Elucidating the Impact of Fiber Source on Polypropylene/Hemp Composite Performance for the Automotive Industry

Amber M Hubbard[1*], Julia Gelfond[1,2], Kathryn Slavny[1,2,3], Komal Kooduvalli[1,4,5], Katie Copenhaver[1], Meghan E Lamm[1], Sanjita Wasti[1], Matthew Korey[1,6], Yunqiao Pu[7], Caitlyn M Clarkson[1], & Umesh Marathe[1]

1. Manufacturing Science Division, Oak Ridge National Laboratory, Oak Ridge, TN 37830
2. ORISE Participant in the U.S. Department of Energy Education Collaboration at ORNL Program, 1299 Bethel Valley Rd, Oak Ridge, TN 37830
3. ORISE Participant in the U.S. Department of Energy Science Undergraduate Laboratory Internships Program, Oak Ridge National Laboratory, 1 Bethel Valley Rd. Oak Ridge, TN, 37830, USA
4. Golisano Institute for Sustainability, Rochester Institute of Technology, 190 Lomb Memorial Drive, Rochester, NY 14623, USA
5. ORISE Participant in the U.S. Department of Energy Graduate Research at ORNL Program, 1299 Bethel Valley Rd, Oak Ridge, TN 37830
6. Department of Mechanical, Aerospace, and Biomedical Engineering, University of Tennessee, Knoxville, TN 37996
7. Biosciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37830

*Corresponding Author: hubbardam@ornl.gov

Supplemental Information

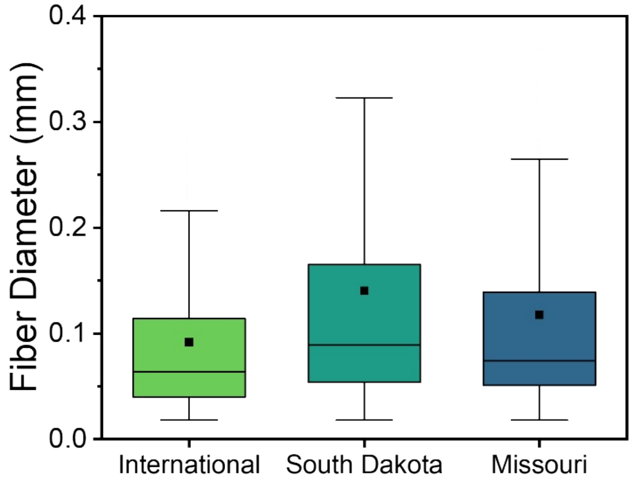


Figure S1. The fiber diameter is shown for all three hemp fiber types, as processed. MO and SD represent hemp fiber sourced from Missouri and South Dakota, respectively while Int'l represents hemp fiber sourced internationally. The fiber diameters were measured via ImageJ after being imaged via optical microscopy; there is no statistical difference between fiber diameters, regardless of fiber type. Micrographs were taken on a Keyence optical microscope at 20x magnification to perform the image analysis. Widths of a minimum of 250 fibers from three different samples were recorded for each fiber type.

Table S1. The TGA and DSC data is shown for all composite formulations of interest.

Sample	T_{onset} (°C)	$T_{2\%}$ (°C)	T_m (°C)	T_c (°C)
Neat PP	271.6	248.8	163.5 ± 3.7	110.1 ± 4.0
PP + MAPP	268.9	239.8	160.4 ± 1.0	110.9 ± 0.3
Int'l HF	309.4	263.3	163.0 ± 2.1	120.0 ± 1.0
Int'l HF + MAPP	287.3	240.2	158.6 ± 2.5	114.8 ± 1.5
MO Hemp Fiber	308.1	255.3	161.8 ± 1.0	119.1 ± 1.3
MO Hemp Fiber + MAPP	278.2	240.4	157.7 ± 1.8	115.2 ± 1.3
SD Hemp Fiber	297.5	247.1	161.7 ± 2.1	117.5 ± 0.5
SD Hemp Fiber + MAPP	261.0	226.4	159.8 ± 1.8	114.4 ± 0.1
Hemp Dust	276.4	240.0	162.6 ± 0.4	119.7 ± 0.5
Hemp Dust + MAPP	272.1	232.5	159.1 ± 0.6	116.3 ± 1.1

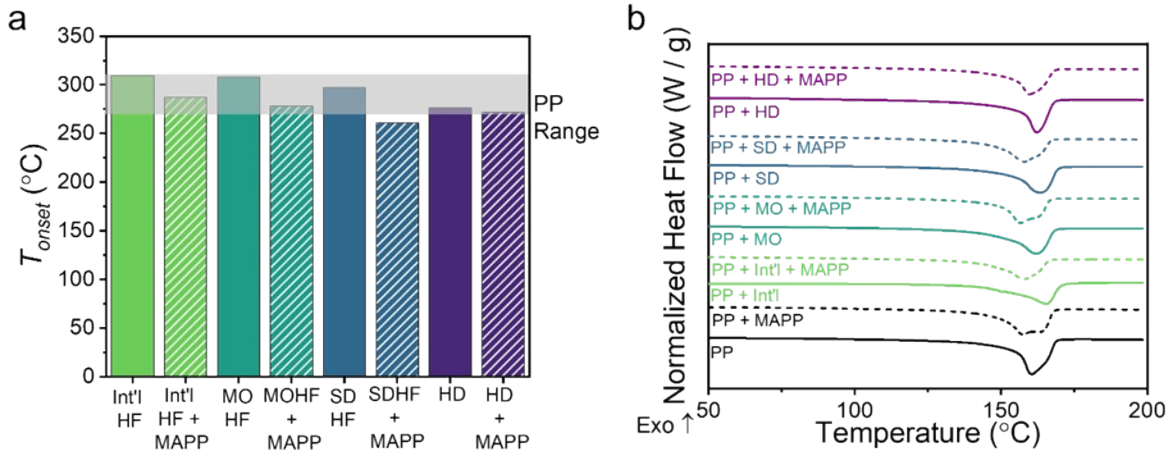


Figure S2. (a)The onset temperature of degradation (T_{onset}) is shown for all composite formulations as measured via thermogravimetric analysis (TGA) where the addition of MAPP lowers the T_{onset}. (b) The second heat curve from differential scanning calorimetry (DSC) is shown for all composites where the addition of MAPP lowers the T_m.

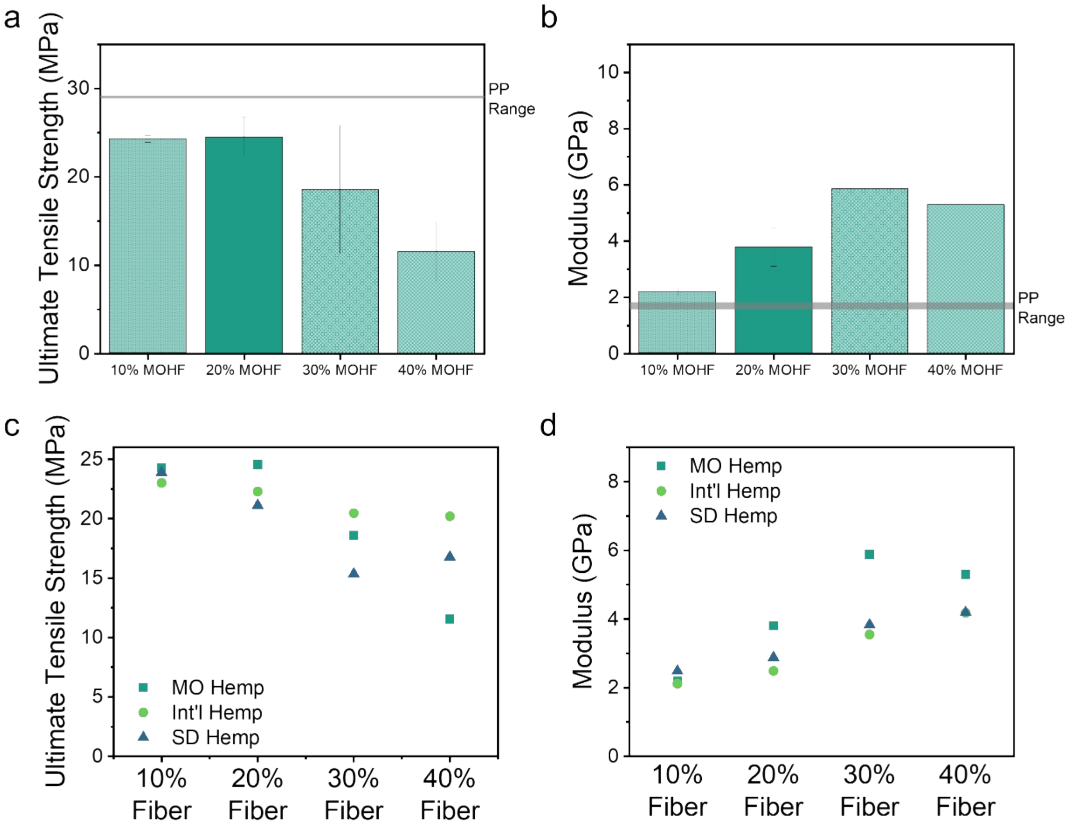


Figure S3. (a-b) The tensile properties are shown for the MO hemp fiber at varying fiber concentrations, where the MO fiber was chosen as a representative fiber. (c-d) Scatter plots show the trend of decreasing tensile strength and increasing modulus for all fiber types.

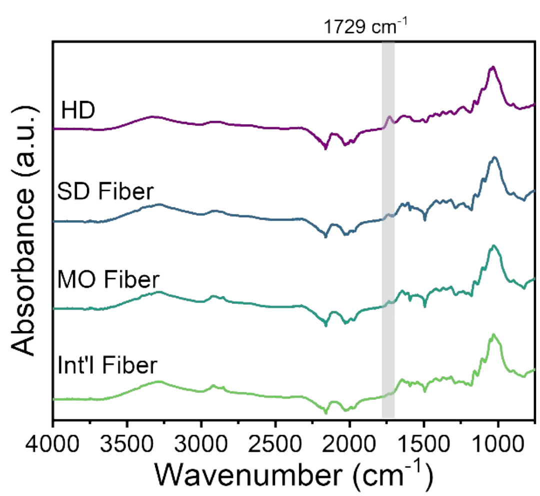


Figure S4. FTIR is shown for all four hemp fillers where each curve was normalized by the 1030 cm^{-1} peak. While there appears to be no significant difference between any of the hemp fiber types, there is a peak difference observed for the hemp dust (HD). There is a peak present at 1729 cm^{-1}, likely due to a carbonyl present in the industrial additives which is not surprising as this is a byproduct from an industrial process.

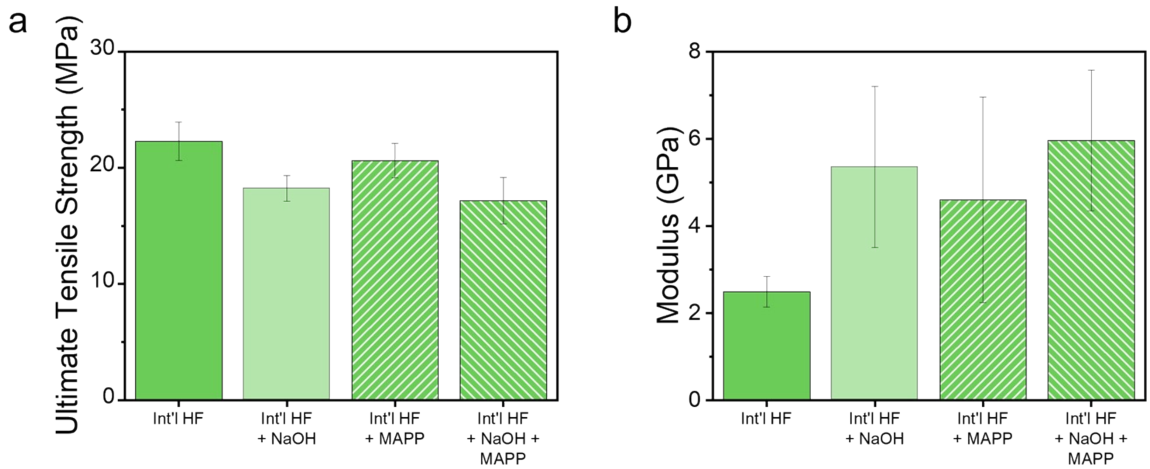
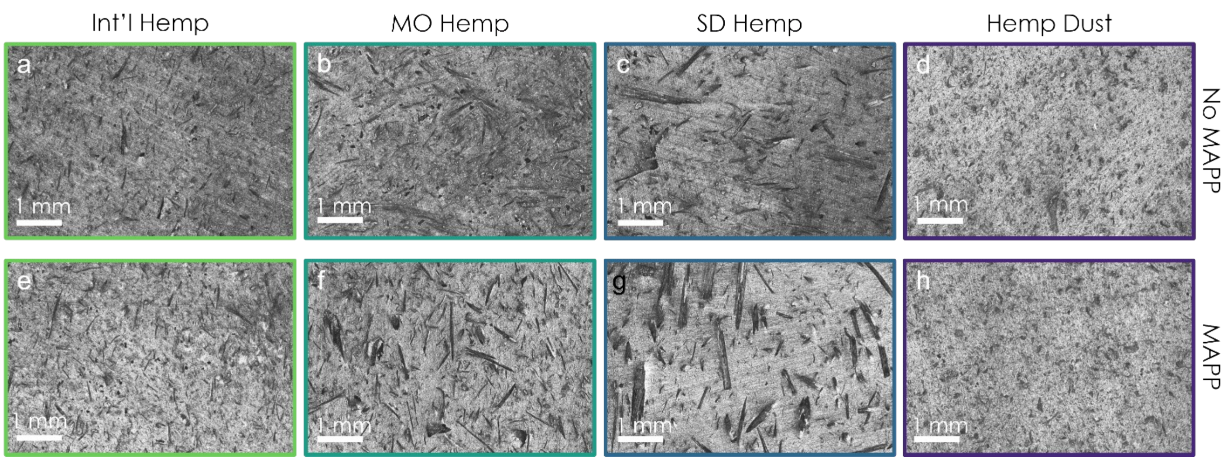


Figure S5. The tensile properties are shown for the international hemp fibers in polypropylene (PP) at a 20wt% concentration where both the ultimate tensile strength (a) and Young's modulus (b) are shown. In this case, the Int'l fiber was chosen as a representative fiber. The results are also shown for fibers treated with a sodium hydroxide (NaOH) treatment and with a malleated polypropylene (MAPP) compatibilizer present in the system. The tensile strength is lower for all composites than neat PP, but there is no significant variation with the addition of either an NaOH treatment or MAPP compatibilizer. The modulus value is higher for all composites than neat PP, where the NaOH treatment and MAPP compatibilizer provide a significant increase in



performance.

Figure S6. All composite formulations were potted and polished so that the surface could be studied via optical microscopy for samples without (a-d) and with (e-h) MAPP present. It is clear from these images that the hemp dust samples have the smallest particle size after melt compounding, followed by the Int'l hemp samples. The SD and MO composites have the largest particle sizes. Qualitatively, all fillers appear to have achieved good dispersion in the matrix. It should be noted that as the fibers were initially ~ 6 mm in length, they clearly experienced significant attrition during compounding.

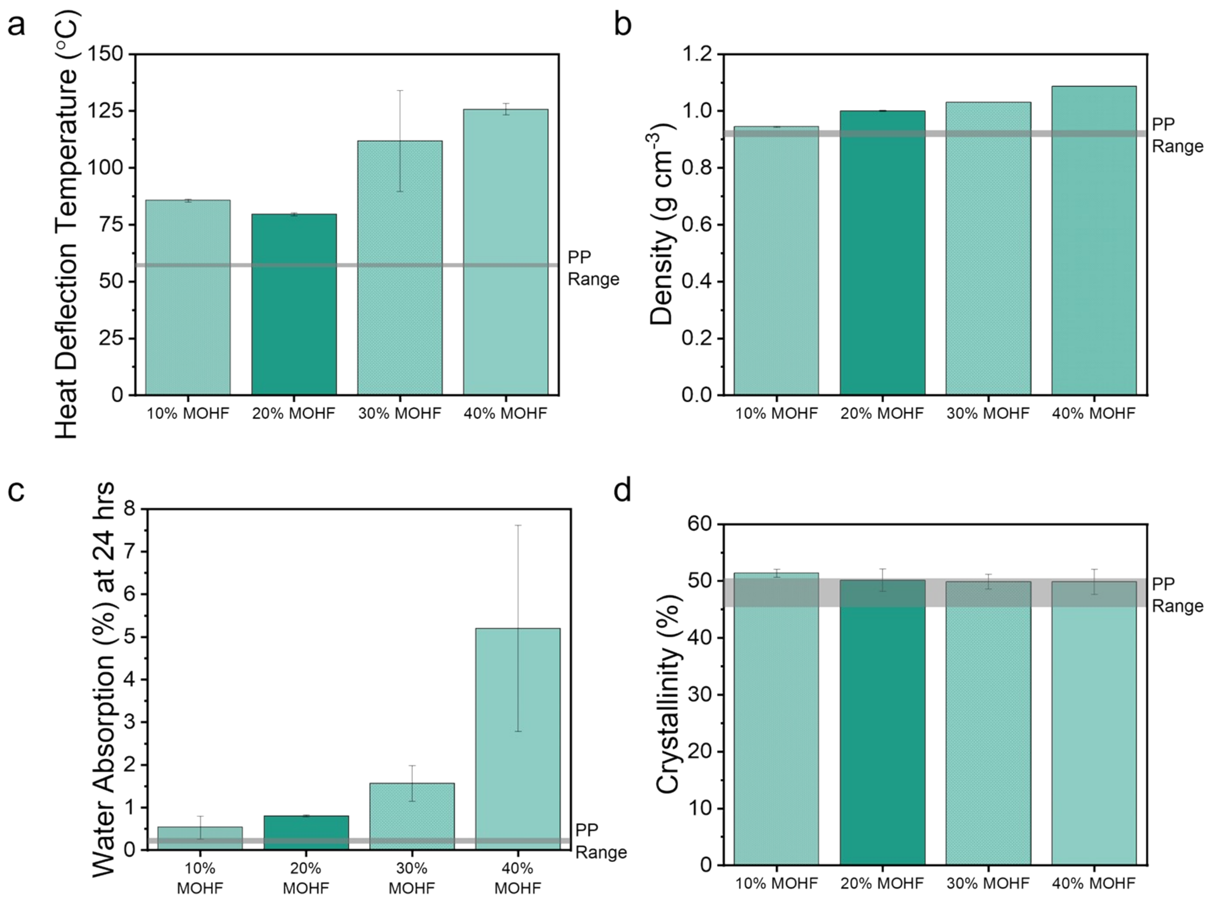


Figure S7. The heat deflection temperature (a), density (b), water absorption and 24 hours (c), and crystallinity (d) results are shown for composites at varying filler loadings from 10wt% - 40wt% where the filler is MO sourced hemp fiber, chosen as a representative fiber. The HDT, density, and water absorption for all composites is higher than neat PP, where increasing fiber loading increases these values; it should be noted that the variability tends to increase with fiber loading as well. The crystallinity of all composites, regardless of fiber content, is comparable to that of neat PP.

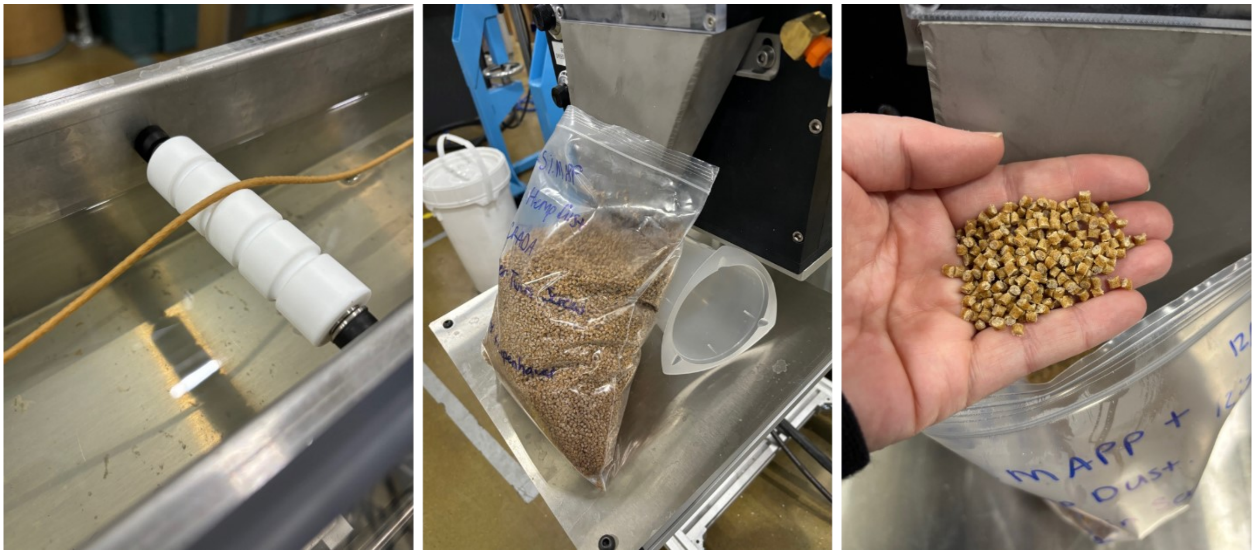


Figure S8. A composite formulation (PP + 20 wt.% HD + 5 wt.% MAPP) has been scaled to produce ~9 kg of composite via a twin-screw extruder. In this case a Brabender Intelli-Torque Plasticorder Torque Rheometer was used in the twin-screw configuration. The temperature profile for the 6 heating zones from feeder to nozzle were the following: 160 °C – 165 °C – 170 °C – 175 °C – 180 °C – 180 °C. The screws were set to an RPM of 75 and the material was fed at a rate of 0.25 kg/hr.

Figure S9. A coin was injection molded from the scaled composite seen in **Figure S8**, to demonstrate the ability of this material to be injection molded. In this case, an APSX-PIM V3 Plastic Injection Machine was used to injection mold these materials at a temperature of 190 °C, an injection pressure of 220 bar, a hold pressure of 18 bar, and a hold time of 6 seconds.

Environmental Transportation Analysis

Life Cycle Assessment (LCA) is a tool that is utilized to help with the "compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle"[1] whose framework and guidelines for practice has been put forth by ISO (14040/44).[2,3] In this study, a comparative screening analysis is performed considering the transportation of hemp fiber regionally and internationally. For this purpose, first, relevant modes of transportation were listed. **Table S2** represents each mode taken from the Ecoinvent 3.10 database with *allocation, cut-off by classification – unit* processes.

Table S2. Life Cycle Inventory (LCI) processes relating to hemp transport modes

Transport Mode	Types of Transport
Truck	Transport, freight, lorry >32 metric ton, EURO5 {RoW}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, U
	Transport, freight, lorry 7.5-16 metric ton, EURO5 {RoW}| market for transport, freight, lorry 7.5-16 metric ton, EURO5 | Cut-off, U
Train	Transport, freight train {US}| market for transport, freight train | Cut-off, U
Ship	Transport, freight, sea, bulk carrier for dry goods {GLO}| market for transport, freight, sea, bulk carrier for dry goods | Cut-off, U
	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship| Cut-off, U
	Transport, freight, sea, container ship with reefer, cooling {GLO}| market for transport, freight, sea, container ship with reefer, cooling | Cut-off, U
	Transport, freight, sea, container ship with reefer, freezing {GLO}| market for transport, freight, sea, container ship with reefer, freezing | Cut-off, U
	Transport, freight, sea, ferry {GLO}| market for transport, freight, sea, ferry | Cut-off, U

The options in grey were deemed unsuitable for this model as the materials taken for this study were found to neither be transported via freight train nor required temperature control, since they were not considered live plants or perishables. Data quality for those that were selected may be affected further due to modeling choices, some of which include:

1. Distance metrics obtained from Google Maps – these routes are known to vary due to roadwork, closures, timings, etc. The distances mentioned in this study were obtained in March of 2025, considering the shortest routes between two given locations. Locations of

various hemp farm locations, processing facilities, and destination were listed out to estimate total travel distances (**Table S3**).

2. All data sources are taken from Ecoinvent v.3.10 with uncertainty attributed to the values inherently contained within the database.
3. Truck sizes considered a range from 7.5-16 metric tons on the lower end and >32 metric tons on the higher end based on inclusion in other hemp-based LCA studies.[4, 5] Although EURO 4 was the choice in one of these papers from 2013,[5] EURO 5 and EURO 6 standards were released in 2009 and 2014, respectively. Therefore, EURO 5 was taken as conservative estimate since the average service life of trucks is typically considered to be 10-15 years.[6, 7]
4. In this case, values relating to transporting 1 kg of hemp were considered. However, bulk shipping will transport thousands of pounds of hemp with specific kinds of packaging occupying certain volumes which have not been accounted for here.

Table S3. The travel distances used for all LCA calculations are shown per starting fiber location. It should be noted that the final location for manufacturing is listed as Knoxville, TN. Specific location names and addresses have not been mentioned due to confidentiality.

International	Missouri	South Dakota	Tennessee
Step 1 Grower & Processor → Int'l Port (truck – 836 km) **Step 2** Int'l Port→ Port of NY & NJ (ship – 5,697 km) **Step 3** Port of NY & NJ → Processor (truck – 995 km) **Step 4** Processor → Compounder (truck – 196 km) **Step 5** Compounder → Manufacturer	**Step 1** Grower → Processor (truck –1001 km) **Step 2** Processor → Compounder (truck – 196 km) **Step 3** Compounder → Manufacturer (truck – 32 km)	**Step 1** Grower → Processor (truck – 2017 km) **Step 2** Processor → Compounder (truck – 196 km) **Step 3** Compounder → Manufacturer (truck – 32 km)	**Step 1** Grower → Processor (truck – 658 km) **Step 2** Processor → Compounder (truck – 196 km) **Step 3** Compounder → Manufacturer (truck – 32 km)

(truck – 32 km)			

One of the scenarios was slightly altered whereby the closest port was chosen for trucking within the international scenario in France, as opposed to the largest commercial one (economic). This change resulted in a 627 km decrease in overall distance leading to substantial savings, as seen in **Table S4** below.

Table S4. Differences in outcomes as a result of using the shortest port distance in France

	Total Distance	Low GWP (kg CO2e)	High GWP (kg CO2e)	Low CED (MJ)	High CED (MJ)
Int'l Farm and Facility to Largest Port	7756	0.26	0.56	3.99	8.32
Int'l Farm and Facility to Closest Port	7129	0.19	0.41	2.94	6.02
Percent Increase		27%	27%	26%	28%

Therefore, it must be noted here that these results are sensitive to the assumptions and data quality that embed the model. There are several modifications to the current model assumptions that could be pursued, which would change the overall results. Some of which include:

1. Transport mode – The most considered transport modes (truck and ship) are not the only variations that may exist. For example:
    a. Depending on truck types and capacity, smaller trucks or alternative roadway vehicles may be used for transporting these fibers within each country/region.
    b. The modeling in this scenario considers a mass of 1 kg being transported across certain distances (km) from Ecoinvent, without consideration for actual hemp volumes.
2. Distance to various facilities – The location of facilities where fibers are pre-processed, processed, and packaged affect the outcome.
3. Fiber growth conditions, pre-processing, and composite production were considered identical. However, it is known that variations relating to growing conditions, processing, and other inputs that are likely to influence outcomes.

References

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