Perspective

Cellulose Textiles from Hemp Biomass: Opportunities and Challenges

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Abstract: Worldwide demand for man-made cellulosic fibres (MMCF) are increasing as availability of cotton fibre declines due to climate change. Feedstock for MMCF include virgin wood, agricultural residues (e.g., straw), and pre- and post-consumer cellulosic materials high in alpha-cellulose content. Lyocell MMCF (L-MMCF) offer large advantages over other MMCF processes in terms of both environmental and social impacts: the solvent for cellulosic dissolution, n-methyl-morpholine-n-oxide, can be recycled, and the process utilizes non-toxic chemicals and low amounts of water. Hemp can be a preferential cellulosic feedstock for L-MMCF as hemp cultivation results in carbon dioxide sequestration, and it requires less water, fertilizers, pesticides, and herbicides than other L-MMCF feedstock crops. These factors contribute to hemp being an environmentally conscious crop. The increased legalization of industrial hemp cultivation, as well as recent lifts on cannabis restrictions worldwide, allows accessibility to local sources of cellulose for the L-MMCF process. In addition, hemp biomass can offer a much larger feedstock for L-MMCF production per annum than other cellulosic sources, such as eucalyptus trees and bamboo. This paper offers perspectives on the agricultural, manufacturing, and economic opportunities and challenges of utilizing hemp biomass for the manufacturing of L-MMCF.

Keywords: man-made cellulosic fibres; lyocell process; hemp biomass; environmental impact; regenerated cellulose fibres

1. Introduction

Worldwide fibre production has nearly quadrupled since 1970, leading to numerous environmental impacts including air and water pollution, textile waste and microplastic creation [1]. Of the over 100 millions tonnes of fibres produced annually, polyester—an energy intensive, petrochemical-based fibre—and cotton—a cultivated fibre requiring large volumes of water and chemical resources to grow—account for the greatest share of fibre volume at 54% and 22%, respectively [1–3]. Lyocell, a man-made cellulosic fibre (MMCF), is created by directly dissolving cellulose in n-methyl-morpholine-n-oxide (NMMO), a non-derivative, non-toxic solvent of which 99.5% can be recovered in the Lyocell MMCF (L-MMCF) process [4,5]. Feedstock for the L-MMCF process can come from any high alpha-cellulose-based material including wood, plants, and even pre- and post-consumer textiles (e.g., cotton garments). However, the use of virgin resources, such as eucalyptus trees or bamboo, as L-MMCF feedstock has been linked to deforestation [6–8]; farming methods can use large amounts of water, fertilizers, and herbicides, as well as lead to soil erosion [9]; and the use of pre- and post-consumer cellulosics can be challenging due to textile sorting, removal of dyes and finishing additives, having consistent feedstock, and reduction in fibre strength after regeneration [10]. Therefore, while the L-MMCF process is itself more sustainable, improvements can be made in terms of utilizing a more environmentally conscious source of feedstock to produce the L-MMCF dissolving pulp.
One such feedstock is hemp, which has been cultivated for textile applications for millennia. Hemp has a high alpha-cellulose content and offers higher cellulose yield than wood sources [11], which is ideal for the L-MMCF process. It also offers an alternative and potentially preferable source of cellulose for L-MMCF as it requires less water, fertilizers, pesticides, and herbicides to grow than other crops such as cotton. Hemp cultivation also aids in carbon dioxide (CO2) sequestration [12] and is considered carbon neutral [13], leading to regenerative agricultural practices [14]. Unfortunately, hemp cultivation and subsequent fibre usage is sparse in the current textile landscape. Prohibition, restrictions on growing cannabis, and a general stigma towards hemp have halted the sowing of this crop. However, the legalization of industrial hemp and cannabinoid cultivation on a global scale has allowed society to once again capitalize on this multi-purpose plant [3,15,16].

Currently, there are no North American (NA) sources of filament or staple L-MMCF despite growing demand for the fibre. It is estimated that global demand for L-MMCF will grow to a $2B industry by 2027 (745,900 tonne/year) [17] due to the vast consumer and commercial market applications of this high tenacity, absorbent, and biodegradable fibre [12]. On the other hand, NA hemp is a readily accessible commodity that is being farmed primarily for oil and seed applications. L-MMCF from residual hemp oilseed straw would assist in whole plant utilization, thus allowing the cultivation of industrial hemp for multiple purposes to be more economically sustainable. In addition, blending the properties of hemp bast and hurd at various ratios may alter the degree of polymerization and thus the properties of the extruded fibre based on desired end-use.

This article gives a critical look at the opportunities and challenges of MMCF, L-MMCF, and L-MMCF from hemp biomass as an alternative to cotton and other natural fibers. It considers different perspectives: environmental, agricultural, manufacturing, and economic. Additional research is also suggested to address the challenges with manufacturing L-MMCF from hemp biomass, as well as how manufacturers can take advantage of the opportunities it provides.

2. Environmental Challenges and MMCF

As of 2021, global textile consumption has risen to an average of 15 kg per capita, with petroleum-based synthetic fibres accounting for the largest segment of textile purchasing at 64% [18]. Consumption is estimated to further increase by 3% every year until 2030, with 70% utilized towards consumer textiles (e.g., clothing, household) due to their versatility and low market price [19,20]. Petroleum-based synthetic fibre usage leads to high emissions of greenhouse gas (GHG), bioaccumulation of microplastics, and contamination of water, amongst other detrimental environmental and social impacts [20]. At end-of-life stage, it is estimated that over 275 million metric tonnes of petroleum-based textiles were landfilled in 2010, with 4.8 to 12.7 million metric tonnes entering oceans [21]. These synthetic textiles are non-biodegradable and require hundreds to thousands of years before they begin to break down [22]; unfortunately, petroleum-based synthetic textile breakdown leads to further bioaccumulation of microplastics within aquatic and terrestrial habitats.

Due to the rising global population and enhanced awareness of “sustainable” natural cellulosic fibres, fibres such as cotton are increasing in demand [23]. However, cotton cannot be grown in northern climates, such as in Canada or the northern United States (US), and its cultivation is highly reliant on pesticides and large quantities of water [24], resulting in loss of arable land throughout the world. Haenmerle estimates that by 2030, the maximum cotton production, based on available arable land, will be approximately 26 million tonnes (Figure 1) [23]. This maximum available production will eventually decline as global arable landmass decreases by an estimated 0.8% to 4.4% due to climate change (e.g., increase in global temperatures, reduced water availability, frequent weather events, and increasing population) [25]. The per capita consumption of cellulosic fibres is estimated to increase from 3.7 kg to 5.4 kg in 2030 [23]. As the world population is expected to reach 8.5 billion by 2030 [26], this will result in a staggering cellulose fibre demand of 45.9 million tonnes. With cellulose fibre demands rising, it is estimated that this would lead to a 19 million tonne
cotton fibre deficit due to unavailability of arable land (i.e., considering that all available land for cotton cultivation is currently being used). Moreover, cotton cultivation consumes “11% of the world’s pesticides while it is grown on only 2.4% of the world’s arable land” [2].

The World Wildlife Foundation has stated that cotton cultivation results in soil erosion and degradation (e.g., loss of topsoil from conventional tillage), pollution (e.g., use of herbicides and pesticides), and water contamination (e.g., nitrate-contaminated leachate from fertilizers) [27]. Furthermore, with every centimeter of top soil erosion, cotton fibre yield reduces by approximately 4% [28]. While there are initiatives to reduce these environmental concerns, including cover crops, conservation tillage, and crop rotations to reduce soil erosion, as well as implementation of water conservation measures, cotton still requires extensive resources to cultivate and process into textiles [28,29]. 70% of the world’s consumption of water is used in the agricultural industry [30], with cotton requiring a large volume of water to grow, as well as process into end-use textiles. For instance, it takes nearly 2700 litres of water to produce one cotton t-shirt [31]. Considering that a t-shirt weighs approximately 150 g, this equates to 18,000 litres of water to produce 1 kg of cotton textile. In comparison, the water footprint of industrial hemp textiles is 2820 m³/ton (3108 L/kg) (Table 1) [32]. While this number is considerably lower than cotton, it is higher than the water footprint for MMCF since these fibres do not have to go through additional water processes (e.g., chemical retting, cottonization).

Table 1. Water footprint of various fibres (data from [32,33]).

<table>
<thead>
<tr>
<th>Staple Fibre</th>
<th>Water Footprint (L/kg)</th>
</tr>
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<tbody>
<tr>
<td>Polyester</td>
<td>84–143</td>
</tr>
<tr>
<td>Cotton</td>
<td>4342–6902</td>
</tr>
<tr>
<td>Hemp (bast)</td>
<td>3108</td>
</tr>
<tr>
<td>MMCF</td>
<td>351–520</td>
</tr>
<tr>
<td>L-MMCF</td>
<td>290</td>
</tr>
<tr>
<td>Hemp L-MMCF</td>
<td>&lt;290 (estimate)</td>
</tr>
</tbody>
</table>
In a life cycle assessment study on MMCF, Shen and Patel [33] determined that the water footprint for staple fibre production was between 84–143 L/kg for petroleum-based synthetics, between 351–520 L/kg for MMCF, 290 L/kg for L-MMCF, and between 4342 and 6902 L/kg for cotton (Table 1). These numbers indicate the opportunity for MMCF in the consumer-based cellulosics market as they have a water footprint that is less than 10% than that of cotton. Shen and Patel [33] noted that they did not include data for finished textile products as finishing processes vary considerably depending on the end product. As such, the water footprint would be higher when including additional processes such as bleaching, dyeing, and finishing. Finally, Shen and Patel [33] based their study on typical MMCF feedstock (i.e., wood and eucalyptus trees), which may require irrigation. The water footprint for L-MMCF from hemp would likely be lower than for L-MMCF from other sources as irrigation is not required for hemp cultivation (Table 1).

Increased natural fibre demand, in addition to an international shortage of cellulosic fibres for consumer and commercial demand (i.e., the Cellulose Gap [19,23], Figure 1), is encouraging manufacturers to seek alternatives to naturally cultivated cellulosic fibres. MMCF provide an alternative to natural cellulosic fibres, such as cotton and flax. Cellulosic feedstock for MMCF production is abundantly available, through agricultural crops, agricultural residues and wastes, pre- and post-consumer textiles, wood wastes, etc.

Unfortunately, manufacturing processes for some MMCF lead to additional environmental and social implications. A report published by Changing Markets in 2017 titled Dirty Fashion: How pollution in the global textiles supply chain is making viscose toxic, outlines the environmental and social impacts linked to viscose fibre production [34]. The report details how chemicals used in the production of viscose (Figure 2), such as carbon disulphide and hydrogen sulphide, have been linked to function impairment, neurological changes, and even death in factory workers. In addition, the viscose process uses large amounts of sodium hydroxide and sulphuric acid, which are considered highly toxic. The report further states that “20–30 g of carbon disulphide and 4–6 g of hydrogen sulphide are emitted” for every kilogram of viscose produced (p. 14). Furthermore, viscose fibre manufacturing leads to water and air pollution, and has been linked to acute aquatic toxicity, as well as increased cancer rates in individuals living in proximity to viscose manufacturing facilities.
Viscose MMCF is produced via a derivatizing process, where xanthate is formed (i.e., xanthation) by the reaction of cellulose with carbon disulphide \([5,8,35,36]\). The original cellulosic molecule is modified for the regeneration process, where the derivative chemicals are dissolved following regeneration \([5,36]\). These derivative waste chemicals end up entering waterways, air, and soil, leading to the environmental and social impacts mentioned above \([37]\). The viscose process is used to manufacture viscose rayon, cellulose acetate, modal, and triacetate MMCF. Cellulose sources for the viscose process include bamboo, wood, and cotton linters \([35]\).

Some sources of cellulose such as bamboo are considered more environmentally sustainable than others \([38]\). Bamboo is a rhizome that regenerates growth after harvest and does not require irrigation, pesticides, or herbicides for cultivation \([38,39]\). In addition, a bamboo rhizome stand can replenish every three to four years and can survive for many decades. While there are varieties of bamboo that grow in temperate climates, the majority of large scale bamboo cultivation is in tropical and warmer temperature climatic zones \([40,41]\), and whole plant utilization is not common. Moreover, while the use of feedstock such as bamboo in the viscose process creates sustainability from an agricultural perspective, all the other environmental and social implications from the viscose process still arise.

Direct dissolution is another process for producing MMCF, whereby cellulose is dissolved in an organic solvent, producing a dope solution without the formation of intermediate compounds \([5,8]\). Cuprammonium MMCF \([42]\) and lithium chloride/dimethylacetamide (LiCl/DMAc) \([43]\) are two examples of this process; unfortunately, both manufacturing processes do not provide any advantages over the viscose process regarding environmental or social impacts.

A third example of direct dissolution is the production of L-MMCF via dissolution in NMMO \([44]\), which was first developed in 1969 by Eastman Kodak and later commercialized by both Courtauld and Lenzing in the 1990’s. This process is sustainable, environmentally friendly, and socially responsible. L-MMCF is made by dissolution in the NMMO solvent, which is greater than 99% recoverable, making it a closed-loop system \([39,45]\). While the dissolution of cellulose in the L-MMCF process does take longer and is more expensive than the viscose process, exposure to toxic chemicals and development of toxic effluents are avoided \([4]\). The viscose MMCF process and L-MMCF process are illustrated side by side in Figure 3.

![Figure 3. The viscose MMCF and L-MMCF processes (reproduced from [46] with permission from Elsevier).](image-url)
The feedstock for L-MMCF has traditionally been beech and eucalyptus trees, which are fast growing and can be harvested using a technique called coppicing [47,48]. Coppicing involves leaving viable stumps for regeneration when the trees are cut down within a thicket, or copse [49]. Each copse is sectioned into coups, which are harvested on an annual rotation, allowing for complete regeneration of the first coups by the time the last coup is harvested. However, growing and harvesting eucalyptus trees consumes 3200 litres of water per tree; additionally, eucalyptus trees only grow in certain climatic regions [47]. Other cellulosic sources, including bamboo, kudzu, cereal crop agricultural residues (e.g., wheat and barley straw) and sugarcane bagasse [50–54], have been utilized as feedstock; however, all of these cellulosic sources have similar drawbacks. Agricultural crops, including sustainable tree farming, lead to deforestation, excess water consumption (i.e., irrigation), changes to ecological diversity (e.g., use of herbicides and pesticides), freshwater pollution, and soil erosion [9,55]. Bamboo stands in Amazonian forests have resulted in anthropogenically induced climate change [40]. Furthermore, these cellulose sources cannot be grown in a multitude of climatic regions. Table 2 outlines the advantages and drawbacks of the various MMCF manufacturing processes.

Table 2. Advantages and drawbacks of MMCF manufacturing processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
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<tbody>
<tr>
<td>Viscose MMCF (viscose rayon, cellulose acetate, modal, triacetate)</td>
<td>Derivitized. α-cellulose feedstock readily available.</td>
<td>Waste chemicals (e.g., carbon disulphide), leading to contamination of water, air, and soil, and health concerns.</td>
</tr>
<tr>
<td>L-MMCF</td>
<td>Direct Dissolution. Environmentally friendly (NMMO 99% recoverable), α-cellulose feedstock readily available.</td>
<td>More expensive to produce than viscose MMCF. Longer manufacturing process.</td>
</tr>
</tbody>
</table>

3. Hemp Biomass Feedstock for MMCF

An alternate cellulose source for L-MMCF is hemp. Two parts of the hemp plant may be utilized for fibre production—the bast (bark) and the hurd (shive) (Figure 4) [56]. In the fibre preparation stage, the bast fibre is separated from the hurd through decortication, scutching, or milling [45]. The process of retting then breaks down lignin (i.e., delignification) and pectin to facilitate further processing.

Both the bast fibres and the hurd may be further dissolved in the NMMO solvent or blended in various ratios, forming a dope solution. The dope solution would then be spun into filaments, which are drawn and washed, mechanically or chemically treated for various properties (e.g., reduction of fibrillation), and dried [46,57,58]. The Thuringian Institute for Textiles and Plastics Research (TITK) has demonstrated this novel use of hemp biomass in the development of Lyohemp® [59]. Using high alpha-cellulose pulps from hemp allows for production of high tenacity L-MMCF [44] that would be applicable for use in various applications such as industrial textiles and apparel (e.g., personal protective clothing), dental floss, healthcare products (e.g., disposable masks, gowns, cleaning wipes), airlaid and wetlaid nonwoven consumer products (e.g., disposable sanitary products, cleaning wipes), nonwoven industrial products (e.g., biodegradable geotextiles, carpet backings), and consumer apparel.

Furthermore, manipulating the bast to hurd blend ratios may alter the viscosity and degree of polymerization of the dissolving pulp, resulting in unique fibre properties for varying end-use applications [19,60]. Organoleptic, or sensory, properties such as comfort (e.g., cold/warm), hand (e.g., thin/thick, heavy/light), and texture (e.g., smooth, rough) [61], may be adjusted based on end-user requirements by varying the amount of bast and hurd within the pulp, resulting in unique fibre and yarn blends. Technical performance, such as tensile strength, abrasion resistance, elongation, moisture management, and antimicrobial properties, may also be adjusted depending on application. Hemp biomass offers a single plant cellulosic source for varying pulp viscosity, which is not possible from other plant feedstocks such as eucalyptus and beech trees or bamboo.

Research by the authors has determined the alpha-cellulose content of Canadian-grown hemp hurd and bast-bleached kraft pulps to be 83.3% and 96.2%, respectively. The whole plant stem has an alpha-cellulose content of 70%, with the bast at 55–72% and the hurd at 34–44% [62]. In contrast, eucalyptus sawdust has a cellulose content of 41.6% [63], and eucalyptus kraft pulp has an alpha-cellulose content of approximately 92% [64]. Furthermore, bamboo chips have a cellulose content of approximately 48% [65], with a kraft pulp alpha-cellulose content of approximately 90% [66]. These results suggest that hemp is a viable alternate cellulose source for L-MMCF production with a greater potential alpha-cellulosic yield than eucalyptus or bamboo. This higher alpha-cellulosic content allows for more versatility for altering the viscosity of the dope solution to potentially modify organoleptic properties and technical fibre performance. Table 3 summarizes the cellulosic content of various cellulosic feedstocks.

Table 3. Cellulosic content of various feedstocks (data from authors and [62–66]).

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Cellulosic Content (%)</th>
<th>Kraft Pulp, α-Cellulose (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemp stalk</td>
<td>70</td>
<td>n/a</td>
</tr>
<tr>
<td>Hemp hurd</td>
<td>34–44</td>
<td>83.3</td>
</tr>
<tr>
<td>Hemp bast</td>
<td>55–72</td>
<td>96.2</td>
</tr>
<tr>
<td>Eucalyptus</td>
<td>41.6</td>
<td>92</td>
</tr>
<tr>
<td>Bamboo</td>
<td>48</td>
<td>90</td>
</tr>
</tbody>
</table>

4. Agricultural Opportunities and Challenges

Industrial hemp in Canada and Europe is defined as a herbaceous cannabinoid annual plant containing a maximum of 0.3% delta-9-trans-tetrahydrocannabinol (THC) [67]. While hemp grows in many different climates, hemp flourishes in temperate climates, with growth rates proportional to the available daytime hours. Hemp can also be grown in tropical and sub-tropical climates, and it is currently being researched for agricultural diversity in these regions [68–70]. As of 2022, there are at least 70 countries growing industrial hemp for commercial or research purposes, an increase of 49% from approximately 47 countries in 2021 [71]. Hemp fibre yields range from 1 to 5 metric ton/hectare (0.4 to 2.2 metric ton/acre) (note—this is not whole plant yield; it is just fibre), whereas cotton fibre yields range from 0.8 to 0.9 metric ton/hectare (0.32 to 0.36 metric ton/acre) [72]; additionally,
hemp fibre cultivation can lead to a 77% cost savings due to higher yield and reduced water, fertilizer, and pesticide use on one third of the land mass required for cotton cultivation. The estimated global cultivation of industrial hemp in 2021 was 510,000 acres [71], and with a compound annual growth rate (CAGR) of the industrial hemp market estimated at 16.8% (2022–2030) [73], cultivation rates will be increasing annually. Northern temperate climates, as found in central and northern Alberta, Canada, can grow industrial hemp plants that are 20% to 30% taller than in more southern regions due to longer sunlight hours [74]. Furthermore, industrial hemp grows extremely fast, coming second to bamboo in growth rate, and yields four times the biomass of a 25-year tree stand in just 90 days [74].

This “northern advantage”, combined with the ability of whole plant utilization for multiple end products, such as fibre, nutraceuticals, food, and bio-fuel, makes industrial hemp a diverse and economically viable agricultural crop [74]. Cultivation and use of hemp for L-MMCF contributes to whole-plant utilization, providing incentives for industrial hemp farmers to grow hemp as an agricultural crop. Agricultural biomass traditionally seen as waste can be diverted to L-MMCF manufacturing, creating value and additional revenue for the hemp industry.

In the 2022 Canadian agricultural growing season, there were 83 approved cultivars of industrial hemp, each grown for specific end uses [75]. Canadian cultivars are typically grown for one of two end products: nutritional seed and oil or nutraceuticals (i.e., cannabidiol oil). Plants grown for nutritional seed and oil are harvested at maturity (e.g., seed stage), resulting in coarser bast fibres that require additional delignification to obtain textile fibres [76]. While these plants are considered dual purpose (e.g., seed and fibre), the coarse fibres are difficult to process into spinnable fibre for flexible textile applications; they require additional processing to “cottonize” or soften the fibre, and field retting results in inconsistent fibres for processing [77]. These fibres are typically utilized towards technical applications (e.g., composites) and paper pulps due to the difficulty in processing to usable textile fibre [78,79]. Nutraceutical plants do not have the stalk growth for quality fibre manufacturing as these plants are harvested at the flowering stage [76,80]; fibres from these plants are often too immature and short to produce quality textile fibre. Other growing conditions influencing fibre quality include rainfall, temperature, and sunlight exposure [80,81]. Producing quality hemp bast fibre for textile applications is additionally challenged in an industry that is growing plants for nutritional and nutraceutical needs, not specifically for textile fibre [62,67,82].

Hemp L-MMCF addresses these fibre concerns since the biomass from both nutritional seed and nutraceutical plants could be used as L-MMCF feedstock, allowing for whole plant utilization. The hemp L-MMCF process avoids additional hemp bast fibre processing requirements, such as retting and decortication, which can damage fibre quality. As a result, the L-MMCF process offers consistent, reliable, and repeatable fibre quality. In summary, hemp biomass may be a preferable feedstock for L-MMCF due to:

- Cultivation in temperate, subtropical, and tropical climates;
- Increased global cultivation (49% increase by country from 2021–2022) at a CAGR of 16.8% (2022–2030);
- Hemp fibre yield 25–500% higher than that of cotton;
- Low pesticide, herbicide, and water consumption requirements;
- High biomass yields in 90 days (4 × that of equivalent 25-year tree stand);
- Whole plant utilization.

5. Manufacturing Opportunities and Challenges

Industrial hemp can be grown in a multitude of climates, including temperate, subtropical, and tropical regions, enabling a local-sourced raw feedstock supply for L-MMCF manufacturers [69]. Local supply allows for increased manufacturing traceability, reduced transportation costs, and reduced lead times for product manufacturing. As previously mentioned, both bast and hurd components of the hemp plant may be used for L-MMCF production [83]. These two parts of the plant possess different characteristics [84]; the hurd
is comprised of 40–48% cellulose, 18–24% hemicellulose and 21–24% lignin, while the bast includes 57–77% cellulose, 9–14% hemicellulose and 5–9% lignin. Hurd pulp is generally associated with a higher kappa number, which determines the degree of fibrous pulp digestion and gives an indication of the lignin content [85]. In the case of bast pulp produced by organosolv pulping using ethanol, a large stability of the crystalline structure of cellulose was observed [86]. By blending different ratios of pulp from the alpha-cellulosic-rich bast and the hemi-cellulosic-rich hurd raw materials, different organoleptic and physical properties may be achieved depending on end-use applications.

One of the main concerns with manufacturing L-MMCF from hemp is the presence of transition metals in the hemp fibres. Hemp plants are fast growing and are often used for contaminated soil remediation due to their quick take-up of nutrients from the soil [87,88]. This leads to accumulation of heavy metals in all parts of the hemp plant. Hemp stalks have been observed to contain high concentrations of heavy metals such as mercury, chromium, nickel, cadmium, lead, and arsenic, as well as high percentages of earth-alkali salts (i.e., sodium, magnesium, potassium, and calcium) [87–91]. The percentage and type of metal and salt content are specific to the soil the hemp plant is grown in, and the percentage of heavy metals and salts in hemp plants can be substantially higher than slower-growing plants and trees, such as eucalyptus.

These latent transition metals can pose significant safety concerns during the L-MMCF manufacturing process as the oxidation states of transition metals can be a catalyst for explosive radical decomposition reactions of NMMO [92,93]. Rosenau et al. have extensively researched these oxidative states, which result in “fast exothermic processes” or radical reactions. To mitigate reactive risks, research has identified stabilizers, such as propyl gallate, to incorporate into the L-MMCF manufacturing process. TITK has performed extensive research to further mitigate risks of transition metal content in hemp cellulose during the L-MMCF production process [13,91,94]. They determined that washing the crude pulps prior to dissolution in NMMO with deionized water successfully isolated metal ions (i.e., iron, copper) below hazardous levels. Additionally, calcium and magnesium ions are addressed within large-scale manufacturing and the use of sequestrants to form complex compounds [91].

Hemp is a novel feedstock for the L-MMCF manufacturing process. As such, additional research is required to determine the effects of the pulping parameters, such as the solid content to NMMO solvent ratio and cooking time, to determine the quality of the dissolving pulp produced. The carbohydrate component content, kappa value, viscosity, and degree of polymerization of the cellulosic raw material and corresponding dissolving pulp solutions need to be characterized to determine the effect of the degree of polymerization of the source of cellulose on the quality of the dissolving pulp and its preservation through the pulping process [95,96].

Additional research is also required to prepare dissolving pulps with the different blend ratios of hemp bast and hurd to manufacture L-MMCF with varying organoleptic and physical properties. Manufacturing processes need to include washing steps for NMMO removal. Process parameters, including extrusion rate, temperature, and residence time in the coagulation bath, need to be evaluated and optimal values determined, based on the performance of the filaments, including tensile strength, elongation, moisture content/regain, and residual NMMO content. This research will determine the effect of the processing parameters and type of cellulose produced by the pulping process (type I, II, III, and IV depending on the location of hydrogen bonds between and within the cellulose molecules) on the properties of the hemp-based L-MMCF.

To further improve the L-MMCF performance to match the requirements of the different end-use applications, one of the proposed solutions considers the introduction of additives into the regenerated cellulose dope before filament extrusion. The introduction of solid particles, in particular nanoparticles, into polymer fibres has been shown to improve fibre mechanical performance [97]. For instance, a concentration of 3 wt% cellulose nanocrystals was shown to produce an increase of 24% in the tensile strength of cellulose
acetate without negatively affecting its elongation at break [98]. In terms of flammability, additives functionalized with zinc oxide nanoparticles were shown to improve the flame resistance of high-density polyethylene matrix composites [99].

Manufacturing opportunities also exist for the exploration of properties naturally occurring within the cellulose fibers, such as biocidal activity in hemp fibers [100], and to determine whether these properties can be preserved through the L-MMCF process. It has been shown that the activity of bamboo’s natural antimicrobial agent, bamboo kun, is maintained through the cellulose dissolution process [53,101]. Hemp hurd contains a high concentration of cannabinoids and similar phenolic compounds as bamboo; its antibacterial activity has been demonstrated against bacteria Escherichia coli [100,102]. Hemp hurd powder exposed to heat treatments of up to 160°C for up to 3 h did not lower its antibacterial efficiency, but rather increased its antibacterial properties by reducing cross-contamination that had occurred at the retting stage. While challenges exist for hemp-based L-MMCF, the opportunities for fibre manipulation towards end-use applications are endless.

6. Economic Opportunities

Dissolving pulps are produced in NA; however, they are derived primarily from wood and are not considered environmentally sustainable for textile manufacturing. Dissolving pulp from alternate cellulose sources (e.g., hemp, post-consumer cellulosic textiles) would be beneficial from an NA agricultural and environmental vantage. Industrial hemp is a readily accessible commodity already being cultivated for various end usages. Therefore, L-MMCF derived from residual hemp biomass are inherently more sustainable due to the use of waste product as feedstock and aids in whole plant utilization. In addition, hemp biomass harvested from 1 acre produces the same as a 20-year tree stand grown on 4 to 10 acres [103]. The crop is environmentally conscious, requiring less water, fertilizers, pesticides, and herbicides than other cellulosic crops. Manufacturing hemp-based L-MMCF aids in whole plant utilization, and growing agricultural hemp for multiple purposes provides greater economic opportunity and environmental sustainability. In addition, end-users of hemp L-MMCF could have their products dissolved and extruded though the L-MMCF process again to create new L-MMCF, lending to a circular economy. Unfortunately, each time these textiles are recycled via dissolution, the degree of polymerization of the cellulose molecular chain is reduced; however, these recycled L-MMCF textiles could be blended with new raw feedstock (i.e., agricultural biomass) to create unique fibre properties.

Textiles are the second most environmentally damaging commodities following oil and gas production [103], and currently, only 15.2% of textiles are recycled [104]. By utilizing hemp as a feedstock, and by creating a circular economy by post-consumer cellulosic recycling via the L-MMCF process, cellulosic textiles can be diverted from landfills, therefore reducing GHG emissions. The estimated CO2e (CO2 equivalent) emissions per ton of cotton fibre is 2.35 to 4.05 kg [105], which would be reduced substantially when recycled in the L-MMCF process. Replacing cotton cellulosics with industrial hemp and hemp-based L-MMCF would lead to increased carbon sequestration and further reduction in GHG emissions. Industrial hemp is capable of sequestering 22 tonnes of CO2e per acre, making it ideal for regenerative agriculture practices [14]. According to Vosper [12], 0.445 tonnes of carbon are sequestered from the atmosphere for each tonne of industrial hemp grown. Therefore, we can estimate that 44 tonnes of carbon would be sequestered for every 100 tonnes of hemp biomass used for L-MMCF extrusion. Furthermore, manufacturing hemp L-MMCF can offset the use of petroleum-based synthetics, reducing the overall global GHG footprint. In 2021, global market demand for cotton was 22% and MMCF was at 6.4%, with L-MMCF only accounting for 0.28% of the global textile fibre demand [3]. The estimated CAGR for cellulosic fibres, including both natural and MMCF, is 4.2% [106].

Worldwide market size for L-MMCF is estimated at $1.13B [107] with the NA market size estimated at $199.4M [108]. These demands are increasing annually as demands for cellulosic fibres rise (i.e., the Cellulose Gap) [19,23]. The manufacturing cost of L-MMCF compared to other MMCF, such as viscose, is substantially higher due to raw material
costs (i.e., NMMO solvent and pulp feedstock) and specialized equipment requirements [4]. Based on global fibre production of viscose and L-MMCF in 2021 of 5.8 and 0.3 million tonnes, respectively [3], and on the global fibre market of viscose and L-MMCF in 2021 of $13.05B [109] and $1.13B [107], respectively, it can be estimated that L-MMCF are approximately 68% more expensive than viscose. However, demand for more sustainable fibres, as well as the use of less expensive, locally sourced feedstocks such as hemp (due to biomass availability and whole plant utilization), will lead to increase market share of L-MMCF [57]. Hemp-based L-MMCF could be a fibre source for the following markets:

1. **Personal Protective Equipment (PPE):** The current worldwide market for commercial PPE is valued at $52.7 B, with $140 M serviceable towards flame resistant (FR) PPE in oil/gas, mining, electrical, and construction applications [110]. The PPE market is expected to increase to $92.5 B by 2025 [110] and $110.85 B by 2029 [111]. The NA market for commercial PPE is $2.9 B, from which $83 M serviceable towards FR PPE applications [112]. Targeted market for FR hemp-based L-MMCF at commercialization is initially estimated at $12.5 M worldwide and $2 M in NA, increasing at scale-up production of hemp-based L-MMCF.

2. **Filtration media/Disposable Consumer Products:** Single-use disposable non-wovens (e.g., facemasks, gowns, flushable wipes, hygiene/sanitation products) are a high-demand commodity. The global non-woven medical textiles market is estimated to exhibit a CAGR of 3.9% with $27.7 B in sales by 2030 [113]. Targeted market for L-MMCF from hemp and post-consumer cellulosic textiles at commercialization for use in filtration media/disposable consumer products is estimated at $23 B worldwide and $8.3B in NA [114], increasing at scale-up. Consumption of cotton, other natural fibres, wood pulp, and rayon fibres for nonwoven applications in NA in 2021 was estimated at 1 million tonnes [115]. Considering a CAGR of 3.9%, the estimated consumption for L-MMCF staple fibres for nonwoven applications in NA at commercialization is 1.2 million tonnes.

3. **Apparel:** The current global hemp apparel market is estimated to be $23.02 B by 2031 (CAGR of 27.1%), with NA and Europe accounting for 65% of global consumption ($15 B by 2030) [116]. The global L-MMCF market for apparel is approximately $447 M US (45% of currently L-MMCF market share) [117]. The global ethical fashion market size is estimated to grow from $6.35 B in 2019 to $15.7 B in 2030 with a CAGR of 9.1% [118]. Targeted market for L-MMCF from hemp and post-consumer cellulosic textiles at commercialization for use in apparel at commercialization is estimated between $6.9 B globally ($4.5 NA) and $10.2 B globally ($6.6 NA).

4. **Dental products:** The global market for dental floss was valued to $540 M US in 2018, with a projected growth to $750 M US in 2025 [119]. There is a growing demand for environmentally friendly alternatives to the plastic-based products currently available [120].

### 7. Conclusions

Global demand for cellulosic fibres is increasing annually due to greater awareness of sustainability in textile products. Currently, cotton is the most frequently utilized cellulosic fibre; however, due to cultivation restrictions, the maximum global production for this fibre is estimated at 26 million metric tons. With the Cellulose Gap increasing, MMCFs offer alternatives to cotton celluloses. With increased awareness of hemp applicability to many different industries, including textile fibre production, industrial hemp as an agricultural crop is making a resurgence internationally. Hemp biomass as L-MMCF feedstock promotes whole plant utilization, reduces deforestation, reduces water consumption, reduces GHG emissions, promotes carbon sequestration, and can be cultivated via regenerative agricultural processes, lending to an overall reduced environmental impact and reduced environmental burden traditionally seen by the textile industry. While additional research needs to be completed regionally to assess hemp biomass characteristics (i.e., composition variance due to remediation properties of industrial hemp growth), the use of industrial hemp biomass as a feedstock towards the production of L-MMCF is a promising prospect.
Author Contributions: Conceptualization, L.L. and P.I.D.; writing—original draft preparation, L.L.; writing—review and editing, P.I.D., L.M.D., B.B., W.C. and D.K. All authors have read and agreed to the published version of the manuscript.

Funding: Work mentioned in the article has received funding from the National Research Council of Canada Industrial Research Assistance Program (NRC IRAP) (#PN937822).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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