DEVELOPING THE NEW YORK HEMP FIBER INDUSTRY

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by

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ABSTRACT

Industrial hemp (*Cannabis sativa* L.) offers the United States a unique opportunity to build a novel industry in a sustainable manner from the ground up. The many end uses of industrial hemp are frequently touted by those in the industry, yet very few applications have come to market in the U.S. Those in operation have limited valuable supply chains, especially in textiles and bio-construction, which are among some of its most popularized uses. More research focus in the U.S should be geared toward aiding the development of the fiber industry for these reasons: 1) hemp crops bred for fiber production are technically a multipurpose crop. Many regard the fibers as the main product of a 'fiber' variety. However, the hurd, or inner woody core, can also be an economic & sustainable source of raw material. 2) Fiber hemp can provide small farmers a profitable, fast-growing, rotational crop to diversify their income. This also contributes to better soil health when hemp is included in a crop rotation. For the fiber hemp industry to successfully enter a competitive marketplace, a focus on sustainability should be considered for the future. This focus satisfies multiple purposes: 1) Sustainability serves as a marketing tool for products for which many consumers are looking. 2) Much of the sustainability focus is on building local supply chains. Local supply chains lead to local products for which consumers are becoming increasingly aware. This review analyzes how this nascent industry can fulfill the expectations that have been created for it, while providing strategies for furthering the fiber hemp industry value chain in New York State.

BIOGRAPHICAL SKETCH

Anthony (Tony) Barraco III, who grew up in Syracuse, New York, has been passionate about the biological sciences since high school. This passion led him to pursue a degree in Biology at Elmira College in Elmira, New York. In 2018, Tony decided to apply his knowledge of biology to the horticulture field by taking hands-on, Cannabis-related courses at SUNY Morrisville during the 2019-2020 academic year. After gaining experience in hemp production, tissue culture, and breeding, Tony decided to pursue an M.P.S in Agriculture & Life Science at Cornell University, specializing in hemp science.

Tony's first experience walking through an outdoor hemp fiber field came at Cornell University. Upon seeing fiber hemp in the field for the first time, many of Tony's preconceptions of hemp were immediately challenged. The hemp in this field looked nothing like the popular cannabinoid hemp that most everyone is familiar with. As his education continued, he became more fascinated in the less popular fiber hemp, while many of his colleagues were drawn to cannabinoid hemp. Tony noticed a trend that seemingly applied on a larger scale in the United States; the majority of people are taking more of an interest in cannabinoid hemp.

During his time at Cornell University, Tony began expanding his professional network in the hemp fiber industry both domestically and internationally. Upon reaching out to Italian hemp fiber processor, South Hemp Tecno, in January of 2021, Tony established collaboration between Cornell University and the European Industrial Hemp Association (EIHA). Since then, Tony has connected with many members of the EIHA, which has provided him with a solid foundation of what the current state of the hemp fiber industry looks like in Europe.

ACKNOWLEDGMENTS

First, I would like to thank my advisor, Dr. Carlyn Buckler for her guidance and mentorship in creating this unique, one of a kind hemp program at Cornell University. Without it, I would not have been able to create the connections that I have over the past year. Carlyn has always been approachable and has made me feel welcome during my time at Cornell. Weekly Zoom meetings with the hemp MPS cohort during the hectic times of COVID-19 allowed us all to connect during an isolated time.

Second, I would like to thank Dr. Heather Grab for the endless hours of support she has provided throughout this project. Without her assistance, the project would not have reached the scale and success it did. Heather's dedication to her students is unparalleled in academia. Heather was an integral part in focusing the topics of the review and giving me the confidence to go above and beyond what I thought I was capable of. Heather's positive attitude and optimistic outlook made the difficult days of this project easier. I cannot thank her enough for the time she has put in to help me with this project. I am grateful for having Heather as a professor, mentor, and friend. I look forward to opportunities that allow us to work together in the future as I begin my career.

Third, I would like to thank my parents for supporting me. It was not easy at first to be open about my interests studying *Cannabis sativa* L. due to the negative stigma surrounding the plant. Throughout the process, my parents have supported the decisions I have made, knowing that these decisions are best for putting me on the right path. I am extremely thankful for their support, faith, and trust in me as I take the next step in my journey. I love you mom and dad.

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Fifth, I would like to thank Rachele Invernizzi of South Hemp Tecno. In January of 2021, I reached out to many hemp fiber companies in the U.S to inquire about their company and didn't receive a single response. After looking at South Hemp’s website I was impressed with their attention to farmers and sustainability. I never thought a genuine message of interest would eventually lead to my first ever opportunity to travel to Europe. I cannot thank Rachele enough for providing me with the chance to see the country where my grandfather was born. My experience in Italy is something I will never forget and will cherish for the rest of my life.

Last, I would like to thank all the friends I have made along the way thus far. During times where I lacked belief in myself, my friends have always been there to remind me of the success that is waiting for me on the other side of all the hard work. I cannot express enough how much the friendships that I have made over the years have attributed to my willingness to keep pushing forward. For this, I am forever grateful.

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LIST OF ABBREVIATIONS

CO_2	Carbon Dioxide
CEO	Chief Executive Officer
EIHA	European Industrial Hemp Association
E.U	European Union
GHG	Greenhouse Gas
GxE	Genotype-by-Environment
IPM	Integrated Pest Management
LCA	Life Cycle Assessment
ML	Middle Lamella
NGO	Non-Governmental Organization
NY	New York
NYS	New York State
PGRU	Plant Genetic Resources Unit
PLA	Polylactic Acid
SUNY	State University of New York
THC	Tetrahydrocannabinol
USDA-ARS	United States Department of Agriculture -Agricultural Research Service
U.S	United States
WUE	Water Use Efficiency

INTRODUCTION

Industrial hemp (*Cannabis sativa* L.) offers the United States a unique opportunity to build a novel industry in a sustainable manner from the ground up. Although early research outputs were greater for fiber hemp, research on cannabinoid hemp in the U.S has accelerated dramatically and has now overtaken fiber hemp publications with nearly double the number of publications per year (Figure 1). More research focus in the U.S should be geared toward aiding the development of the fiber industry for these reasons: 1) hemp crops bred for fiber production are technically a multipurpose crop. Many regard the fibers as the main product of a 'fiber' variety. However, the hurd, or inner woody core, can also be an economic & sustainable source of raw material (Pretot, et. al 2014). 2) Fiber hemp can provide small farmers a profitable, fast-growing, rotational crop to diversify their income. This also contributes to better soil health when hemp is included in a crop rotation. It has been shown that wheat yield can increase in a 2-year time span when rotated with hemp (Gorchs, et al., 2017).

The many end-uses of industrial hemp are frequently touted by those in the industry, yet very few applications have come to market in the U.S. Those in operation have limited valuable supply chains, especially in textiles and bio-construction, which are among some of its most popularized uses. Europe is a particularly interesting market to analyze because countries in the E.U. have been focused on industrial hemp production longer than the United States. Research and industry advancement were able to occur during times when nations such as the U.S were limited due to government restrictions.

For the fiber hemp industry to successfully enter a competitive marketplace, a focus on sustainability should be considered for the future. This focus satisfies multiple purposes: 1) Sustainability serves as a marketing tool for products for which many consumers are looking. 2)

Much of the sustainability focus is on building local supply chains. Local supply chains lead to local products for which consumers are becoming increasingly aware.

For sustainability to be used as a reliable marketing tool in the fiber hemp industry, empirical research regarding the life cycle of the products that are being created needs to be conducted. Furthermore, realistic products and applications should be of main concern in said life cycle assessments. Products derived from fiber hemp fulfill more “needs" applications, such as replacing synthetic plastic products, whereas the majority of current market products derived from the cannabinoid industry fulfill more “wants” applications, such as recreational use. This is another reason why research in the U.S should begin focusing more on industrial hemp for fiber.

This review will analyze how this nascent industry can fulfill the expectations that have been created for it, while providing strategies for furthering the fiber hemp industry value chain in New York State. New York contains climates suited for hemp fiber production. Short growing seasons, fertile soil, and ample rainfall make New York a suitable location to be a major producer of hemp fiber. New York State also offers the benefit of being in close proximity to New York City. This creates opportunities for collaboration with European hemp companies. For fiber hemp, the U.S has yet to reach its potential on the domestic market. In order to maximize profitability and efficiency of raw biomass, the first types of product applications in the United States should focus on those that need relatively low volume of biomass to produce high-value products. Simultaneous change still needs to occur for both large companies that can substitute hemp raw materials into their products, and farmers allocating land for hemp cultivation.

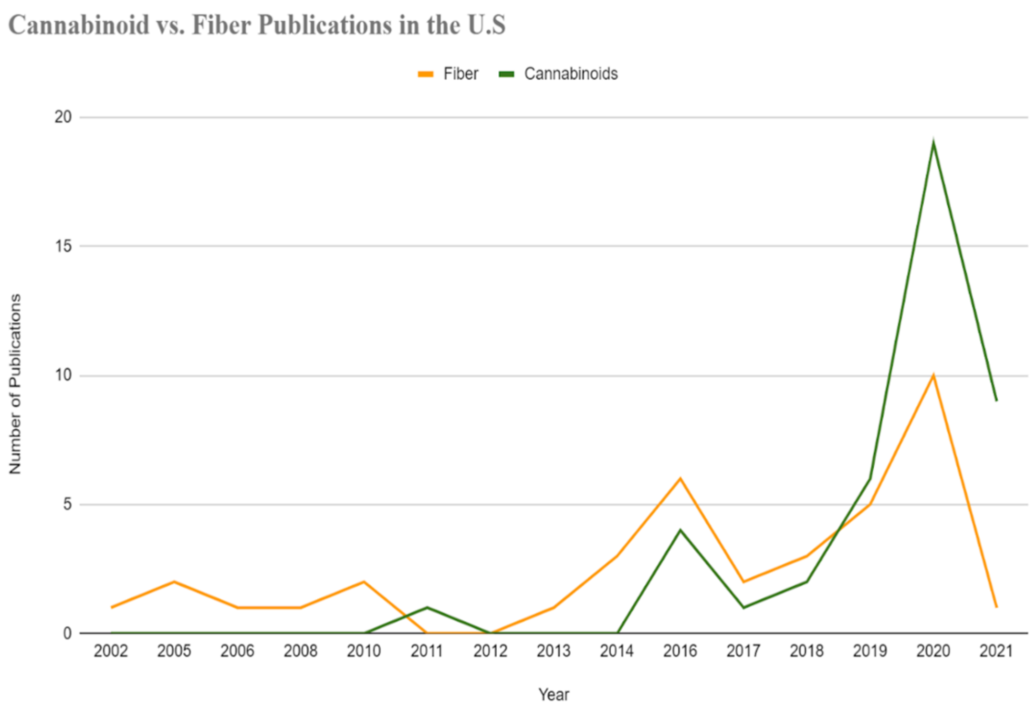

Figure 1. Web of Science search comparing search terms ‘Fiber AND Hemp’ to ‘Cannabinoid AND Hemp.’ Refined search by country, choosing ‘United States’. Further refined each search to contain Web of Science Categories: ‘Agronomy’, ‘Plant Sciences’, ‘Genetics’, and ‘Horticulture.’ Excluding everything else. Searches were then manually screened to eliminate irrelevant publications not regarding *Cannabis sativa* L.

METHODOLOGY

The goal of this search method was to create a repeatable, unbiased, comprehensive, structured literature review. The search included peer-reviewed articles, government and non-governmental organization (NGO) reports, extension documents, agricultural trade publications, and student dissertations/theses. Search criteria consisted of articles dating from 1900 to the present day. Searches were conducted on the Web of Science's Core Collection and ProQuest Research databases and supplemented with bioRxiv and Google Scholar searches. Additionally, the Web of Science 'shared references' feature was used to discover literature not initially recovered from the search terms. A formal list of search terms can be found in the Appendix. This review also uses a unique case study on an emerging hemp fiber company based in southern Italy. The company, South Hemp Tecno, has connected farmers across Italy. This case study is important in realizing the challenges that an emerging fiber hemp business faces, while providing unique details of their approach to sustainability in the industrial fiber hemp sector and potential solutions to the challenges they face. While Italy and New York State differ in many ways, the goal of creating a valuable hemp fiber supply chain remains the same.

Scope and Limitations of literature review

Despite popular conception of the *Cannabis* plant, "hemp" is an umbrella term that attempts to define many different end-uses of the same species (*Cannabis sativa* L.), though the products and markets differ dramatically. Additionally, equipment for production and processing of hemp varies drastically depending on the desired end product (Jacobs, et al., 2020). Whenever "hemp" is used in this review, it is referring to the plant *Cannabis sativa* L. Industrial hemp referred to in this paper will solely focus on fiber/hurd production and processing. *Cannabis* *sativa* L. grown for grain or cannabinoids falls outside the scope of this paper and therefore will not be discussed in detail. All references that focused on cannabinoid hemp, controlled environment production, medicine, pharmacology, etc. were excluded from the review. Dual-purpose grain & fiber cultivars were not a focal point of this review. Even though these cultivars can produce fiber and hurd products, the agronomic practices and supply chain of dual-purpose varieties differ enough to not be relevant for this review. The timeframe of this project was five months, from April 2021 to August 2021. Throughout the literature review it was discovered that many sources are publicly available in Chinese, Russian, Dutch, German, French, & Italian, but have not been translated into English. While language barriers present a limitation to accessing available information in the search, it is not believed that this limitation has a strong effect on the validity of the findings, given the focus on the Northeastern United States. While the core focus of this work is on the New York State industry, this review also evaluated relevant data from various states in the U.S to identify supply chain and market structures.

Scope and Limitations of Case Study

It is important to define the scope and limitations of the case study to give readers a clear idea of how it was conducted. This case study was limited to 2 weeks from June 15th to June 30th of 2021. Field visits were made to farmers near Milan, Rome, and Taranto, Italy (Figure 2). Discussions with the CEO of the company were conducted daily to ascertain the day-to-day challenges of running a hemp fiber company in Italy. Although this case study focuses on one company, additional insights were gained through engaging with the European Industrial Hemp Association (EIHA) and many of its members across Europe. The EIHA is a non-governmental organization that aims to establish valuable industrial hemp supply chains in Europe. The EIHA policy advisors consolidate and provide reliable, peer-reviewed information to the European Commission, Parliament, & European Union law makers. The EIHA accomplishes this information gathering through working groups and scientific committees, which consist of industry leaders and university researchers, respectively. These meetings support collaboration between the industrial and academic sectors to identify issues and opportunities to optimize the standardization of industrial hemp as a crop in Europe. Insights from these meetings have been gained through participating in working groups, including Fiber and Textile (April 16th, 2021) and Agriculture & Environment (July 7th, 2021), along with attending a scientific committee meeting: Farming, Fiber, and Biomaterials (June 30th, 2021). Francesco Mirizzi, Senior Policy Advisor at the EIHA, provided insight via online Zoom meetings to prioritize the importance of several topics related to the development of the hemp fiber industry in Europe.

Figure 2. Heat map showing the location of pictures taken during the 2-week case study in Italy. Red circles indicate locations of the hemp fields that were visited near Milan, Rome, and Taranto. Retrieved from Google Maps and Google Photos.

RESULTS & DISCUSSION

Genetics

Cannabis sativa L. is an annual plant and a naturally dioecious, outcrossing species. Consequently, the hemp genome is highly heterozygous, meaning allelic loci across the genome are highly variable (Campbell, et al., 2019). Although there is a wide range of phenotypes in the *Cannabis sativa* L. species, hemp grown for fiber tends to be what is considered a "short-day" photoperiodic plant, which means its physiology transitions from a vegetative growth pattern to a terminal flowering growth pattern due to the lengthening of the night (Petit, et al., 2020). When the length of the night exceeds the length of the day, hemp plants will shift from a vegetative state of growth into a flowering state. This seemingly holds true for all cultivars except for "day-neutral" or "autoflower" varieties, which flower independently of the day/night length. When it comes to plant breeding, germplasm is important for the successful replication of studies. In the United States, all *Cannabis sativa* L. germplasm held by the federal government was eradicated throughout times of prohibition (Cherney and Small, 2016). Due to this, germplasm became more and more difficult to source for both industry growers and scientists.

Recently, researchers at Cornell University have found that much of the feral hemp in the United States is most closely genetically related to Italian fiber cultivars (Figure 3; Carlson et al., 2021). These Italian-bred fiber varieties and their feral relatives may be a potential starting point for breeders in the United States for creating locally adapted fiber cultivars. Developing hybrid hemp cultivars suited for local NY latitude will be key in generating optimized harvests and yields for farmers. Fiber varieties that flower too early will not generate the necessary biomass needed for a successful harvest. A lack of published studies on hemp hybrids and the lack of a unified genotyping platform has delayed hybrid development progress in the research community (Carlson, et. al., 2021). Cultivars bred for the future should focus on conferring resistance to diseases such as downy mildew and powdery mildew (Cala, et al., 2020; Weldon, et al., 2020) while having an appropriate photoperiod to coincide with the upstate NY latitude of approximately 41.5-43.5 degrees North.

One of the biggest opportunities for the hemp fiber industry lies in Geneva, NY at the newly established national hemp germplasm repository. The USDA-ARS Plant Genetic Resources Unit, in collaboration with Cornell University, will aid in establishing a national archive of hemp germplasm. This seed bank has the potential to become the largest collection of hemp accessions in the world. With this database of characterized hemp germplasm, research in the United States will exponentially increase, as scientists will be able to better replicate their studies with reliable germplasm. Private breeding companies will also benefit from the creation of the germplasm repository. Better established cultivars will be available on the market for producers from all states, which will result in less risks for the future hemp farmer.

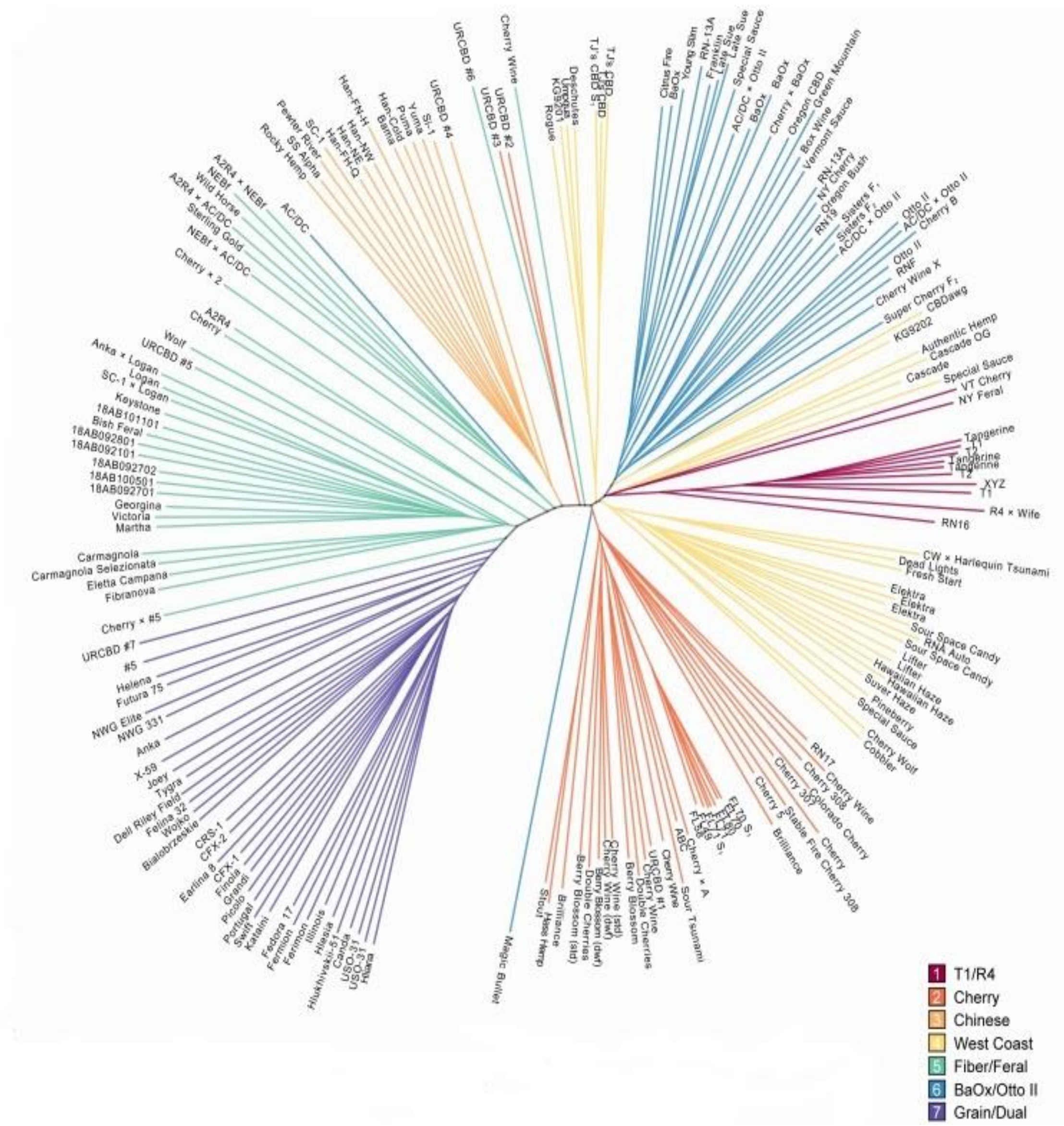

Figure 3. Phylogenetic map of 192 samples of Cannabis sativa L. accessions. Italian hemp fiber cultivars, such as Carmagnola, are most closely related to feral accessions found in the U.S. Retrieved from (Carlson, et al., 2021).

Production Practices

Just like other agricultural crops, hemp requires soil refinement and fertilization. Soil that is suitable for hemp production consists of well-aerated loams with high fertility and high organic matter (Cherney & Small, 2016). Marginal soils with poor drainage are not suitable for quality hemp production. Planting density varies depending on cultivar type. However, hemp grown for fiber production is commonly sown at a high density of 45 to 70 kg/ha and at a depth of no more than 3cm (Miller, 1991). High density plantings of fiber hemp allow competition between plants, which creates tall, thin stems ideal for decortication. When fiber hemp is sown at a lesser density, stems can become too thick and more difficult to harvest and process. Fertility requirements for hemp production are similar to that of a high-yielding wheat crop, with approximately 110 kg of nitrogen per hectare (Williams & Mundell, 2016). Hemp has a reputation of being drought tolerant. When compared to similar crops such as cotton, it has been found that hemp uses water more efficiently (Schumacher, et al., 2018). This allows hemp to be a viable crop in climates that receive little to no rain during the growing season. Irrigation of hemp has shown to improve yields of biomass and stem mass by 7% and 9% respectively, however, effects of irrigation have been shown to be lower for hemp than in maize or kenaf (Amaducci, et al., 2000). These findings suggest that the extra yields of irrigating hemp for fiber may not be worth the investment of resources that is seen with other crops.

It has been shown that hemp cultivars can use different acclimation strategies to cope with changing soil and climatic conditions (Herppich, et al., 2020). 'Ivory' cultivars established large leaf areas and high CO_2 uptake rates per plant relatively early in the growing season, but photosynthesis and growth was reduced due to the early onset of senescence compared to 'Santhica 27' plants (Herppich, et al., 2020). While 'Ivory' plants used water more efficiently due to their “optimistic” strategy of high carbon gains during a shorter growing season, the cultivar ‘Santhica 27’ established a higher plant density and almost double the yield with low, but long-term, constant CO_2 gain and leaf area per plant (Herppich, et al., 2020). These findings align with some of the genotype by environment (GxE) interactions that have been identified in hemp by Campbell, et al., (2019). Thirteen genotypes of European and Asian origin were evaluated in Colorado, and it was found that not all cultivars responded equally to irrigation (Campbell, et al., 2019). These results suggest that cultivar selection is an important factor for farmers due to the extreme variance observed in a hemp population.

Hemp has also developed a reputation for being fairly “pest free.” While pesticides are generally not needed for hemp production, there is still much that is unknown about economically damaging insects of hemp. In Colorado, it has been found that many insects can damage crops of hemp. Mainly, defoliators such as aphids, spider mites, and leafhoppers can be found on leaves, while insects such as the European corn borer have been found to penetrate the stalks of hemp and have the potential to weaken plants, making them more susceptible to breakage (Cranshaw, et al., 2019). Fungal diseases of hemp are some of the most prominently identified. Downy mildew, powdery mildew, and many species of *Fusarium* have been reported to cause significant damage to hemp crops (McPartland, et al., 2000). Powdery mildew has been a particularly prevalent disease of hemp in NYS since its reintroduction as an agricultural crop (Cala, et al., 2020). As hemp acreage increases in NYS, it is important to be aware of potential cross-infectivity of diseases between other susceptible emerging crops in the Cannabaceae family, such as *Humulus lupulus* (hop) (Weldon, et al., 2020).

Weeds can be a particularly troublesome pest in hemp fiber fields during the emergence stages after planting (Figure 4). It has been shown that many herbicides can be harmful to hemp

(Maxwell, 2016). Until promising herbicides are tested and approved for *Cannabis sativa* L., the best way to practice weed IPM (Integrated Pest Management) is through cultural management of good sowing practices. Sowing seeds at the proper depth and having proper irrigation for germination provides the best opportunity for good stand establishment. Without proper stand establishment, weeds will be able to outcompete young hemp plants and will cause problems downstream when it comes time to harvest. If fiber fields are sown correctly, high-density plantings will outperform and out-shade weed species (Mark, et al., 2020).

Hemp stalks are mainly composed of chemical components such as cellulose, hemicelluloses, lignin, and pectin. These components are bound by a lignin-rich middle lamella (ML) (Nykter, et al., 2008). Fiber hemp is mechanically harvested using a sickle bar mower or a combine with a “double-cut” system to separate the top flower heads from the stalk (Pari, et al., 2015). Fiber hemp should be harvested at the onset of flowering, fibers harvested at seed maturity are significantly lignified and these fibers will be tougher to extract compared to fibers at the beginning of flowering (Liu, et al., 2015). Once hemp stalks are harvested, a retting process is needed to degrade the ML to make separation of the fiber bundles easier when processing (Liu, et al., 2015). The process of retting can take on different forms. Field retting (also known as “dew retting”) is the most common method of retting. Harvested stalks are laid into windrows (a heaped row of harvested stalks allowed to dry in the field before processing) where, over time, microorganisms--mainly composed of fungi--express pectinolytic enzymes that break down the pectin holding the fibers together (Henriksson, et al., 1997). This process of ‘field retting' is known to use significantly less resources than the alternative method of water retting, and is more economically feasible (Liu, et al., 2015). Due to the highly variable nature of field retting, stalks are typically less uniform when compared to water retting. Field retting is also limited to geographical areas where weather conditions are suitable for microorganism activity. Dry climates with little rain are difficult for field retting. Once the stalks have been successfully retted, the stalks can be baled with either a square or round baler. Round bales can typically be stored outside for a short period of time without significant yield loss, however indoor storage is preferred and should be sought out whenever possible to protect the quality of the raw material.

To standardize hemp as a crop in New York, farmers must be willing to grow it. Taking on a new crop is not an easy task, especially when it comes to hemp. Due to its long period of prohibition, information regarding its production has taken time to become commonplace in the farming community. Farmers should not be replacing their current crops with hemp. Instead, farmers should trial on a small acreage with proper consulting to become familiar with hemp. Adding hemp as a rotational crop not only increases the diversity of a farmer's income, but it also increases the biodiversity of their agro ecological landscape. Monocropping often results in increased pest and disease pressure. Rotating hemp with other crops such as corn, wheat, and leguminous crops can reduce disease and insect pressure (Cherney & Small, 2016). In China, fiber hemp has been shown to be useful in a wheat intercropping system (Zhao, et al., 2021). Cannabis has come under public scrutiny recently due to findings that show indoor production leads to significant levels of greenhouse gas emissions (Summers, et al., 2021). When it comes to the sustainability of Cannabis production, it should also be recognized that hemp cultivation for fiber offers a much different production style, one that can potentially be viewed as carbon negative and environmentally friendly (Nordby & Shea, 2003). Determining the realistic environmental impact of producing fiber hemp products should be a focus for the future of the industry.

Figure 4. Hemp fiber research plot in southern Italy, using overhead sprinkler irrigation. Weed emergence can easily take place in areas where stand establishment is poor. Common reasons for poor stand establishment can be due to poor soil quality, improper sowing depth, and lack of water during the germination phase.

Environmental Impact of Hemp Fiber

Quantifying sustainable development is a difficult process which can take on many forms. Sustainable development [in this review] refers to “development that meets the needs of the present, without compromising the ability for future generations to meet their own needs” (Rees, 1989). A Life Cycle Assessment (LCA) is a method scientists can use to measure the sustainability of a process through various benchmarks of environmental impact throughout each step of the supply chain lifecycle (Finkbeiner, et al., 2006). A drawback of LCA studies lies in the subjective nature of choosing system boundaries and benchmarks in which to measure environmental impact. Along with this, LCA’s are naturally difficult to replicate, as many are limited by focusing on the interests of a particular company’s products and region. Over 10 years ago, an LCA meta-analysis was conducted in Europe regarding fiber-based applications that could be replaced using hemp (Haufe and Carus, 2011). The studies in this meta-analysis took place when technology in the hemp industry was in its infancy, therefore machinery and supply chain development are significantly different from that of present-day innovations and advancements.

Environmental impact categories are compared across LCA’s that were found in the previous meta-analysis as well as newer studies recovered in this review (Table 1). While many impact categories are similar across studies, such as Carbon dioxide (CO_2) flow and water use efficiency (WUE), it is still difficult to realistically analyze the sustainability of hemp compared to similar crops due to differences in the measurements of functional units, lack of comparative crops, differences in products created, and the development of the supply chains of different crops. Hemp fiber is in competition with many established supply chains for the textiles market, including but not limited to cotton, flax, kenaf, coir, bamboo and jute. Some research shows that when it comes to WUE, hemp is among one of the most competitive crops, needing significantly less amounts of water than cotton (Schumacher, et al., 2020). While irrigating may lead to higher yields, it should be noted that once fiber hemp is established it is fairly drought tolerant (Herppich, et al., 2020). This bodes well for many Mediterranean climates in Europe, such as southern Italy, where rain is extremely limited during the summer months. Climates that receive adequate rain during the growing season, such as the Northeast U.S, can provide sufficient amounts of water for hemp without the need for irrigation.

LCA's found in this literature review focused on products such as specialty pulp paper, bio-based insulation, and hemp concrete (Schulte, et al., 2021; Gonzalez-Garcia, et al., 2010; Pretot, et al., 2014). The largest contributor to the environmental impact of hemp cultivation is in regard to fertilizer runoff, which leads to eutrophication (Van der Werf, 2004). Many studies note the agricultural process of cultivating hemp is often more sustainable than other crops, however the post-harvest processes often offset its environmentally friendliness. In the example of hemp concrete, results showed that hemp appears to be an environmentally friendly material, however further improvements can be made by reducing the environmental impact of the lime binder (Pretot, et al., 2014). It is apparent that some LCA studies analyze impact categories on a much more in-depth level than others, while some studies do not offer comparison materials/processes in which to measure against hemp (Table 1). Moreover, it is evident that not every study provides the information necessary to analyze net carbon flows (Table 2). It would be interesting for future studies to identify if the products focused on in past LCA studies accurately portray products currently represented in the industrial hemp market. Research should identify which fiber/hurd products will realistically make up the market share of the industrial hemp industry. LCA studies surrounding the sustainability of those hemp-derived products would represent a much more realistic outlook on product development and more standardized LCA's could be accomplished and peer-reviewed.

One of the most important environmental categories that should be considered for future studies is the carbon sequestration potential of hemp. 'Credits' for carbon storage is a policy mechanism that can provide companies with economic incentive to sequester and store carbon that is to be used for a carbon negative product. While hemp has been shown to not be among the best crops for carbon sequestration (Finnan & Styles, 2013), it has the potential to diminish the inputs of plastics and composites, which have experienced unprecedented growth over the past 50 years (Pervaiz & Sain, 2003). Trends in sustainable "green packaging" are becoming popular, and hemp has the potential to fill that niche by producing a valuable polypeptide used in compostable plastic (Siracusa, et al., 2008). Replacing approximately 20% of fiber glass reinforced plastics with natural fiber composites can not only be a positive step forward in curtailing greenhouse gas (GHG) emissions, but it can also contribute to obtaining 'carbon credits' for companies transitioning towards more sustainable methods (Pervaiz & Sain, 2003). The carbon storage potential of hemp-based thermoplastics has been estimated to be around $8.78 USD/t of composite (Nowak & Crane, 2002). All but one LCA study investigated in this literature review noted that biogenic carbon sequestration was not considered for CO_2 data. If carbon sequestration was included in carbon accounting, it would make a great impact and greatly favor biomass materials (Nordby & Shea, 2013). Carbon credit estimates should be investigated and updated for each country. The significant energy savings of 60% per ton of product by using natural fiber reinforcements is possible through four means; reducing use of petroleum plastics by using higher proportion of natural fibers, actual substitution of high energy consuming glass fibers, low weight of natural fiber composites compared to fiberglass, and finally, saving by reducing the burden of landfills (Pervaiz & Sain, 2003).

Study	**Product**	**Comparison Material**	**Impact categories measured (units)**
Schulte et. al 2021	Bio-based insulation	Wood fiber Flax Miscanthus	Fine Particulate matter formation (kg $PM_{2.5}$ eq) Fossil resource scarcity (kg oil eq.) Water consumption (m^3) Land use (m^2*a crop eq.) Global Warming (kg CO_2 eq.) Freshwater ecotoxicity (kg 1.4-DCB) Freshwater eutrophication (kg P eq.) Human carcinogenic toxicity (kg 1.4-DCB) Human non carcinogenic toxicity (kg 1.4-DCB) Marine ecotoxicity (kg 1.4-DCB) Marine eutrophication (kg N eq.) Ionizing radiation (kBq Co-60 eq.) Mineral resource scarcity (kg Cu eq.) Stratospheric ozone depletion (kg CFC11 eq.) Terrestrial acidification (kg SO_2 eq.) Terrestrial ecotoxicity (kg 1.4-DCB) Ozone formation -human health (kg NOx eq.) Ozone formation -terrestrial health (kg NOx eq.)
Gonzalez-Garcia et. al 2010	Non-wood pulp mills: Straw Fiber Woody core Dust flax/hemp	N/A	Acidification (kg SO_2 eq. t^{-1}) Eutrophication (kg PO_4^{-3} eq. t^{-1}) Global Warming (kg CO_2 eq. t^{-1}) Photochemical Oxidant Formation (kg C_2H_4 eq. t^{-1}) Non-Renewable Energy Resources (GJ t^{-1}) Pesticide Use (kg active ingredient t^{-1})
Pretot et. al 2014	Hemp concrete wall	N/A	Energy Raw Consumption (MJ/FU) Water consumption (1/FU) Photochemical ozone (kg eq ethylene/FU) Climate Change (kg CO_2 eq./FU) Atmospheric Acidification (kg SO_2 eq/FU) Air Pollution (m_3 /FU) Water Pollution (m_3/FU) Eutrophication (kg$(PO_4)^{3-}$)
Van der Werf, 2004	Field Production & Harvest	Sunflower Rape Seed Pea Wheat Maize Potato Sugar Beet	Eutrophication (kg PO_4)-eq Climate Change (CO_2-eq) Acidification (SO_2-eq) Terrestrial ecotoxicity (kg 1,4-DCB-eq) Energy Use (MJ) Land Use (m^2/year)

Zampori et. al 2013	Thermal-based insulation wall	Rockwool based insulation wall	Greenhouse Gas Protocol (CO_2 eq) • Fossil • Biogenic • Land transformation & Uptake Cumulative Energy Demand (MJ) EcoIndicator99 H • Carcinogens • Resp. organics • Resp. inorganics • Climate Change • Radiation • Ozone Layer • Ecotoxicity • Acidification • Land use • Minerals • Fossil fuels
Mungkung et. al 2016	Hempstone sheet	N/A	Impact assessment method:ReCiPe • Climate Change • Freshwater ecotoxicity • Terrestrial ecotoxicity • Freshwater eutrophication
Florentin et al 2017	Hemp concrete wall	Poured Concrete AAC Plaster EPS Plaster	*ISO14041
Ip and Miller et al 2012	Hemp concrete wall	N/A	*ISO14041
Sinka et. al 2018	Hemp-lime binder	Magnesium based binders: MPC MOC	Abiotic depletion (kg Sb eq.) Eutrophication (kg PO_4 eq) Acidification (kg SO_2 eq) Human Toxicity (1,4-DB eq.) Freshwater aquatic ecotoxicity (kg 1,4-DB eq) Global Warming Potential (kg CO_2 eq) Ozone layer depletion (kg CFC-11 eq.) Photochemical oxidation (kg C_2H_4) Terrestrial ecotoxicity (kg 1,4-DB eq.) Marine aquatic ecotoxicity (kg 1,4-DB eq)

Nordby and Shea, 2013	Building materials	Rockwool/ Concrete Wood fiber	Embodied Carbon (kg CO_2 eq/m^2) Sequestered Carbon (kg CO_2 eq/m^2) Thermal buffering (kJ/m^2K) Moisture buffering (g/m^2%RH)

Table 1. Comparison of environmental impact categories measured between studies found in the literature search. *Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., & Klüppel, H. J. (2006). The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *The international journal of life cycle assessment*, *11*(2), 80-85.

Study	**Product(s)**	**Comparison Material**	**GHG Savings (kg CO_2 eq)**
Schulte et. al 2021	Bio-based insulation	Wood fiber Flax Miscanthus	-8.98 1.92 -8.75
Sinka et. al 2018	Hemp-lime binder	MPC MOC	32.1 6.00
Nordby and Shea, 2013	Building materials	Concrete Wood fiber	230* 103*
Florentin et. al 2017	Hemp concrete wall	Aerated Autoclaved Concrete (AAC) wall	7.50
Zampori et. al 2013	Thermal-based hemp wall	Rockwool based insulated wall	18.55

Table 2. Greenhouse Gas (GHG) differences when compared to hemp-based starting materials. GHG differences were calculated using the results for CO_2 emission/sequestration for each material in each study, then finding the difference in values for hemp results. Negative values indicate that the comparison material outperformed hemp. *CO_2 savings over a 60-year period.

Supply Chains

Currently, China dominates the global industrial hemp textile market due to its large cultivation area, textile manufacturing infrastructure, and cheap labor (Cherney & Small, 2016). While China provides many market outlets for textile applications, valuable supply chains for other plant parts such as the hurd and flowers are severely underutilized in the country (Zhao, et al., 2021). This presents an opportunity for countries such as the United States to investigate sustainable, high-value applications for raw materials such as hemp hurd. An increase in textile manufacturing infrastructure will be needed to create local American-made products if the U.S is to compete with countries such as China. Currently, most American companies outsource their textile manufacturing to China. This not only leaves fewer jobs for Americans, but also results in non-American made products.

Hemp fiber processors are a vital step in creating a valuable supply chain. These processors are currently few and far between in the state of New York. Establishing more fiber processing facilities in NYS should be a focus for the future. Hemp fiber farms should always seek to secure a contract with a processor to guarantee payment at the end of the season. As long as the quality of the raw material meets contractual standards, the farmer can rest assured they will have a buyer for their crop. It is also important for processors to receive buyer-specific attributes in the raw materials from manufacturers (Bignon, 2020). Properties such as cellulose content, fiber length and color, and hurd size are some examples of attributes that processors will have to adhere to depending on their buyer. In the case of a cooperative business model, decisions regarding post-harvest treatments--such as retting--are typically made by the cooperative (Royer, 1995). This allows for more quality control throughout the processing phase since retting has a large effect on the quality of the raw material. In order to maximize profitability and efficiency of producing and processing raw hemp biomass, research regarding product development in the United States should focus on applications that need relatively low volume of biomass to produce high-value products. A potential application investigated could be using hemp wood as a replacement for lumber flooring. This would allow companies to receive the most value for their raw material without having to significantly increase the acreage allocated for hemp. For hemp fiber supply chains to compete, simultaneous change still needs to occur between large companies that can substitute hemp raw materials into their products, and farmers allocating land for hemp cultivation.

A bottleneck in the current supply chain of hemp resides in the lack of education and knowledge surrounding the processes of transforming hemp into useful products (Mark, et al., 2020). Product method development will play a significant role in developing the supply chain in New York. Currently, companies of all industries have well-developed methods for producing their current products. These methods will likely need to be changed or modified to accommodate the inclusion of hemp. For example, a construction company using traditional methods of fiberglass insulation and concrete walls cannot instantly transition to using hemp-based insulation and hempcrete. Hemp fiber processors, architects, manufacturers, and construction companies will have to collaborate and experiment to create innovative and sustainable hemp-based projects. These knowledge gaps regarding product development should be a research focus for both academia and industry.

Economics

When deciding to produce hemp for fiber, farmers ultimately need to know the economic risks and benefits associated with it. The value of hemp fiber production in New York State during the 2019 growing season generated approximately $794 per acre of revenue for farmers

(Hanchar, 2019). After incorporating the costs of production (variable inputs + fixed inputs) the profit per acre of fiber hemp is estimated to be between $248.26 and $403.96 (Hanchar, 2019). It should be noted that these values for fiber production are for expected yields of 3.97 tons per acre. Since no pesticides are registered for use on industrial hemp in the United States, pesticide inputs are not included. This being said, growing hemp for fiber on a small scale does not generate significant revenue for a small farmer. This begs the question; how can small farmers generate sufficient profit growing industrial hemp?

Agricultural cooperatives are not uncommon in New York State. A cooperative is a private business that is composed of members who coordinate between themselves (horizontal coordination) to achieve vertical integration (Royer, 1995). Cooperatives have been successful in aiding the development of the dairy industry in New York State; therefore, it is not far-fetched to believe the hemp industry could evolve in a similar manner. In Europe, countries such as Germany, France, Spain, and Ireland have well established agricultural cooperative models for industrial hemp (Franceso Mirizzi, 2021, pers. comm.). Entrepreneurs interested in getting into the industrial hemp sector should keep an open mind in regard to a cooperative business model as an alternative strategy to individual vertical integration. The returns one can make when successfully integrating a company are lucrative, and dividing the investment in a company between members can reduce the burden of start-up costs. Cooperatives also create local networks of individuals who are interested in furthering common goals.

Currently, growing industrial hemp is a big risk for farmers. Incorporating cooperative business models in New York State can help to reduce some of the risk for farmers interested in growing hemp. In this scenario, the cooperative takes on most of the risk once a contract is in place (Royer, 1995). In France, agricultural cooperatives make up approximately 75% of farmers

(Chantelot, et al., 2011). About a decade ago, there was a resurgence of legislation to aid in the development and incentivization of cooperatives in France (Juban, 2016). Founders of cooperatives in France have attributed their recent success to legislation that incentivizes investment in cooperatives by allowing members to save on taxes based on the money they put into the cooperative (Matthieu Ebbesen-Goudin, 2021, pers. comm.). In the U.S, traditional banks were reluctant to aid hemp companies as many saw lending as too risky due to the blurred regulatory landscape between hemp and marijuana. Many processors rely on venture capital for their business as other sources can find the financial and regulatory risks outside of their guidelines for lending (Mark, et al., 2020). This extremely high cost of entry creates a barrier that limits the types of people who can enter the industry. Cooperative models could be a potential solution to aid in the high startup cost of creating and operating a fiber processing facility, while allowing people of underrepresented communities to become industry leaders.

For hemp to be economically viable, local supply chains are needed. It is recommended that processing facilities be no further than 80 km (~50 mi) from a farm (Pari, et al., 2015). Due to the economics of shipping--which is based on volume and not mass--hemp fiber is especially expensive to transport because it is not dense. Due to high production costs, hemp products are typically marketed at higher values than competing products, creating niche markets for those that can afford the products. Lowering the cost of hemp fiber production and processing must be a focus for the future development of the industry if products are going to be able to compete for popular consumer attention.

Regulatory

For decades, federal law in the United States did not distinguish hemp from other types of *Cannabis sativa* L. With the Agricultural Act of 2014, federally funded research for hemp was allowed for the first time since 1937 (Malone & Gomez, 2019). With the addition of the 2014 Farm Bill, farmers were allowed to grow hemp under state pilot programs; however, during this time there was a severe shortage of processors, leading to significant oversupply. While this bill allowed for the cultivation of hemp, it severely lacked the infrastructure to create a valuable hemp supply chain. Under the pilot programs, United States industrial hemp acreage reported by states increased from zero in 2013 to over 90,000 acres in 2018, the largest U.S. hemp acreage since the 146,200 acres planted in 1943 (Mark, et al., 2020). A lack of reliable seed from seed companies, combined with strict maximum 0.3% delta-9-THC on a dry weight basis, led to an amalgam of regulatory problems for farmers. Inconsistency between state requirements, and a lack of basic data and information for decision-making are just some of the challenges that arose from the introduction of hemp cultivation in the U.S (Mark, et al., 2020). Since the pilot programs began, the market for fiber has been unclear. Large-scale investments in fiber processing facilities have been made, however buyers are not available in every region and transportation costs limit profitability for fiber. U.S. fiber processors must engineer their equipment or import from Europe or China (Mark, et al., 2020).

Legislation has played a major role in shaping the hemp industry. In 2018, hemp was recognized by the federal government to be different from marijuana (Mark, et al., 2020). The subsequent descheduling of hemp--so long as it remains below 0.3% delta-9-THC on a dry weight basis--was a step forward in the right direction. However, there are still many blurred lines between federal and state regulations, which further complicate standardizing the crop. Legislation has also played a role in developing both the wine industry in the 1980’s and more recently, the craft brewing industry in New York State. Led by the New York State Brewers Association, the Craft NY Act of 2014 was designed to increase demand for locally grown products (NYS Brewers Association, 2021). This initiative has helped create new businesses surrounding the brewing industry. Until the end of 2018, NYS breweries had to source at least 20% of their hops and 20% of their other ingredients from NYS. From January 1st, 2019, to December 31st, 2023, no less than 60% of hops and 60% of other ingredients must be from NYS. After January 1st, 2024, farm breweries in NY will source no less than 90% of hops and 90% of other ingredients from NYS. A similar model could be implemented for the NY hemp fiber industry to increase demand for locally grown hemp. If lumber companies, paper corporations, and plastics manufacturers were held to similar standards, a sustainable and valuable hemp fiber supply chain would be much more attainable.

Decoupling hemp and marijuana is imperative for the successful future of the hemp industry. Advocacy for hemp is often clouded by marijuana legalization, as many believe it is hard to imagine the passionate advocacy for hemp is unrelated to its link to drug policy (Caulkins, et al., 2012). While this may hold some truth, states such as Colorado, which have established recreational industries, also have some of the more established valuable hemp supply chains. While some supply chains for fiber hemp exist in the Midwest, the Northeast U.S and particularly New York State have limited valuable supply chains.

Case Study: South Hemp Tecno

The objective of this case study was to inquire about the sustainability goals and practices of South Hemp Tecno's supply chain and identify challenges of an emerging hemp fiber processing company. There is still much debate surrounding the overall sustainability and environmental friendliness of hemp production. This case study can potentially illuminate hidden insights surrounding the sustainability of the fiber hemp supply chain, garnering attention for a much-needed direction for future research. Can companies tap into the sustainability of the hemp fiber supply chain to increase consumer awareness and demand toward hemp products? Many consumers are becoming increasingly aware of sustainable approaches to agriculture. This, coupled with a sense of pride from purchasing locally owned products, could potentially create the consumer demand needed for local supply chains in the industrial hemp industry.

Rachele Invernizzi is president of South Hemp Tecno, a hemp fiber processor in Crispiano, Taranto, which is located in southern Italy. She guided the development of a decortication facility that went online in 2015 (Figure 5), and her company incubates new hemp businesses. Rachele is also a founding partner of Federcanapa, the Italian federation that backs hemp initiatives throughout Italy's regions and has organized the first international hemp expo and seminar, Salone Internazionale della Canapa, in Milan. Her company is focused on developing the first step in the hemp fiber supply chain in Italy through the primary transformation of hemp straw by decortication. Rachele is a member of the European Industrial Hemp Association and has established worthwhile relationships with many in the hemp industry through her sincere advocacy of the Cannabis plant. Ms. Invernizzi's passion has fueled South Hemp Tecno's success in becoming well known in Europe and abroad. Managing relationships has helped create positive, honest environments for those she forms partnerships with. Consulting farmers under contract with South Hemp Tecno is one of the many responsibilities Ms. Invernizzi takes on. This is important as farmers do not know how to grow the crop. Farmers are typically trialed on one hectare (~2.5 acres) of land for the first year. Then, depending on the size of the farm, farmers can upscale based on their comfort. Ms. Invernizzi advises farmers to rotate hemp with cereal crops like wheat, and leguminous crops, such as chickpeas.

The southern region of Italy is known for its hot, dry summers. While this climate does not impede the growth of hemp, it is a challenge for yields to reach their full potential. Irrigation is only used immediately following sowing, therefore the lack of rain throughout the summer makes it difficult to achieve 10 tons of biomass per hectare. The dry climate also makes field retting more difficult for microorganism proliferation. Another challenge resides in the mechanical aspect of the equipment. Many farmers in southern Italy are small farmers and typically have older technology not adapted for hemp production. It is common for equipment to break down, which can make the process of sowing and harvesting tedious and difficult. To solve this, South Hemp Tecno sources a third-party company to harvest fields in which farmers do not have the equipment for (Figure 6). Each year, farmers are required to purchase new seed and cannot reuse seed from previous years due to purity and germination issues when seeds age. A risk can occur when farmers reuse seeds and germination percentage becomes a problem. As seed prices continue to rise, the value that is generated from a harvest must increase if the production process is to be sustainable.

Due to the physiology and growth of hemp, male plants tend to mature, and thus senesce, quicker than female plants (Van der Werf, 2004). Having uniform fields of gender is important for successful harvests. Cultivar development will play a major role in potentially solving yield issues. As described earlier in this review, hemp is a photoperiodic plant. Long term varieties tend to work well in the South of Italy. Cultivars such as ‘Finola’ and ‘Futura-75’ do not accommodate the growing season or climate of southern Italy. ‘Finola’ transitions into the flowering stage too quickly, which does not generate sufficient biomass needed for profitable harvests. ‘Futura-75’ is a cultivar that is popularly grown in France but needs levels of humidity that the climate of southern Italy does not provide. Breeding for well-adapted varieties for southern Italy will surely aid in optimizing yields in the future.

Sustainability is a focus in every step of the supply chain for South Hemp Tecno. To create a more local and sustainable supply chain, the company’s goal is to have a processing facility within 50 km (~31 mi) of their farms. This not only cuts down on cost of transportation, but also helps to generate more control over the raw materials. Companies around the world are beginning to experience pressure from the public to produce more sustainable products. South Hemp Tecno has an opportunity to supply raw material to a major producer of feminine products, baby wipes, paper towels, and diapers. The Italian manufacturer currently uses 100% polylactic acid (PLA) material to create their products. Interest has arisen from the manufacturer to seek out natural fiber replacements for their products, such as utilizing 20% hemp hurd in their baby wipes. While this is only a small portion of the total product production, it is a step in the right direction and will help generate the need for increased cultivation of hemp in Italy.

By valuing and assisting farmers, setting up local supply chains, and experimenting with sustainable production practices, South Hemp Tecno has created a unique opportunity in Italy for the fiber hemp industry. Managing the beginning of the supply chain allows South Hemp Tecno to have more opportunities to enter different markets; if one market dies, they have the raw material to supply other markets. Collaborating with researchers, customers, and partners has been vital to the success of the company. Setting realistic goals with farmers and collecting data is important so that the company does not take on more than it can realistically handle. The trustworthy connections that Rachele Invernizzi have made has propelled the company into what it is today. Increasing consumer awareness through sustainable practices should be a focus for all companies invested in the hemp fiber industry.

Figure 5. South Hemp Tecno's fiber processing (decortication) facility. Retted hemp stalks are fed through the machine and separated into long fibers and different sizes of hurd.

Figure 6. South Hemp Tecno president, Rachele Invernizzi, walking alongside a third-party harvester in Taranto, Italy. This machine is built for dual-purpose grain and fiber harvests. The combine (in red) harvests the top flower heads of the plant, while the lower portion (in green) cuts the base of the stalks.

CONCLUSION

Research focused on optimizing agronomic practices, cultivars, life cycle assessments, and local supply chains will only legitimize the question surrounding the sustainability of hemp. More light should be shown upon those that are passionate about sustainable agriculture and the interesting applications for which hemp fiber & hurd can be used. *Cannabis sativa* L. is a plant that people are generally excited to learn about and grow. Standardizing hemp as an agricultural crop, communicating what hemp is realistically used for and why it is important, and escalating collaboration between academia and industry should be the goal and focus of those in the scientific community and industry alike. Furthermore, the communication between the scientific community and those in the hemp industry needs to become more standardized. When communicating information, much can be lost within specific jargon and terminology. Finding more efficient ways to communicate and understand one another will only aid in the development of the industry. The industry should become more pragmatic about the opportunities of hemp. Marketing industrial hemp as a plant that can “save the world” creates unrealistic expectations. Advancements in plant breeding, production practices, local supply chains, and government regulations will all play a major role in developing the New York hemp fiber industry. Establishing trustworthy, honest relationships in cooperation with furthering common goals paves a path toward sustainable development of the hemp fiber industry in New York State.

Future Directions

In future reviews, Google Translate should be considered as a tool to be used for making non-English documents of interest readable to monolingual English speakers.

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APPENDIX

The following databases were searched:

- Web of Science's Core Collection
- ProQuest Research
- bioRxiv
- Google Scholar

The search strategy was to combine searches of:

- Hemp AND Genetics related terms
- Hemp AND Production related terms
- Hemp AND Supply Chain related terms
- Hemp AND Environment related terms
- Hemp AND Economic related terms
- Hemp AND Regulatory related terms

Hemp terms

1. Hemp
2. Fiber
3. Cannabis sativa

Genetics terms

1. Genetics
2. Breeding

Production terms

1. Production NEAR/5 practice*
2. Cultivation
3. Fertility
4. Outdoor

Supply Chain terms

1. Supply chain
2. Market
3. Processing
4. Textile

Environment terms

1. Environment*
2. Sustainability
3. Biomaterial
4. Life cycle assessment

Economic terms

1. Economics
2. Cost
3. Cooperative
4. Business

Regulatory terms

1. Regulat*
2. Bill
3. Law
4. Legal
5. Political