the main problems to be solved for advancing bio-based nonwoven products.

Keywords Nonwoven · Bio-based · Fibers · Binders

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Introduction

Nonwovens are “engineered fibrous assembly, primarily planar, which has been given a designed level of structural integrity by physical and/or chemical means, excluding weaving, knitting or papermaking” (ISO 9092:2019 2019). They belong to an important fraction of the fiber industry, competing with conventional textiles such as woven and knitted fabrics, and paper and board products. Nonwovens are versatile regarding fiber composition, structure and performance and their manufacturing industry is generally profitable and very sophisticated (Farrington et al. 2005; Wilson 2010; Pourmohammadi 2013). In 2019, the global consumption of nonwovens was 11.2 million tones or 307.0 billion square meters, valued at $46.8 billion (Pruden 2019).

Nonwoven production started in 1936 and is credited largely to Dr. Carl Nottebohm (Russel

2007; Karthik et al. 2016). Initially, natural fibers such as wool, cotton, jute, and natural binders such as starch and rubber were employed. Later, synthetic fibers and binders were utilized in nonwovens industry due to the many advantages of their performance (Association of the Nonwovens Fabrics Industry 2003; Blackburn 2005; Chapman 2007; Russel 2007; Bhat and Parikh 2010; Ramamoorthy et al. 2015; Yan 2016; Senthil Kumar and Suganya 2017; Shogren et al. 2019).

In 2018, it was reported by EDANA (EDANA 2018), which is the leading global association of the nonwovens and related industries, that there was an increase of the use of recycled polyethylene terephthalate (PET) as raw material for nonwoven production. It was also revealed an increase of the use of natural or man-made materials (both fibers and resins) from renewable polymers to about 20%. However, the use of synthetic fibers and binders is still as high as 66% (EDANA 2019). These materials are usually traditional thermoplastic resins, such as polypropylene (PP), polyethylene (PE), polyester, polyamide and polycarbonate, which are not biodegradable (Bhat and Rong 2005; Bhat and Parikh 2010).

A large fraction of nonwoven products has a relatively short life span, which leads to disposability problems for products rich in synthetic materials. The environmental impact of disposable nonwoven products has become a major concern throughout the world. Common disposable nonwovens are wet-laid pulp/PP spunlaced fabrics, mainly for industrial and professional wipes, and spunbonded or dry-laid that are chemically or thermally bonded, for household and hygienic wipes (Bhat and Rong 2005; Bhat and Parikh 2010). Due to global trends for improved sustainability, there is intense interest to use more natural, biodegradable and renewable raw materials in nonwovens (Bhat and Parikh 2010). Additionally, there is pressure to develop ever higher performance nonwoven products that have a long lifespan and can compete with woven textile products.

Bio-based materials are derived from renewable bio-based sources and biodegradable materials are those that breakdown into simple components such as carbon dioxide, methane, and water, from the action of naturally occurring microorganism such as bacteria and fungi. Therefore, most bio-based materials are eco-friendly and they are biodegradable (Zhang 2010; Bezwada and Srivastava 2016; Debnath 2017). Bio-based binders, for instance, can be used as such or after modifications (derivatization, substitution, and chemical cross-linking) to reproduce the behavior and performance of synthetic ones (Imam et al. 2013; Pizzi 2016; Lacoste et al. 2018; Echavarri-Bravo et al. 2019). Air-laid and wet-laid techniques seem the most suitable processes for utilizing natural materials. The spun-laid technique uses polymers hard to break down while the air-laid and wet-laid forming processes utilize short fibers to form webs and bonds them with binders that are biodegradable or water-soluble (Blackburn 2005; Russel 2007). However, nowadays, there is a lot of work seeking the inclusion of bio-based materials in the spun-laid technology, as the recent work by Willberg-Keyriläinen et al. (Willberg-Keyriläinen et al. 2020) which shows the use of thermoplastic cellulose fatty acid esters with a polyolefin-like rheology properties for fiber production. The authors concluded that these novel cellulose-based fibers can provide a renewable and recyclable alternative for spun-laid PP in several hygienic textile.

Raw materials for nonwovens

Fibers are the main raw materials for nonwoven products, which determine the basic properties of the final products (Sherwood 1959; Flory et al. 2013; Yan 2016). Generally, in nonwovens, the fibers are held together by a bonding material, the binder, which is applied to attain target tensile strength of the webs. Each system of fiber and binder is selected based on the nonwoven end use (Sherwood 1959; Flory et al. 2013; Yan 2016). The binder is the film-forming element of a coating or adhesive (De Smet et al. 2020). Commercially, binder systems are applied at levels ranging from 5 to 150% based on the dry weight of the nonwoven. 5% of binder is enough to bond fibers at the surface and 150% is used as reinforcement for components such as those found in shoes. With a binder content of about 10% the nonwoven is a bulky, porous, and flexible structure with a relatively low strength. At high binder levels the nonwoven becomes non-porous and dense (Chapman 2007; Roy et al. 2011).

Binder fibers are fibers used in thermal bonding, which have lower melting points than other fibers in the web. By means of heat and pressure, these fibers soften and adhere to other fibers. Often these fibers are thermoplastic, such as PVC, PA, PET, PP, and PE fibers. In other cases, a solvent can be used (*e.g.,* water) to soften and active binder fibers which are swellable but may not be thermoplastic. It is desirable that the binder fibers have a high melting speed, a low melting shrinkage and a narrow melting point range (INDA 2002; Russel 2007; Russell and Smith 2016).

Bicomponent fibers consist of two polymeric compounds in which one component softens at a lower temperature than the other. Consequently, one component acts as a binder fiber while the other maintains the structural integrity. Bicomponent fibers are applied in thermal bonding for air-laid structures, such as wet wipes, and also in spunlaced nonwovens, like medical disposable textiles and filtration products (EDANA 2016; Kalebek and Babaarslan 2016).

The selection of polymers, either fibers or binders, will affect properties as strength (both tensile and compressive), stiffness, softness, waterproofness, breathability, and flammability, among others. Additionally, the choice of raw materials will also influence the ability of the nonwoven to be recycled or biochemically degraded at the end of its useful life. Thus, these features are dependent on the fiber and binder composition, adhesion of the binder to the fibers, binder cohesion and binder distribution (Chapman 2007; Russell and Smith 2016).

Currently, man-made materials from synthetic polymers, which include man-made fibers/polymers (mainly polypropylene) and polyester virgin, assume the biggest share in nonwovens production (66%) (EDANA 2018). Renewable polymers as wood pulp and viscose represent 17% of the raw materials, followed by polyester at 12%. EDANA reported a clear increase in the use of materials from natural or recycled source, highlighting the worldwide trend of a more sustainable production and the importance of circular economy.

Nonwovens web formation methods

Nonwovens are formed by laying or extruding a fiber suspension (usually a mixture of synthetic and natural fibers) onto a conveying surface. The physical environment at this phase can be dry, wet or molten: dry-laid, wet-laid or spun-melt (Wilson 2010; Karthik et al. 2016). In the dry-laid forming process, the fibers are carded or aerodynamically formed (air-laid) and then bonded by mechanical, chemical or thermal methods. Both methods are very versatile regarding raw materials that can be processed, such as natural fibers, recycled fibers (if length is long enough), and staple fibers. In carding, a wide range of staple fibers lengths can be processed, contrary to air-laid systems in which short fibers are preferred (Pourmohammadi 2013; Karthik et al. 2016) The carding process starts with the separation of bales of fibers that are combed into a web by a carding machine, which is a rotating drum or series of drums covered in fine wires or teeth. The formed web can be parallel-laid with most of fibers laid in the machine direction (MD), or the web can be random-laid (EDANA; Larkomaa et al. 2009; Wilson 2010). Carding allows to blend different types of fibers, since staple fibers are used, and to create multilayer structures, depending on the number of cards employed (Karthik et al. 2016). Carded structures can be either disposable (hygiene medicals, wipes) or durable products (apparel and shoe interlinings, support for plastics, packages), high-loft products for mattress, insulation, among others (Karthik et al. 2016).

In the air-laid forming, separated fibers are dispersed into a fast-moving air stream and then transferred to a moving screen by means of pressure or vacuum. Typically, heat sensitive binders are used to bond the fibers together. Both single and multilayer production concepts are used. Traditionally, wood pulp in blends with man-made fibers are employed, along with binders applied by spray (INDA 2002; Wilson 2010). Compared to carded nonwovens, air-laid nonwovens have lower density, higher isotropy and greater softness (EDANA). Air-laid webs have high porosity, high absorbency and wicking rate, which encourages their use for absorbent articles, such as diapers, feminine/incontinence products, napkins, table cloths, wipes, medical items as disposable gowns and wound-care dressings as well as filtration media and insulation (Russel 2007; Zhang 2010).

The wet-laid process is conceptually very similar to paper manufactures. Fibers are dispersed in water at very high dilution, deposited on a moving wire screen and drained to form a web. The forming wire is often inclined to facilitate removing high amounts of water and avoiding machine direction (MD) fiber orientation. The web is dewatered, consolidated, and dried, resulting in a uniform, largely isotropic sheet. Raw materials for wet-laid include short synthetic fibers and wood pulp (INDA 2002; Russel 2007; Larkomaa et al. 2009; Pourmohammadi 2013; Russell and Smith 2016; Gong and Ozgen 2018). Although this process requires high capital investment, it yields outstanding product uniformity at very high production speeds. The end products can be utilized for conventional applications, such as surgical clothing and drapes, bed linen, tablecloth and napkins, towels, kitchen wipes, and hygiene products, and for technical applications, such as glass fiber roofing substrate and insulation materials. Wall covering papers are typically produced in the wet-laid process because the isotropic sheet structure leads to even dimensional changes when water-based glues are applied (EDANA; Larkomaa et al. 2009; Pourmohammadi 2013; Russell and Smith 2016; Gong and Ozgen 2018).

Spun-melt processes includes spun-laid, melt-blown and flash-spun. This technology uses extrusion spinning, in which filaments are directly collected onto a moving conveyor to form a randomly orientated web. Generally, it uses thermoplastic polymers such as different types of rayon and bicomponent fibers (INDA 2002; Russel 2007; Pourmohammadi 2013). This process offers high-quality products at a modest capital investment and relatively high production capacity. Spun-laid webs are obtained by extrusion of a polymeric melt or solution through spinnerets to form filaments that are laid down on a moving screen. These hot filaments are still sufficiently molten to adhere to themselves and bond at their crossover point (EDANA; Pourmohammadi 2013). Spun-laid process offers high strength-to-weight ratio and is employed for automotive sector, construction, hygiene and medical, and packaging (EDANA 2016; Pourmohammadi 2013). The difference between spun-laid and meltblown processes is that meltblown technology uses finer spinnerets combined with high temperature air to weaken the filaments during their formation until they break. The resulted fibers are shorter in length compared to the continuous filaments formed by spun-laid process. This technology also requires polymers with lower melt viscosity. Melt-blown products have a high surface area and are applied for enhanced filtration efficiency, excellent barrier properties and good wicking action (EDANA 2016; Pourmohammadi 2013; Zhu et al. 2020). Flash-spun nonwovens were developed by DuPont for their Tyvek product. The difference with this technique is that it employs a solution of the selected polymer, which evaporates so fast while emerging the spinneret that the individual filaments are disrupted into a highly fibrillar form. These fibers are then deposited on a moving screen to form a web (Pourmohammadi 2013; EDANA 2016).

Nonwovens web bonding methods

Once the web is formed, it is mechanically, thermally, or chemically bonded. Mechanical bonding includes hydroentangling/spunlacing, needle-punching or stitchbonding. Hydroentangling or spunlacing (or also known by hydraulic needling) employs high pressure water jets to entangle a web of loose fibers on a porous belt or forming wire. It is usually applied to wet-laid and dry-laid webs but also suitable for spun-laid webs. The fibers that compose the web for hydroentangling need to be flexible enough and capable of entwining between them. Along with the fiber's mechanical properties (modulus, fineness, cross section, length, crimp, and fiber wettability), the water stream and the conveyor surface during the process will influence the formation and the structure of the resulted nonwoven, which can be applied for wipes, medical gauzes and clothing, sheets and drapes, protective clothing liners and moisture barriers, automotive components, and filtration. This technique is seen as a possibility to replace chemical binders, while giving softer, absorbent, strong and flexible fabrics (INDA 2002; Wilson 2010; Ramamoorthy et al. 2015; Karthik et al. 2016; Russell and Smith 2016).

Needle-punching (or needle-felting) bonds the web by penetrating it with an array of barbed needles that carry tufts of the web's own fibers in a vertical direction. The fibers may be natural or synthetic (INDA 2002; Wilson 2010; Ramamoorthy et al. 2015; Russell and Smith 2016). The resulted structure is influenced by the raw material (type of fiber, length, fineness, cross-section, crimp, mechanical properties), web characteristics as the orientation of the fiber in the web, machine variables (needle-punching density and penetration, entry and exit speed) and design parameters (pattern arrangement of needles, type of needle, etc.). This bonding process is usually employed to long-fiber air-laid and spun-laid webs to form structures for filtration, geosynthetics, papermakers' felts, synthetic leather, floorcoverings, automotive headliners, and wound dressings (Karthik et al. 2016; Russell and Smith 2016).

Stitchbonding uses warp knitting and sewing techniques to produce the completed fabric (INDA 2002; Wilson 2010; Ramamoorthy et al. 2015; Russell and Smith 2016). It processes mainly long-fiber air-laid mats yielding products that are textile-like, soft, and flexible, with similar strength in the MD and cross-machine direction (CD). The products are used for curtaining, lamination, ticking for mattresses, blankets, geotextiles, insulating materials and packing textiles (Karthik et al. 2016; Russell and Smith 2016). EDANA clarifies that stitchbonded materials are only considered as nonwovens if they are produced without the use of threads (the MALIVLIES process) (EDANA 2016).

Thermal bonding uses heat to bond or stabilize a web structure consisting of a thermoplastic fiber, in which the fibers are binder fibers. It is applicable to webs made by all formation methods if binder fibers are used. It includes calendering and through-air. In through-air, high temperature air is used to fuse the binder fibers. This method is especially suitable for the bonding heavyweight webs uniformly through their thickness and to produce high-loft or low-density fabrics. In calendering, the web of loose fibers passes between the nip of a pair of calender rollers, of which one or both are heated, and they can be plain or patterned. The resulted structure is flexible and relatively soft, thanks to the unbonded areas provided the patterned rollers, while maintaining reasonable strength, particularly for spun-laid webs. They can be applied as a substrate for tufted carpets, geosynthetics, filtration media, protective/disposable clothing, as coating substrates and as hygiene cover stock (INDA 2002; Russel 2007; Roy et al. 2011; Russell and Smith 2016).

Chemical bonding consists in treating the formed web with an adhesive. The web can be formed by any the method, but air laid webs most commonly employ chemical binders. The binder is applied to the web, and it can be in a solid form (powder, film or fiber), foam, or in liquid form (emulsion, dispersion, solution) to bond the constituent elements or enhance their adhesion. Blends can be made between additives and binders to increase the fiber–fiber bonding. The final web will be influenced by the chemical composition of the binder (its wet and dry mechanical properties when cured), its attritional and thermal properties as its glass transition temperature. After the application of chemical binders, their curing is necessary, and the drying can be done by subjecting the subtracts to the thermal bonding processes mentioned before. Chemical bonding application methods include: saturation, foam, spray and print bonding (New Cloth Market; Chapman 2007; Wilson 2010; Russell and Smith 2016; Çelikten et al. 2018; Gong and Ozgen 2018; Zhang et al. 2019a, b).

Saturation bonding implies the impregnation of the entire web with bonding agents, covering all the fibers in a film or binder. In the cases that the web is very open or weak, prebonding by other methods is carried out to increase mechanical stability. This method creates structures with high modulus and stiffness, which can be used as interlining fabric for textile clothing (Karthik et al. 2016; Russell and Smith 2016). Foam bonding was developed to allow water saving, since the binder is dispersed in a bubble structure formed in a liquid by agitation. Similar to saturation, prebonding with mechanical techniques can be employed to increase the strength of the substrate (EDANA 2016; Karthik et al. 2016; Russell and Smith 2016).

Print bonding involves applying the binder to the web in limited areas of a predefined pattern. This technology provides adequate tensile strength, good water absorption and permeability and softness, suitable for applications that require textile-like handle, such as disposable protective clothing, cover stock and wipes, domestic dishcloths and dusters (Chapman 2007; Karthik et al. 2016; Russell and Smith 2016). The binders can also be sprayed on the web on a perforated conveyor by means of compressed air or airless spray systems, in fine droplet form. It is necessary that the binder system has adequate shear stability. The depth of penetration of the binder into the substrate is related to the wettability of the fibers, the permeability, and the quantity of fibers. Additionally, suction can be used to improve through-thickness penetration. This process allows to make highly porous and bulky products, adequate for high-loft waddings, insulation, filtration media, upholstery, absorbent and sanitary product components and industrial fabrics (Watzl et al. 2001; Chapman 2007; Karthik et al. 2016; Russell and Smith 2016).

Sustainable nonwovens

In addition to the use of bio-based materials for the production of nonwovens, there are other ways to improve the sustainability of nonwoven products. One way is the improvement of the intrinsic hydrogen bonding capability of the natural fibers present in the structure. This can be done by increasing the moisture contents to the air-laid sheets in the case where cellulosic fibers are present. A study performed by Byrd (1974) showed that air-laid sheets made of separated unbleached softwood kraft fibers can obtain tensile properties comparable to those of linerboard (cross-machine direction—CD) by adding more than 60% of moisture and pressing to 20% moisture. It was demonstrated that a critical amount of moisture of 40% lowers the temperature at which polymer-softening occurs during the press-drying cycle in air-laids, enhancing web consolidation and consequently leading to higher sheet strength (Byrd 1981).

Another approach relies on the use of ionic liquids to promote a self-bonded cellulosic nonwoven web. The solvent partially dissolves the cellulosic material of some of the fibers. The dissolution can be accelerated by raising the cellulosic fibers and/or the ionic liquid to a higher temperature (Morrissey 2017).

Still another approach to produce nonwovens with reduced use of binder relies on the functionalization of lignin-containing fiber surfaces with enzymes. For this treatment laccases are the most common enzymes, although peroxidases has been used (Echavarri-Bravo et al. 2019). Other technologies, such as plasma, which introduce free radicals to fibers surfaces can also be used to promote interfiber covalent bonding and potentially reduce synthetic binder use (Fuqua et al. 2012; Singh et al. 2020).

Plant-based materials

Bio-based materials are mainly derived from plants and are very diverse regarding their physicochemical properties. Plant-based materials can be divided into carbohydrate and protein polymers, in which the carbohydrate polymers represent the majority of the materials (Imam et al. 2013; Pizzi 2016; Lacoste et al. 2018; Echavarri-Bravo et al. 2019). Inside of this group, lignocellulosic materials are probably the most versatile materials, yielding cellulosic fibers that can be processed as such or derivatized/regenerated for man-made cellulosic fibers production, nanomaterials and lignin and lignosulfonates, with a wide variety of strength performance.

Non-wood fibers

Cotton

Cotton is a fiber widely accepted by consumers that has been used since ancient times. It is the purest industrial form of cellulose that can be found in nature. It is recognized as durable, and soft fiber. Cotton is a water absorbent fiber, non-allergic and has high wet strength (opposite to viscose) but does not have the slippery touch of synthetic fibers. It also exhibits thermal and sound insulation properties (Watzl et al. 2001; Bhat and Parikh 2010; Ramamoorthy et al. 2015). Moreover, it is a naturally breathing fiber, which means that it largely prevents the passage of fluids but let gas and water vapor pass. The quick absorption of water by cotton is a result of its structural network of microfibrils. Therefore, cotton fibers are good candidates for absorption of body fluids in medical and cosmetic applications and wipes (Watzl et al. 2001). Additionally, the natural structure of cotton having both hydrophilic and hydrophobic interfaces means that cotton can absorb both water and oil (Yan 2016).

Spunlaced cotton market has been growing, including applications of disposable products such as cosmetic wipes (Bhat and Parikh 2010). In the field of composite nonwovens, recent works have focused in the use of cotton for compostable automotive composites (Kamath et al. 2005), nonwoven composites with excellent thermal insulation properties made of waste cotton (Yachmenev et al. 2002), the microencapsulation of Aloe Vera in cotton nonwoven fabric for functional textiles (Fiedler et al. 2020) and the use of recycled cotton fibers for nonwovens suitable as sound absorption materials (Santhanam et al. 2019).

Despite the attractive technical properties of cotton, there are significant roadblocks blocking its wider application in nonwovens. Cotton fiber requires heavy cleaning and homogenization, its production requires high use of pesticides (about 17% of all insecticides used worldwide are used in cotton production) and cotton agriculture requires high amounts of irrigation water. Organic cotton uses less pesticides and is a small but growing niche market, which achieved approximately 118 MT in 2017/2018 (10% grow compared to previous year) (Sawhney and Condon 2008; Giljum et al. 2014; Eija-Katriina Uusi-Tarkka 2016; Yan 2016; Pepper 2018). Overall, high cost and poor sustainability place pressure on manufacturers to find other bio-based fibers for nonwoven applications (Watzl et al. 2001; Eija-Katriina Uusi-Tarkka 2016; Yan 2016).

Hemp

Hemp fibers were once the world's largest agricultural crop in the early nineteenth century, but their demand decreased with the rise wood pulps and then synthetic fibers. They have been used for centuries in household linens and work clothes and as a potential source for papermaking, sails/canvas and building materials. Their interest has been renewed in the last decades with the global environmental issues (Wool and Sun 2005; Karthik et al. 2016). Hemp is an interesting plant that grows quickly without fertilizers or treatment, does not damage soils and requires less water than other crops (Le et al. 2014). Hemp fibers are cost-effective with high strength, elasticity, ease of processing, hygroscopic nature, low thickness and four to six times stronger than cotton (Table 1). Furthermore, hemp has been recognized for its elasticity, ease of processing and recycling. Bast fibers extracted from hemp are reported to be long and strong enough to meet the requirements of high strength in demanding applications (Hubbe and Koukoulas 2016).

Nowadays, this fiber is widely used in automotive and construction sectors, reinforcement composites, nonwovens, among others (Bhat and Rong 2005; Blackburn 2005; Mehta et al. 2006; Bhat and Parikh 2010; Dhakal et al. 2012; Shah 2013; Karthik et al. 2016; Senthil Kumar and Suganya 2017). Regarding nonwovens, hemp fibers have been used in combination with cellulose with fibrillated synthetic polymers, processed by wet-laid technology for production of tea bags (Kellie 2016). Freivalde and collaborators (2013) produced nonwovens made of hemp fibers by thermal bonding (mixed with PP fibers), needlepunching and spunlacing, which showed the same or better thermal properties than other commonly used materials for thermal insulation (*e.g.* mineral wool). Recent work also includes the use of hemp and flax fibers for the processing of air-laid nonwovens in air-laying nonwoven machine (SPIKE air-laying technology from the Formfiber Denmark APS company) (Hýsek et al. 2015).

Flax

Flax fibers are long and strong fibers, containing high cellulose content and high degree of crystallinity, which is desirable for use for reinforcement since it helps for stronger and stiffer composites (Shah 2013; Ramamoorthy et al. 2015). As a result, flax fibers are an excellent substitute of synthetic fibers in disposable nonwovens, where they improve mechanical properties (Blackburn 2005; Shah 2013; Maity et al. 2014). Compared to other plant-based fibers, flax benefits from the fact they its cultivation does not requires special soil conditions or pesticides and needs minimal water (Maity et al. 2014).

A study performed by van Roekel and de Jong (1999) showed the use of flax fibers for the production of wet-laid and spunlaced sheets on a pilot unit, suitable for disposables articles in medical sector (Blackburn 2005; Maity et al. 2014). Flax fibers were tested in moldable, cellulosic-based nonwoven composites and revealed excellent thermal insulation properties (Yachmenev et al. 2002). They are also suitable for various automotive applications (headliners, wall panels, and trunk liners) (Yachmenev et al. 2006; Martin et al. 2016). Recent work showed the use of flax fibers for nonwovens in technical insulation applications (Fages et al. 2013) and in wet-laid processing to form flax-PP nonwovens for eco-friendly composites (Fages et al. 2012). Flax fibers in combination with hemp has been used in optimization process of air-laid nonwovens, with the possibility to control the web density (Hýsek et al. 2015).

Jute

Jute fibers are interesting due to their inexpensiveness character and physical properties, since they have high tenacity, low tensile elongation and low crimps, particularly useful for floor coverings, filling pieces in upholstery, and for acoustic insulating materials (Yan 2016; Kalebek and Babaarslan 2016). Jute fibers have been used in reinforcement composites (Ramamoorthy et al. 2012), automotive applications (Yachmenev et al. 2006), spunlacing (Maity et al. 2014), needlepunched products in civil engineering applications (Premkumar and Thangamani 2017), thermal insulators for automotive applications (Yachmenev et al. 2002; Vasile and Langenhove 2004) and geotextiles (Rowell 2012). The air-permeability of needle-punched nonwovens made of jute has been modelled by Debnath et al. (Debnath et al. 2000; Patanaik and Anandjiwala 2010).

Bamboo

Bamboo has a high growth rate and its fiber has properties in between hardwood and softwood fibers. It is better resistant to storage degradation than other non-wood biomasses (De Assis et al. 2018). The internode cells of bamboo are arranged strictly in the longitudinal direction, with no radially oriented cells such as ray cells. These unique microstructural features provide low density, high strength and stiffness (Scurlock et al. 2000; Qiu et al. 2019). Due to its excellent durability, fire safety, environmental impact, user safety, energy efficiency, among others, bamboo is one of the ideal raw materials for the production of sustainable household/building products (Qiu et al. 2019).

In nonwovens production, bamboo has been used either blended with synthetic fibers or in products only containing bamboo as the fiber source. The use of bamboo in wipes is widely recognized and there are many products available in the market. One example is a bamboo wipe incorporating essential oils (Sheasley 2011). Another example reported by Devaki and collaborators (2019) is a functionalized 100% bamboo nonwoven fabric produced by spun-laid technique. The final product is said to be an eco-friendly wet wipe with antibacterial finish, provided by herbal extracts. A recent work (Manjula and Shanmugasundaram 2017) showed the influence of surface treatment (glow discharge oxygen plasma) in purchased bamboo spunlaced nonwoven fabrics, revealing promising future for medical textile applications, due to the improved hydrophilic properties. Blends of bamboo with synthetic fibers were prepared by needle-punching, in which the highest tensile strength and elongation of the nonwoven was observed for blends of 20% bamboo/80% PP (up to 1692 N in CD and up to 116%, respectively) (Senthil Kumar et al. 2018). Recent studies have also shown the fabrication of nonwoven composite membrane supports made from bamboo fiber bonded with PLA, in which the membrane supports showed a porous structure (porosity of 0.719 ± 0.132) with tensile strength (32.7–73.3 MPa) comparable to conventional materials (*e.g.* PP) (Le Phuong et al. 2019).

Straw

Straw is a byproduct of crops production (rice, wheat, barley, etc.), in which 1/3 of the cells are fibers (Ramamoorthy et al. 2015; De Assis et al. 2018). For wheat straw, it was shown that the fiber length distribution for the pulps was similar to the recycled pulp (deinked pulp), but with a higher fines content and short fibers (length < 0.5 mm) (De Assis et al. 2019). Although straw fibers are not as strong as other plant fibers (Table 1), they are used in low stress applications (Ramamoorthy et al. 2015). A study showed that straw fibers blended with polyester resins in composites led to an increase of tensile strength up to 46 MPa (46% more than that of pure polyester). This composite was tested for structural board products (Ratna Prasad et al. 2007). Palumbo and collaborators (2015) produced insulation materials based on food crop byproducts (rice husk, barley straw and corn pith) and natural binders (corn starch and sodium alginate) in which the materials satisfied the necessities for their application as building insulation.

Sugarcane bagasse

Sugarcane bagasse is the remaining fiber obtained after crushing sugarcane stalks. Around 60–70% of bagasse pulp is composed of useful fibers (Verma et al. 2014; De Assis et al. 2018). It has been used as reinforcement material in polymer matrix and for paper, tissue and nonwovens applications (Chiparus 2004; Chen 2005; Yadav et al. 2015). For nonwovens, works report that bagasse fiber is extracted and cleaned and further opened and mixed. The nonwovens are produced by carding and subsequently needle-punched or thermal bonded, using synthetic binder fibers. Bagasse nonwovens can be applied for horticulture (flowerpots), animal bedding and aquaculture (bank weed control, filtration and pile wraps) (Chiparus 2004; Chen 2005). A recent patented work aimed the production of tea and coffee filter/bag—One Earth®—that is certified as biodegradable and compostable. This nonwoven product is sourced from sugarcane, which is used to produce PLA fibers to

Table 1 Summary of properties of non-wood, wood and cellulosic man-made fibers, and described nonwoven process employed and respective applications using each fiber

Fiber type		Properties				Process	Application
		Fiber length, mm	Tensile strength, MPa	Young's modulus, GPa	Elongation at break, %		
Non-wood	Cotton	20–60 (Willför et al. 2011)	287–800 (Ramamoorthy et al. 2015)	5.5–12.6 (Ramamoorthy et al. 2015)	7.0–8.0 (Ramamoorthy et al. 2015)	Spunlacing (Sawhney and Condon 2008; Bhat and Parikh 2010; Hubbe and Koukoulas 2016; Wilson 2020) Air-laid (Yachmenev et al. 2002; Dieckmann et al. 2018) Air-laid, thermal bonding with binder fibers (synthetic) (Jr. and Jr. 2002; Hurley 2007; Zhu et al. 2015; Ben Mlik et al. 2016) Carding, needle-punching (Tao et al. 1998; Yachmenev et al. 2002) Spun-laid (blends with polyester) (Santhanam et al. 2019) Wet-laid (Hubbe and Koukoulas 2016)	Medical and wipes (Watzl et al. 2001; Sawhney and Condon 2008; Gupta and Edwards 2009) Hygiene products (Jr. and Jr. 2002; McIntyre 2014) Compostable automotive composites (Kamath et al. 2005) Thermal insulation (Yachmenev et al. 2002; Zhu et al. 2015) Sound absorption (Hurley 2007; Dieckmann et al. 2018; Santhanam et al. 2019) Upholstery (Sawhney and Condon 2008) Cosmetics (Sawhney and Condon 2008) Filtration (Maity et al. 2014)
	Hemp	5–55 (Willför et al. 2011)	690 (Ramamoorthy et al. 2015)	30–60 (Ramamoorthy et al. 2015)	1.6 (Ramamoorthy et al. 2015)	Wet-laid (Kellie 2016) Air-laid (Hýsek et al. 2015) Thermal bonding (mixed with PP fibers), needlepunching and spunlacing (Freivalde et al. 2013)	Tea bags (Kellie 2016) Thermal insulation (Freivalde et al. 2013)

Table 1 continued

Fiber type	Properties				Process	Application
	Fiber length, mm	Tensile strength, MPa	Young's modulus, GPa	Elongation at break, %		
Flax	16–60 (Willför et al. 2011)	345–1100 (Ramamoorthy et al. 2015)	27.6 (Ramamoorthy et al. 2015)	2.7–3.2 (Ramamoorthy et al. 2015)	Wet-laid and spunlacing (van Roekel and de Jong 1999; Fages et al. 2012) Air-laid (Hýsek et al. 2015)	Disposable nonwovens (Blackburn 2005; Shah 2013) Thermal insulation composites (Yachmenev et al. 2002; Fages et al. 2013) Automotive composites (Yachmenev et al. 2006; Martin et al. 2016)
Jute	0.8–7 (Willför et al. 2011)	393–773 (Ramamoorthy et al. 2015)	13.0–26.5 (Ramamoorthy et al. 2015)	1.2–1.5 (Ramamoorthy et al. 2015)	Spunlacing (Maity et al. 2014) Needle-punching (Premkumar and Thangamani 2017)	Composites (Ramamoorthy et al. 2012) Automotive and thermal insulation (Yachmenev et al. 2002, 2006; Vasile and Langenhove 2004) Civil engineering (Premkumar and Thangamani 2017) Geotextiles (Rowell 2012)
Bamboo	1.7–4.0 (Willför et al. 2011)	140–230 (Ramamoorthy et al. 2015)	11–17 (Ramamoorthy et al. 2015)	2.7–3.2 (Ramamoorthy et al. 2015)	Spun-bonding (Devaki 2019) Spunlacing (Manjula and Shanmugasundaram 2017) Needle-punching (Senthil Kumar et al. 2018)	Wipes (Sheasley 2011; Devaki 2019) Composite membranes (Le Phuong et al. 2019)
Straw (wheat)	1.0–1.5 (Willför et al. 2011)	21.2–31.2 (O'dogherty et al. 1995)	4.76–6.58 (O'dogherty et al. 1995)			Composites (Ratna Prasad et al. 2007; Ramamoorthy et al. 2015) Insulation (Palumbo et al. 2015)

Table 1 continued

Fiber type	Properties				Process	Application
	Fiber length, mm	Tensile strength, MPa	Young's modulus, GPa	Elongation at break, %		
Sugarcane bagasse	0.8–2.8 (Yadav et al. 2015)	180–290 (Yadav et al. 2015)	15–19 (Yadav et al. 2015)	1–5 (Yadav et al. 2015)	Carding, needle-punching, thermal bonding (Chiparus 2004; Chen 2005)	Horticulture (flowerpots), animal bedding and aquaculture (bank weed control, filtration and pile wraps) (Chiparus 2004; Chen 2005) Source for production of PLA used in tea and coffee filter/bags manufacture (Foss and Turra 2018)
Wood	1–5	–	–	–	Air-laid (Laursen et al. 1987; Watzl et al. 2001; Wierer et al. 2002; Çelikten et al. 2018; Parsons et al. 2019) Airlacing (Knowlson et al. 2016a) Wet-laid (Lindberg 2015; Pan et al. 2019) Wet-lace (wet-laid and spunlacing) (Zhang et al. 2017) Spunlacing (Zhang et al. 2019a, b)	Absorbent disposable articles, tablecloth and medical industry (Watzl et al. 2001) Sound insulation (Dieckmann et al. 2018) Agricultural (Boehmer and Hurley 2004) Wipes (Zhang et al. 2017) Dispersible nonwovens (Nandgaonkar 2020) Air filtration (Mao et al. 2008; Pan et al. 2019)

Table 1 continued

Fiber type		Properties				Process	Application
		Fiber length, mm	Tensile strength, MPa	Young's modulus, GPa	Elongation at break, %		
Man-made	Viscose	–	308 (Kabasci 2013)	11 (Kabasci 2013)	24 (Kabasci 2013)	Wet-laid, spunlacing (Anand et al. 2007; White 2007; Wilson 2007)	Wipes (Anand et al. 2007; White 2007; Wilson 2007)
	Rayon	–	825 (Kabasci 2013)	19.5 (Kabasci 2013)	13 (Kabasci 2013)	3-layer carded-air-laid-carded (Anand et al. 2007) Spunlacing (Association of the Nonwovens Fabrics Industry 2003; Brydon and Pourmohammadi 2007) Needle-punching (Kalabek and Babaarslan 2016)	Medical industry (Watzl et al. 2001; Gupta and Edwards 2009)Flushable wipes (Durukan and Karadagli 2019) Filtration (Maity et al. 2014) Feminine hygiene (Jr. and Jr. 2002) Nonwoven bags (Wilson 2007; Patnaik et al. 2019) Composites (Carrillo et al. 2010; Ramamoorthy et al. 2014, 2015) Floor covering (Kalabek and Babaarslan 2016) Functional pillows and bed linen (Yan 2016)
	Lyocell	–	603 (Kabasci 2013)	31 (Kabasci 2013)	9 (Kabasci 2013)	Spunlacing (Blackburn 2005; Russel 2007) Wet-laid, spunlacing (Deng et al. 2018; Zhang et al. 2019a, b) Wet-laid (Eija-Katriina Uusi-Tarkka 2016)	Personal hygiene care (Deng et al. 2018) Dispersible moist wipes (Zhang et al. 2019a, b) Composites (Carrillo et al. 2010; Ramamoorthy et al. 2015)

Table 1 continued

Fiber type	Properties				Process	Application
	Fiber length, mm	Tensile strength, MPa	Young's modulus, GPa	Elongation at break, %		
Cellulose acetate (CA)	–	195 (Kabasci 2013)	5.1 (Kabasci 2013)	20 (Kabasci 2013)	Thermal bonding (Turbak 1993; Blackburn 2005; Bhat and Parikh 2010; Roy et al. 2011; Hubbe and Koukoulas 2016)	Binder fiber in nonwovens (Turbak 1993; Blackburn 2005; Bhat and Parikh 2010; Roy et al. 2011; Hubbe and Koukoulas 2016) Cigarette filter and filtration materials (Si et al. 2015; Strader 2015) Fiber tow (marker tips) (Si et al. 2015; Strader 2015) Composites (Si et al. 2015; Strader 2015)

form a nonwoven web through thermal bonding (Foss and Turra 2018).

Other non-wood fiber

The use of other vegetable fibers as coconut (coir), banana, pineapple leaf, lotus and kapok fibers is reviewed by Yan (2016) for nonwoven production. Milkweed floss, which is a silky white seed, hydrophobic fiber with a high chemical resistance, can be useful in nonwovens production (Bhat and Rong 2005; Bhat and Parikh 2010). Oil palm fiber is commonly used in needle-punched nonwoven process due to its thick and rough fiber. Recently, it was used with kenaf PP nonwoven composites for the preparation of needle-punching nonwoven process followed by compression molding, revealing comparable fiber quality to kenaf fibers (Anuar et al. 2019). A recent study explored nonwoven formation made of fibers produced from okra stem wastes, showing tensile strength, elongation and young modulus up to 6.5 N, 9% and 2.4 respectively (Duman et al. 2017). Banana fiber, which can have an elongation at break of 5.4%, was studied mixed with PP fibers for application as car interior. It was shown that the banana/PP nonwoven had a lower thermal conduction (0.0178 W/m/k) than bamboo/PP and jute/PP (Thilagavathi et al. 2010). Kudzu fiber is a fiber crop native to southern Japan and southeast China, used for centuries for basketry and clothing. Today, kudzu fiber grows all over the world (Fuqua et al. 2012). Other crop residues which have been explored are husks (corn, rice, wheat, barley, and rye husk). Studies focused on the use of these husks as reinforcing composites showed that their low moisture absorption makes them particularly suitable for moisture sensitive applications. Additionally, barley husk has a thermal stability close to that of softwood (235 °C and 245 °C respectively) (Ramamoorthy et al. 2015).

Wood fibers

Wood pulp fibers are one of the most important raw material sources for current and future sustainable nonwoven products. A wide spectrum of pulp is available at a reasonable cost structure and at high volumes. Although a wide fiber property space exists, most wood pulps have a relatively short fibers in the length scale of 1–5 mm and contain at least some water loving hemicelluloses. Thus, many nonwovens will require blends of non-wood pulp fibers to obtain the strength, permanence and wet strength that is critical in many product applications (Watzl et al. 2001; Association of the Nonwovens Fabrics Industry 2003; Hubbe et al. 2007; Mao et al. 2008; Bhat and Parikh 2010; Kinn et al. 2012; Rowell 2012; Pourmohammadi 2013; Karthik et al. 2016; Çelikten et al. 2018).

Cellulosic fibers can contribute to absorbency, softer feel, bonding, and opacity, among other attributes. In nonwovens manufacture, the addition of cellulosic fibers allows to use same wet-strength additives used in papermaking, which, due to their cationic charge, adsorb readily onto cellulose fiber surfaces (Hubbe and Koukoulas 2016). Modifications can be applied to cellulosic fibers by using different fibers with varied shapes/structures, mechanical refining that results in the liberation of more hydroxyl groups (related to cell wall delamination), as well as by the use of hydrogen bonding polymers or covalent bonding polymers (Xu et al. 2013).

The main use of wood pulp is found in the production of absorbent disposable articles, such as diapers, sanitary napkins, incontinence products, wiping cloths for the medical industry, tablecloths, napkins, tissue, surgical drapes, bed sheets and surgical gowns. It is also common to find blends of wood pulp fibers and synthetic fibers. Although cotton is an alternative for the disposables market, it cannot replace wood pulp due to the cost (Watzl et al. 2001; Çelikten et al. 2018).

Wood pulp is the main raw material in air-laid technology, where is converted from rolled sheet into individual fibers by hammer mills (Laursen et al. 1987; Wierer et al. 2002; Çelikten et al. 2018). A recent study shows the production of latex-bonded air-laid nonwovens produced with different wood pulps, latex and processing cylinder surface types, used for wet/dry towels and toilet papers (Çelikten et al. 2018). By the same process (air-laid), wood pulp was used to prepare a support for seeds for agricultural applications (Boehmer and Hurley 2004), and also spunlaced disposable nonwovens made of 50% wood pulp and 50% staple fibers (Knowlson et al. 2016a, b). Wet-laid technique is also very common to process wood pulp, as explored by Lindberg (Lindberg 2015) and Uusi-Tarkka (Eija-Katriina Uusi-Tarkka 2016). Recently the development of biodegradable wood pulp/Lyocell moist wipe made from wet-laid/spunlace (called wet-lace) technology has been investigated (Zhang et al. 2017). More recently, this research group developed a dispersible moist wipe, made of 70% wood pulp, 28% Lyocell and 2% bicomponent fiber, by wet-laid and spunlacing processes. Their results showed similar wet strength (MD = 9.5 N/50 mm and CD = 6.3 N/50 mm) but greater softness and dispersibility compared to currently dispersible products (Zhang et al. 2019a, b). Recently, Georgia-Pacific Nonwovens LCC (Baker et al. 2017) patented the manufacture method of an air-laid nonwoven material made of cellulosic fibers (wood pulp), mixed with other fibers or bicomponent fibers and binder polymers. Nandgaonkar (2020) provided the manufacture of a multi-ply dispersible nonwoven fabric in which each of the individual webs comprises 50–95% of wood pulp and 5–50% of short cut man-made fibers and/or natural fibers, with a basis weight of 20–100 g/m^2. Among these webs, at least one is spunlaced and all the other webs are chemically bonded (binders applied through printing or spraying). The nonwoven can be dispersed because the hydrogen bonds provided by the particle binders are broken after flushing. Wood pulp fibers have also been successfully tested in air and aerosols filtration, useful for the production of nonwoven face masks, blended with synthetic fibers (Mao et al. 2008; Pan et al. 2019).

Man-made cellulosic fibers

When natural cellulose is dissolved, it can be modified and formed into various products such as spun fibers or transparent films (Turbak 1993; Bhat and Rong 2005; Strader 2015). Spun cellulosic fibers are currently a major research direction of the forest products industry where the target is to replace either cotton or viscose rayon with more sustainable cellulosic alternatives (Klemm et al. 2005; Hammerle 2011; Röder et al. 2013; Ramamoorthy et al. 2015; Hubbe and Koukoulas 2016; Woodings 2016). The first commercial regenerated cellulose fiber was viscose, also known as rayon, more than a century ago. Nowadays, there are several processes for manufacturing regenerated cellulose fibers. Wide ranges of fiber length, denier, and morphology of cellulosic fibers can be provided by various processes of cellulose regeneration, followed by chopping. Contrary to natural fibers, the properties of regenerated cellulose fibers are more homogenous. Furthermore, man-made cellulosic fibers are the only fibers produced by using directly natural polymer, contrary to synthetic fibers like polyester, nylon, and acrylic (Woodings 2016; Alam and Christopher 2017; Jedvert and Heinze 2017).

It is important for the forest products industry that regenerated cellulose fibers are not classified as plastics. Bearing this in mind, EDANA, the European Disposables and Nonwovens Association, has recently declared that "Current European legislation, as well as technical expertise, concludes that lyocell and viscose are not chemically modified natural polymers and as such should be excluded from the definition of plastics". EDANA added that the number of studies demonstrating the biodegradability and flushability of both lyocell and viscose in several environments show that they are more sustainable than fossil-based plastic fibers (Cottonworks 2019; Wilson 2020; European Commission 2021).

Man-made cellulosic fibers can be tuned to meet many requirements and often accomplish similar functions of synthetic fibers while still being derived from natural origins. This means that they have a higher potential for biodegradation and recycling while still giving high functionality. Moreover, contrary to synthetic fibers they are ideal for applications where moisture management and physiological performance are of high importance (Bredereck and Hermanutz 2005; Hammerle 2011; Woodings 2016). Current challenges for man-made cellulosic fibers include up-scaling new technologies, cost-effectiveness compared with synthetic fibers, recycling of solvents, and the environmental impact of the viscose and other processes (Woodings 2016; Alam and Christopher 2017; Jedvert and Heinze 2017; Lenzing Group 2019).

Rayon/viscose

Rayon fibers, which are commonly used in the textile industry, are a form of cellulose II produced from low hemicellulose dissolving pulp, which is xanthanated, dissolved in alkali and spun into a continuous filament. Filaments can be cut into staple fibers for use in nonwoven products (Lönnerbeg 2001; Kim and White 2009; Kihlman 2012; Kalebek and Babaarslan 2016; Alam and Christopher 2017; Senthil Kumar and Suganya 2017; Lenzing Group 2019). Rayon is soft, highly absorbent, easy to dye and drape like natural fibers (Kim and White 2009; Kalebek and Babaarslan 2016; Senthil Kumar and Suganya 2017). Compared to cotton, rayon is more flexible (has a lower modulus, especially when wet), has a higher elongation and is less resistant to swelling in water and in alkaline solutions. Thus, rayon absorbs much more moisture and water than cotton because of its more amorphous structure. Likewise, both rayon and cotton do not melt and can be heated up to around 232 °C before they start to char, so they do not act as binder fibers (Turbak 1993; Woodings 2016).

Viscose rayon plays a key role in the spunlaced wipes market due to its low wet modulus and is an important fiber for wet-laid web formation process (Anand et al. 2007; White 2007; Wilson 2007). A recent work shows the reduction in bending stiffness and rigidity of viscose fibers during spunlacing process due to their absorption capacity, making the resulting structure more pliable and leading to better consolidation properties (Maiti et al. 2020). In medical applications, rayon can be found in wound dressings blended with cotton (Anand et al. 2007). A web made of 75% rayon and 25% chitosan is a commercial product, derived from the functionality of the chitosan polymer and has antimicrobial activity and even deodorizing characteristics (Gupta and Edwards 2009). A study from Watzl and Eisenacher (2001) states that a blend of 70% rayon and 30% polyester can replace cotton in gauze materials, once these fibers can provide similar absorption capacity as cotton but avoiding the linting problems characteristic of cotton (Anand et al. 2007). Rayon can be modified by adding chemical compounds to viscose dopes or to the coagulation bath. Hollow rayon fibers can be produced by injecting gas or by adding gas-forming compounds like sodium carbonate to the viscose dope (Bredereck and Hermanutz 2005). A recent study evaluated the potential of this hollow viscose rayon fiber with carboxymethyl cellulose (CMC) in laminates with PP spunbond nonwoven, for wound dressings. It was shown an improvement of the wet dimensional stability and wet tensile strength without sacrificing the excellent liquid handling properties of CMC/hollow viscose rayon fiber. The use of hollow rayon viscose fiber contributed for higher intrinsic absorbency compared to conventional rayon (Kim et al. 2019). A work by Kramar and collaborators (2013) showed that corona treatment with ambient air could enhance the antimicrobial effect of silver and copper ions in rayon fabric. Scott, Jr. and Bailey Jr. described the production of feminine hygiene tampons of long rayon or cotton fibers or mixtures thereof (Jr. and Jr. 2002). Viscose rayon is also used for the production of nonwoven bags that are 100% reusable and recyclable (Wilson 2007; Patnaik et al. 2019). It is common to find blends of rayon fibers with fluff pulp in carded webs, which are further spunlaced for several applications, such as absorption articles (Association of the Nonwovens Fabrics Industry 2003; Brydon and Pourmohammadi 2007), as reinforcement in composites (Carrillo et al. 2010; Ramamoorthy et al. 2014, 2015), carpets and needle-punched floor covering products (Kalebek and Babaarslan 2016). Regarding technical applications, a scented rayon-based fiber has been produced by the blending of microcapsules with polymer matrix and further spinning into fibers. These scented rayon fibers are suitable for pillows and bed linen manufacture, claimed to improve sleep (Yan 2016).

Several approaches to make viscose process greener and cheaper have been tested, which include increasing the reactivity of dissolving pulps, by mechanical treatment, enzymatic treatment, caustic extraction, ionic liquid extraction, acid treatment, ozone treatment, thermal degradation, and their combination (Li et al. 2018).

Lyocell

Lyocell is made 100% cellulosic fiber and it is fully biodegradable. It is produced by dissolving wood pulp in a solution of hot N-methyl morpholine oxide (NMMO), spinning and washing. Compared to the viscose process, the production of Lyocell requires significantly less chemicals, due to the conversion of pulp into fiber in a closed loop process (Blackburn 2005; Lenzing Group 2019; White 2007). Lyocell fibers are very strong, particularly in the wet state (at least twice as strong as regular viscose) and entangles efficiently, because of its smooth surface and its fibrillar cellulose structure. This encourages the use of lyocell in spunlaced nonwovens, resulting in very strong and stable nonwovens, but still preserving the drape and softness of the final fabric (Blackburn 2005; Russel 2007). A recent study showed the production of wet-laid spunlaced nonwovens made of pulp/Tencel^{TM} fibers with high water absorbency and good flushability (Deng et al. 2018). The same web forming and bonding processes were investigated for the development of dispersible moist wipe, made of 70% wood pulp, 28% Lyocell and 2% bicomponent fiber (Zhang et al. 2019a, b). This nonwoven is suitable for personal hygiene care. A recent thesis work (Eija-Katriina Uusi-Tarkka 2016) aimed the production of bio-based nonwovens by paper machines. They selected softwood kraft pulp, dissolving pulp, PLA and lyocell fibers, in different levels of incorporation. Their results showed that samples containing lyocell generally had better tensile properties than those containing PLA, probably a result of the fact that lyocell is cellulose-based so it should be able to bond with pulp fibers, although to a lesser extent than pure pulp fiber–fiber bonds. Lyocell is also used as reinforcement in composites (Carrillo et al. 2010; Ramamoorthy et al. 2015). Lyocell was blended with PLA fibers in beverage filters to avoid the problem of heat effect on coffee and tea bag formation (Foss and Turra 2018).

Tencel^{TM}, a man-made cellulosic fiber patented by Lenzing, has been popular in wipes for several years, for their flushability and strength. Tencel^{TM} exhibits a dry tenacity significantly higher than other cellulosic fibers and approaching that of polyester. In the wet state, Tencel^{TM} retains 85% of its dry strength and is the only man-made cellulosic fiber to be stronger than cotton when wet. In addition, Tencel^{TM} has a high modulus that leads to low shrinkage in water. Thus, fabrics and garments demonstrate good stability when washed (Blackburn 2005). The main drawback of lyocell is that it is very expensive compared to natural fibers as cotton or even viscose (Ramamoorthy et al. 2015).

Cellulose acetate (CA)

Cellulose acetate (CA) is an important regenerated cellulose fiber used in textile industry, produced from cellulose and acetic acid through esterification reaction. CA fibers have a partly hydrophobic and hydrophilic nature. Generally, increased acetylation imparts more hydrophobic characteristics; thus, cellulose triacetate is more hydrophobic than cellulose acetate (Si et al. 2015; Strader 2015). CA is a soft and flexible fiber, which has low modulus (Table 1). It is thermoplastic, which makes it suitable to be used as binder fiber in nonwoven applications. It has a high softening point of 180–205 °C and thus solvent treatment has been introduced in order to modify its softening temperature and lower the calendering temperature, while maintaining enhanced tensile properties (Turbak 1993; Blackburn 2005; Bhat and Parikh 2010; Roy et al. 2011; Hubbe and Koukoulas 2016). CA fibers has dominated the cigarette filter market for decades and assume a key role as filtering materials in general. Electrospinning of nanofibers to nonwoven meshes are a common method to prepare CA membranes with large surface-to-volume, high porosity and microscale interstitial space (Sun et al. 2015). They have also been used in fiber tow as marker tips (Si et al. 2015; Strader 2015).

CA, as others cellulose esters, are generally biodegradable over a period of months to a few years with rates of degradation decreasing as degree of substitution (DS) increases (Puls et al. 2011). For DS < 2.5, CA is usually biodegradable and its functionalization may benefit many sanitary and bio-related fields (Teramoto 2015). However, the concerns around CA biodegradability have led to several studies, which have shown several approaches to enhance its biodegradability, such as the use of esterases for the first step in biodegradation (Puls et al. 2011; Mostafa et al. 2018; Shogren et al. 2019). Recently, Sebastian et al. (2018) patented a method for a biodegradable cigarette filter made of CA and biodegradable bi-component fiber (e.g. polyhydroxyalkanoates (PHA)).

Table 1 presents a summary of the properties of non-wood, wood, and cellulosic man-made fibers, described nonwoven processes employed and respective applications for their use.

Starch and derivatives

As mentioned before, initially, natural binders as starch were used to produce nonwovens, being later replaced by thermoplastic binders and binder fibers (Association of the Nonwovens Fabrics Industry 2003; Chapman 2007; Shogren et al. 2019). Nevertheless, starch is rising back. The revival of the use of starch in nonwoven production is due to the response of the need of more environmentally sustainable materials (Russel 2007; Karlovits 2017; Lochel Jr. and Tolfa 2018) and is observed in recent work focused on biodegradable (Sebastian et al. 2018) and flushable nonwovens (Bhat and Rong 2005; Chapman 2007; Rowell 2012) or even blended with other agents for nonwoven applications (Tseitlin et al. 2017). Among the plant-based polymers, starch is probably the most popular binder, because it is non-toxic, water-dispersible, inexpensive and is a very effective binder (Association of the Nonwovens Fabrics Industry 2003; Chapman 2007; Shogren et al. 2019). Starch is a polysaccharide material consisting of amylose and amylopectin arranged in a granular structure with both amorphous and crystalline domains (Cummings et al. 2019). Starch is rich in hydroxyl groups that allows hydrogen bonding, helping in the bonding in nonwovens (Kabasci 2013; Delgado-Aguilar et al. 2015; Hubbe and Koukoulas 2016; Shogren et al. 2019). Starch-based binders can be applied as aqueous dispersions or polymer solutions, since it has enough low viscosity for web penetration (Chapman 2007; Fahmy et al. 2010). Starch is used both in native and modified form (Lucia et al. 2020).

It has been pointed out that water solutions of starches, natural gums, proteins and some synthetic water-soluble polymers are only applied as primary binders when stiffness can be tolerated, as in cheaper decorative fabrics. Sometimes, these materials are used as pre-bonding agents before other treatments (Sherwood 1959; Karthik et al. 2016). It was pointed out that one third of the biodegradable polymers being commercially produced are starch based. Additionally, nowadays there is a wide range of technologies used for the production of starch-based products, such as polymerization reactions, blending and thermoforming (Cummings et al. 2019).

van Herwijnen (2007) patented the production of a renewable binder made of starch and a multi-functional cross-linking agent (monomeric polybasic acid, such as citric acid), in which this curable mixture can be heated at 120–300 °C for sufficient time to effective cure. It is recommended the use of a starch having greater than 80% of amylopectin, due to the improved solubility resulting from the branched chains of glucose residues. The resulted nonwoven may be used in building insulation, roofing fiberglass mat or filtration material. Starch is indicated as a suitable binder in patents describing air-laid nonwoven materials for absorbent products (Jr. and Jr. 2002; Parsons et al. 2019). A study performed by Tsuyumoto et al. (2011) showed the use of starch in binding sodium polyborate on thermally bonded nonwovens. The results showed a significant flame-retardant effect of the mixture of starch and the sodium polyborate by simply coating with the mixture.

Starch dextrin is a modified starch, produced by hydrolyzing the starch polymer physically, chemically, or enzymatically. It offers many different advantages compared to native starch, such as the ability to be used at higher solids levels, having higher tack and superior bonding, and dries faster. Dextrin-based adhesives have low cost, can be dispersed in water and easily applied either hot or cold, have long curing times, it is considered safe and easily processed (Imam et al. 2013). In nonwovens manufacture, it is used in heat resistant nonwovens (Cossement and Henrion 2005) and recent works addressed the use of dextrin as biopolymer binder in nonwoven mats (Tseitlin et al. 2017), and particularly for fiberglass bonding in nonwovens for insulation (Hawkins et al. 2011, 2014; Lochel Jr. and Tolfa 2018).

Thermoplastic starch (TPS) or destructurized starch is obtained when moistened starch is heated under shear, enabling melting (Hassan et al. 2019). TPS has also been employed along with biodegradable thermoplastic polymer (crystallizable PLA) for the production of nonwovens webs and disposable articles (Bond et al. 2005). It may also be added in the manufacture of disposable absorbent article that are thermally bonded (Weisman et al. 2012). It was found that thermoplastic starch formulations have tensile strengths below 6 MPa, which is a challenge compared to commodity oil-based polymers. Several authors noted that when only water was used as plasticizer, tensile strength is 40 MPa at 50% humidity but declined rapidly as humidity increased over 80%. Strength, resistance to moisture and flexibility could be improved by increasing amylose content (Zhang et al. 2014; Shogren et al. 2019) or by the addition of plasticizer other than water, which makes starch able to be processed like synthetic plastics (Hassan et al. 2019). TPS can be used as an alternative for conventional thermoplastics for disposable absorbent articles (Weisman et al. 2012). Dialdehyde starch is indicated as a wet-strength binder (Deng et al. 2018; Parsons et al. 2019; Pelton et al. 2019).

Latex

Latex is a very common binder in nonwoven production, commonly used in chemical bonding of air-laid nonwovens, alone or blended with other polymers (Ciechañska and Nousiainen 2005; Roy et al. 2011; Osong et al. 2016; Çelikten et al. 2018). The possibility to use latex from renewable sources, instead of from its emulsion polymerization to obtain styrene butadiene, has attracted some interest. However, natural rubber production is not very sustainable. Bio-latex can be prepared by co-extruding a biopolymer feedstock (carbohydrate, starch, or protein), a plasticizer under shear forces and reacted with a cross-linking agent under shear forces. Compared to synthetic latex, bio-latex dispersions are more complex and polydisperse systems (Lee and Leeuwen 2010; Shin et al. 2012; Bloembergen et al. 2013, 2014; Tseitlin et al. 2017; Cummings et al. 2019). In papermaking, there are several studies showing similar behavior of bio-based latex dispersions compared to synthetic latex binders (Lee and Leeuwen 2010; Shin et al. 2012). A work from Bloembergen et al. (2014) demonstrated that with an intermediate level of cross-linking in the bio-based latex, improved runnability, rheology and water retention can be obtained. Thus, bio-based latex can replace styrene butadiene latexes binder in paper industry. The bio-latex systems show unusual rheological, water retention, and wall slip properties that suggest better coater runnability. A commercial bio-latex binder from Ecosynthetix branded EcoSphere has been applied for natural organic fiber products and nonwovens mats (Tseitlin et al. 2017).

Cellulose derivatives

Carbohydrates from the pulping industry, mostly cellulose but also hemicelluloses, are a promising potential source for nonwoven. They can be applied as adhesive without any modification, once the polysaccharide chain already gives a "polymer character" to the resin structure, preventing the need of being generated by condensation reactions. Moreover, carbohydrates already have a number of highly reactive groups (hydroxyl groups and partly carbonyl or carboxyl functions) (Hubbe et al. 2015; Hubbe and Koukoulas 2016; Lucia et al. 2020). Fibers can also be manufactured from cellulose by both regeneration process (as seen before) and derivatization. Cellulose derivatives like cellulose esters can be prepared, dissolved, and extruded as continuous filaments, maintaining their chemical nature after the fiber formation process. (Bredereck and Hermanutz 2005; Woodings 2016).

Cellulose is a non-thermoplastic polymer that decomposes before it softens. Derivatization enables the modification of original bulk material properties such as thermal behavior through relatively simple reactions that effectively exploit side-group reactivity. Cellulose derivatives originated with nitrate (celluloid), which was the first man-made thermoplastic that still has limited applications because of its spinnability, film formability and transparency, strength and tenacity, sorption performance, and other useful properties. Currently, the search for more sustainable materials has led to the development of more cellulose derivatives which are CA, cellulose acetate propionate (CAP), cellulose acetate butyrate (CAB), carboxymethyl cellulose (CMC) and ethyl cellulose (EC) (Teramoto 2015; Larsson and Wågberg 2016). CA can act as binder fiber (as seen before) and also as binder. Farrugia and collaborators (2018) stated CA (molecular weight of 30,000) and CAB (molecular weight of 16,000, 20,000 and 30,000) as suitable binders for the production of a reversible color-changing sanitizer-indicating nonwoven wipe, made of cellulosic and bicomponent fibers. They also refer CAP, CMC and EC as suitable binders without limitations.

Similar to starch, Na-CMC and other water-soluble cellulose derivatives give the possibility to break down in the flush to disposable nonwovens articles (Bhat and Rong 2005; Chapman 2007; Rowell 2012). CMC is a polyanion and is generally used in the form of its sodium salt (Na-CMC), but it is also used as a calcium salt (Ca-CMC) for the disintegration and dispersion of tablets. Na-CMC is soluble in water, whereas Ca-CMC is not completely soluble but swells to several times its original volume upon contact with water and turns into a gel (Kim et al. 2018). A recent work provides the manufacture of a multi-ply dispersible nonwoven fabric comprising wood pulp and other natural fibers (Nandgaonkar 2020) employing particle binders of crystalline nature and hydrophilic, for joining the two nonwoven webs together. The particle binder employed is a co-processed composite of microcrystalline cellulose and Na-CMC, commercially available. The binder could be applied either by size press or spraying and after dried at 160 °C. Within health application, wet-laid blend nonwovens of Ca-CMC fibers and chitosan powder were prepared as hemostatic agent. It was demonstrated that the formation of polyelectrolytes complexes between Ca-CMC and CS contributed to the structural integrity of the nonwoven in the wet state and the resultant nonwoven structures were effective hemostatic agents (Kim et al. 2018).

Lignin and lignosulfonates

Lignin is an amorphous, three-dimensional polymer produced by all vascular terrestrial plants, obtained as a byproduct in wood pulping processes. It is a cross-linked phenolic polymer held together via ether and alkyl bonds (Imam et al. 2013; Pizzi 2016; Lucia et al. 2020). The lignin macromolecule has a variety of functional groups that have an impact on its reactivity. Lignin mostly contains methoxyl, phenolic hydroxyl and a few terminal aldehyde groups. Only a small proportion of the phenolic hydroxyl groups are free because most are occupied in linkages to the neighboring phenylpropane units (Kabasci 2013). Most industrial-graded kraft lignins have an average molecular weight of 1500–7000 g/mol and a glass transition temperature values between 100 and 150 °C (Solt et al. 2019). Lignin-based thermoplastic materials are low-cost, partially carbon–neutral, and biodegradable alternatives to synthetic thermoplastics (Wang et al. 2016). The drawback of lignin is its dark color and often its unpleasant odor.

The interest around lignin and tannins has been directed primarily at substituting phenol–formaldehyde resins because of the phenolic nature of these two classes of compounds (Pizzi 2016). In addition to lignin thermal properties and hydrophobicity, lignin has been pointed out as a promising wood adhesive by several authors, due to its thermal properties and hydrophobicity (Wool and Sun 2005; Imam et al. 2013; Collins et al. 2019; Solt et al. 2019). Pizzi et al. (2011) described the manufacture of a nonwoven made of cellulosic fibers (non-wood or viscose fibers) bonded my a mixture of tannins and lignin pre-reacted with a low molecular-weight aldehyde. A recent work demonstrated the potential of several carbohydrates, proteins and phenolic compounds as binders for air-laid pressed paper and showed that Salix lignin, when dried at 200 °C, was the only phenolic compound able to provide the same wet tear strength as vinyl acetate binder, currently used in the manufacturing process (Flory et al. 2013).

Tannins

Tannins are plant polymers present in the soft tissue of plants (*e.g.*, inner bark and leaves). They are rich in phenolic and aliphatic hydroxyl groups, divided into hydrolysable and condensed tannins, with flavonoids as structural units. However, only condensed tannins have a sufficient chemical reactivity to be developed as binders or adhesives (Pizzi et al. 2011; Pizzi 2016; Lacoste et al. 2018). The interest in tannins primarily started at substituting PF resins, because of the phenolic nature of these two classes of compounds. It is thought that due to the phenolic structure, tannins may exhibit similar reactivity as phenol. However, tannins are far more reactive than phenol due to the resorcinol and phloroglucinol nuclei present in the structure of condensed tannins (Pizzi 2016). Tannins extracts are usually sold as spray-dried powders, without the need of a purification step in industrial-scale production (Pizzi 2016; Echavarri-Bravo et al. 2019). The use of tannins in wet-laid nonwovens is described by Inagaki (cited in Russel 2007) in which long fibers of 15–17 mm length are formed into sheets and subsequently treated with mannan glue and reinforced with persimmon tannin. Condensed tannins have been used in binding natural fibers for bio-based nonwoven in mixture with lignin, as seen previously (Pizzi et al. 2011).

Soy-based

Soybeans are an industrial crop mainly used to produce oil and for human and animal feed. Soy protein molecules are complex macromolecules, composed of 20 different amino acids, each with a common backbone and a different sidechain. Side-chains of the amino acids are able to bond with different materials, including cellulose and lignocellulosic material (Lin et al. 2012; Imam et al. 2013; Vnučec et al. 2017). Soy proteins are currently viewed as promising binder in many sectors, as paper composites and particle boards manufacture, due to its low cost, high protein content and easy processing (Imam et al. 2013; Vnučec et al. 2017).

Bio resin derived from vegetal protein such as soybean has been used in natural fiber composites, but the final product has low water resistance. Fahmy et al. (2010) showed that the addition of denatured proteins resulted in a significant increase in all paper strength properties (increase up to 32% in breaking length compared to the blank without binder). Soy was used in a recent research to reduce the amount of PP used. The two polymers were mixed and spun into fibers. They concluded that a spinning temperature of 190 °C and a soy content of 15 wt% facilitated the processability with adequate retention of tensile properties of soy flour/PP fibers for potential use in disposable nonwoven fabrics (Guzdemir and Ogale 2019). Flory et al. (2013) tested bio-based binders in air-laid products and showed that binders as soy protein, gelatin, zein protein, pectin, and *Salix* lignin provided wet tear strength equivalent to that of the vinyl acetate binder currently used in the manufacturing process.

A recent work employed bio-based thermoset resin derived from soybean oil in manufacture of composites developed from nonwoven regenerated cellulose fibers, by compression molding (Ramamoorthy et al. 2014). Soy protein isolate and sodium dodecyl sulphate modified soy protein isolate based water-soluble binder composition have been prepared for binding viscose fiber by foam bonding for nonwovens used for industrial wipes and disposable articles, such as diapers. The results showed comparable thermal and mechanical properties and moisture absorption with that of the same fabric bonded with acrylic binder (Kumar et al. 2015). Lacoste et al. (2018) pointed out that the high cost of the purification of the oleaginous part have limited the use of this bio resin.

Cottonseed protein

Cottonseed protein is abundantly available and relatively inexpensive, and its adhesive potential is known as wood and paper adhesive. Cheng and collaborators (2017) tested cottonseed protein and observed that applying 11% of protein solution to the paper, both dry and wet strength increased (by 33% and 16% respectively). More recently, cottonseed protein was tested as a polymeric additive and binder for nonwovens made from cotton fiber. It was observed an enhanced dry strength of nonwovens. Moreover, the characterization evidenced a possible linkage between arginine from cottonseed with negatively charged cellulosic fibers, a possible interaction between the amide functionality from the protein with an appropriate functionality on cotton and possible Maillard and other reactions (Villalpando et al. 2019).

Other plant-based polymers

Naturally, a range of gums can be found, such as karaya, tragacanth, guar, carageenens and pectins, which are carbohydrate polymers. These are added to nonwovens as binders but also as thickening, emulsifying and gelling agents (Turbak 1993; Imam et al. 2013; Tseitlin et al. 2017).

Plant or animal-based and microbial fermentation-based materials

Microfibrillated cellulose (MFC), cellulose nanocrystals (CNCs) and bacterial cellulose (BC)

Microfibrillated cellulose (MFC) and cellulose nanocrystals (CNCs) are derived from plant biomass (e.g. wood, cotton, diverse fibrous vegetable material such as straw) and bacterial cellulose (BC) from bacteria via a fermentation process production (which can be fed from forest, agricultural and food waste streams) (Klemm et al. 2011; Cavka et al. 2013; Tsouko et al. 2015). Bacterial cellulose (BC) is a highly crystalline nano-sized cellulose with diameter of approximately 50 nm and several micrometers in length synthetized by cellulose-producing bacteria, such as from the *Acetobacter* species (Fortea-Verdejo et al. 2016). These cellulosic nanomaterials exhibit very useful properties such as high surface area, high tensile strength, and a surface rich in hydroxyl groups that enables their functionalization, as well as a very high water holding capacity (De France et al. 2017; Kedzior et al. 2017; Echavarri-Bravo et al. 2019). Although BC has the same chemical structure as that of plant-based cellulose, it may exhibit better mechanical properties (higher tensile strength and water holding capacity) due to its greater crystallinity and a higher degree of polymerization (Koutinas et al. 2014).

A work by Lee and collaborators (2014) showed the use of BC as a binder in the manufacture of sisal fiber composite plates, obtained by a method based on papermaking (wet-laid process). During the manufacture, the filtration of the fiber/BC suspension against the surface of the fibers formed a BC coating. The authors explained that when the suspension of loose fibers/BC was filtered and dried, the adjacent BC formed a network, which allowed to hold the otherwise loose fibers together. It was observed an increased bonding provided by the BC, thus an improvement of the mechanical properties. BC was shown as an effective binder to produce rigid and robust natural fiber nonwovens without the need for polymer binders. Fortea-Verdejo et al. (2016) have shown that both BC and nanofibrillated cellulose serve as excellent binders for loose flax fibers, compared to pulp fibers, due to their higher surface area (BC = 41.6 m^2/g, nanofibrillated cellulose = 4.5m^2/g and pulp fibers = 1.8m^2/g). These nonwovens were obtained by a single filtration process resembling a papermaking process (wet-laid). Nanofibrillated cellulose modified by a hydroxyethyl cellulose polymer coating was used to produce a nonwoven porous membrane as an alternative to those made from electrospinning. This bio-based membrane was obtained by vacuum filtration followed by supercritical CO_2 drying, originating a softer, more ductile, permeable porous structure and with higher surface area. The strain to failure was 55% with tensile strengths varying between 80 and 93 MPa, substantially higher than that for common electrospun membranes (Sehaqui et al. 2012). CNC has a high elastic modulus (120–150GPa) and biocompatibility, so it is a suitable reinforcing material in nonwoven (Peresin et al. 2010; Vallejos et al. 2012; Sun et al. 2015). A recent work reported the effect of CNC in nonwoven meshes made of CA by electrospinning, in which was observed enhanced mechanical properties (Sun et al. 2015).

Alginate

Alginate is a negatively charged polysaccharide found in brown seaweed and also produced by bacteria genera *Pseudomonas* and *Azotobacter* (Remminghorst and Rehm 2006). Alginate fiber is obtained by wet-spinning sodium alginate aqueous solution into calcium chloride coagulation bath, seen as a green and environmental process. This fiber has been widely used for wound dressing and other medical applications due to its excellent biocompatibility, degradation, non-toxicity and intrinsic flame retardancy (Watthanaphanit et al. 2009; Cuadros et al. 2012; Palumbo et al. 2015; Yan 2016; Zhang et al. 2016).

Alginate can also act as a binder once it is soluble in cold water and do not need a heating and cooling cycle to form gel. It is able to form stable gel through carbohydrate functional groups (Lacoste et al. 2018;

Echavarri-Bravo et al. 2019). Alginate gums have been used in printing textile fabric and as thickener in food industry (Imam et al. 2013). It was seen that alginate used as a binder in bio composites obtained from crop by-products (rice husk, barley straw and corn pith) can enhance fire-retardant properties of the final material (Palumbo et al. 2015). A recent work (Lacoste et al. 2018) showed the use of sodium alginate as an adhesive binder for wood fibers/textile waste fibers bio-composites, with results comparable with several aldehyde-based cross-linking agents (glyoxal, glutaraldehyde).

Chitin and chitosan

Chitin is one of the three most abundant polysaccharides found in nature. It is an amino polysaccharide extracted from the shells of crabs, shrimp and lobster but also produced via microbial (from fungal or bacterial fermentation). Mushrooms are an alternative source for isolating these biopolymers because their cellular wall has a high content of chitin, which may be transformed into chitosan through a deacetylation reaction. Chitosan, organic linear cationic polymer, is the deacylated form of chitin which is a random distribution of D-glucosamine and N-acetyl D-glucosamine. The different functional groups in chitosan provide tunable electrolyte properties, high adsorption capacity, and gel-forming capability, showing application as a glue in some materials (Bhat and Parikh 2010; Ploydee and Chaiyanan 2014; Challener 2016; Johney et al. 2016; Echavarri-Bravo et al. 2019; Hemamalini et al. 2020). Chitinous compounds differ from cellulosic by the presence of (acetyl) amino groups in their structure, resulting in distinct biological functions, such as bio-assimilability and antibacterial activity. Therefore, chitin and its derivatives, chitosan, chitin oligosaccharide, and chitosan oligosaccharide, are suitable for a wide variety of health-related applications (Blackburn 2005; Teramoto 2015).

Chitin fiber can be obtained by dry-spinning and wet-spinning and is characterized by soft handle, absorbency and breathability. Chitin can be processed in nonwovens production by a special wet-laid process and the obtained structure presents soft handle, absorbency, breathability, compact texture, softness and smoothness. These properties make chitin nonwovens good for dressing for extensive burns, scalds and other traumas (Yang et al. 2002; Blackburn 2005; Bhat and Parikh 2010; Ramamoorthy et al. 2015; Yan 2016; Senthil Kumar and Suganya 2017). A study showed that the formation of a chitosan film allowed to increase the dry-strength of paper (Jahan et al. 2009). The authors stated that chitosan has a compatible structure with cellulose, tending to promote efficient inter-diffusion, essentially welding the fibers together upon drying of the paper. Recently, OrganoClick AB developed OC-biobinder, a bio-based fiber-binding system used to make nonwovens and textiles stronger and stiffer (Challener 2016; Aydin et al. 2019). It was utilized a biopolymer-based polyelectrolyte complex (PEC), which is environmentally benign, renewable and biodegradable. The PEC is composed of chitosan as a cationic polymer and an anionic polymer represented by polyanions (in concentration of 0.005–30%, such as CMC and alginic acid). These binders provided higher dry and/or wet strength (Aydin et al. 2019). A recent work (Hemamalini et al. 2020) shows the development of a nonwoven web by dissolution of chitosan with short cellulose fibers using wet-laid technology. Citric acid was used to promote cross-linking between cellulose and chitosan and the resulted structure has potential application in controlling blood loss at trauma and surgery.

Microbial fermentation-based materials

The production of second-generation cellulosic biofuels relies on the deconstruction of the cell wall polysaccharides into monomeric hexose and pentose sugars that are then converted to fuels such as ethanol or butanol via microbial fermentation. The use of different microbial strains enables the production of chemical feedstocks that can be used for the production of bio-based products, including polymers (Ten and Vermerris 2013). These polymers can be turned into fibers using conventional melt spinning equipment and processes (Farrington et al. 2005).

Polylactic acid (PLA)

PLA is a linear aliphatic thermoplastic polyester produced from the microbial fermentation of plant sugars (*e.g.,* cornstarch, sugar beet or wheat starch) where fungi and bacteria can be sourced from agricultural and food industry waste streams. Filament and spun yarns can be obtained for application in nonwoven products, as binder fibers, for instance to produce strong point bonded nonwoven webs, requiring relatively low bonding temperature (Farrington et al. 2005; Bhat and Parikh 2010; Pourmohammadi 2013; Echavarri-Bravo et al. 2019; Liu et al. 2019; Shogren et al. 2019; Zhu et al. 2020). Depending on the catalysts used, PLA can have varying ratios of optical isomers L or D. PLLA (100% L) is semi-crystalline while PDLA (racemic) is amorphous. Once the melting temperature of PLLA is about 180 °C and thermal degradation begins around 200 °C, a small amount of D isomer is often added to lower the melting temperature and expand the processing window (Shogren et al. 2019). The glass transition temperature is typically between 55–65 °C, so PLA is a stiff polymer at room temperature (Farrington et al. 2005). PLA has replaced conventional plastics like PP and PE, since it has the same melting point as PP. Additionally, PLA fiber shares the same properties as many other thermoplastic fibers, such as controlled crimp, smooth surface and low moisture regain. A typical commercial PLA polymer having 96/4 L/D has 69 MPa tensile strength and elongation of about 2–7% (Farrington et al. 2005; Echavarri-Bravo et al. 2019; Shogren et al. 2019).

The wet-laid nonwoven fabrics made of PLA fiber are reported to be useful for packaging paper, corrugated cardboard, tissue paper, wiping paper, toilet paper and filter paper and for agriculture (Bhat and Rong 2005). Ahlstrom opened a line in 2009 for the production of BioWeb, which is a silky, fine filament web made from PLA, intended for the production of spunmelt nonwovens for tea bags (Kellie 2016). Spunbond and meltblown nonwovens made of PLA are intended for disposable hygiene, agriculture, diapers, sanitary napkins, and medical applications, such as protective clothing, surgical masks, and drapes. A recent work (Zhu et al. 2018) shows the performance of 100% bio-based melt-blown nonwovens for separation and filtration, made of PLA PLA/polyamide blends.

A recent review pointed out that NatureWorks, Total-Corbian, Weforyou, Synbra and Hisun have been producing PLA from sources as corn, sugarcane and cassava. It was stated that the non-renewable energy used to manufacture these plant-based materials is generally lower than for petroleum-based materials (Shogren et al. 2019). CorbionPurac initially launched its bio-based PLA resin portfolio for extrusion, thermoforming, injection moulding and fibers spinning in 2015 in Europe (Challener 2016). A recent work shows the use of different PLA resins as a matrix for bio-based composites made of waste textile fibers are used (Agrawal et al. 2017).

Polyhydroxyalkanoates (PHA)

Polyhydroxyalkanoates (PHA) are produced from the bacterial fermentation of several carbon sources, particularly vegetable oils (soybean oil and palm oil). PHA are a family of natural and biodegradable polyesters that can be processed similarly to various commodity plastics (Sudesh and Iwata 2008; Lu et al. 2009; Isikgor and Becer 2015; Shogren et al. 2019), being able to act as binder fibers in nonwovens. Nodax® is an example of a PHA used for flushable nonwoven products and other biodegradable nonwoven materials (Bhat and Parikh 2010).

Conclusions

The wide availability of natural and bio-based fibers and binders, together with the technology allow the production of fully biological materials. These could completely replace some of the existent conventional nonwovens used as disposable articles, bringing light to environmental issues. During past periods, advancements in the increase of nonwoven products sustainability were done, by the improvement of intrinsic hydrogen bonding capability of natural fibers, by the use of ionic liquids and by the functionalization of fiber surfaces. The engineering work on the machinery allowed to introduce natural fibers in the production of nonwovens and the developments in materials science, polymer chemistry and fermentation technology allowed to improve the properties of natural and cellulosic man-made fibers and of renewable polymer binders and produced via microbial. Many natural polymers can be tuned according to the desired properties to input in the final product, such as wood and non-wood fibers, starch and cellulose derivatives, chitin and chitosan, among others.

Many challenges and concerns posed by renewable polymers have been addressed by researchers. It is essential that research and industry work close to really introduce bio-based solutions in their process and subsequently products in the market, at the same time that consumers seek for more sustainable products. Wood pulp is among the most promising sources for sustainable materials, once it origins fibers and these can be dissolved to obtain lyocell, and also because cellulose can be derivatized to obtain polymers which can act as binders. The use of microbial strains enables the production of polymers that can be turned into fibers, which behave similar to conventional thermoplastic fibers. However, work is still needed to improve their biodegradability and improve composting requirements.

In the future, more research is needed to understand the biodegradability of bio-based polymers and after modification, allowing to meet the requirements of both performance products and sustainability. The choices must rely on the materials that have a sustainable production, despite their bio-based origin and have in mind the whole process to obtain the final nonwoven.

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Declarations

Conflict of interest The authors declare no conflicts of interest.

Ethical approval This article is a review, with no original research. Therefore, this article does not contain any studies with human or animal subjects performed by any of the authors.

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