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Review

Beyond cotton and polyester: An evaluation of emerging feedstocks and conversion methods for the future of fashion industry

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ABSTRACT

As the global population grows, the demand for textiles is increasing rapidly. However, this puts immense pressure on manufacturers to produce more fiber. While synthetic fibers can be produced cheaply, they have a negative impact on the environment. On the other hand, fibers from wool, sisal, fique, wood pulp (viscose), and man-made cellulose fibers (MMCFs) from cotton cannot alone meet the growing fiber demand without major stresses on land, water, and existing markets using these materials. With a greater emphasis on transparency and circular economy practices, there is a need to consider natural non-wood alternative sources for MMCFs to supplement other fiber types. However, introducing new feedstocks with different compositions may require different biomass conversion methods. Therefore, based on existing work, this review addresses the technical feasibility of various alternative feedstocks for conversion to textile-grade fibers. First, alternative feedstocks are introduced, and then conventional (dissolving pulp) and emerging (fibrillated cellulose and recycled material) conversion technologies are evaluated to help select the most suitable and promising processes for these emerging alternative sources of cellulose. It is important to note that for alternative feedstocks to be adopted on a meaningful scale, high biomass availability and proximity of conversion facilities are critical factors. In North America, soybean, wheat, rice, sorghum, and sugarcane residues are widely available and most suitable for conventional conversion through various dissolving pulp production methods (prehydrolysis kraft, acid sulfite, soda, SO_2-ethanol-water, and potassium hydroxide) or by emerging cellulose fibrillation methods. While dissolving pulp conversion is well-established, fibrillated cellulose methods could be beneficial from cost, efficiency, and environmental perspectives. Thus, the authors strongly encourage more work in this growing research area. However, conducting thorough cost and sustainability assessments is important to determine the best feedstock and technology combinations.

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1. Introduction

In 2022, the global population reached eight billion (United Nations, 2022). Besides increasing demands on food, water, and shelter, this rise also increases clothing demand. This demand, combined with fast fashion trends, has shot clothing production up to twice the amount it was 15 years ago, and the environmental consequences are astounding (Bettenhausen et al., 2022). The textile industry generates 1.2 billion metric tons of CO_2 annually, making up between 4 % and 10 % of total global greenhouse gas emissions (Bettenhausen et al., 2022). Synthetic fibers such as polyester (ex. polyethylene terephthalate (PET)) can be manufactured quickly and cheaply, but these petroleum-based products harm our environment. Each year, over 100 million t of textiles end up in landfills (Igini, 2022), and millions of microplastics enter our oceans, negatively affecting marine ecosystems. Existing natural fibers from cotton, woold, sisal, fique, and wood can help meet the heightened fiber demand, but cotton production cannot meet all of the demand for renewable fibers and applications using continuous filament. Using wood pulp to meet this demand is difficult, as most existing commercial wood resources are used for paper and wood products. With increased efforts to encourage transparency and create a more circular textile economy to reduce this alarming trend, the adoption of natural non-wood alternatives has been introduced to the conversation.

Textiles for the fashion industry comprise about 60 % of the textile market and can be made from various fiber types (Bettenhausen et al., 2022). The PET makes up 52 % of the global market, followed by cotton at 24 %, MMCFs at 6 %, nylon at 5 %, wool at 1 %, and the last 12 % representing other fiber types (Fig. 1) (Bettenhausen et al., 2022).

1.1. Textile industry trends

1.1.1. Polyester

Polyester is the clear market leader, making up over half of the global textile fiber market. The PET dominates the global synthetic fiber industry because of its high functionality and low production cost at high volumes (Fig. 1). However, the production of this fiber alone represents 342.16 million tons of CO_2 released to the environment annually (Moazzem et al., 2018; Juanga-Labayen et al., 2022). In the United States alone, textile waste equates to around 17 million tons per year (Vera et al., 2022). It is estimated that approximately 0.55 million tons of microfibers per year are discharged from plastic-based textiles (polyester, nylon, and acrylic) to aquatic environments, an amount that is mainly associated with the life cycle of polyester textiles (Ellen MacArthur Foundation, 2017; Vera et al., 2022). Additionally, there is a bottleneck in the supply of petroleum for resin for producing synthetic fiber (Biswas et al., 2020). In response, there is increasing interest in producing textiles from alternative and more sustainable raw materials (West, 2021).

1.1.2. Cotton

Cotton is the second most widely used textile fiber and the most widely used natural fiber in textile production (Vera et al., 2023c). However, its production is expected to not fulfill future market needs due to population growth. This population growth will limit the amount of available land for cotton farming, and available land may be used for additional demanded food production. Additionally, the large population will increase demand. Cotton farming requires large quantities of water; cotton cultivation practices in central Asia have led to water depletion and ecosystem damage in the Aral Sea (United Nations, 2022). World population to reach 8 billion on 15 November 2022.). Due to these issues, replacing synthetic fibers with cotton would not be the most suitable option (Rosa and Grammatikos, 2019; Meister, 2021). Additionally, some of the most desirable properties of synthetics are their hydrophobicity, durability, and elasticity. Cotton is hydrophilic and less elastic and requires additional finishing steps to achieve properties similar to synthetics.

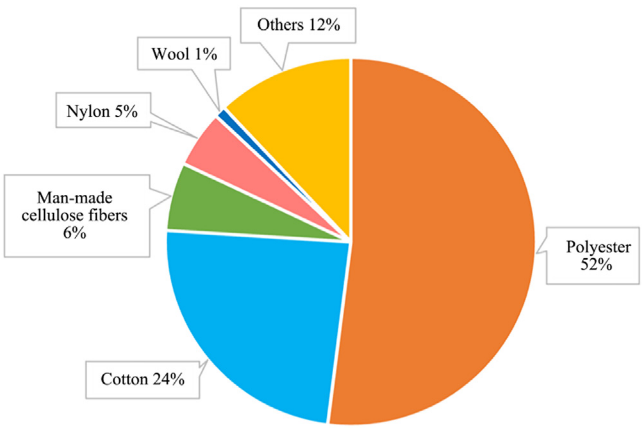

Fig. 1. Market share of each major fiber type in the fashion industry, 2020 (Bettenhausen et al., 2022).

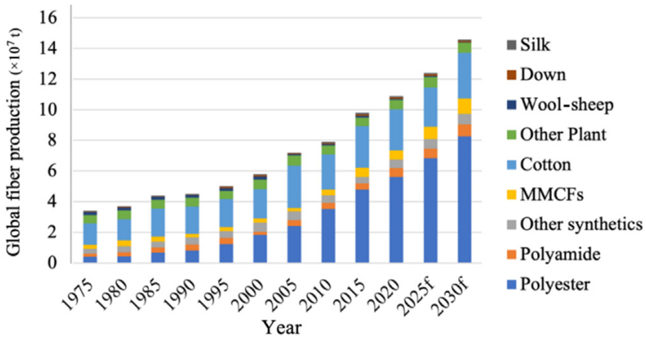

Fig. 2. World fiber production trend (1975–2030e) by fiber type, f stands for forecasted (Opperskalski et al., 2021).

1.1.3. Regenerated cellulose

The MMCFs have the potential to compete in the market against synthetic fibers and possibly cotton. The demand for and interest in MMCFs has increased with time (Fig. 2). In 2018, regenerated cellulose fibers had a market share of 6.4 % of total fiber production volume (Win Win Textiles, 2018). Although the production of cellulosic fiber fell by 10 % globally in 2020 due to a drop in demand for apparel spurred by the Covid-19 pandemic (Gschwandtner, 2022), this value is predicted to grow in the future and has doubled since 1990 (Win Win Textiles, 2018). Currently, the primary sources of cellulose for MMCFs are cotton linters and wood-based pulps (Meister, 2021). China is the leading producer of MMCFs. In terms of MMCFs made from recycled content, the market share is lower (< 1 %) (Win Win Textiles, 2018). However, this value is expected to increase since cellulose recycling has seen recent advances and innovation (Win Win Textiles, 2018), and future regulations requiring the use of recycled fibers are anticipated (Gschwandtner, 2022). The global methods for MMCF fiber production are shown in Fig. 3. Several brands, such as H&M Group, Benetton, Marks and Spencer, Zalando, Primark, and adidas, among others, plan to increase product lines based on MMCFs and recycled textiles or have made key partnerships with sustainable MMCF manufacturers (Bettenhausen et al., 2022). Table 1 lists the current leading MMCF manufacturers in the fashion industry.

(1) Conventional MMCF feedstocks

Conventionally, regenerated cellulose is made from dissolving wood pulp. Dissolving pulp describes a very pure pulp of high cellulose content and low hemicellulose, lignin, and other chemical components. About 85 %–88 % of the dissolving pulp produced uses wood as a starting material (Heinze and Liebert, 2012). Cellulosic fibers (cotton and man-made) are the major resources used for textiles, and total demand is predicted to increase by 50 % by 2030 (Ma et al., 2018). Further, demand and interest in dissolving pulp as a raw material for MMCFs have increased since its properties are very similar to cotton (Sugesty et al., 2015). Countries with greater forest resources, such as the US, Europe, Brazil, and South Africa, tend to manufacture mostly wood-based dissolving pulp, whereas dissolving pulps in China are made mainly from cotton linter (Jiang et al., 2020). The conventional production of wood-based viscose fiber requires the use of toxic carbon disulfide (Textiles Inside, 2022).

(2) Alternative MMCF feedstocks

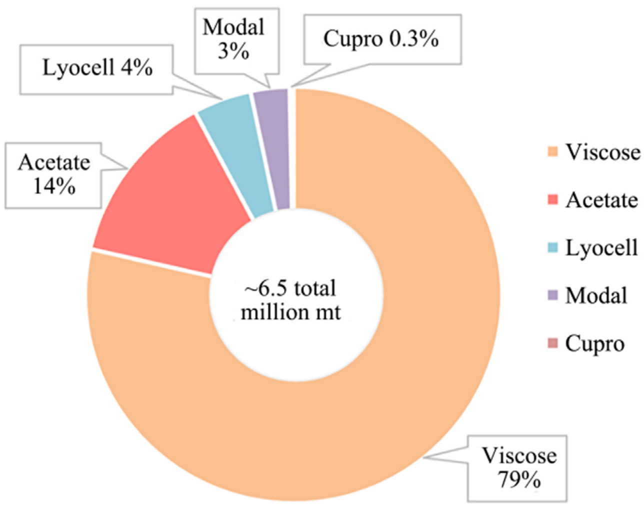

Fig. 3. World fiber production of major man-made cellulose fiber (MMCF) types in 2020 in million metric tons (Opperskalski et al., 2021).

Table 1
Major and emerging manufacturers of man-made cellulose fibers (MMCFs) for the fashion industry.

MMCF Manufacturer		Market share	Product	Location
Established	Lenzing	15 %	Lyocell fiber	Austria
	Sateri	16 %	MMCF	China
	Birla Cellulose	13 %	Viscose fiber	India
	Tangshan Sanyou	12 %	Viscose fiber	China
	Asahi Kasei	44 %	Cupro fiber	Japan
Emerging	Evrnu		MMCFs	US
	Infinited Fiber Company		Carbamate fiber	Finland
	Algalife		Dyes and MMCFs	Israel
	Inspidere		MMCFs	Netherlands
	Orange Fiber		MMCF	Italian
	Nanollose		Rayon fiber	Australia
	Spinnova		Textile fiber	Finland
	Others			

Source: Hugill et al. (2020).

Another source gaining interest is alternative feedstocks, which can include non-wood crops, plants, recycled material, and waste material. MMCFs from lignocellulosic non-wood pulps (such as wheat straw, bamboo, hemp bast or hurd, etc.) have been identified as a good opportunity for improvement (Vallejos et al., 2016). The use of non-wood feedstocks in the pulp and paper industry began several decades ago, originating mainly in China and Asia-Pacific regions, but now non-woods are pulped globally (Buchheit, 2022). From 1999–2003, there was a 10 % increase in non-wood feedstock used for papermaking (Behin et al., 2008). Fig. 4 shows the non-wood pulping capacity of different regions around the world in 2015 and 2020, as well as the expected 2025 capacity.

The use of alternative pulps in the paper industry is more established and, therefore, can help guide and inform the textile industry on adopting alternative raw materials. Using non-woods to replace conventional wood sources helps to decrease deforestation. It allows for other sources to be used in countries where woody raw materials are in short supply and where MMCFs must be imported (Huang et al., 2019). As reflected in Fig. 4, non-woods are more important in the Asia-Pacific region, where woody biomass is less available. Non-wood use is growing in this region, but also in North America. The authors expect to see growth trends in the textile industry similar to those in the paper industry. In some cases, non-woods may perform even better than wood in terms of textile properties due to unique fiber morphologies (fiber lengths and composition) (Huang et al., 2019). Both planted crops and agricultural residues have been entering the market as great prospects for dissolving pulp production (Meister, 2021). Agricultural residues offer great opportunities, such as additional revenue for farmers, fields available in a shorter time for the next planting session, and a decrease in CO_2 emissions in cases where farmers normally burn these biomasses as a waste management process.

Additionally, manufacturing products from these residues could help address the growing demand for sustainable goods. Adopting MMCFs made from sustainable, renewable sources and advancing conversion processes could help improve environmental pollution, waste management, and depletion of fossil fuels. Notable trends in consumer behavior towards sustainable products, especially in younger generations, will continue to drive business and technology down this route (Szegedi, 2023). Using non-woody biomass and residue from farms instead of petroleum-based materials will allow the positive impacts of sustainable fibers to reach farmers and

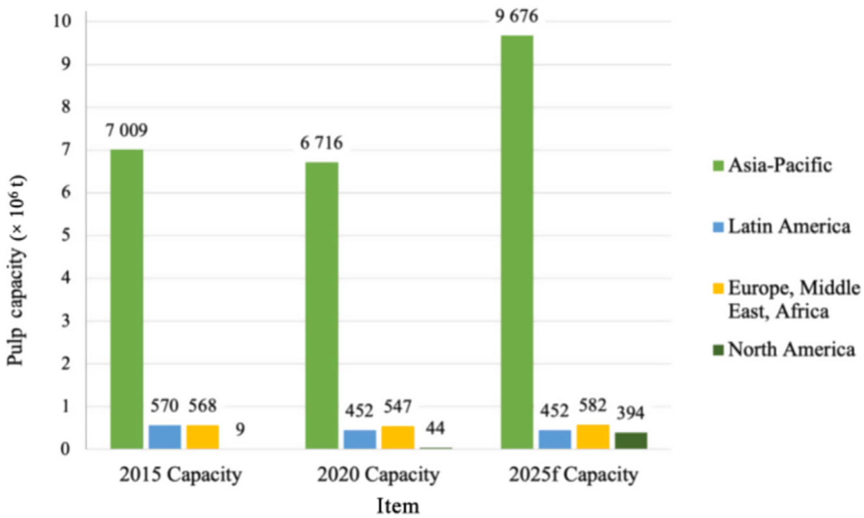

Fig. 4. Trends in non-wood pulp capacity for the paper industry in major global regions, f stands for forecasted (Buchheit, 2022).

consumers alike. In the next ten years, the sustainable MMCF market is anticipated to exceed 10 % (Textiles Inside, 2022). Due to the novelty of this field, competition is propelling technological developments. Emerging companies in the industry are beginning to commercialize their products and are looking towards industrial-scale manufacture. Innovation has largely originated in Finland, with the following companies and university labs paving the way: Aalto University, Metsä Spring Oy, Spinnova Oy, and Infinited Fibre Company, each with their trademarked fiber (Textiles Inside, 2022).

Influence of new feedstocks on certification of clothing: With emerging regulations and standards such as the European Green Deal in Europe, Federal Trade Commission Green Guides in the United States, and the new global ISO 14068 standard for greenhouse gas management, both new and conventional feedstocks will likely be required to have certification to go to market in a product (Halliday et al., 2023; The International Organization for Standardization, 2023). For wood, certifications such as Forest Stewardship Council (FSC) and Program for the Endorsement of Forest Certification (PEFC) are well-known and established, and for textile waste, Recycled Claim Standard (RCS) and Global Recycled Standard (GRS) have been more recently established. Non-wood sources will likely require their own certifications to be implemented in garments in the near future. One such certification, the International Sustainability & Carbon Certification (ISCC), supports product supply chains that are deforestation-free, achieve a minimum level of greenhouse gas savings, and avoid land use of areas with high biodiversity value or carbon stock (International Sustainability & Carbon Certification, 2023). Besides commonly used animal fibers such as wool, silk, and leather, which have some guidelines such as the Responsible Wool Standard (RWS) or REACH (registration, evaluation, authorization, and restriction of chemicals) Regulation, the utilization of non-woods as regenerated cellulosics in the textile industry is not yet prominent enough for mandatory certifications to exist (CBI Ministry of Foreign Affairs, 2020).

Before this certification is required, companies will likely be able to advertise their use of non-wood feedstocks as an environmental advantage. This may in some cases lead to greenwashing, such as if the non-wood percentage within the garment is very low, or if the life cycle analysis (LCA) results of the non-wood textile fiber manufacturing are not truly advantageous compared to conventional fiber types.

(3) Limitations of alternative MMCF feedstocks

Using alternative feedstocks to make MMCF is potentially a good opportunity to improve the textiles industry's sustainability, but new challenges come with new materials.

Scale and availability: Alternative feedstocks have lower availability in terms of biomass density per area compared to woody raw materials. This lack of availability translates into higher sourcing transportation distances and costs which presents a challenge for developing conversion pathways that can process smaller volumes. As a result, the capital investment per ton of product manufactured is significantly affected (Pirraglia et al., 2013). However, supplementing existing MMCFs from wood with other fiber types, such as non-woods in specific regions, may help meet consumer fiber demand.

Raw material composition: Besides availability, another challenge with alternative raw materials is their differences in composition, not only from conventional woody materials but from each other as well (Table 2). Compared to wood, alternative feedstock sources such as agricultural residues and planted crops typically have higher contents of ash, silica, or extractives, which can be difficult to separate from the cellulose fraction (Abd El-Sayed et al., 2020).

Impurities: Impurities in non-wood materials, such as dirt and resins, may make achieving dissolving-grade pulp with high cellulose content more difficult (Sixta, 2006). Due to these limitations, different conversion methods may need to be considered for processing these alternative biomass sources. These methods might include smaller-scale systems or methods capable of handling entire lignocellulosic biomasses or those with higher impurity contents. Different methods will be necessary for the two major systems of feedstock to textile transformation: 1) processes for biomass conversion and 2) processes for manufacturing regenerated cellulose from this converted biomass. This review is focused on the first system and describes both conventional and emerging technologies for biomass conversion to prepare material for subsequent regeneration into a textile filament.

2. Scope and structure

Research into converting non-wood raw materials into dissolving grade pulp has great potential. A significant amount of literature will aid in evaluating the technical feasibility of converting various alternative feedstocks to textile-grade fibers. This review focuses on converting non-wood raw materials into pulp or intermediary material that will subsequently be spun into textile filaments. Availability and chemical composition of non-woods in the US are reported, established and emerging conversion processes are reviewed, and testing and characterization of the converted material are described. Details on regeneration and spinning methods are outside of this article's scope and may be addressed in future work. Based on the scope, over 100 documents, including research papers and patents, were reviewed and examined, and a keyword search was used to find published data on using alternative feedstocks as a starting material for manufacturing MMCFs. This literature search included searching scholarly and reputable databases by keywords such as "regenerated cellulose" + "non-wood" + "textile" + "dissolving pulp" + "fibrillated cellulose" + "MMCF" + "fiber". Fig. 5 shows the frequency of peer-reviewed journal articles and patents describing the conversion of alternative feedstocks published per year (2000–2022) referenced in this review. The earliest source found was a work by Abou-State et al. (1979) on dissolving pulp from Egyptian bagasse from 1979. In the past decade, the scientific research community has shown increased interest in using non-wood sources for novel applications.

This work begins with reviewing established and emerging feedstocks for MMCF conversion, including biomass availability and raw material composition. Next, processes for biomass conversion are discussed, including both conventional methods for producing dissolving pulp and emerging methods such as fibrillated cellulose or fiber recycling techniques. Tests used to measure the pulp properties and the specified requirements for engineered fiber applications are detailed. Tables 5–7 detail existing work on converting

Table 2
Non-wood biomass potential based on feedstock raw material and fiber composition.

Residue	Cellu-lose (%)	Hemi-cellu-lose (%)	Lig-nin (%)	Ash (%)	Fiber length (mm)	Fiber width / diam (μm)	Refs.
Agricultural residue							
Sugar-cane bagasse	32–60	20–30	18–24	1–5	0.9–1.5	16–25	Andrade and Colodette, 2014; Costa et al., 2016; Saeed et al., 2017; Abd El-Sayed et al., 2020; Rieland and Love, 2020; Ferdous et al., 2021; Mahmud and Anannya, 2021; Ochica Larrota et al., 2021; Sun et al., 2021; Periyasamy et al., 2022
Corn stover	38–40	22–28	7–21	4–7	0.99	13.2	Reddy and Yang, 2005; Liu et al., 2015; Han et al., 2019; Rieland and Love, 2020; Periyasamy et al., 2022
Corn stalk	53.6	16.2	22.2	3	0.9–1.3	14–24	Shakhes et al., 2011; Abd El-Sayed et al., 2020; Ferdous et al., 2021
Wheat straw	33–45	20–31	13–20	6–11	0.7–1.5	9.3–23.0	Reddy and Yang, 2005; Liu et al., 2015; Haisong, 2017; Sundarraj and Ranganathan, 2018; Abd El-Sayed et al., 2020; Rieland and Love, 2020; Delucis et al., 2021; Ferdous et al., 2021
Rice straw	28–49	18–28	8–19	14–20	0.78– 1.41	8.0–14.8	Lim et al., 2001; Reddy and Yang, 2005; Bekalo and Reinhardt, 2010; Shakhes et al., 2011; Liu et al., 2015; Abd El-Sayed et al., 2020; Rieland and Love, 2020; Delucis et al., 2021; Ferdous et al., 2021; Periyasamy et al., 2022
Rice husk	35–45	19–28	19–21	15–19	0.21–2.36	250–830	Reddy and Yang, 2005; Zhang et al., 2013; Reddy and Yang, 2014; Wu et al., 2015; Bisht et al., 2020; Delucis et al., 2021; Plakantonaki et al., 2022
Tobacco stalk	30–40	10–20	20–30	7.4	1.23	24.3	Shakhes et al., 2011; Huang et al., 2019
Coconut Husk	25–42	15–28	30–54	1–4	103	400	Gaspar et al., 2020; Azeta et al., 2021; Anuchi et al., 2022
Hemp hurd	40–48	18–24	21–24	1.4-3	15–30	4 000–6 000	Stevulova et al., 2014; Naithani et al., 2019
Cotton linters	90	2	0	2	2–7	17–27	Sczostak, 2009; Abd El-Sayed et al., 2020
Sorghum straw	35.4–58.2	19	10–30	5.3	0.50–1.2	12.1–26.8	Liu et al., 2015; Saeed et al., 2017; Andrade Alves et al., 2019
Soybean straw	43.97	25.51	24.07	2.64	0.46	24.2	Liu et al., 2015
Coffee husk	19–26	24–45	18–30	6–7	0.3	20	Bekalo and Reinhardt, 2010
Coffee hulls	40–49	25–32	33–35	0.5–1.0	0.3	20	Bekalo and Reinhardt, 2010
Planted crop							
Hemp bast	57–77	9–25	4–9	4	5–60	20–40	Thygesen and Forskningscenter Risø, 2006; Stevulova et al., 2014
Switch-grass	30–44	24–30	19–25	1.8–7.0	0.76	13.89	Kim et al., 2018; Abd El-Sayed et al., 2020

alternative feedstocks into converted pulp or fiber, along with associated experimental data. These tables compile existing experiments utilizing emerging feedstocks, and based on this information, the authors make conclusions about the feasibility of these emerging feedstock and process combinations. A short section covers the conversion of converted pulp to a regenerated cellulose filament. Finally, the authors review the opportunities and challenges of conventional and emerging dissolving pulp technology, concluding with remarks about which feedstocks and conversion processes show the most promise.

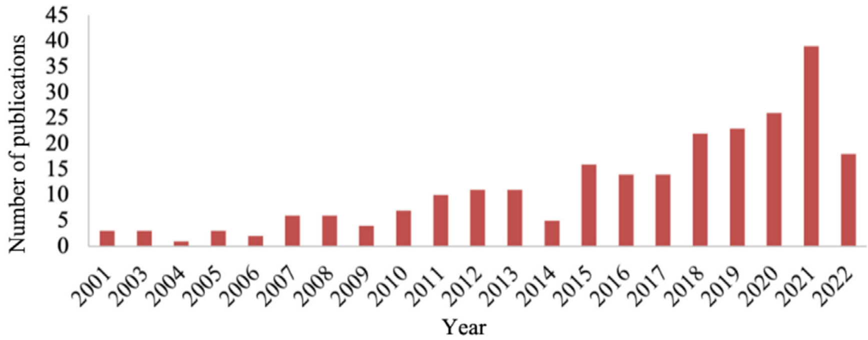

Fig. 5. Frequency of publications and patents per year (2000–2022) related to the study of converted biomass from alternative feedstocks included in this review.

3. Alternative feedstocks

Residues, forest biomass, and dedicated energy crops represent renewable lignocellulosic feedstocks that are naturally abundant and can be used to make materials and chemicals. In the future, more non-wood lignocellulosics will begin to enter the market replacing some of the conventional woody materials. Historically, bamboo and cotton linters have been the major sources of non-wood cellulose in the dissolving pulp industry. Natural fibers, including seed hair, leaf- and bast-fibers, have been utilized widely (Nguyen et al., 2019). In China, bamboo pulp has entered the market as a rayon-grade dissolving pulp (Chen et al., 2016). Lignocellulosic materials from different resources such as banana, pineapple, jute, coconut, sisal, and cotton provide natural fibers for home products, vehicles, textile applications, and construction (Nguyen et al., 2019). There has also recently been a shift toward using recycled cellulose, which may also be economically beneficial.

Agricultural residues specifically represent a promising solution to the sustainability problems in the textile and agricultural industries, as they are often inexpensive and highly available (Reddy and Yang, 2007; Behin et al., 2008). Woody materials typically have lignin contents between 20 % and 30 %, while non-wood sources have lower lignin content (corn stalk: 17 %–19 %; wheat straw: 12 %–14 %; and bagasse: 18 %–22 %) (Behin et al., 2008). This compositional difference means these non-woody biomasses with lower lignin contents would likely be easier to pulp than wood (Behin et al., 2008). Dedicated crops can also provide new and innovative feedstock sources for the paper and textile industries. This work mainly focuses on the potential of North American crops and residues as alternative feedstocks but also briefly reviews other relevant and promising feedstocks worldwide.

3.1. Major US feedstocks

The following feedstocks are sorted by available tonnage, from the highest to the lowest. Specific values for each biomass can be found in Table 3.

Soybean: Straw from soybean is a residue with great potential due to biomass abundance and lower silica and ash contents compared to other non-woody biomasses (Liu et al., 2015). Soybeans are a type of annual legume originating in Asia, with stems, leaves, and pods (Liu et al., 2015). The stems or straw residue is currently used for animal feedstock or as an energy source. Still, it could also be used as an alternative raw material source in the paper industry (Liu et al., 2015). US soybean production is abundant, making it a good option for larger-scale industrial paper or textile production.

Wheat: Over 46 million acres of wheat crop exist around the US, with a total annual supply capacity of 85 million tons of wheat straw (United States Department of Agriculture (USDA), 2022. National Agricultural Statistics Service: Quick Stats Tools.). Wheat straw is typically unused; most of the supply remains on the field to decompose or is burned, further contributing to greenhouse gas emissions (He et al., 2020; Venkatramanan et al., 2021). Straw fibers from wheat tend to be narrow, with thick cell walls and sharp or hulled ends (Abd El-Sayed et al., 2020). Besides its availability, wheat straw pulp mills already exist in some parts of the world, demonstrating that commercial production of wheat straw pulp is technically feasible. Straw pulp mills are common in China and Germany, where wheat straw is used commercially for hygiene tissue products ((Han et al., 2015; Essity, 2021). These commercial applications show promise for agricultural wastes to be used as alternatives to woody fiber.

Sorghum: Sorghum is a widely bred grassy agricultural crop originating in Africa, with advantageous characteristics such as drought resistance, rapid growth, and high biomass production yield (Pennells et al., 2021). The sorghum biomass is a diverse family of grasses with varying plant heights and leaf sizes (Pennells et al., 2021). Most non-grain sorghum biomass, up to 90 % of the total biomass, has been used for low-value applications (Pennells et al., 2021). Therefore, there exists a lot of opportunity for these leftover materials to be used in the paper and textile industries.

Rice: Rice straw has been used for papermaking in countries such as India, China, and Sri Lanka, but the high silica content (sometimes as high as 18 % of the entire straw) and expensive collection and storage have limited its use (Abd El-Sayed et al., 2020). Besides having a higher portion of leaves in the residue and a higher silica content, rice straw is similar to wheat straw in physical structure (Abd El-Sayed et al., 2020).

Table 3
Non-wood biomass potential based on US feedstock availability.

Crop/ Product	Crop production in US (t) and year reported	Residue-to-product ratio	Residue	Total amount obtained, US (t)	Refs.
			Agricultural residue		
Soybean	133 961 460[a] (National), 2021	2.50	Straw	334 903 650	Alhassan et al., 2019; Adhia et al., 2021; SSGA, 2022; United States Department of Agriculture USDA, 2022
Wheat	49 387 620[a] (National), 2021	0.85	Straw	41 979 477	Kansas Wheat, 2015; Adhia et al., 2021; United States Department of Agriculture USDA, 2022
Rice	10 740 576 (National), 2021	1.25	Straw	13 425 720	Adhia et al., 2021; United States Department of Agriculture USDA, 2022
Sorghum	1 894 230[a] (National), 2017	2.62	Stalks + leaves	4,962,882	Bean, 2018; Adhia et al., 2021; United States Department of Agriculture USDA, 2022
Sugar	33 087 000 (National), 2022	0.15	Bagasse	4 797 615	Melati et al., 2017; Adhia et al., 2021; United States Department of Agriculture USDA, 2022
Rice	10 740 576 (National), 2021	0.26	Husk or hull	2 792 550	Elauria et al., 2005; Alhassan et al., 2019; Adhia et al., 2021; United States Department of Agriculture USDA, 2022
Cotton	4 205 520 (National), 2021	0.03	Linter	126 166	Adhia et al., 2021; United States Department of Agriculture USDA, 2022
Tobacco	238 987 (National), 2021	0.27	Stalk	64 526	Ronzon et al., 2015; Berbeć and Matyka, 2020; UUnited States Department of Agriculture USDA, 2022
Coffee	12 708 (National), 2017	2.13	Husk	27 068	Adhia et al., 2021; United States Department of Agriculture USDA, 2022
Hemp	16 625 (National), 2021	0.52	Hurd	8 645	Matassa et al., 2020; United States Department of Agriculture USDA, 2022
Corn	1 102 (National), 2017	0.50	Stover	551	Adhia et al., 2021; United States Department of Agriculture USDA, 2022
Coconut	77 (Puerto Rico & Outlying Areas), 2018	0.60	Husk	46	Adhia et al., 2021; United States Department of Agriculture USDA, 2022
			Planted crop		
Crop/Product	Total amount obtained in US (t) and year reported				Refs.
Biomass sorghum	1 894 230[a] (National), 2017				Bean, 2018; United States Department of Agriculture USDA, 2022
Ryegrass	177 176 (National), 2017				United States Department of Agriculture USDA, 2022
Hemp bast fiber	16 625 (National), 2021				United States Department of Agriculture USDA, 2022
Switchgrass	6 246 (National), 2017				United States Department of Agriculture USDA, 2022

Note: a, converted from bushels of that respective biomass.

Sugarcane (Bagasse): In the American states of Florida and Louisiana, sugarcane is an important crop, classified as a perennial grass that is produced in 124 countries around the world (Li, 2003; Singh et al., 2021). Bagasse from sugarcane has been identified as a feedstock with much promise as an alternative fiber for the paper industry (Abd El-Sayed et al., 2020). Bagasse can be used for in-house fuel and landfilling; however, if the rind of the sugarcane can be mechanically separated from the stalks, the cellulosic fibers can be removed after chemical and mechanical treatment (Li, 2003; Singh et al., 2021). This residue has also been used in producing pulp for the paper sector in products such as packaging, newsletters, and printing paper (Rainey and Covey, 2016). It is a non-wood with high cellulose and low lignin contents, making delignification easier compared to some common feedstock sources such as eucalyptus (Vena et al., 2013). Bagasse fibers inherently have dense fiber walls and primarily blunt ends, making them unique fibers and advantageous for certain applications (Abd El-Sayed et al., 2020).

Ryegrass: Short-rotation grasses have great potential as an alternative feedstock source since they tend to be fast-growing and abundant (Sun et al., 2021). Ryegrass is an abundant grass used globally as a forage and cover crop (Sun et al., 2021). Grasses typically have lower lignin contents, making them good candidates for both dissolving pulp and fibrillated cellulose conversion, but high levels of hemicellulose must be dealt with accordingly (Sun et al., 2021).

Cotton: Cotton linters have been used widely for many years. These linters are the fibers remaining on the cotton plant husk after the longer cotton fibers have been extracted (Abd El-Sayed et al., 2020). Mechanical action is required to remove the linters from their seeds (Abd El-Sayed et al., 2020). Linter tends to be even better than softwood because it has close to 90 % cellulose content and a higher degree of polymerization (DP) (Abd El-Sayed et al., 2020). Although advantageous in many aspects, these fibers are expensive agricultural waste (Abd El-Sayed et al., 2020).

Tobacco: Tobacco is an important crop in America. Its leaves are used for the manufacture of cigarettes, while its stalks are burned or left on the field (Huang et al., 2019). These stalk residues have compositions similar to wood, making them suitable materials for dissolving pulp production (Huang et al., 2019). If these residues are converted and used for paper or textile applications, this would help mitigate the disposal issues related to the crop (Huang et al., 2019).

Coffee: When coffee beans are refined, a large quantity of waste material in the form of coffee husks or hulls is produced (Tolesa et al., 2018). This leftover material is typically burned or returned to the field (Tolesa et al., 2018). Using the husks and hulls to produce paper or textile material would add value to the entire coffee production chain (Tolesa et al., 2018). Compared to the husk, the coffee hull as higher cellulose, hemicellulose, and lignin contents with lower extractive and ash contents (Bekalo and Reinhardt, 2010).

Hemp: Hemp is another crop with the potential to become a leading sustainable feedstock for various industries (United States Department of Agriculture USDA, 2022). Hemp bast has been used in durable and "hard-wearing" textile applications, encouraging the establishment of hemp fiber crops (Meister, 2021; Rehman et al., 2021). However, there are challenges to implementing hemp bast and leaf fibers due to the harsher chemical pretreatments required (Meister, 2021). Hemp hurd, making up approximately 60 wt% of the fiber hemp plant, represents an emerging agro-industrial residue. Hurd is mostly used for animal bedding and building materials but may have other applications (Williams, 2019). Short staple fibers are not ideal for textile processing, but if isolated from the residue, these fibers could be converted into dissolving pulp for spinning into MMCFs (Meister, 2021).

Switchgrass: Switchgrass is a fast-growing tall perennial grass that can be harvested up to two times a year for ten years before replanting (Kim et al., 2018). This crop is native to North America and is advantageous due to its renewability and lower cost of production (Kim et al., 2018). Further, it has been reported that switchgrass has larger soil CO_2-sequestration potential compared to several other biomass sources, making it a good option for a more sustainable starting material (Bai et al., 2022).

Corn: Corn is a possible feedstock for alternative fiber sourcing. Cornstalk, the major residue from corn, can be produced annually, has lower lignin content, and tends to be delignified easier. Further, pulping cook time is quicker and less severe than wood (Behin et al., 2008). Cornstalk fibers tend to be narrow, with thick fiber walls and pointed ends (Abd El-Sayed et al., 2020).

Coconut: Coconut plant is mainly grown in Thailand, India, and several African countries, but the waste from this plant is widespread globally (Azeta et al., 2021). The shells and husks of the coconut are the most abundant wastes from cultivation, and since they are unused, they are considered an underutilized feedstock (Azeta et al., 2021; Anuchi et al., 2022). However, coconut is not as commonly grown in the US compared to other countries.

Recycled paper: In the US, paper and board represent around 15 % of landfilled material (Ma et al., 2016). Reusing this material to make dissolving pulp for MMCFs is a good solution for waste management. Since paper and board generally have higher allowances for hemicellulose and lignin, further purification would likely be necessary when converting these recycled materials to textiles. However, depending on the conversion and regeneration process, the number of recyclings the paper has undergone may not be an issue for reuse in MMCFs, like it is for paper applications. Nevertheless, wood-based paper and board feedstocks serve as great cellulose sources for MMCFs (Ma et al., 2016).

Recycled textiles: Post-consumer cotton textile waste has been increasingly used as a feedstock for MMCF production. Using this material as a feedstock helps to close the loop and make the textile industry more circular (AFRY, 2022). Since so much cotton-rich textile waste ends up in landfills, recovering this material will help decrease the environmental burden of its waste. Challenges with this material source include difficulties separating cotton from polyester or other blended materials, lower durability after regeneration, fewer possible recycles due to its previous life, and efficient removal of dyes and finishes in the cotton purification process (AFRY, 2022). The higher crystallinity of cotton compared to wood also makes enzymatic hydrolysis treatment, often used to separate synthetics from cotton, more difficult (Cho et al., 2023).

3.2. Other notable feedstocks worldwide

Since non-woods' success in production systems will be highly related to their availability within a region and proximity to mills and industrial facilities, this article does not consider in detail the feasibility of other non-woods outside of the US. However, short descriptions of additional non-wood feedstocks with high potential are included since work on these feedstocks could be translated to other starting materials.

Bamboo: Bamboo is a non-wood species with similar properties to hardwoods and softwoods (long fibers, similar α-cellulose content) and is typically ready for harvest in 3–5 years (Sugesty et al., 2015; Yuan et al., 2017). Due to a high growth rate, bamboo has an exceptionally high yield of biomass per acre of land, in some cases up to four times that of eucalyptus (Down to Earth, 1999). Bamboo can also grow on land that cannot be used for food crops, which is advantageous (Win Win Textiles, 2018). Sembilang and Mayan bamboo have been determined as suitable species for dissolving pulp raw material (Sugesty et al., 2015). Fiber lengths are typically shorter than softwoods but longer than hardwoods, and the fibers have additional layers with complex orientation and thick cell walls (Chen et al., 2016). These structural differences can hinder the cooking liquor penetration and may affect dissolution, requiring stronger bleaching and cooking conditions than wood species (Chen et al., 2016). The ratios of lignin to hemicelluloses are like that of hardwood species, but ash and silica contents are typically higher in bamboo (Chen et al., 2016). Traditional pulping and biorefinery processes are unsuitable for this feedstock and require significant modifications (Yuan et al., 2017). Moreover, bamboo is not native to the US, and therefore, its availability is not comparable to that of other feedstocks.

Jute: Jute is a flowering plant mainly grown in India, China, Bangladesh, and Thailand (Abd El-Sayed et al., 2020). Jute fibers have optimal physical properties for fiber making, with high cellulose content and relatively long fiber length (Abd El-Sayed et al., 2020). Although not abundant in the US, jute stick has been reported as a source of non-wood dissolving pulp (Sarkar et al., 2018) and fibrillated cellulose (Alila et al., 2013; Chaker et al., 2013; de Souza Fonseca et al., 2019).

Kenaf: Originating in Africa, this plant has an unbranched stalk with a woody internal core and bark outer layer. In China and Thailand, kenaf has been utilized to complement wood in the paper industry (Abd El-Sayed et al., 2020).

Dhaincha: Dhaincha, an annual plant grown mostly in Bangladesh, has also been reportedly used to make dissolving pulps (Jahan and Rahman, 2012). This crop is typically grown to enhance soil nutritional value and has a tall, straight stem and hardwood-like composition (Jahan and Rahman, 2012).

Oil palm: Oil palm trees provide vegetable oil, which is a very important product for Indonesia (Harsono et al., 2016). During the milling process, shell, fiber, empty fruit bunches (EFB), and other residues are also produced (Harsono et al., 2016). The shells and fibers have been used to fuel the boilers of palm oil mills, but the EFBs are left unused (Harsono et al., 2016). These leftover residues could be used to make dissolving pulp or fibrillated cellulose to add to oil palm's overall biomass value.

3.3. Alternative feedstock summary and analysis

For US operations, using widely available biomasses such as soybean straw, wheat straw, rice straw, sorghum stalk, and sugarcane bagasse makes the most sense. Other biomass sources could also be feasible and cost-effective depending on the location of conversion facilities. In terms of the fiber compositions of the raw material sources, those with inherently lower lignin, ash, and hemicellulose contents will be easier to convert with lower energy and chemical requirements. Planted crops such as hemp bast and switchgrass have relatively low ash and lignin contents, making conversion of these biomass types more efficient. Of the higher-availability biomasses, soybean straw and sugarcane bagasse have lower average lignin and ash contents.

4. Conversion technologies

Although the conversion of non-wood biomass into textile-grade fibers is not well represented in literature, a thorough review of scientific publications, patents, and reports has been completed herein to evaluate several different conversion pathways. These are detailed in the following sections.

4.1. Conventional technique *(*dissolving pulp*)*

Dissolving grade pulp contains mostly α-cellulose (upwards of 90 %), with less than 10 % hemicelluloses, lignin, extractives, and minerals (Li et al., 2012). Compared to paper-grade pulps, dissolving pulp is typically brighter and has a more uniform distribution of molecular weights (Li et al., 2012). There are three main cellulose sources for producing dissolving pulp 1) woody biomass, 2) non-woods, and 3) recycled cellulose; nevertheless, the common industrial sources are wood and cotton. For over a century, manufacturers have been converting fine short fibers from woody biomass into fine long filaments for non-wovens and textiles (Andrade and Colodette, 2014; Batalha et al., 2011; Pennells et al., 2020). The process of creating dissolving pulp is composed of several different unit operations. Initially, wood chips are cooked and passed through a defibrating process to transform these chips into pulp, then this pulp goes to a washing and bleaching stage, and finally, once dried, it is cut and packed into sheets (Fig. 6) (Chen et al., 2016). The quality of the produced dissolving pulp can be enhanced by chemical, mechanical, or enzymatic treatments, either alone or in combination (Chen et al., 2016).

Feedstocks can be pulped by a variety of processes and conditions to achieve suitable dissolving pulp (Fig. 7). To make usable fiber from the pulp, this dissolving pulp must be of a certain quality in terms of high α-cellulose content and degree of polymerization (DP), low levels of ash and metal ions, and good solubility properties. Prehydrolysis kraft (PHK) and acid sulfite pulping methods are typically used to make dissolving pulp that meets the requirements (Jiang et al., 2020). Wood-derived celluloses, accounting for about 85 %–88 % of the total dissolving pulp market, are made by these processes with additional purification stages such as hot or cold caustic extraction (Sixta, 2006). Other methods include bisulfite, SO_2-ethanol-water (SEW), and Methanol or Ethanol Organosolv (Ma et al., 2018; Vera et al., 2023b). The main objective of pulping is to remove hemicellulose and achieve the highest α-cellulose content without causing excess cellulose deterioration. Lignin content should be minimized, and pulp yield maximized. Batch digesters are typically used for dissolving pulp cooking, but continuous processes could also be used (CNBM, 2021).

Prehydrolysis kraft: Prehydrolysis Kraft (PHK) is responsible for 56 % of global dissolving pulp capacity and 78 % in China alone (Jiang et al., 2020). This process is adaptable to various raw materials and can control the degree of polymerization (DP) and viscosity well, especially compared to acid sulfite (Jiang et al., 2020). The PHK combines acidic and alkaline process (Li et al., 2012). The acidic phase is the prehydrolysis portion, in which most of the hemicelluloses and some lignin are removed from the chips, and the alkaline phase is the kraft cooking process, in which most lignin is removed, along with more hemicellulose and a small fraction of cellulose (Chen et al., 2016). Multi-stage bleaching is usually implemented to remove residual lignin (Chen et al., 2016). Kraft pulp without acid prehydrolysis is not sufficient for dissolving pulp purposes. This pulp is not used for viscose or acetate processes due to poor reactivity (Rydholm, 1965). Limitations of the PHK process include potential lignin condensation, which negatively impacts delignification potential, and xylan enrichment at the surface of the fibers, which impairs properties (Rydholm, 1965; Sixta, 2006). Xylan enrichment can be decreased by gradually intensifying prehydrolysis conditions while keeping kraft cooking constant (Sixta, 2006).

Acid sulfite: Acid sulfite pulping is another common method used to manufacture dissolving pulp for MMCFs. This pulping is typically sodium, potassium, calcium, magnesium, or ammonia-based, and in this process, hemicellulose, lignin, and other residues are dissolved from the chips into the sulfite liquor (Linero, 1977). This liquor can then be used to make various by-products (ethanol,

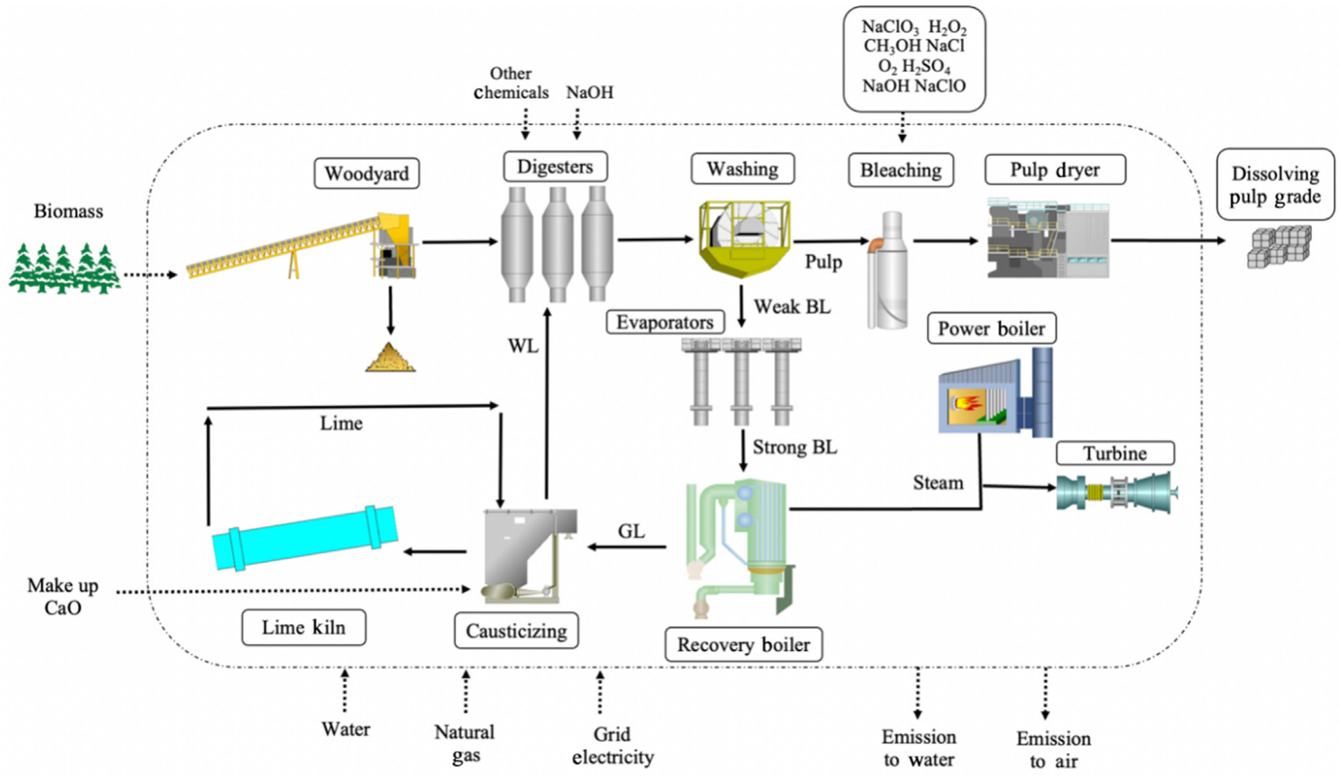

Fig. 6. Dissolving pulp operations schematic (kraft).

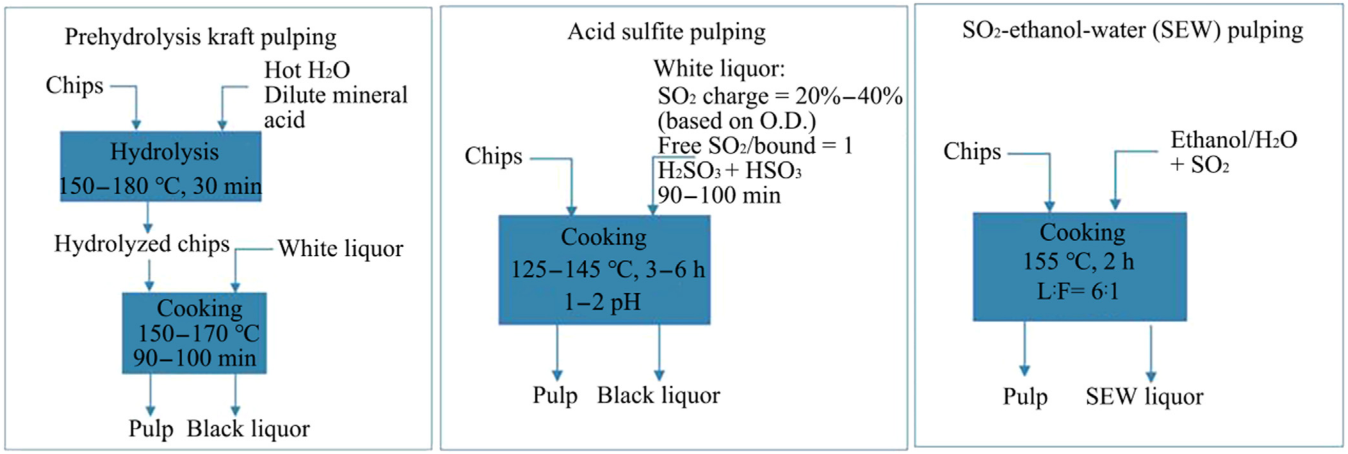

Fig. 7. Common pulping processes for dissolving pulp (Behin et al., 2008; Sixta et al., 2013; Sklavounos, 2014; Duan et al., 2015; Wei et al., 2020).

xylitol, lignosulfonates, and vanillin) (Chen et al., 2016). The stock can be converted into dissolving pulp after purification steps, such as hot or cold alkali extraction and bleaching (Chen et al., 2016). Acid sulfite pulps are easy to bleach and have low lignin and hemicellulose contents, making them suitable for regeneration. There are variations of the sulfite cooking process using different bases and two-stage sulfite cooking, in which a soluble base is used in the initial stage to help avoid precipitation and is followed by the acidic stage (Rydholm, 1965). This method results in a very similar pulp to single-stage acid sulfite cooking if the pH of the initial stage remains below six (Rydholm, 1965). For this two-stage process, sodium and ammonium bases are common, though sodium has generally given better results (Rydholm, 1965). Magnesium is occasionally used as a base, and calcium is also a possible base for the second acid stage (Rydholm, 1965). Changing the temperature and charge of liquor is useful for finding the optimum pulping condition (Sixta, 2006). Higher pHs yield more carbohydrates and better fiberizing, but more hemicellulose in bisulfite and acid sulfite pulps will decrease strength (Rydholm, 1965). During the final stage of acid sulfite cooking, some reduction in molecular weight occurs as the cellulose and hemicelluloses begin to degrade. This degradation mostly occurs in the amorphous region and can affect crystallinity (Sixta, 2006). Additional pre- or post-treatments may be used to improve the properties of the dissolving pulp to make it more suitable for MMCF conversion. The acid sulfite process requires more raw material demand than PHK and is unsuitable for woody material with a higher phenolic content because this prevents delignification (Li et al., 2012; Chen et al., 2016).

SEW: The SO_2-ethanol-water (SEW) is a pulping process that combines elements of acid sulfite and organosolv (Sklavounos, 2014). During this process, SO_2 dissolves, and lignosulfonic acid is formed, resulting in acidic conditions (Huang et al., 2019). This method can more easily fractionate biomass into its major components of cellulose, hemicellulose, and lignin and is suitable for both woody and non-woody raw materials (Huang et al., 2019). Hemicelluloses are hydrolyzed in the acidic treatment, and the pure sugars can then be recovered and used in applications such as biofuels (Sklavounos, 2014). Lignin undergoes a dissolution process after being sulfonated with SO_2. The benefit of incorporating ethanol in this treatment is the increased liquor penetration into the biomass (Sklavounos, 2014). Compared to traditional pulping methods, this method uses lower temperatures and does not require a base in its liquor, yielding overall lower energy requirements, decreased capital costs, and simpler chemical recovery (Sklavounos, 2014).

4.1.1. Dissolving pulp pretreatment

Often, the production of dissolving pulp requires pretreatment steps to make the subsequent pulping more effective by improving reactivity, removing a fraction of the impurities, and aiding in cellulose accessibility. Pretreatments may be even more important for non-woods due to typically higher levels of impurities in the biomass. Combined enzymatic treatment and additional pulp refining can increase pulp reactivity (Mamon Sarkar et al., 2021). Enzymes are beneficial because they typically yield high performance, innately have a high selectivity on substrates, and are mostly non-toxic compared to chemical reagents, making enzymatic pretreatment a good option for decreasing environmental impacts (Li et al., 2012). Time, temperature, and pH are all important parameters in enzymatic treatment that affect cellulose reactivity and accessibility (Li et al., 2012). Specifically for non-woods, alkaline pretreatment has been used to remove silica before pulping bamboo for dissolving pulp (Yuan et al., 2017). In this case, the silica and dissolved lignin, hemicellulose, and cellulose in the liquor were recovered and used for high-value biobased fuel and chemicals (Yuan et al., 2017).

4.1.2. Dissolving pulp post-treatment

Post-treatments are often used in dissolving pulp production to improve brightness and further delignify the pulp, to tune viscosity or molecular weight distributions of the pulp, and to prepare the pulp for future dissolution or chemical treatment when it is converted to a MMCF. When using alternative fiber sources, especially those with higher impurity and hemicellulose contents, post-treatments can enhance final product properties to better match those of conventional biomass sources.

Bleaching has an important role in dissolving pulp production, increasing sample brightness and improving purity, viscosity, reactivity, and molecular weight distribution (MWD). Typically, bleaching is done by combinations of oxygen delignification, chlorine dioxide delignification, and hypochlorite and hydrogen peroxide bleaching (Behin et al., 2008; Liu et al., 2016). Caustic extraction (cold or hot) is often used in dissolving pulp production to improve final product properties by removing short-chain carbohydrates not removed during pulping (Sixta, 2006). This type of treatment often precedes or is part of the bleaching stage and is very common in acid sulfite cooking. An increase in NaOH concentration yields a decrease in hemicellulose content and improves R18, a measure of alkali resistance (Sixta, 2006). The MgO has been suggested as an alternative alkali source to NaOH for caustic extraction because it tends to be more selective than the common method (Sixta, 2006). However, this method requires higher temperatures for purification than the conventional method. Other post-treatments include acid treatment to dissolve alkali-resistant hemicellulose and metal cations, fractionation to further improve brightness, remove fines, and increase mechanical strength, enzyme treatment to improve the accessibility of the cellulosic fiber due to swelling, and mechanical treatment to open the fiber wall structure and in turn increase the specific surface area (Reddy and Yang, 2007; Behin et al., 2008; Sixta et al., 2013; Wang and Chen, 2013; Reddy and Yang, 2014; Tian et al., 2014; Chen et al., 2016; Costa et al., 2016; Liu et al., 2016; Qi et al., 2017).

4.1.3. Dissolving pulp conversion to fiber

After biomass has been converted to dissolving pulp, it is typically used to make regenerated cellulose for various cellulose-derived products (Fig. 8), primarily MMCFs and cellulose derivatives (Sixta, 2006; Jiang et al., 2020). Dissolving pulps are often categorized as low, medium, or high quality, depending on their α-cellulose contents (90 %–93 %, 94 %–95 %, > 96 %, respectively) (Andrade and Colodette, 2014; Liu et al., 2016). High-level pulps are generally used for cellulose acetate, cellulose nitrate, high-viscosity cellulose ethers, or other specialty materials, while low to medium-level pulps are used for textiles and cellophanes (Andrade and Colodette, 2014; Liu et al., 2016). Textile fiber applications from MMCFs comprise 80 % of the dissolving pulp use, including clothing, apparel, home textiles, and non-wovens (Cavanagh, 2021). Hi-alpha products, coming from cellulose ethers and

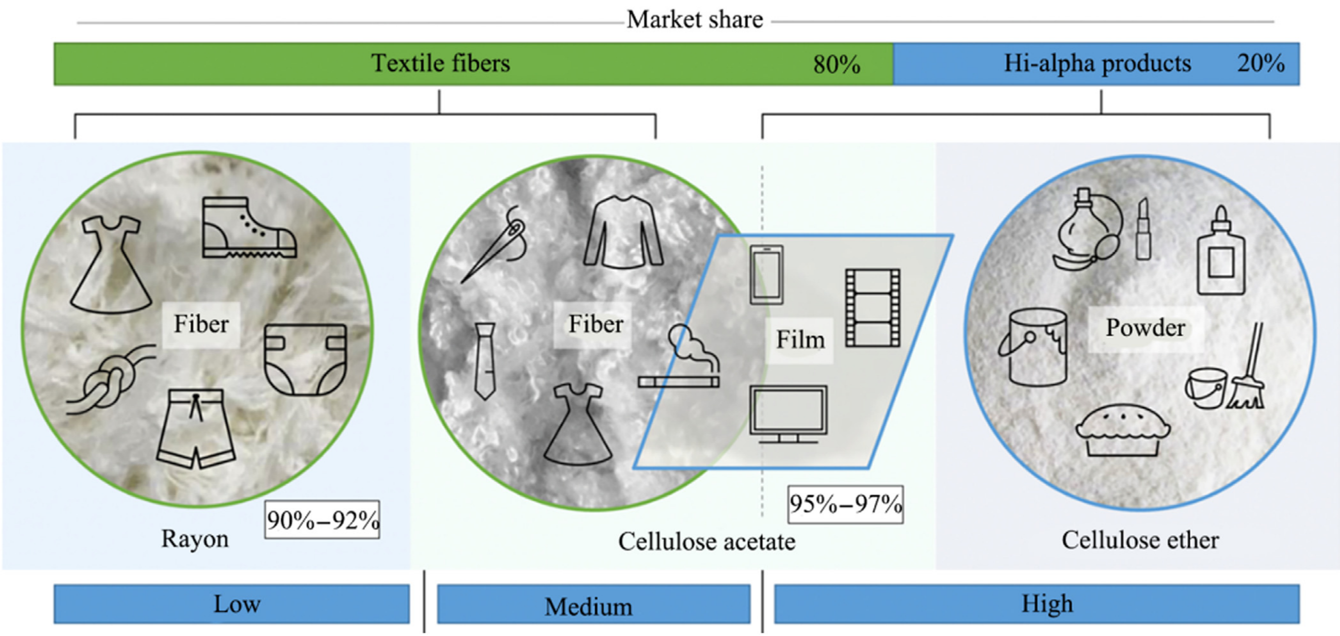

Fig. 8. A schematic of dissolving pulp grades in the market. Depending on the final application of dissolving pulp, the α-cellulose requirement changes.

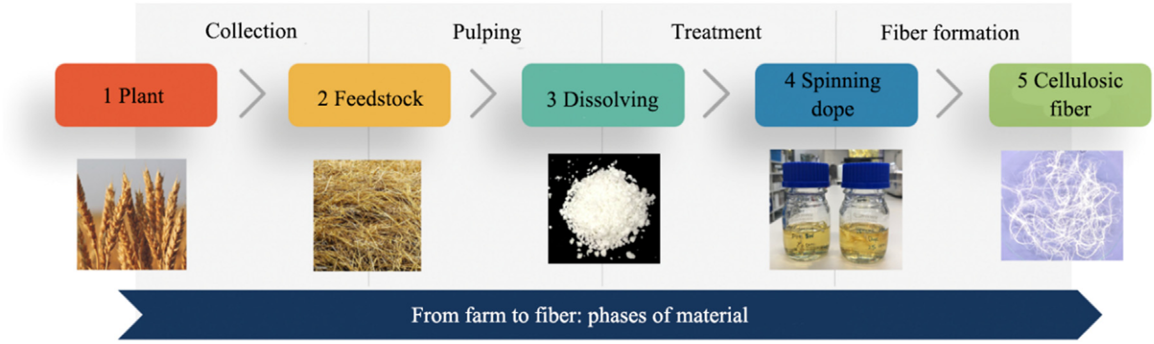

Fig. 9. Conversion of non-wood biomass to man-made cellulose fiber (MMCF).

acetate derivatized from dissolving pulp, make up the last 20% of dissolving pulp use and include additives, paints, oil services, and cigarette filters, to name a few (CNBM, 2021).

Regenerated cellulose fibers are then made using this dissolving-grade pulp (Win Win Textiles, 2018). This secondary conversion usually involves either dissolution or derivatization methods in which the native cellulose structure, Cellulose I, is converted into Cellulose II. For MMCFs, the material is then spun into a filament and cut into staple fiber length. A summary of the biomass to MMCF conversion process is visualized in Fig. 9. The MMCFs include all variations of rayon: viscose, modal (a specific high wet-modulus viscose), lyocell, carbamate, cuprammonium, and polynosic (higher modulus and strength viscose) (Li et al., 2018). Aside from cellulose acetate, which is dry spun or, in some cases, can be melt spun, solution spinning is most commonly used to spin regenerated cellulose filaments. Cellulose in its native form is not thermoplastic, so it cannot be directly melt-extruded into a filament without degrading at elevated temperatures. Regenerated cellulose is synthetic or man-made by process, but the cellulose raw material comes from natural sources, so the properties of regenerated cellulose more closely resemble natural fibers (cotton, flax, hemp) than synthetics (nylon, polyester) (Win Win Textiles, 2018). The details of the transformation of an intermediary converted biomass to a regenerated cellulose filament are out of the scope of this article. Still, they are critical to understanding the larger picture of this work.

4.1.4. Dissolving pulp testing

Once dissolving pulp is obtained from the chosen pulping process, it must be characterized to determine if it can be converted into cellulose-based products. Besides typical pulp tests such as yield and kappa number, tests include α-cellulose, hemicellulose, ash content, DP, viscosity, solubility, and brightness, among others. Brightness is measured by ISO 2471-1 standard to determine the whiteness of the samples. Kappa number is measured by TAPPI T236 cm-85 as an indication of the degree of delignification of the pulp, and α-cellulose content is determined by ASTM D588-42 and represents the content of pure cellulose remaining in the pulp. Viscosity and DP are determined by ISO 5351:2010 (Moşulică et al., 2018) to evaluate polymer chain length distributions and to indicate fiber degradation due to pulp treatments and TAPPI method T234 cm-84 measures alkali solubility to provide further information regarding the retention or loss of hemicellulose after pulp treatments (Vallejos et al., 2016). Chemical compositional analysis to determine structural carbohydrates, lignin, and ash content is measured using the National Renewable Energy Laboratory's (NREL) procedure (Sluiter et al., 2010).

The biomass after pulping must produce a dissolving pulp that generally fulfills the following conditions: high α-cellulose content (> 90 %–92 %), low content of hemicellulose (< 4 %), low lignin content (~0.05 %), low extractive (< 0.2 %), high brightness (> 90 % ISO), DP between 500 and 800, narrow MWD, intrinsic viscosity between 400 and 600 cm^3/g, relatively high reactivity (~50 %–60 % fock reactivity, expressed as cellulose reacted) (Tian et al., 2013; Andrade and Colodette, 2014; Win Win Textiles, 2018; Hertzberg, 2019; Huang et al., 2019). Specifically for rayon-grade dissolving pulp, the minimum requirements based on SNI-14-0398-1989 are as follows: α-cellulose, 90.5 %; S18, 6.50 %; S10, 10.0 %; extractive, 0.30 %; ash, 0.15 %; viscosity, 18 mPa·s; brightness, 90 GE (Wawan Kartiwa Haroen Dan Nyoman Wistara, 2008). Note that these property requirements may change slightly depending on the dissolution or derivatization technology used to convert this dissolving pulp into regenerated cellulose fibers. Acetate-grade pulps will have higher brightness and α-cellulose content requirements and harsher minimum allowable hemicellulose, lignin, and extractive contents. A catalog of specified requirements by process type is summarized in Table 4.

4.1.5. Non-wood dissolving pulp production

More recently, a new type of dissolving pulp has emerged, one made from unconventional feedstocks, including entire lignocellulosic biomasses instead of highly selective materials. Dissolving-grade pulps made from non-wood biomass sources are summarized in Table 5 and visualized in Fig. 10. Due to the excellent properties achieved in most of these studies, most of these pulps would be appropriate quality for subsequent conversion into textile-grade fibers.

4.1.6. Non-wood dissolving pulp summary and analysis

Note that although these dissolving pulps were made targeting rayon or acetate-grade fibers, they may not all be suitable for spinning into textile fibers. Most of the literature studied and reported does not detail fiber spinning trials following dissolving pulp

Table 4
A summary of dissolving pulp property requirements for various MMCF conversion processes.

Conversion Process	Min. α-cellulose (%)	Max. hemi-cellulose (%)	Min. DP	Max. ash (%)	Refs.
Acetate	95	1.5	250	0.07	Hertzberg, 2019; Rasooly-Garmaroody et al., 2022
Cupram-monium	95	0.20	2 000		Woodings, 2003; Park et al., 2013
NaOH/Urea	95		350		Valta and Sivonen, 2003; Chen et al., 2007; Reddy and Yang, 2014; Yang et al., 2017; Fu et al., 2018
Carbamate	92		270		Valta and Sivonen, 2003; Jiang et al., 2011; Wei et al., 2020
Lyocell NMMO	92	2.5	400	0.10	Jiang et al., 2011; Biswas et al., 2021
Ioncell Ionic Liquids	90	8.0	400	0.10	Sixta et al., 2013; Yang et al., 2020; Moriam et al., 2021; Vocht et al., 2021
Viscose	90	3.0	450		Valta and Sivonen, 2003; Batalha et al., 2011; Biswas et al., 2021
LiCl/DMAc			400		Biswas et al., 2021

Notes: ordered from the highest to the lowest α-cellulose required. Blank values have not been well-specified in references. DP: degree of polymerization.

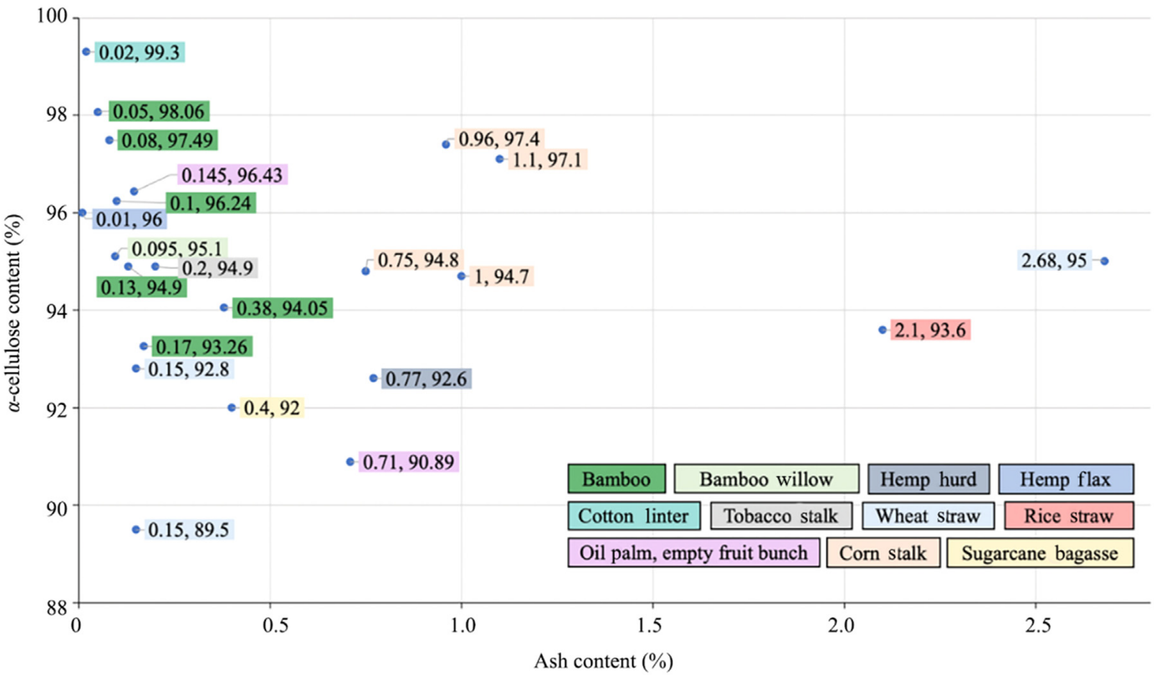

Fig. 10. Dissolving pulp α-cellulose and ash contents achieved by various alternative feedstock and pulping combinations (globally).

processing. Properties such as viscosity and ash content will be most critical to spinning success. In addition, to sustain the fashion industry, the dissolving pulp must fit current operations for MMCF viscose, lyocell, and acetate.

According to the literature, dissolving pulps have been converted from the following non-wood feedstocks available in the US: corn stalk, wheat straw, sugarcane bagasse, hemp, tobacco stalk, rice straw, and cotton linters (Table 5). The US-based alternative feedstocks and process combinations with the best results based on the combination of the lowest ash contents, high α-cellulose content, and a DP in the optimal range for rayon-grade dissolving pulp include 1) hemp flax by aqueous sulfuric acids, 2) tobacco stalk by SEW pulping, 3) corn stalk by kraft pulping, 4) wheat straw by NaOH/soda AQ pulping, and 5) sugarcane bagasse by soda pulping. All these scenarios reported α-cellulose contents at or above 92 % and ash contents of 1 % or less. Although some publications did not specify the dissolving pulp's DP, most combinations with > 92 % α-cellulose and < 1 % ash are in the acceptable dissolving pulp

Table 5
Summary of existing literature on pulping processes and conditions used to make dissolving pulp from US-based alternative non-wood sources and properties achieved, by target product.

Raw material	Pretreatment, pulping method, post-treatment	Result		Refs.
Target product: rayon-grade pulp				
Corn stalk	Prehydrolysis (H_2O, 150 °C, 1 h) KOH pulping (150 °C, 2 h, 14 % KOH) D_0(EP)D_1 bleaching, cold KOH extraction (24 % KOH)	Yield: 35.1 % α-cellulose: 90.4 % Kappa: 8.80 Brightness: 79.7 % ISO	Viscosity: 7.37 cP S_{10}: 12.3 %; S_{18}: 10.5 % Fock reactivity: 59.3	Mamon Sarkar et al., 2021
Wheat straw	H_2O, acid prehydrolysis (150 °C, 1 h) KOH pulping (150 °C, 2 h, 14 % KOH) D_0(EP)D_1 bleaching, cold KOH extraction (24 % KOH)	Yield: 34.5 % α-cellulose: 91.2 % Kappa: 4.50 Brightness: 82.1 % ISO	Viscosity: 5.74 cP S_{10}: 12.3 %; S_{18}: 7.03 % Fock reactivity: 66.2	Mamon Sarkar et al., 2021
Rice straw	H_2O, acid prehydrolysis (150 °C, 1 h) KOH pulping (150 °C, 2 h, 14 % KOH) D_0(EP)D_1 bleaching, cold KOH extraction (24 % KOH)	Yield: 32.4 % α-cellulose: 90.9 % Kappa: 5.70 Brightness: 85.4 % ISO	Viscosity: 6.25 cP S_{10}: 15.1 %; S_{18}: 13.6 % Fock reactivity: 61.6	Mamon Sarkar et al., 2021
Hemp hurd	No pretreatment Aqueous caustic soda pulping (160 °C, 1 h, 24 % NaOH) H_2O_2 + NaClO bleaching, (55 °C, 2 h each)	α-cellulose: 97.8 % DP: 670		Paulitz et al., 2017
Target product: cellulose derivates (acetate, nitrate, CMC, etc.)				
Wheat straw	Prehydrolysis Kraft (165 °C, 2.5 h, active alkali at 16 % Na_2O)	Yield: 28.4 % α-cellulose: 95.0 %	DP: 1950 Ash: 2.68	Abdul-Karim et al., 1994
Hemp hurd	Prehydrolysis Kraft (170 °C, 3 h, active alkali at 14 % Na_2O)	Yield: 42.4 % α-cellulose: 92.6 %	DP: 560 Ash: 0.77 %	Abdul-Karim et al., 1994
Hemp flax	Hydrolysis Aqueous sulfuric acid (80 min, 200 °C), boiling by 10 %–19 % NaOH (120–180 °C, 80–100 min) Alkali refining (60 °C, 20 min) + H_2O_2 bleaching	α-cellulose: ≥ 96.0 % DP: 800–1 000	Ash: ≤ 0.01 % Brightness: ≥ 80.0 %	Yunnan Reascend Tobacco Technology Group Co. Ltd., 2009
Cotton linters	Acid Prehydrolysis (H_2SO_4 0.1 %, 100 °C, 4 h) Soda pulping (1 % NaOH, 0.1 % AQ, 100 °C for 2 h) Cold alkali refining (15 % NaOH, 20 °C, 1 h)	Yield: ~86.1 % α-cellulose: 99.3 % Brightness: 92.0 % ISO	DP: 820 Ash: 0.02 % Reactivity (in-sol cellulose): 36.6 %	Abd and El-Ghany, 2010; Sugesty et al., 2015
Target product: not specified				
Corn stalk	Steam explosion, mechanical carding fractionation Kraft (160 °C, 1 h, 20 % NaOH, 25 % sulphidity) Totally chlorine free (TCF) bleaching, cool alkali extraction, xylanase treatment	Yield:10.1 %–12.4 % Brightness: 78.7 %–82.3 % ISO α-cellulose: 93.1 %–97.1 %	Hemicellulose: 8.30 % Ash: 1.10 % Viscosity: 14.4–24.0 cP	Wang and Chen, 2013
Corn stalk	Prehydrolysis (H_2O, 160 °C, 0.5 h) Kraft (170 °C, 1.5 h, 20 % NaOH, 25 % sulphidity) HEH (ClO^- + NaOH extraction + ClO^-) + HEHP (ClO^- + NaOH extraction + ClO^- + H_2O_2) bleaching	Yield: 43.5 %–51.8 % α-cellulose: 94.7 % Ash: 1.00 %	DP: 269 Kappa: 38.9–59.0	Behin et al., 2008
Corn stalk	Prehydrolysis (H_2O, 160 °C, 0.5 h) Kraft (170 °C, 1.5 h, 20 % NaOH, 25 % sulphidity) HEH + HEHP bleaching	Yield: 45.5 % α-cellulose: 94.8 %	Ash: 0.75 % DP: 279	Behin et al., 2008
Corn stalk	No pretreatment Pulping with waste water of Merox unit HEH + HEHP bleaching	Yield: 47.3 % α-cellulose: 97.4 %	Ash: 0.96 % DP: 241	Behin and Zeyghami, 2009
Sugar-cane bagasse	Prehydrolysis (H_2O, 180 °C, 15 min) Soda (180 °C, 80 min, 12.5 %–15 % NaOH) O-D-(EP)-D-P bleaching	Yield: 35.1 %–33.8 % Kappa:16.9–9.20 Brightness: 88.1 %–88.5 % ISO α-cellulose: ~92.0 %	Hemicellulose: ~5.00 % Ash: ~0.40 % Viscosity: 295–270 dm^3/kg	Andrade and Colodette, 2014

(continued on next page)

Table 5 (*continued*)

Raw material	Pretreatment, pulping method, post-treatment	Result		Refs.
Sugar-cane bagasse	Prehydrolysis (H_2SO_4 1.5 %, 120 °C, 1.5hr) Soda (165 °C, 2 h, 25 % NaOH, 0.05 % anthraquinone (AQ)) Four stages of chlorine-based bleaching	Yield: 32.8 % Kappa: 6.20 α-cellulose: > 95.0 %	Ash: < 0.15 % DP: 780	Ibrahim et al., 1996
Sugar-cane bagasse	Prehydrolysis (H_2SO_4 6 %, 100 °C, 6 h) Soda (100 °C, 6 h, 12 % NaOH) Multistage bleaching	Yield: 38.5 % α-cellulose: 95.0 % Brightness: 88.0 % ISO Hemicellulose: 4.50 %	DP:1 000 Crystallinity: 71.0 % Reactivity (in-sol cellulose): 68.0 %	Abou-State et al., 1979
Wheat straw	Strong prehydrolysis NaOH/AQ (soda-anthraquinone) pulping Bleached by CEH (chlorination + extraction + hypo oxygen enzyme)	Yield: 21,0 % α-cellulose: 92.8 % DP: 775	Ash: 0.15 % Brightness: 87.0 % Reactivity (in-sol cellulose): 41.8 %	Abou-State et al., 1979; Abou-State et al., 1988
Wheat straw	Mild prehydrolysis NaOH/AQ (soda-anthraquinone) pulping Bleached by CEH	Yield: 24.0 % α-cellulose: 89.5 % DP: 1 070	Ash: 0.15 % Brightness: 87.0 % Reactivity (in-sol cellulose): 58.0 %	Abou-State et al., 1979; Abou-State et al., 1988
Rice straw	No pretreatment Acetic acid/formic acid/ H_2O mixture (40/50/10) at boiling temperature 4 h Alkaline extraction (8 %, 90 °C), DED (ClO_2 + alkaline extraction + ClO_2) bleaching	Yield: 29.6 %, before bleach Kappa: 12.5, before bleach α-cellulose: 93.6 %	Viscosity: 10.6 cP Ash: 2.10 % Brightness: 80.0 % S_{10}: 6.49 %; S_{18}: 5.13 %	Jahan et al., 2015
Tobacco stalk	No pretreatment SO_2-ethanol-H_2O fractionation (6 % SO_2 charge at 135 °C, 3 h) Alkali extraction (1 % NaOH), $OD_0(E_p)D_1P$ bleaching	Yield: 24.4 % Brightness: 88.1 % ISO α-cellulose: 94.8 % Viscosity: 15.8 cP	Kappa number: 56.8 Hemicellulose: 4.40 % Ash: 0.20 %	Huang et al., 2019

Note: Any viscosity measurements in mPa·s were converted to cP (1 cP = 1 mPa·s).

range for subsequent conversion to MMCFs by fiber spinning. Generally, the DP target should be 400 or higher, but the minimum DP for spinning has been reported at 200–220 (Iqbal and Ahmad, 2011). Note that cotton linter is not considered an emerging alternative feedstock; it is used as a benchmark to compare other non-wood biomasses.

4.2. Emerging techniques *(*fibrillation/suspension, recycled cellulose*)*

As described in Section 4.1.3, the pulp is typically dissolved or derivatized with chemicals to regenerate it into a fiber. However, recently there has been increased interest in skipping the dissolution step entirely when making a fiber. Not only would this be more efficient in terms of time and cost, but it would also decrease environmental burdens associated with the chemicals in dissolution. Further, when using alternative biomass sources with different inherent properties and compositions, unconventional methods of conversion should be considered in addition to typical methods.

4.2.1. Fibrillated cellulose

One possible emerging biomass conversion method is cellulose fibrillation, in which a slurry is formed that can then be transformed into various products. Depending on the degree of fibrillation, the properties and applications may change.

Nanocellulose has been gaining interest over the last 20 years. Most of this interest is in paper, packaging, and composite applications, but some work has also been done in apparel applications (Gröndahl et al., 2021). It has been reported that spinning cellulose nanofibrils into textile filaments is a way for individual fibrils to reach their theoretical maximum mechanical performance (Reyes et al., 2022). However, commercialization of these nanocellulose applications will not happen until industrial-scale nanocellulose production is optimized (Gröndahl et al., 2021).

Besides renewability, cellulose nanofibers (CNFs) are advantageous in that they tend to have exceptional mechanical and strength properties due to high degrees of crystallinity and high aspect ratios (Besbes et al., 2011). There are several ways to produce nanofibrillated cellulose, but the simplest method is creating a fiber suspension of 1 %–2 % (*w*) concentration and mechanically fibrillating this dilute slurry. Different types of equipment can be used for this mechanical treatment: homogenizers, grinders, supermass colloiders, ultrasound sonicators, and fluidizers, among others (Kajanto et al., 2015). During refining, the cellulosic material is subjected to high shear forces, and this mechanical abrasion causes the fiber wall structure to loosen so that fibrils can separate from the fiber (Kajanto et al., 2015). Compared to conventional pulps, CNF dispersions become gel-like in nature after the refining process (Kajanto et al., 2015). Multiple passes through the equipment are required to increase the level of fibrillation (and decrease particle size)

(Besbes et al., 2011). Note that nanoscale is not the only possible size for this type of conversion. Micro-scale fibrillation has also been done, but the term micro-fibrillated cellulose (MFC) is often used as a synonym for CNF, even though the micro-scale is specific to the mm-length scale (Gröndahl et al., 2021). Both MFCs and CNFs have high aspect ratios, but the diameters of CNFs are generally below 200 nm and can be as small as 2 nm (Kajanto et al., 2015).

Perhaps another reason for the lack of commercialization is that grinding up good quality, long, woody fibers for nanocellulose applications is not viewed as a productive use of a resource that already has a function (Gröndahl et al., 2021). Therefore, a solution may be to use agricultural residues, industrial wastes, or recycled materials instead of virgin wood for nanocellulose applications. Using these alternative materials would be beneficial from both economic and environmental standpoints.

(1) Fibrillated cellulose pretreatment

Recently, improvements have been made in the pretreatment stage of fibrillated cellulose processing, and this has resulted in a decrease in the energy required in the grinding stage. This makes processing more cost-effective and decreases environmental burdens (Gröndahl et al., 2021). Typically, the first step of pretreatment is a purification of the cellulosic raw material. This purification usually involves cooking and bleaching steps, which help remove hemicellulose, lignin, and other impurities or extractives in the raw material (Gröndahl et al., 2021). It also often includes alkalization to aid in subsequent fibrillation and sometimes includes a depolymerization step (Owonubi et al., 2021).

Chemical or enzymatic pretreatments are not required to produce fibrillated cellulose; however, they improve the fibers' cohesion and flexibility, making the final mixture more homogeneous. These improvements also reduce the energy required in the following grinding step. Three major mechanisms occur upon applying a pretreatment (chemical or enzymatic). The first and most common is the application of a repulsive charge, another is the limitation of hydrogen bonds, and the third is a reduction of the degree of polymerization of the material (de Souza Fonseca et al., 2019). Oxidation is generally used as a pretreatment to improve the ensuing fibrillation process. It allows fewer passes through the grinding equipment and uses less energy overall. Enzymatic treatment has also been used, as it aids in fibrillation and avoids additional degradation (Besbes et al., 2011). Other pretreatments include physical treatments such as cryo-crushing or ultrasonication (Besbes et al., 2011). It has been found that the more crystalline the starting material, the more difficult fibrillation becomes. Highly crystalline samples may require additional passes in the refining equipment (Besbes et al., 2011).

TEMPO-oxidation: The TEMPO-oxidation is a common pretreatment for CNFs (de Souza Fonseca et al., 2019). TEMPO ((2,2,6,6-Tetramethylpiperidin-1-yl)oxyl) oxidizes the cellulose, creating anionic fibrils that have been used to make materials with high optical transparency (Reyes et al., 2022). The yield from this pretreatment process is typically above 90 % (Besbes et al., 2011). Further, for textile applications, it has been found that TEMPO has improved the orientation of the fibrils during the wet-spinning process due to the higher aspect ratio and charge of the fibrils. The fibrils, in turn, become more entangled, creating stronger filaments (Lundahl et al., 2017).

Carboxymethylation: Another method of pretreatment is carboxymethylation, in which fibrils achieve surface charges lower than TEMPO-oxidized fibrils but higher than unmodified fibrils (Lundahl et al., 2017). This method forms carboxyl groups on nanofibril surfaces, which adds to the anionic charge, making defibrillation easier (de Souza Fonseca et al., 2019). The strength and stiffness properties of the spun filaments are then heightened compared to the untreated filaments but are not as great as those from TEMPO-oxidized fibrils (Lundahl et al., 2017).

Acid hydrolysis: Acid hydrolysis is a common pretreatment for cellulose nanocrystals (CNCs), but this is not a typical method for CNFs or MFCs. Since CNCs will not likely be used for making textile filaments, this method would not be as highly recommended for fibrillated cellulose pretreatment.

Enzymatic Treatment: Another method of pretreatment uses the cellulase enzyme to treat lignocellulosic pulp before fibrillation (Kajanto et al., 2015). The exocellulase activity from the enzymatic treatment causes the cell wall of the fiber to open, allowing easier fibrillation. Additional pretreatments are not required with this method as long as the starting slurry has a consistency of at least 10 %. This higher consistency also decreases the total amount of water used in processing.

(2) Fibrillated cellulose conversion to fiber

After the biomass has been converted into a slurry, this intermediary material must be further transformed into a regenerated filament for textile application. Fibrillated cellulose conversion is typically quite simple and direct, unlike dissolving pulp conversion to fiber, which requires dissolution or derivatization methods. Fibrillation of the fibers during refining along with pretreatments helps to align the cellulose chains without dissolving the cellulose or transforming its structure. The transformation of an intermediary converted biomass (pulp or slurry) to a regenerated cellulose filament is out of the scope of this article.

(3) Fibrillated cellulose testing and analysis

There are several ways to analyze the resulting fibrils to determine their quality and properties. The X-ray diffraction can be used to determine the crystallinity of the cellulose nanofibrils (Besbes et al., 2011). A field emission scanning electron microscope (FE-SEM) can be used to determine the widths of the fibrils, ensuring either nano or micro-scale achievement by fibrillation (Besbes et al., 2011). Transmission electron microscopy (TEM) or Atomic Force Microscopy (AFM) is often used to explore fibril morphology (Mohammadi et al., 2017). This characterization could include measurements of fibril diameters, which may be helpful in the determination of suitable applications (de Souza Fonseca et al., 2019). Viscosity may also be assessed to determine the level of fibrillation and spinnability. Raman spectroscopy can be useful for evaluating the chemical composition of the materials (Besbes et al., 2011). Fourier transform infrared spectroscopy (FT-IR) can be applied to evaluate the crystal structure before and after treatments (Tao et al., 2019). Depending on pretreatment, the fibrillated cellulose may also be analyzed by additional methods, such as conductometric titration to determine carboxylic content or thermogravimetric analysis (TGA) to evaluate changes in thermal stability due to treatments (Tao et al., 2019).

(4) Fibrillated cellulose from non-woods

Several articles highlight the great opportunity of adopting lignocellulosic biomass as a raw material source for nanocellulose production due to availability, cost, and expected environmental benefits (Gröndahl et al., 2021). The major concern of using non-woods is the great variation of compositions among sources, so a single method of conversion may not be effective for all biomass types (Owonubi et al., 2021). This research pathway is still very new, but there is some published work on nano-fibrillated lignocellulosics to guide researchers. Table 6 summarizes the various non-wood biomass sources that have been used for fibrillated cellulose (CNF or MFC). Some non-woods have also been used to create CNCs, but as this work focuses on conversion for textile applications, only nano- and micro-fibrillated celluloses will be included. Some published articles demonstrate fibrillated cellulose conversion from food waste, but due to challenges in waste collection and generally lower availability of this waste, the authors have focused on agricultural residues and planted crops as feedstocks.

(5) Fibrillated cellulose summary and analysis

Based on these studies, it is clear that a variety of lignocellulosic biomasses can be successfully converted to nano- or micro-fibrillated cellulose, and several different chemical and mechanical treatments can be used for this conversion. Most biomass sources produced fibrillated cellulose with small fiber diameters and relatively high crystallinities. Some of the best results (in terms of high crystallinity and minimized fiber width) were achieved with flax, hemp, and sugarcane bagasse. Common fibrillation methods include ultrasonic processors, high-pressure homogenizers, supermass colloiders, and microfluidizers. Biomass pretreatment varies more but generally includes an alkali step followed by bleaching. Additional treatments for fiber alignment were also often applied in several of these studies, including TEMPO-mediated oxidation, acid hydrolysis, and enzyme treatments. Overall, the cellulosic source does not significantly impact the major processing steps for nanocellulose production (Gröndahl et al., 2021), making fibrillated cellulose conversion advantageous if commercialized. However, biomass sources with lower lignin contents allow for more efficient energy use and lower chemical requirements during processing because other fiber elements can be more easily accessed (Gröndahl et al., 2021). This low lignin content, of course, is advantageous from both environmental and economic standpoints. Due to lower lignin contents and successful conversion evident in literature, the authors suggest the following feedstocks for lower energy fibrillated cellulosic conversion: hemp bast, wheat straw, rice straw, and corn stover.

4.2.2. Recycled fiber

Recycled paper: A few studies and patents have converted recycled paper, board, or paper residue from mills into textile fibers. Most of these studies convert cellulosic waste into dissolving pulp for subsequent conversion into textile fibers. Unlike recycling wastepaper for new paper production, in which repeatedly shortened fibers reach a limit for reuse, textile fiber production is not sensitive to fiber length shortening and is more dependent on the degree of polymerization (Ma et al., 2016). Recycled paper can be treated like wood pulps and can be converted to a pulp that can be dissolved or derivatized. However, prior to this step, the recycled material must be refined, pulped, or treated with other purifying methods. One study that converted fine paper and cardboard waste to textile fibers included a refining step to remove inorganics and fines, pulping for lignin removal, cold caustic extraction, and bleaching (Ma et al., 2016). To prepare the pulp for subsequent dissolution, enzyme treatment, and acid washing were used to improve the viscosity and remove any metal residuals (Ma et al., 2016). Table 7 outlines published work on recycled paper and board conversion.

Recycled textiles: Although there are still several challenges to large-scale textile recycling, regulations in this area are imminent, and many companies have already responded to the movement towards circularity by creating technologies to convert post-consumer apparel waste back into a usable starting material for textile manufacturing (Bettenhausen et al., 2022). Methods for conversion vary depending on the starting textile and its fiber composition, dyes, finishes, or additives. However, the general method for converting textile waste into new fibers includes collecting waste, removing zippers, buttons, and coloring, then chemical or enzymatic treatment to separate cellulose and polyester components (Bettenhausen et al., 2022). Once separated and purified, the cellulosic portion of the waste can be regenerated as new filaments through dissolution or derivatization methods. The synthetic portion is typically depolymerized, then purified, and finally repolymerized to make new pellets that can be melt-extruded into new textile filaments (Bettenhausen et al., 2022). Textile waste can include pre-consumer waste, such as waste from fiber spinning and manufacturing, post-consumer waste, and post-industrial waste, such as leftover fabric (Kamble and Behera, 2021). Reusing textile waste is not limited to the re-manufacturing of MMCFs, but can also include ethanol, biogas, glucose production, nanocellulose production for composites, and papermaking (Kamble and Behera, 2021). Major recycling methods include chemical and mechanical processes (Roos et al., 2019). Published work related to converting waste textiles into new raw materials for MMCFs is summarized in Table 7.

Although most studies have mechanically or chemically treated the starting material before spinning to ensure low contents of impurities, lignin, ash, etc., there are also a few cases where lignocellulosic raw materials have been directly dissolved as entire biomasses and spun into fibers (Sun et al., 2011).

5. Opportunities and challenges

Major challenges for converting non-woods to MMCFs include production costs, storage of non-woods (being annual crops rather than perennial woody materials), complex assessment of sustainability, and ability to spin suitable fibers due to specific processes and purity requirements. However, if these feedstocks and conversion methods can show overall cost reduction, decreased environmental impact, or ability to convert impurity-containing biomasses, then these challenges become opportunities.

Table 6
Summary of existing literature on processes and conditions used to make fibrillated cellulose from alternative non-wood sources and properties achieved.

Purification of biomass and pretreatment	Mechanical treatment	Width (nm)	CI (%)	Refs.
Wood				
Dewaxed, alkaline (KOH) treatment, bleaching with acidified $NaClO_2$	Ultrasonic processor	10–20	71.0	Chen et al., 2011
[hardwood] Kraft pulping, bleaching (OZADP)	Supermass colloider	13 ± 8	79	de Souza Fonseca et al., 2019
[softwood] Kraft pulping, bleaching	Supermass colloider	20 ± 9		de Souza Fonseca et al., 2019
Rice				
Toluene and ethanol, alkali, H_2O_2 bleaching, $(NH_4)_2S_2O_8$ treatment	Ultrasonic processor	14	41.3	Oun and Rhim, 2018
Soda pulping, $NaClO_2$/acetic acid bleaching	Supermass colloider, high pressure homogenizer	3–21		Hassan et al., 2012
NaOH-Na_2SO_4, NaClO bleaching, papirindustriens forskningsinstitut (PFI) refining	Supermass colloider	41–169	49	Adel et al., 2016
[hulls] Alkaline (NaOH) treatment, $C_2H_4O_3$ and H_2O_2 bleaching, acid hydrolysis at mild temperature	Ultra-sonication	< 100	70	Nascimento et al., 2016
Sugarcane bagasse				
Kraft pulping, bleaching	Supermass colloider, high pressure homogenizer	5–22		Hassan et al., 2012
NaOH-Na_2SO_4, NaClO bleaching, PFI refining	Supermass colloider	33–127	55	Adel et al., 2016
Bleaching, Citric acid hydrolysis	Ultra-sonication	30–60	60–65	Ji et al., 2019
Caustic soda pulping, xylanase, cold alkali (NaOH) pretreatment	Ultra-micro grinding, high pressure homogenization	15–30	53–55	Nie et al., 2018
Alkaline (NaOH) treatment, H_2O_2 bleaching, acid hydrolysis with sulfuric acid	Ultra-sonication	4	87.5	de Morais Teixeira et al., 2011
Steam explosion, dilute alkali-catalyzed hydrothermal treatment with NaOH, bleaching with H_2O_2	Ultra-sonication	20–40	71.2	Feng et al., 2018
Corn				
[stalk] Organosolv pulping, PFI refining, TEMPO-mediated oxidation	Homogenizer	6		Balea et al., 2016
[stover] Alkali (NaOH) treatment, delignification with NaCl + acetic acid	High pressure homogenization	5–50		Xu et al., 2018
[stalk] acidic lactic acid–choline chloride and alkaline K_2CO_3-glycerol DESs	Ultra-turrax mixer, microfluidizer	4–6	42-52	Suopajärvi et al., 2020
Hemp				
Bleaching, TEMPO-oxidation (5–15 mmol/g)	High pressure homogenizer	8–21		Serra-Parareda et al., 2021
Alkaline (NaOH) pulping, $NaClO_2$ bleaching, TEMPO-mediated oxidation	High pressure homogenizer	23	86	Alila et al., 2013
Alkali treatment with NaOH, bleaching (DEAP), Acid hydrolysis (HCl), cryo-crushing in liquid N_2	High pressure defibrillation	30–50	71.2	Wang et al., 2007
Cooked in 16 %–17 % NaOH at 165 C, 1–2 h, $NaClO_2$ bleaching, TEMPO-mediated oxidation	High pressure homogenizer	20–40	78	Chaker et al., 2013
NaOH + HCl, refined in beater, cellulase enzyme	Ultrafine friction grinder	5–12	80	Dalle Vacche et al., 2021
Wheat straw				
Soda pulping in NaOH, PFI beating	Supermass colloider	22		Espinosa et al., 2019
Soda pulping in NaOH, PFI beating, enzymatic treatment-endoglucanase	Twin-screw extruder	15		Espinosa et al., 2019
Soda pulping in NaOH, PFI beating	High pressure homogenizer	13		Espinosa et al., 2019
Acidic lactic acid–choline chloride and alkaline K_2CO_3-glycerol deep eutectic solvents (DES)	Ultra-turrax mixer, microfluidizer	4–6	38–54	Suopajärvi et al., 2020
Soda-AQ pulping, bleached by elemental chlorine free (ECF) process, alkaline extraction with NaOH, TEMPO-mediated oxidation	Homogenizer	30	56	Djafari Petroudy et al., 2018
Soda (NaOH) pulping, $NaClO_2$ bleaching, PFI refining	High pressure homogenizer	19		Espinosa et al., 2020
Soda (NaOH) pulping, $NaClO_2$ bleaching, PFI refining	Twin-screw extruder	44		Espinosa et al., 2020
Soda (NaOH) pulping, $NaClO_2$ bleaching, PFI refining	Ultrafine friction grinder	30		Espinosa et al., 2020
High-speed rotor mill/grinder, alkaline (NaOH) treatment, acid hydrolysis (HCl), NaOH soak, TEMPO-mediated oxidation	Micro-fluidizer high shear processor	6		Sinclair et al., 2018
Dewaxed, alkaline (KOH) treatment, bleaching with acidified $NaClO_2$	Ultrasonic processor	15–35	63.4	Chen et al., 2011
Soybean hull				

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Table 6 (*continued*)

Purification of biomass and pretreatment	Mechanical treatment	Width (nm)	CI (%)	Refs.
Wood				
High-speed rotor mill/grinder, akaline treatment with NaOH, acid hydrolysis (HCl), NaOH soak, TEMPO-mediated oxidation	Micro-fluidizer high shear processor	5		Sinclair et al., 2018
Flax				
Cooked in 16 %–17 % NaOH at 165 °C, 1–2 h, $NaClO_2$ bleaching, TEMPO-mediated oxidation	High pressure homogenizer	50–100	78	Chaker et al., 2013
Alkaline (NaOH) pulping, $NaClO_2$ bleaching, TEMPO-mediated oxidation	High pressure homogenizer	22	84	Alila et al., 2013
Dewaxed, alkaline treatment with KOH, bleaching with acidified $NaClO_2$	Ultrasonic processor	15–100	81.6	Chen et al., 2011
Cotton stalks				
NaOH-Na_2SO_4, NaClO bleaching, PFI refining	Supermass colloider	50–119	58	Adel et al., 2016
Tobacco stem/stalk				
Steam explosion, NaClO bleaching	Supermass colloider	20–70	63.8	Tuzzin et al., 2016
Ammonium sulfite cooking, formic acid hydrolysis, H_2O_2 bleaching	Homogenized in N,N-Dimethylacetamide (DMAc)	5–50	45–51	Wang et al., 2018

Notes: CI, crystallinity index. Average values or ranges of values reported for fibril widths and crystallinities.

5.1. Techno-economic feasibility

Costs come from raw material costs, capital costs, chemical costs, production rates, and inventory and storage spaces (Köpcke, 2010). Other challenges include insufficient data on non-wood facilities and trials and lower yields. Additional workers are necessary for dissolving pulp manufacturing, adding to labor costs. Techno-economic evaluation, which evaluates capital investment, manufacturing costs, financial returns, and scalability, is a helpful way to estimate a technology's or process's feasibility should be applied (de Assis et al., 2017; Abbati de Assis et al., 2019).

The techno-economic feasibility of MMCF conversion is highly influenced by fiber sourcing, the pulping method, the method used for cellulose regeneration, and the transportation and distances between pulping and spinning operations. The techno-economics could be positively impacted by an integrated bio-refinery concept, in which the refinery used to pulp the non-wood biomasses could also produce value-added products, which would improve process efficiency, economics, and sustainability (Mongkhonsiri et al., 2018). An integrated biorefinery design for producing dissolving-grade pulp from non-woods has been proposed by Mamon Sarkar et al. (2021) and describes the utilization of both silica and organic biomass in a variety of bio-based products (Mamon Sarkar et al., 2021). In order to ensure a sustainable and cost-effective process, the spent cooking liquor from pulping must be dealt with effectively, such as by applying it as a fertilizer. The spent liquor from the potassium hydroxide pulping system has useful components, such as organics and potassium. Spent ammonium sulfite liquor can provide valuable soil nutrients in the form of nitrogen and sulfur for agriculture (Drown et al., 1997). Additionally, lignin-rich black liquor containing phosphorus and potassium has been cited as useful in agricultural processes (Jahan et al., 2021). Fuel or chemicals can be chemically converted from leftover carbohydrate sugars from the process, and other valuable materials can be manufactured from lignin by-products (Mamon Sarkar et al., 2021).

5.2. Assessment of sustainability

Another challenging yet critical part of new fiber and process innovation is sustainability assessment. Since sustainability is one of the major drivers of alternative feedstock adoption, these alternatives must be compared to commercial benchmarks in terms of emissions. Sustainability assessments are complex by nature, especially for alternative feedstocks. Evaluations should include production, supply chain, and conversion processes related to each feedstock and impacts on soil and land use. From an environmental standpoint, a major advantage of adopting natural-based MMCFs is displacing a portion of the synthetic market. Two major organizations set standards for sustainable forest management and offer certification: Program for the Endorsement of Forest Certification (PEFC) and Forest Stewardship Council (FSC) (Win Win Textiles, 2018). Canopy Audits have been leading the assessment of MMCF suppliers' raw material sourcing practices to protect ancient and endangered forests (Win Win Textiles, 2018). These assessments will be critical to certain alternative biomass sources' commercial success or failure.

It is difficult to compare how utilizing different non-wood raw materials for MMCFs affects their sustainability. The integration of such fiber types into textile manufacturing is relatively new, and changing one process step (for example making a viscose fiber in a mill in Asia for one raw material and a viscose fiber in a mill in Austria for another) can largely affect the final fiber's impact. The complexity further increases, as the harvesting, pulping, spinning, and production processes will likely differ for each raw material type, depending on inherent fiber structure, chemical composition, cleaning requirements, etc. To fairly compare the different fibers, the mill locations, equipment and operations, spinning methods, among other variables, must be maintained as constant as possible (while still adapted to the specific biomass) to understand the true impact of changing raw material sources. Very few studies have evaluated the sustainability of non-wood sources, and even fewer have evaluated their impact for applications in man-made cellulosics. That being said, one LCA study has been conducted in an attempt to evaluate the global warming potential of using different raw

Table 7
Work published converting recycled waste material (paper, board, textiles) into new raw material for MMCFs.

Raw material	Conversion treatment	Intended application	Properties/Results	Refs.
Recycled paper				
Old corrugated containers (OCC)	Soda cooking (150 °C, 2 h, 12 % NaOH), hypochlorite bleaching, acid treatment	Dissolving pulp	Yield: 78 %, α-cellulose: 70 %, lignin 0.3 %, hemicellulose: 7.76 %, reactivity (fock): 85.7 %, DP: 913.4, CI: 76.95 %, brightness: 72.9 %	Ghahrani et al., 2022
OCC	Formic acid (90 %, 3.5 h), alkaline extraction (90 °C, 8 % NaOH), $D_0E_pD_1E_pD_2$ bleaching	Dissolving pulp	α-cellulose: 94.7 %, brightness: 85.4 %, pentosan: 3.2 %, R10: 89.2 %, R18: 94.2 %, viscosity: 3 mPa·s, reactivity (fock): 60.2 %, ash: 0.46 %	Jahan et al., 2016
White ledger paper	Cold alkali extraction (8 % NaOH) 1 h (~20 °C), xylanase (200 U/g) treatment ~60 °C, 2nd cold alkali extraction (10 % NaOH, ~20 °C)	Dissolving pulp	Hemicellulose: 2.1 %, viscosity: 11.6 cP, R10: 99.3 %, S18: 0.8 %, yield: 81.6 %	Jackson et al., 2001
Envelope clippings	Cold alkali extraction (8 % NaOH) 1 h (~20 °C), xylanase (200 U/g) treatment ~60 °C, 2nd cold alkali extraction (10 % NaOH, ~20 °C)	Dissolving pulp	Hemicellulose: 2 %, viscosity: 8.7 cP, R10: 99.3 %, S18: 0.8 %, yield: 78.9 %	Jackson et al., 2001
Recycled wastepaper, deinked fine paper	Deinking, super DDJ filtration, cold caustic extraction, DEpD bleaching, Enzymatic treatment with endoglucanase, acid wash	Dissolving pulp for MMCFs	Brightness: 87.1 %, Kappa: 0.9, viscosity: 510 mL/g, ash: 0.04 %, R18: 93.9 %, reactivity (fock): 62.9 %, xylan: 4.8 %, lignin: 0.2 %, extractives: 0.08 %	Asikainen et al., 2014
Recycled wastepaper, cardboard	Super DDJ filtration, alkaline soda cooking (20 % NaOH, 165 °C), oxygen delignification, cold caustic extraction, DEpD bleaching, acid wash	Dissolving pulp for MMCFs	Brightness: 85.9 %, Kappa: 0.6, viscosity: 250 mL/g, ash: 0.11 %, R18: 90.7 %, reactivity (fock): 81.1 %, xylan: 4.2 %, lignin: 0.6 %, extractives: < 0.05 %	Asikainen et al., 2014
Recycled fine paper	Super DDJ, cold caustic extraction, endoglucanase enzyme treatment and acid wash	MMCFs for textiles	Viscosity: 428 mL/g (intrinsic), cellulose: 88.1 %, hemicellulose: 11.3 %, lignin: 0.6 %	Ma et al., 2016
Recycled cardboard	Super DDJ, selective kraft (160 °C, 190 min), cold caustic extraction, DEpDP bleaching, endoglucanase enzyme treatment and acid wash	MMCFs for textiles	Viscosity: 460 mL/g (intrinsic), cellulose: 89.1 %, hemicellulose: 10 %, lignin: 0.9 %	Ma et al., 2016
Recycled textiles				
Poly/Cotton Waste 66/34	200 mg/g cellusoft L (50 °C, 9 h); mechanical agitation	Textile fiber	80 % insoluble microfibrils	Kamble and Behera, 2021
Orange Poly/Cotton Waste 50/50	85 % N-methyl-morpholine-N-oxide (NMMO), (120 °C, 2 h)	Textile fiber	95 % cellulose	Kamble and Behera, 2021
Poly/Cotton waste	H_2SO_4 (95 °C, 60 s); mechanical beating (0.25–4 h, 20 °C)	Textile fiber	Satisfactory separation	Kamble and Behera, 2021
Waste jeans	85 % phosphoric acid (50 °C, 7 h)	Textile fiber	100 % PET; 79.2 % glucose	Kamble and Behera, 2021
Poly/Cotton waste 65/35	[Hmim] H_2SO_4 (100 °C, 12 h), acetylation	Textile fiber	49.3 % cellulose acetate; 96.2 % PET	Kamble and Behera, 2021
Poly/Cotton waste 50/50	50 % NMMO (120 °C, 3 h), carboxymethylation	Textile fiber	Satisfactory separation	Kamble and Behera, 2021
Blended yarns	AMiMCi (120 °C, 6 h)	Textile fiber	Satisfactory separation	Kamble and Behera, 2021
Poly/Cotton waste, white 40/60	12 % NaoH (−20 °C, 1 h); novozym 188 and celluclast 1.5 l (45 °C, 72 h)	Textile fiber	Satisfactory separation	Kamble and Behera, 2021
Poly/Cotton yarns, non-dyed 50/50	Separation (20 °C) heat–treatment 20 g/L MgCl2, 4 g/L Al2(so4)3, (180 °C)	Textile fiber	95 % cotton degraded	Kamble and Behera, 2021
Poly/Cotton waste	H_2SO_4 (50 °C, 0.5 h, 20–40 Hz)	Textile fiber	Satisfactory separation	Kamble and Behera, 2021
Waste jeans Poly/Cotton 40/60	Na2Co3 (150 °C, 2h)	Textile fiber	80.83 % cellulose, 10.5 % PET	Kamble and Behera, 2021
Poly/Cotton 35/65 waste	HCl Hydrothermal Method (150 °C, 3h)	Textile fiber	48.21 % cellulose, 96.24% PET, 15.57 % glucose	Kamble and Behera, 2021

(*continued on next page*)

Table 7 (*continued*)

Raw material Recycled paper	Conversion treatment	Intended application	Properties/Results	Refs.
Wool/polyester 45/55	2–10 KU/mL of protease (37 °C), reducing agent (sodium thioglycolate), 1,1,1,3,3,3-hexa fluoro-2-propanol (HFIP) for PET extraction	PET yarn	Satisfactory separation, wool degradation, ~100 % PET recovered	Navone et al., 2020
Cotton-PET blended textile waste, white	Alkaline wash, disk refining, ozone, hydrogen peroxide, acid wash, [DBNH][OAc] to dissolve cellulose, hydraulic pressure filtration and ionic liquid to separate polyester and residue	MMCFs	Satisfactory separation	Haslinger et al., 2019
Pulverized cotton from recycled T-shirts	Microfibrillation in Masuko Grinder (3 %, 1 500 r/min, 9 passes), freeze dried at –50 °C	MFC/ CNF for compos-ite fillers	Crystallinity: 77 %, specific surface area: 26.9 m^2/g, cellulose I structure, diameter: 10–100 nm, Td: 374.1 °C	Farahbakhsh et al., 2014; Farahbakhsh et al., 2015
Waste jeans	Textile dye leaching with HNO_3 at 50 °C 20 min, DMSO dissolution 7–9 h, bleaching with NaClO and HCl	Cotton fiber	~93 % recovery of material: 77 % cotton, 16.2 % polyester	Yousef et al., 2019
Jeans waste, polyester/ cotton	Milling, phosphoric acid (85 %, 50 °C, 7 h)	PET yarn	100 % polyester recovery, 79 % yield	Vera et al., 2023a
Polyester/Cotton 40/60 waste	Milling, 7 % NaOH, 12 % Urea, –20 °C, 1 h	PET yarn	98 % polyester recovery, 91 % yield	Vera et al., 2023a
Polyester/Cotton 20/80 waste	Freezing alkali (7 % NaOH)/Urea soak (–20 °C, 6 h)	PET yarn	100 % polyester recovery, 70.2 % yield	Vera et al., 2023a

Note: DDJ, dynamic drain jar.

material sources from different locations for making man-made staple fiber. Although this study mainly focuses on wood from different locations, a few non-woods are included as well. The results are summarized in Fig. 11 (Schultz and Suresh, 2017).

Fig. 11 shows the net results for global climate change, including warming and cooling impacts, forest carbon storage impacts, and carbon stored in the final product (Schultz and Suresh, 2017). The main takeaway from this study is that changing the sourcing and operating location along with the raw material type can greatly affect the results. However, the raw material choice is critical to determining the impact. The study was not able to conclude that a single raw material source was preferred across all impact categories; however, two of the evaluated scenarios (utilizing Belgian flax and German recycled pulp) were favorable for most impact categories, specifically in global climate change results (Schultz and Suresh, 2017). When specifically focused on non-woods in the study (recycled pulp, flax, cotton linter, and bamboo), in some cases these non-woods performed better in terms of global climate impact, but for other scenarios, certain wood from managed forests had a lower impact. This goes to show the importance of minimizing the impact of every step of the process, from raw material harvesting to fiber spinning. The region from which the raw material is sourced, the land-use practices and changes in this region, the supply chain operations, as well as technology at pulping and spinning mills can all create a great variability in impacts related to MMCF sourcing (Schultz and Suresh, 2017).

Despite the challenges associated with comparing the impact of textile fibers made from different non-wood raw material sources, it is clear that the impact of man-made cellulosics is on average below the impact of both synthetic fibers and cotton. This is evidenced in a study by Shen et al. (2010), results of which are summarized in Fig. 12 (Shen et al., 2010).

Despite the complexity of understanding and comparing the sustainability of these alternative fibers, there are several ways to improve the sustainability of textile processing. In a report prepared by Fashion for Climate "Identifying Low Carbon Sources of Man-Made Cellulosic Fibers", it was stated that replacing wood pulps with lower-carbon non-wood feedstocks such as agricultural or textile wastes would reduce greenhouse gas emissions of the final man-made cellulose fiber if clean energy is used in production and the operations are optimized and scaled (Suresh, 2022). Besides the raw material source, applying low-carbon production practices for manufacturing dissolving pulp can improve the overall sustainability. This may include utilizing energy-efficient biorefinery technology, optimizing and minimizing the chemicals in the bleaching stage of dissolving pulp production, and increasing pulp yields (Suresh, 2022). Specifically for non-wood sources since they may require slightly different conditions and processes than wood sources, it is a great opportunity for the design of innovative low-impact pulping technologies. Low-carbon practices should also be applied in the spinning mill to reduce emissions. These practices could include utilizing renewable electricity and heat and combining pulping and MMCF production lines into one integrated facility (so that pulping by-products such as black liquor may be used as a renewable energy source for spinning operations). High recovery of solvents in the spinning process in a closed-loop design is also critical for low-emission spinning operations (Suresh, 2022).

5.3. Purity requirements

One issue with agricultural residues is the higher contents of silica and fines, which impede the chemical recovery process during pulping (Mamon Sarkar et al., 2021). Extractives and resins such as acetone or dichloromethane can also affect dissolving pulp processing (Sixta, 2006). Resins can cause problems in the spinning and finishing processes, such as precipitation due to changes in

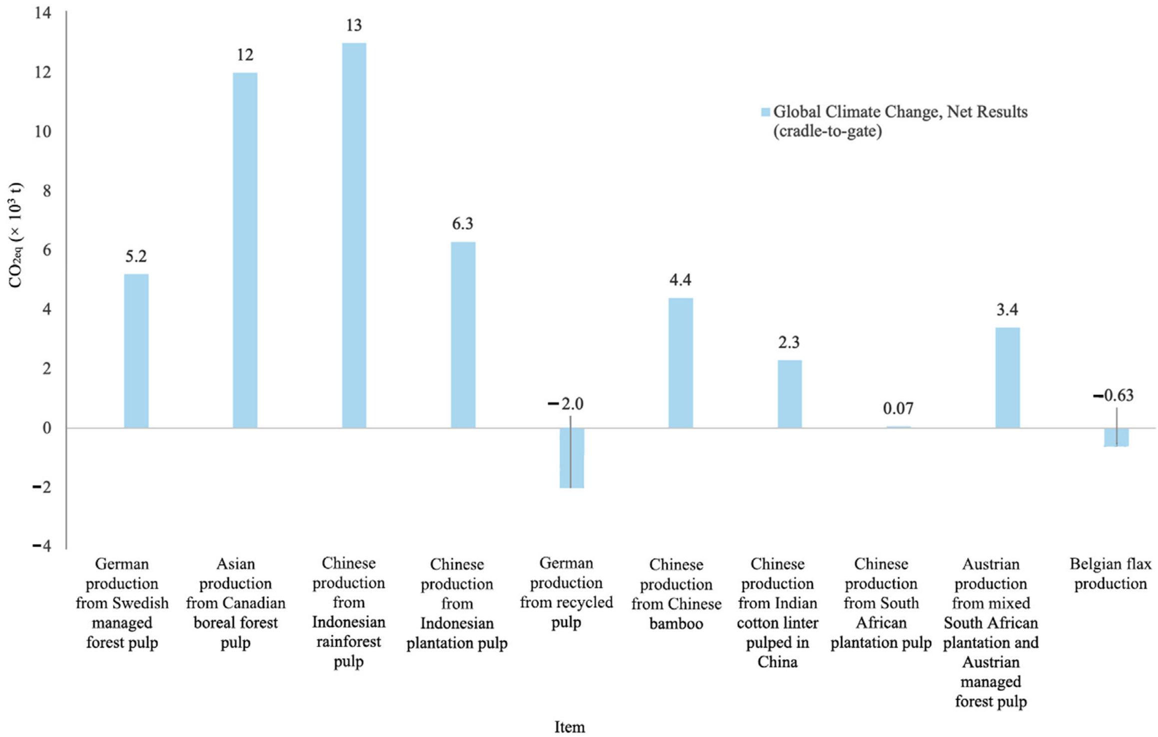

Fig. 11. Summary of life cycle analysis (LCA) results of net global climate change for 1 000 t of MMCF, by scenario, taken from the Scientific Certification Systems (SCS) Global Services report (Schultz and Suresh, 2017).

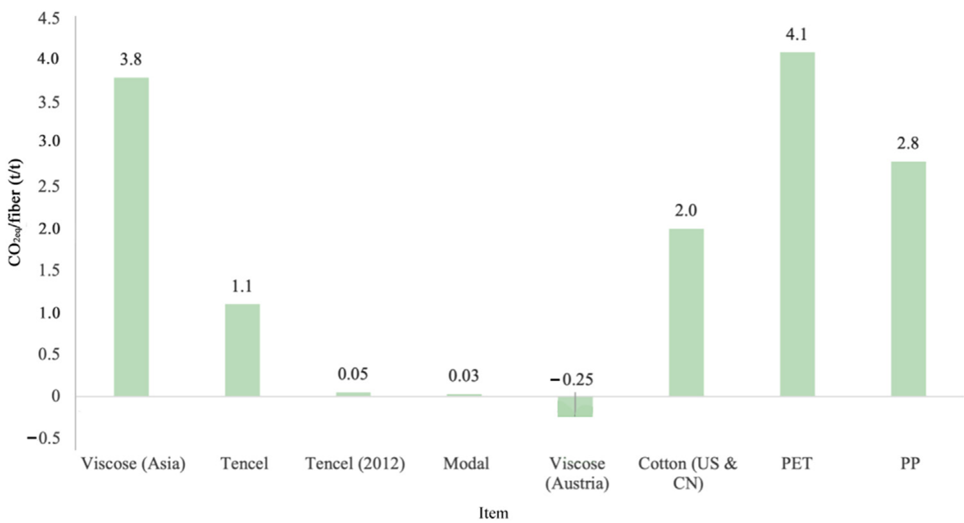

Fig. 12. Summary of net global warming potential of 1 tonne of staple fiber types (cradle-to-factory gate GWP 100a), taken from Shen et al. (2010).

pH, haze in dope, clogging of spinnerets, and yarn yellowing (Sixta, 2006). Inorganic compounds such as silicates, calcium salts, and catalytically active transition metal ions (Iron, Manganese, Cobalt) impair the filterability and spinnability of spinning dope, often leading to clogged spinnerets and altered fiber uniformity (Sixta, 2006). Catalytically active cations thus must be removed through an acid wash, chelating stage, etc. (Sixta, 2006). For fibrillated cellulose, the quality of the suspension and the final product properties will depend on the pretreatment, extraction, and fibrillation processes. These processes will be affected by the feedstock composition (especially the amounts of hemicellulose, lignin, or other impurities), the fiber morphology of the starting material, and the spinning parameters (Owonubi et al., 2021).

6. Conclusions

The use of alternative feedstocks will be based on local feedstock availability and processing infrastructure, as these feedstocks cannot be transported long distances. Residues widely available in North America, such as soybean straw, wheat straw, rice straw, sorghum stalk, and sugarcane bagasse, are most promising for dissolving pulp production for sustainable textiles in the US market. Based on limited non-wood pulping studies, the authors recommend further research on the production of dissolving pulp for these non-woods by PHK, soda, potassium hydroxide, acid sulfite, or SEW pulping. Before declaring the most sustainable options, the emissions of these feedstock and pulping combinations must be assessed.

In terms of emerging conversion technologies, several lignocellulosic feedstocks have been well-studied in the fibrillated cellulose field, although most of these studies were made with composite applications in mind. Still, it is evident that this technique can successfully convert lignocellulosic biomass. For North American implementation, based on availability, previous work, and easier fibrillation due to biomass purity, the most suitable feedstocks include wheat straw, rice residues, sugarcane bagasse, and soybean residues. Although most work in the field of fibrillated cellulose is related to paper, board, and composite applications, the authors see textile filaments as another application of these fibrillated celluloses due to the advantageous mechanical properties that can be achieved with this lower energy processing. Recycled materials are also a good cellulose source for MMCFs. Additional sustainability assessments are needed to truly determine the most impactful feedstock and conversion technology combinations. It will be critical to evaluate the environmental impact of both biomass sources and cultivation practices, transportation, and conversion technologies.

7. Future implications

Converting biomass into intermediary pulp or slurry is only half the journey; this material will then need to be successfully converted into regenerated cellulose fibers for future use in a textile application. There are many pathways for this second step, and optimization of technology and processes will be critical to the success or failure of these alternative feedstock sources; however, that research is out of the scope of this article. The authors intend to investigate and report on such a topic in the future. If successful on an industrial scale, this type of work can revolutionize the textile and agricultural industries and represent huge steps in environmental conservation.

Declaration of Competing Interest

The authors have no financial or personal competing interests to declare which could have influenced this manuscript.

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