Life cycle analysis for green composites: A review of literature including considerations for local and global agricultural use

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Abstract
Increasing concerns regarding human-driven effects on the biosphere have led to the development and adoption of environmentally friendly “green” composites. Unlike conventional synthetic composites, green composites are made of natural materials in either the matrix or the fiber reinforcement (or both). They are claimed to have lower negative environmental effects due to their sustainability and easier recyclability. To assess the environmental impacts associated with any product, a life cycle assessment (LCA) is needed. This literature review summarizes the individual steps undertaken in an LCA study and discusses their relevance within the field of green composites. Similarly, an outline of life cycle costing (LCC), a type of study which determines the economic implications of a product, is incorporated. Since some phases of a product’s life cycle can have significant environmental effects, parameters affecting the time-dependant degradation of green composites and their significance in LCA studies were also explored. Finally, criteria for choosing natural fibers and biopolymers for green composites in engineering applications were considered, and case studies of hemp and flax as candidates for fiber cultivation in Alberta, Canada are provided throughout.

Keywords
Braiding, composite fabrics, life cycle analysis, green composites, textile composites

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Introduction
With increasing awareness of human-driven climate change, there is a push to take steps to reduce environmental impact and carbon footprint. One approach to decrease the amount of carbon dioxide and other greenhouse gases (GHG) released to the atmosphere is to incorporate sustainable practices into commercial production and consider the environmental effects of the product for production, use, and end of life-cycle/recycling phases. Although industrialization has enabled inexpensive mass production, the vast amount of resources used and waste produced contributes to the depletion of natural resources and pollution.

Life cycle assessment (LCA) is a tool that can be utilized to determine the total environmental impact of a...
product throughout its lifetime. An important aspect within LCA is tracking and estimating the inputs and outputs of resources for a specific product and/or process. By completing an LCA, the environmental impact of a product can be compared to another product and improved upon. The different stages of a product’s life can be assessed to determine where the most resources are used or the most GHG are released so that the process can be improved upon toward a more sustainable approach.

Fiber-reinforced composites are materials composed of fiber bundles embedded in a matrix material. In this review we will focus on polymeric fiber reinforced composites where, typically, a polymeric resin, that is homogeneous and isotropic, is used as the matrix material. Composite materials are designed and built to combine the properties of their constituents to produce a superior end-product. Fiber-reinforced composites can be manufactured in several ways depending on the size and orientation of the reinforcement, as well as the type of matrix material used. Synthetic fibers are conventionally used in these composites because their properties are more consistent and controllable than naturally sourced fibers. However, entirely synthetic composites can have a large, negative environmental impact. This is a result of the resources required and waste disposed to produce and process these materials. Composites made of synthetic fibers are not biodegradable and cannot be recycled at the end of their life due to the dissimilarity between the fibers and the matrix. Furthermore, most composites are manufactured using petroleum-based synthetic polymer matrices. These non-biodegradable artificial polymer matrices contribute to global warming, accelerate land fill deposits, and promote toxic environmental effects.

In contrast, natural fibers are biodegradable at their end-of-life, or they can be incinerated for energy return. Further, if the matrix is also biodegradable, the entire composite can be decomposed at the end of its usable life. Usage of biopolymer matrices made from renewable materials also minimizes human dependence on non-renewable fossil fuels. A bio-composite is made from either a natural fiber reinforcement or natural matrix. A “green” composite is made from both natural fibers and natural matrix. Thus, developing “green” composites with significantly lower environmental impact than synthetic-based composites is promising. LCA can be applied to present environmental comparisons between natural fiber composites and synthetic fiber composites in all stages of their life cycle. These comparisons are important to determine the sustainability of further developing green composites.

Currently, available review literature in this area is limited to the properties of natural fibers, bio-composites, and green composites. Further, existing LCA reviews have been limited to select polymers or bio-composites, but not green composites. Accordingly, the purpose of this review is to present and examine the requirements of LCA when applied to green composites while incorporating aspects of economic impacts (life cycle costing) and durability. The lack of literature on LCA applied to green composites is an obstacle in presenting green composites as viable alternatives to synthetic composites. Additionally, this review will cover an introduction to choosing a type of natural fiber with a consideration of location. This will include consideration for a case study of natural fiber cultivation in Alberta, Canada. This paper aims to demonstrate the value of this analysis in all future work that wish to undertake valuable R&D and technological development using green composites.

**Life cycle assessment**

LCA is “an analytical tool specifically designed to assess the environmental impacts relating to the whole production chain of a good.” To ensure a complete analysis, LCA also examines the product’s impacts during use and at the end-of-life disposal. As a tool, LCA is very broad and can be applied to various industries, areas, and types of products. Thus, a guideline cannot specify how to carry out each individual step because the exact procedure can vary drastically between products. Rather, the International Organization for Standardization (ISO) has organized a general protocol to follow and necessary steps to complete an LCA. However, as ISO defines LCA, it does not involve an analysis of other factors apart from environmental, such as social or economic factors which are important considerations.

LCA is useful to analyze a single product, but can be used to compare two products. In this case, LCA assists in determining if a new product, when compared to a previous one, would be more or less environmentally friendly. In the process of performing an LCA, the steps of a product’s life are broken down so that data of each significant input and output of resources and energy can be accounted for. This rigorous procedure is vital to the design process so that changes can be made in phases of the product’s life cycle where there is potential to improve environmental effects. Accordingly, LCA is an important step in the development of green composites as it enables the production of material with much lower environmental impacts than its synthetic equivalents.

**Basic requirements**

ISO has established guidelines for LCA to harmonize the basic procedure of studies. ISO 14040 outlines the principles and framework of LCA, and ISO 14044 outlines the requirements and guidelines of LCA. From the standards, the steps are (1) identify the goal and scope of the analysis, (2) compile a life cycle inventory (LCI), (3) complete a life cycle impact assessment (LCIA), and (4) interpret the results. These steps are described below.
Goal and scope. From ISO 14040, the first step of LCA is to define and clearly state the goal of the study. This involves explaining the purpose of the analysis and the applications of the results. The scope of the study must also be defined, which includes setting system boundaries. The system boundary defines where the system is separated from the environment so that all inputs and outputs can be tracked. With the system boundary, it should also be stated and reasoned what stages of the product’s life cycle will be analyzed. Most studies use a cradle-to-grave approach, which is defined from production to disposal. It is important to distinguish the boundary for the production and the end-of-life stages, where systems like forests, fields, and landfills are involved. Consistency is critical when determining where the system is divided from the environment.

A functional unit must be established in this step. The functional unit is a set amount of product which is to be analyzed, or some other quantity that describes what is being studied. By establishing a functional unit, all the input and output flows of all processes in a system can be compared and compiled. Further, a functional unit is useful for a comparative study of two different materials. In this case, the overall input and output value units are equivalent between the two types of materials so that individual environmental impacts are simpler to compare. While the functional unit is often an amount of product, it can also be a value of time for the product to be in use. This definition depends on the function of the product. An example of a time-based functional unit is illustrated in an LCA study by Pegoretti et al., which compared three acoustic panels in the Brazilian automotive sector. One was made of mainly synthetic plastics and the other two were made of recycled cotton. By following ISO 14040, the goal was defined to “evaluate and compare the potential environmental impacts of the three acoustic panels... considering the environmental concerns of the automotive industry in Brazil.” For the scope of the study, it was stated that the LCA would consider three phases: production, use, and end-of-life. The functional unit of the study was “maintaining an acceptable acoustic level inside a vehicle during 10 years.” Although this is not a unit to describe the amount of product made, it is applicable for this study. The panels are made such that they would all maintain the acceptable acoustic level throughout their use over a 10-year period. They all achieve the same function, although the amount of product used for each panel may be different. It is important to note that there are no calculations for data collection completed in this step.

Life cycle inventory. The second step of LCA is life cycle inventory (LCI) analysis. As the most time-consuming and extensive phase, LCI requires identifying and quantifying the resource flows for the system. The purpose of LCI is to create an inventory of all inputs and outputs of materials, wastes, and natural resources for all processes, in relation to the functional unit. Before a quantitative analysis, all unit processes must be defined inside the system boundaries. Unit processes are elementary steps in a product’s life that can consist of a single or grouped operation. All the unit processes can be connected to form the product system. Next, all flows of water, energy, and raw materials into the system, the waste released to the atmosphere, land and water, and use of land are traced and recorded for each unit process. Here, it is important to be detailed and consistent with system boundaries. A flow chart can then be made to visualize and connect the flows for unit processes. The flows must be quantified so that they are relatable in terms of the functional unit. To help with data accuracy and consistency for LCA, databases have been created for common areas of study such as energy, waste treatment, and chemical production. However, it would not be practical to have a complete database for LCA due to the vast number of different materials and specific processes that are possible. Hence, the databases could be too general for a thorough analysis or for LCA in a different sector. For these reasons, or for lack of available data, some processes would require the collection of primary data for a complete analysis of a more specific case study. Once data collection is completed, it is organized into a list or “inventory table” to be further analyzed in the next step.

In a study by Leejarkpai et al., three boxes of polystyrene (PS), polyethylene terephthalate (PET), and polylactic acid (PLA) were compared for their impact on global warming using cradle-to-grave LCA. PS and PET are both petroleum-based plastics, whereas PLA is a bio-based plastic. In the LCI step, the system was broken down into unit processes. However, unit processes were compiled into two general stages of the product’s life cycle: production and waste management. For production, data for all three boxes were gathered from a previous LCA study. Waste management was separated into transportation of used boxes, sanitary landfill, and controlled composting. The transportation data was estimated based on the distance traveled and the amount of product transported. Sanitary landfill disposal and controlled composting data were obtained from a primary biodegradation study.

The LCI method described here is used in what is called “process-LCA,” which is the most extensive and most popular method. There are ways to simplify this method, such as vertical cut-offs to reduce the detail in the information required for each unit process. An alternative method exists based on industry input/output called “I/O-LCA.” Modeled with supply chains using economic databases, I/O-LCA focuses more on combining economic analysis with environmental assessment. Applications suitable for I/O-LCA utilization include assessing the overall environmental impact of a system or for comparing highly dissimilar options on a regional, national, or international level.
The third step of an LCA process is a life cycle impact assessment (LCIA). The purpose of LCIA is to determine and evaluate the overall environmental impacts within the system. This step builds on the analysis completed in LCI because the outcome of LCI, the inventory table, is usually very long and complicated, and requires further assessment. To do this, LCIA converts the results of the inventory analysis to common units within several impact categories. In the ISO standard for LCA, LCIA is broken down into steps, some of which are not mandatory. In order, these steps are: (1) selection of impact categories, (2) selection of impact category indicators, (3) classification of inventory results into categories, (4) characterization, (5) normalization, (6) grouping, and (7) weighting. The first four steps are mandatory, whereas the remaining three are optional.

First, impact categories must be selected. Impact categories are groupings of resource flows and environmental factors that cause a common and general type of damage. The impact categories must also follow the goal and scope of the study. In general, ISO defines three broad impact categories to be included: damage to human health, ecosystem health, and resources. If the LCA uses these general categories, the study can be classified as an “end-point damage” model. However, a “mid-point damage” model can instead be used when impact categories are made more specific. For example, some of these categories used could be climate change, ozone depletion, human toxicity, and acidification. Further, land use is an impact category that has been used more frequently. Although it may seem unnecessary, land use is an important impact to consider since an occupied area is a limited resource. Once the impact categories are established, they must be further defined in terms of characterization model, category indicators, and characterization factors. This definition is usually based on global models unless the category is a local issue. Characterizing the impact categories will assist in the third step, which is the process of assigning inventory results. Each inventory result is classified into an impact category in a qualitative manner for further analysis. In step four, characterization is when all the results in each impact category are given a common unit so that the numbers can be aggregated to get a final value for the category, called the category indicator result. The complete list of category indicator results is then called the environmental profile.

The first four steps in LCIA are required but three further steps can be taken to recognize the information and prepare it to relate to current trends and previous studies. Normalization is the first optional step, which involves expressing the category indicator results in relation to reference information. When compared, the magnitude of the results cannot be interpreted as the degree of impact on the environment. For instance, a category with a large value could cause less critical damage than a category with a smaller value. This is due to impact categories often having different units, so the values after characterization may not reflect the actual impact. In the grouping step, the results of all impact categories are organized by ranking based on the importance of their impact. Weighing occurs in the final step for the normalized, grouped indicator results. For each result, a numerical weighting factor is generated based on the determined importance. This factor is then multiplied by the indicator result value to yield a weighted value.

Interpretation of results. The final step of LCA is an overall analysis and interpretation of the results in LCI and LCIA with the purpose of answering the initial study goal. This step evaluates and analyses the results so that conclusions and recommendations can be made. Part of this analysis is to determine the consistency and reliability of the data and procedure. Limitations presented by the study should also be discussed. To fulfill the purpose of the LCA, the results must meet the goal and be within the initial scope. If not, the LCA may have to be redefined and repeated as it is not complete.

Although the above information is comprehensive, more information about the LCA process can be found in literature.

LCA of green composites

LCA is a valuable tool for the production and development of green composites. Considering time and resource investments, LCAs aid in determining if advancing these composites is worthwhile. To accomplish this, LCA is typically used as a comparison tool for petroleum-based composites and biodegradable composites. Between fully synthetic composites and fully degradable composites, a natural fiber reinforced petroleum-based matrix is also possible. LCAs can have a “cradle-to-gate” analysis, where only the production phase is analyzed to compare to other studies. However, “cradle-to-grave” assessments could be more important for green composites since the end-of-life disposal can vary significantly from those of synthetic composites.

A central aspect of an LCA study is the choice of impact categories such that they reflect the goal and scope of the study. Green composites are typically sourced from crops produced by agricultural processes. Therefore, it is likely the LCA will have impact categories that are influenced by agriculture. For example, some common impact categories for these studies are: global warming potential, acidification, eutrophication, abiotic depletion, and land use.

Production phase. The production phase is typically where the most materials and resources are used, and the most wastes are produced. Both the fibers and the matrix must be considered separately in this phase as they both will
contribute significantly to resource flow.¹⁰ For the fibers, production typically includes crop growth, harvesting, transportation, and manufacturing. The matrix likely requires an extraction or processing of raw material, then transportation and manufacturing. Like natural fibers, many biodegradable matrices are made from agricultural crops.¹⁶ During the production phase in an LCA for green composites, it is important to consider location. First, the crops must be grown in a climate that supports their growth. Then, if that optimal growth location is far from the manufacturing location, the raw material must be transported. Additionally, location can be significant for determining how the area responds to certain practices. For these reasons, it may be less accurate to use secondary data rather than collect primary data for the study.

Since the production of raw materials for green composites requires land and influences the surrounding area, LCA should incorporate land use impacts as well. In recent studies, natural land is considered a resource as the use of land for agriculture reduces the amount of available land.¹⁸ As the characteristics of land varies with geographical region, the impact on the land will also change, meaning the location of the production should be considered.

The production of natural fibers involves plowing and sowing of land, irrigation, fertilization, pest control, then harvesting and processing. Environmental impacts of each production step can vary significantly between fiber types based on what the crop requires for optimal growth. For instance, hemp cultivation typically does not require the use of pesticides or herbicides since it naturally deters insects and suppresses harmful fungi growth.⁶ Plowing and sowing requires use of machinery and fossil fuels for power, with equipment also releasing pollutants into the air. Depending on the system boundaries, the impact of the machinery can be considered as well.²¹ Agricultural land often lacks the necessary nutrients for crops to thrive. Consequently, usage of fertilizers is common, but contributes to eutrophication in the surrounding ecosystems. Eutrophication occurs when high levels of nutrients are present and encourage excess biomass production in aquatic and terrestrial ecosystems, resulting in a harmful imbalance in the environment. During growth, herbicides and pesticides are usually required to protect crops from invasive weeds and insects. Although this practice will provide protection for the agricultural land, the chemicals used will negatively impact the surrounding area.¹⁸ Once fully grown, the crops will again require machinery to be harvested.

After harvesting, transportation is likely to occur to move the raw, harvested waste to a manufacturing location, and then again to transport the final product to the consumer. The transportation aspect is typically characterized by distance traveled and estimating the type and weight of the vehicle, which then leads to the amount of gas used.²¹,²² Processing of raw material prior to production of the final product could vary significantly between types of plants and the intended use. Further, different machines could be used depending on the manufacturing technique. Therefore, the focus is to determine significant resource inputs and outputs for the process. Waste produced by harvesting and processing could be used as fuel to burn and produce heat for a different process. In a study by La Rosa et al.,²² on cork polymer composites, the scraps from the production were burned for heat for the boiling process. This process of using harvest waste is not new, and several studies have investigated the potential uses of harvest waste.²³ Kengkhokit and Amornsakchai²⁴ investigated the use of pineapple leaf waste for composite reinforcement and showed favorable results in the performance and stiffness of the composites. In a study by Nisticò et al.,²⁵ on manufacturing composite films from tomato plant waste, the waste was grinded in several steps and used as a filler in composite sheets. Accordingly, utilizing industrial by-products as fuel sources can minimize the environmental impacts of harmful, non-renewable fuels.

**Use phase.** Typically, the use phase can be omitted in an LCA because the products compared in the study have the same, or similar, uses. Therefore, they should produce and consume a similar amount of resources over their use phase.¹⁶ In a study by La Rosa et al.,⁶ a comparison LCA of glass fiber and a natural fiber composite was performed. The composites were manufactured to be elbow-fittings for a pipeline. The use stage of this study was excluded because it was assumed that this stage would be equal for both composites. Although such assumptions are common amongst LCA studies, they are not always valid. Often, material durability has considerable influence on environmental impact, since longer service lives lead to less material maintenance and replacement. However, inadequate knowledge of use phase behavior and deterioration processes limit proper consideration of the use phase within LCA studies, especially for unconventional materials like green composites.²⁶ Applications of green composites are limited due to many durability-related parameters, including ambient moisture content, biodegradation, UV exposure, and weathering effects.²⁶–³⁰ A weathering study conducted on green composites by Miller et al.²⁶ has signified the importance of geographic location and weather conditions on use phase material degradation, with warm, moist climates inducing faster degradation rates and more severe ecological effects.

Differences between natural and synthetic fiber use should be noted when the product’s purpose is influenced by the weight of the component.¹⁶ Natural fibers in green composites can have a higher volume fraction, but lower density than synthetic fiber composites. A benefit of this property is the reduced weight of green composites. In the automotive sector, green composites are attractive since
components can be made to be lightweight by substitution of synthetic fibers for natural fibers, thereby improving fuel efficiency.\textsuperscript{31} Several advantages arise from enhancing fuel efficiency within automobiles. A lower rate of fuel consumption is economically beneficial as money can be saved on fuel cost overtime. Additionally, better fuel efficiency decreases environmental impacts as less non-renewable resources are used and less pollution is released to the atmosphere. However, it is important to note again life expectancy of the component in this analysis and consequently the need for replacement parts.

**End-of-life phase.** For natural fiber composites, consideration should be shown for how the composite will be disposed of at the end of its usable life. Green composites could potentially have favorable end-of-life-phase environmental effects compared to typical synthetic fiber composites. Composites with synthetic fibers and a non-biodegradable matrix typically cannot be reused or recycled inexpensively, often ending up in landfills instead. However, using landfills is expensive and may not fully prevent the leaching of waste into the environment.\textsuperscript{32} It is important to find a way for all composites to be waste-free at the end of their usable life.

Incineration is an alternate option for natural fiber composites. Plant fibers have stored carbon when harvested, which is retained throughout its use. At the end of the composite’s service life, these fibers can be incinerated to release the stored carbon as energy. Burning natural composite will still produce carbon dioxide. However, this carbon was sequestered by the plant from the atmosphere and stored throughout its life, so there is theoretically no increase in emissions.\textsuperscript{31}

Another option is to only use materials that are biodegradable, so that at the end of their life, they can be broken down naturally without any waste left. Further, if both the matrix and the fibers are biodegradable, they do not need to be separated at disposal. Biodegradable materials need controlled conditions and bacteria or enzymes to break them down. If the material is fully compostable, it can break down naturally in a compost pile with other biodegradable scraps under suitable temperature and oxygen conditions.\textsuperscript{32}

Although disposal and incineration are sought for natural fibers, these disposal processes tend to have large disposal costs and are unable to generate new value-added products. Other options available for natural fibers include recycling, reusing, and reducing.\textsuperscript{33} For textile composites, recycling and reusing have been considered viable options for end-of-life processing of these materials.\textsuperscript{34–36} Recycling is a general term that can also include upcycling and/or downcycling. Natural fibers from the process can be used in the production of products of similar quality and value (recycling), higher (upcycling), or lower (downcycling). Upcycling in particular is not only a more environmentally valuable approach to dealing with natural fibers, but also more cost effective. Innovations in recycling textile waste is expected to undergo significant research in the future.\textsuperscript{35}

**Life cycle costing\textsuperscript{31}** While LCA is focused on the environmental concerns caused by a product or system, the process does not consider the economic implications of the product’s life cycle. Often, further studies must be done to form a more complete analysis of the impact of the product. One way to accomplish this is by performing a life cycle costing (LCC) study. LCC serves as a tool to analyze, from the short to long term, the full costs and benefits of a product.\textsuperscript{37} Like LCA, there is no single, broad methodology to follow for all LCC.\textsuperscript{38} Instead, there are many standards and guides to assist in creating a study-specific scope and procedure.\textsuperscript{37} Further, methods have been developed for specific application studies in certain industry sectors. Regardless, the general goal of LCC is to “ensure that all the costs of a product or system incurred over its entire life cycle are integrated into the decision-making process” in the early stages of development.\textsuperscript{38}

There are three classifications of LCC: conventional, societal, and economical. Conventional LCC was developed first to assess the real, internal costs that are expenses for either the producer or user of the product. However, this approach may not always address the entire lifecycle of the product if use and disposal phases are not the financial responsibility of the producer. Additionally, conventional LCC does not address other sustainability aspects such as environmental and social, as it focuses more on the cost for an individual. Thus, environmental LCC was developed to improve conventional LCC by including all life cycle phases and anticipated costs while linked to LCA. Moreover, societal LCC assesses costs covered by anyone within society throughout the product life cycle. Societal LCC builds on environmental LCC while including an assessment of external costs. Societal LCC focuses on society overall and on all people in society affected, including those in the future.\textsuperscript{38} As this review is focused on LCA of natural fiber composites, the environmental LCC approach will be presented in more detail.

The main purpose of environmental LCC is to utilize an assessment of both environmental and economic performance to guide product development and create an optimized weighting between environmental and economic concerns.\textsuperscript{38} Although environmental LCC closely follows an LCA study, the economic system will not follow the exact goals and boundaries of the LCA product system. Instead, the studies must be done in conjunction through the life cycle of the product while setting individual and equivalent system boundaries. An element that is not significant in LCA can still be included in the LCC if it is of economic interest.\textsuperscript{39} Although cradle-to-gate studies are often used for LCA of a product, a partial life
cycle for cost is an inaccurate method for determining the economic impact of a product. The product has a monetary value that is increased and decreased throughout all phases of its life cycle.\textsuperscript{40} Hence, the framework for environmental LCC follows five stages: R&D, material production, manufacturing, use and maintenance, and end-of-life.\textsuperscript{38} R&D stages are usually not included in LCA because this phase does not significantly contribute to environmental impact. However, in LCC, the R&D phase is often included since costs are required to develop the product. If the LCC is performed following an LCA, the LCI can be used. LCI lists and quantifies all the flows of resources into and out of the system. By multiplying the LCI flows by the specific company cost or market price, the costs of the flows can be found.\textsuperscript{39} Then, only the phases excluded in the LCA must be determined separately for the LCC. Caution must be taken when performing LCC due to the danger of double counting costs. LCA includes upstream processes, where materials are extracted and compiled. In LCC however, when a raw material is extracted/harvested and then is used to make another material, the cost for the raw material can be counted twice. For example, if steel is required, the cost of the iron used in the steel may be counted, but that cost is also included in the total cost of the steel. So, if both the costs of the steel and the iron are counted, the iron is double counted. The upstream costs for purchasing a good or service during one stage should be summarized in the price of that good or service, instead of separately counting all the individual inputs.\textsuperscript{40} Finally, an important aspect of LCC scope that must be addressed and carefully considered is the perspective from which the study is performed. Unlike LCA, the values of each stage depend on which perspective is considered, such as the manufacturer or user. The manufacturer is focused on the costs of production and the price of selling the product, whereas the user may only be concerned with the cost of the product, the maintenance required during product use and the disposal costs.\textsuperscript{39,40} These decisions depend on the goal of the LCC study and whether it follows an LCA.

Durability and life prediction

In recent times, scientists and engineers are being encouraged to explore green alternatives in engineering processes and material use to reduce their collective ecological footprint.\textsuperscript{27} One area of innovation emerging to meet this objective is natural composites made from environmentally friendly renewable materials. Widespread availability, low cost of production, biodegradability, and similar specific stiffness to glass fibers are some of the advantages of natural fibers and composites.\textsuperscript{26,28,30} However, certain limitations of the durability of natural fibers exist when compared to synthetic fibers. When evaluating the overall environmental impact of a composite, its durability within its use phase is an important factor to consider. The durability of a composite material is defined as “the ability of resistance to damage developed during the service life or utilization periods.”\textsuperscript{27} The main environmental parameters affecting the durability and lifespan of a composite which will be considered are moisture absorption, UV absorption, biodegradation, and weathering and climate effects. Furthermore, material parameters such as fiber volume fraction and the type of fiber and matrix used within a composite material can also influence a composites durability under certain environmental conditions. The time-dependent degradation of composites poses challenges to engineers when choosing the correct material for long-term applications, as it is often accompanied by significant reductions in mechanical properties which can lead to material failure.\textsuperscript{26–30}

One method of integrating the effects of durability on environmental impact is by using an LCA.\textsuperscript{26,41,42} Multiple environmental impact categories can be utilized to quantify the ecological effects of composite durability. Furthermore, comparing the LCAs of a composite material with and without considering the consequences of durability demonstrates the importance of this variable in conducting a comprehensive analysis.\textsuperscript{26} Most studies including weathering effects on composites prefer using artificial accelerated weathering inside aging chambers instead of natural weathering for organizational and economical reasons. Since artificial weathering’s regularity of cycles, duration, intensity, and exposure conditions often cannot perfectly reproduce natural environments’ more unpredictable qualities, these studies cannot be directly correlated with natural weathering processes. Instead, they serve to provide basic understanding on composite degradation mechanisms under predetermined exposure cycles.\textsuperscript{30}

Moisture absorption

Moisture uptake is an important variable in determining a given composite’s durability. Moisture absorption is particularly important in the context of composites made of natural fibers, as these fibers tend to be hydrophilic and more readily sorb water than synthetic fibers.\textsuperscript{26–28,30} The presence of hemicellulose, a structural component in natural fibers, is the main source of this hydrophilic tendency.\textsuperscript{30} Moisture uptake inside the composite also causes intermolecular hydrogen bonding between the water and fibers, which reduces interfacial fiber-matrix adhesion.\textsuperscript{30} Furthermore, swelling of the fibers via moisture uptake induces stress at the fiber-matrix interface, causing microcracking within the matrix promoting capillarity. Water soluble substances then leach from the fibers, furthering debonding between the fiber and matrix.\textsuperscript{27,30} Finally, water due to humidity can significantly alter the mechanical properties of some polymers due to the hydrolysis or plasticizing effect of water on the polymer chains and molecules.\textsuperscript{43}
The net effect of moisture absorption within natural fibers is considerably lower mechanical properties and compromised long-term durability.\textsuperscript{26–30} Water absorption tests conducted by Dhakal et al.\textsuperscript{44} tested the change in mechanical properties of composites composed of hemp fibers and an unsaturated polyester matrix. Multiple composite samples of different fiber volume fractions were dried in an oven before being immersed in deionized water for 888 h. Tensile and flexure tests were conducted before and after immersion to measure mechanical property deterioration. The results indicated that lower maximum flexural stresses were endured by the wetted samples, as expected. Higher failure strain values were recorded for all the wetted samples, which is likely a consequence of plasticization of the fibers or the fiber-matrix interfaces caused by moisture absorption. However, tensile test results varied between test samples of different volume fiber fractions, as one wetted sample with higher fiber content had a higher tensile strength than when it was dry. The paper suggested that crosslinking or some “other mechanism” could explain this deviation. Another similar study by Maslinda et al.\textsuperscript{45} observed the effects of water absorption on the mechanical properties of hybrid composites consisting of interwoven kenaf/jute and kenaf/hemp yarns combined with an epoxy matrix. The composites were tested while dry and after reaching water saturation following submersion for 1400 h in a container filled with tap water at room temperature. The tensile strength and modulus of the water-saturated composites were found to decrease by up to 67%–75% and 74%–83%, respectively, compared to when they were dried. Furthermore, the flexural strength and modulus reduced by 57%–73% and 68%–78%, respectively, when comparing the dry and wetted samples. Higher tensile and flexural strains experienced by the wetted samples are suggested by the authors of the study to be a plasticization effect induced by lower cellulose content during water ingress. Accordingly, natural fiber hydrophilicity necessitates measures to inhibit moisture absorption to improve green composite performance.

Several methods can be employed to mitigate the negative effects of moisture absorption on natural fiber composite properties. Fiber volume fraction in natural composites, consisting of natural fibers and synthetic matrices, directly influences composite longevity and environmental impact.\textsuperscript{26} The longevity of a composite can be increased by reducing its fiber volume fraction, and vice versa, as the hydrophilic nature of natural fibers ensures increased moisture absorption which leads to accelerated degradation.\textsuperscript{26,30} However, the use of lower fiber contents, which consequently increases the synthetic polymer matrix content, has a negative environmental effect as synthetic matrices are less biodegradable.\textsuperscript{26} Fiber treatments with chemical compounds is another method utilized to minimize moisture absorption. Modifying fibers with specific compounds through an alkalization process decreases the hydrogen bonding capabilities of cellulose and dissolves the hydrophilic hemicellulose within natural fibers. The result is fibers with reduced hydrophilicity, improved fiber/matrix bonding, and overall improved moisture durability.\textsuperscript{30}

**Ultraviolet absorption**

Long-term exposure of both natural and synthetic composites to ultraviolet radiation (UVR) reduce their durability and longevity. Due to their organic compositions, photodegradation effects from UVR exposure are significant in natural composites. Covalent bonds within organic polymers are broken upon exposure to UVR, consequently inducing yellowing, color fading, surface roughening, embrittlement, and overall mechanical property deterioration.\textsuperscript{27,30} UV absorption weakens the polymer matrix through shorter chain scission, embrittling the matrix material, and reducing the tensile strength of fiber-reinforced polymer composites.\textsuperscript{27} Furthermore, photo-oxidation of the polymer’s surface promoted by UVR uses up surrounding oxygen before it can diffuse into the center of the matrix. Subsequently, degradation is concentrated at the surface of the polymer, and an oxygen gradient is generated. The oxygen gradient results in a density gradient, which in conjunction with shorter polymer chains from chain scission initiates and propagates cracks which deteriorate mechanical properties.\textsuperscript{30}

Several studies from literature have investigated the effects of UVR on composite material degradation and their mechanical properties. A weathering study conducted by Joseph et al.\textsuperscript{46} exposed sisal/polypropylene (PP) composites of various fiber weight fractions to UVR inside of a controlled weatherometer for 12 weeks. Afterwards, tensile tests on the samples were conducted using an Instron machine. The neat (pure) PP samples had a 92.57% reduction in tensile strength, the largest drop of any of the samples. Samples with 10%, 20%, and 30% fiber weight fractions experienced drops in their tensile strength of 58%, 37%, and 23%, respectively, suggesting that increasing fiber weight fractions within the composite correlates to an increase in the retention of tensile properties after UV exposure due to the photodegradation effects endured by the polymer. Research conducted by Da Silva et al.\textsuperscript{47} tested hybrid composites made of cararamid reinforcement combined with unsaturated polyester resin under UVR and gamma radiation. The samples irradiated with UV light were placed inside an aging chamber for exposure times of 300 and 600 h. Three-point bending tests was performed on the samples after irradiation. As expected, the samples irradiated for 300 h showed degradation and a reduction in flexural strength and modulus of 30% and 41%, respectively, when compared to the non-irradiated samples. Interestingly, the samples irradiated for 600 h only show a decrease in flexural strength...
and modulus of just 1.5% and 14%, respectively, in comparison to the non-irradiated samples. It is suggested that longer UV exposure times allowed free radicals generated from UV exposure to recombine, causing greater cross-linking between neighboring particles from both fiber and resin and ultimately increasing the mechanical properties of the composite from their previous degraded state. These studies indicate a strong correlation between UVR exposure and material degradation, while also suggesting at additional complex mechanisms responsible for inhibiting deterioration in certain composites. Developments from research have found solutions to minimize UVR damage on composite materials.

Recommended methods of engineering UV degradation resistance within natural composites include the hybridization of the reinforcement material within natural composites and the use of synthetic plastics as the matrix.\(^{28,48}\) Including plastics combined with photostabilizers and UV inhibitors as the matrix material reinforced with natural fibers may help to reduce UV damage to the fibers, with the added benefit of increased water absorption resistance.\(^{28}\) An investigation by Fiore et al.\(^{48}\) concerning the use of hybrid jute-basalt laminate with an epoxy resin found that a “sandwich” like structure of the laminates with basalt laminas situated near the outer layers of the structure and jute laminas near the center exhibit greater resistance to weathering effects including UVR exposure when compared to pure jute laminates. Efforts by Yu et al.\(^{49}\) to understand the complex interactions between UV light and textiles lead to the development of an optical model, verified by experimental results, to understand the effects of fiber parameters on UV protection. The findings show that shorter diameter fibers are ideal for UV protection as their transmittance of UVR is low. Furthermore, materials with high refractive indices absorbed less UVR, and fibers with low porosity proved to provide more UV protection as well. These parameters should be considered when designing composites for UV intense environments.

**Biodegradation**

Biodegradation is a key factor in determining the service span and methods for end-of-life disposal for composite materials. Microorganisms including fungi, bacteria, and actinomycetes utilize enzymes to break down organic polymers. Enzymatic reactions are specific and only take place under defined environmental conditions. Natural products in particular are more susceptible to enzyme degradation. Cellulose is biodegraded by bacteria and fungi in a wide range of temperatures (up to 85°C) and pH (up to 9). Different materials can have vastly different biodegradation mechanics because of the specificity of enzymes. Some of the important factors in determining degradation rate are molecular weight, crosslinking, crystallinity, environmental conditions, and structure porosity.\(^{30}\)

Biodegradation reduces mechanical properties of composites during their service time. The degree of degradation incurred after a given period can be estimated by the weight loss percentage of the tested composite.\(^{29,51}\) Takagi and Ochi\(^{51}\) conducted testing of green composite samples with unidirectional hemp reinforcement and a starch-based biodegradable resin to examine changes in mechanical properties after biodegradation had taken place. These samples were placed in a home-use garbage processing machine filled with compost to undergo degradation for 20 days, during which samples were tested on days 0–5, 10, 15, and 20 for tensile strength and weight loss. The tensile strength of the composite fell from about 250 MPa initially to just 50 MPa after the full 20 days, with the biggest drop in strength observed during days 2–5. Under the same 20-day duration, the composite’s degree of degradation was just over 15%, with the rate of degradation rapidly increasing after 15 days. Another study by Peterson et al.\(^{29}\) examined the biodegradation of Biopol™, alongside woodfiber-Biopol™ composites. Samples of pure Biopol™ and woodfiber-Biopol™ composites of fiber weight fractions of 15%, 20%, and 25% were placed in sludge oil for 5 weeks, after which they were cleaned, and their masses measured. The composites samples degraded significantly faster than the pure Biopol™ samples, with maximum degradation experienced by the 15% fiber weight fraction sample. It was proposed that the woodfibers act as conduits for bacteria, thereby accelerating the degradation process in comparison to pure Biopol™.

Depending on the intended service life and use of the composite, biodegradation may be intended as an environmentally friendly end-of-life disposal method. Research conducted by Ji et al.\(^{52}\) tested starch-sisal green composites combined with both organic and inorganic fillers for their mechanical properties, moisture absorption, and rates of biodegradation to see if the fillers had any effect. The inorganic fillers included talcum powder (TP) and CaCO₃ (CC), while the organic filler used was eggshell powder (EP) with the control group having no filler (NF). The fillers were mixed with the starch matrix and fiber using a blender, with the resulting slurry being hot-pressed to create the final composite. Biodegradation was conducted via soil burial for 30 days, after which the samples were recovered, and their initial and final masses compared. Biodegradation of the NF-composite was the highest at 71% weight loss, followed by 67%, 61%, and 60% for the EP-, CC-, and TP-composites, respectively, with the masses of the fillers being excluded from the calculations for better comparison. The NF-composite had the largest degradation rate as the filler samples tightly combined with the matrix, preventing microorganisms from decomposing them. Water absorption experiments as well as tensile and compressive tests showed superior mechanical properties and water resistance from the EP-composite in comparison to the other three. Considering the results, bio-
fillers are a feasible, inexpensive method to produce high-performance, biodegradable green composites.

If the intention is to reduce biodegradability of a composite material to reduce degradation within its service life, the usage of biocides should be considered. Biocides are a broad group of chemical additives widely used in industry to protect materials by killing microorganisms responsible for biodegradation. Multiple blended biocides provide a larger scope of protection from microbial attack. Other properties of biocides, such as toxicity, working pH, temperature, and UV stability, water solubility and cost effectiveness should also be considered within the scope of a particular application and environment to maximize its potency and minimize any ecological damage.50

Weathering, temperature, and climate effects

Combinations of moisture absorption, UV absorption, and biodegradation on material samples are often carried out by weathering studies in literature. Natural weathering involves a material being aged “by natural elements, weathering or the action of the environment in which the material is subjected to conditions of use.”30 Although natural weathering studies can accurately mimic the conditions a material undergoes throughout its lifecycle, these studies are often impractical due to the amount of time they require to collect years worth of data. Regardless, multiple natural weathering studies confirm the degradation of material and subsequent loss of mechanical properties following material exposure to natural environments.30,49

Accelerated or artificial weathering is a process occurring in aging chambers which attempts to “simulate a natural environment and the damaging effects of long-term outdoor exposure by exposing test samples to ultraviolet radiation, moisture, and heat in a controlled manner.”30 Different UV, moisture, and temperature conditions can be cycled through in steps to reproduce environmental aging.48 However, results from accelerated weathering have no exact correlation with real conditions due to the regularity of cycles, duration, intensity, and exposure conditions.30 A study conducted by Fibiyi et al.53 compared the effects of natural and accelerated weathering of a wood plastic composite (WPC) with formulations based on high density polyethylene and polypropylene. Their results indicated WPC degradation from the 2-year natural test (17,520h) to be greater than that of 400h of accelerated ageing, but less than that of 2000h of aging. Like natural weathering tests, accelerated weathering tests reduce mechanical properties, degrade material, and show color fading.30,53 Despite their limitations, the fast, convenient and reproducible nature of accelerated aging makes them the preferred weathering method in most modern research.30

Varying climate conditions and temperatures subsequently result in differing durability of composite materials. Miller et al.26 performed durability analysis on 11 WPCs with formulations of varying wood fiber weight fractions, different polymer matrices, different carbon feedstock sources, and the addition of maleic anhydride for improved water resistance. By utilizing a stochastic degradation model developed earlier by Srubar et al.,41 these WPCs were considered for outdoor decking applications. The degradation model exposed these samples under the environmental conditions of three different American cities: Phoenix, Arizona (dry climate), Seattle, Washington (marine climate), and Lihue, Hawaii (humid climate). Finite element implementation simulated fluctuations in temperature, relative humidity, and wet-day statistics for all three cities using data from the National Weather Service. Moisture absorption, property degradation, and deflection were considered to determine exceedance of defined service-lifespan limit states, with a maximum lifespan of 20 years. Composites exposed to higher moisture levels, such as rain in Seattle or humidity in Lihue, displayed considerably shorter service lives than the composites from the more arid climate conditions of Phoenix. The most common failure mode resulted from strength reduction exceeding the allowable limit because of moisture absorption. High temperature environments exacerbate the effect of humidity on material lifespan, as demonstrated by the relatively short service life of the WPCs tested in the high-temperature, high-humidity environment of Lihue. Moisture uptake is accelerated at higher temperatures as high-temperature, humid environments allow for microcracks to form within the surface and bulk of the composite, thereby inducing non-Fickian water absorption behavior and increasing the material’s permeability coefficient.30,44

Durability considerations within life cycle assessment

Studies investigating the environmental impacts of biobased composites and bioplastics often adopt a cradle-to-grate analysis, overlooking the use-phase of the material within its lifespan.26 Limitations on knowledge of in-service behavior and deterioration properties, especially for novel materials such as green composites, pose barriers into assessing the environmental implications of material service life.26,41 Material behavior and maintenance through its use phase can increase its overall environmental impact, and in some cases exceed that of its production phase. Thus, service life performance should be integrated into LCAs and material design procedures to provide a more complete assessment of environmental impact.26

From the aforementioned weathering study, Miller et al.26 integrated durability-based service life predictions within LCAs of all the WPCs tested. The LCIA categories considered in the study included “resource consumption during cultivation of wood and carbon feedstock for polymers; energy and material flows during biosynthesized or synthetic polymerization; refinement processes resulting in the wood by-product and the polymer; manufacturing of
composites; and end-of-life disposal” and the LCIs considered were developed to represent 1 kg of material for each of the 11 WPCs. The functional unit considered in the study was “based on the volumetric amount of material required to safely resist structural design loads,” though additional LCAs were also made based on the volume of material needed to meet the serviceability design criteria assuming material replacement occurred once the defined service-lifespan limit states were exceeded. Life cycle models were developed using Monte Carlo simulations which incorporated the quantities of material, processing, and transportation distance required for each of the WPCs. Four different categories were assigned to assess environmental impacts: global warming potential (GWP) in kg of CO₂, fossil fuel demand (FFD) in megajoule surplus, acidification (H+ moles equivalent), and eutrophication (g of N equivalent). Environmental impacts were drastically different between the LCAs that included and excluded material degradation with replacement for most of the WPCs. Composites with 40% fiber weight fractions, which deteriorated more rapidly within the degradation model, had far greater GWP, FFD, and acidification than composites with 20% fiber weight fractions when deterioration and replacement were accounted for. In contrast, these three categories for the 40% fiber weight fraction composites were only slightly higher than those with just 20% when degradation was not considered. Furthermore, smaller differences in all four environmental categories between the LCAs including and excluding deterioration were observed for WPCs tested under the dry conditions of Phoenix, Arizona, as less material replacement was required in this environment. Thus, the study concluded that service conditions in different regions worldwide aids in utilization of plant by-products for WPCs when pursuing environmentally friendly alternatives for industrial use.

Choosing constituent materials

When choosing natural fibers for engineering applications, some important factors to consider include fiber cultivation requirements, locality, mechanical properties, and cost. Knowledge of fiber plant usability across many regions worldwide aids in utilization of plant by-products to reduce waste. Alongside cultivation requirements, economic and industrial factors influence the type of fibers grown in certain countries or regions. For the authors, flax and hemp are strong candidates for natural fiber cultivation due to Alberta, Canada’s favorable geo-climatic conditions, recent harvesting regulation changes for hemp and market demand from multiple market channels. Selection of biopolymers for industrial purposes is highly dependant on application-specific criteria. For composite materials, favorable biopolymer attributes include high strength, weather resistance, biodegradability, biocompatibility, and hydrophobicity.

Requirements for fiber cultivation

Natural fibers have a diverse range of environmental and climatic requirements to obtain optimal growth. Some plant fibers such as jute only grow within tropical and subtropical environments, whereas hemp fibers can be cultivated within various environments around the world. Cultivation conditions and typical cultivation regions for some common natural fibers are summarized in Table 1.

Fiber properties requirements for application

Different natural fibers possess distinct mechanical properties, thereby warranting their use in various engineering applications. Often, designing composite materials requires knowledge of constituent properties to predict their combined properties using tools such as the rule of mixtures. Table 2 presents the mechanical properties of some common natural fibers as well as conventional synthetic fibers for comparison purposes. Higher mechanical properties are exhibited by bast fibers (hemp, kenaf, flax, jute, and ramie) which possess higher amounts of cellulose with more cellulose microfibrils oriented in the fiber direction. Large variances within reported values of natural fiber mechanical properties arise from factors inherent to fibers, including plant maturity, age, location, source, fiber extraction methods, and microstructure. Growing and extraction conditions also impact natural fiber strength, as
previous studies have shown strength reductions of 15% by waiting 5 days after the optimum harvest time to extract the fibers. Furthermore, flax fibers were found to have 20% higher tensile strength when harvested manually rather than mechanically. Different testing methods conducted on natural fibers within literature often add to reported mechanical property variabilities as well. Using unconventional fiber cross-sectional area measurements may help to mitigate mechanical property variability within natural fibers.

Several limitations exist when reporting the mechanical properties of natural fibers as opposed to synthetic ones. Standard simplifying engineering assumptions assume fibers have a circular cross-sectional area (CSA) that is constant throughout its length. Such assumptions rarely hold for natural fibers. An investigation into natural fiber CSA variability conducted by Thomason et al. measured the CSAs of flax and sisal fibers. Four different locations along the fibers’ longitudinal axis were used to measure the average CSAs of the fibers with conventional circular area calculations using average diameter estimations made from microscopic images. Then, separate fiber micrographs were taken and traced to find the fibers’ true average CSA. The study found that the conventional method overestimated the CSAs by a factor of two or more, with these differences translating directly into tensile strength and modulus differences of the same magnitude. Furthermore, using additional measurements along the direction of the fiber, the average deviations from the mean CSA were about 11% and 14% for sisal and flax fibers, respectively. However, a model developed in the study that treated each fiber as having short cylinder constituents connected in series indicated that these deviations would result in at most a 3% error in the experimental modulus calculation, thereby eliminating cross-section variation as a major source of variability for fiber modulus.

Table 1. Cultivation conditions and regions for some common natural fibers.

| Fiber type | Cultivation conditions | Cultivation regions | References |
|------------|------------------------|---------------------|------------|
| Abaca      | Typically grows within tropical climates. Optimal development of fibers occurs at 28°C–30°C with good relative humidity and 2000–2500 mm of water annually. The first fiber takes approximately 2 years to produce, with subsequent harvests occurring every 2–3 months. | Commercialization and production of abaca is led by the Philippines at 60% market share, followed by Ecuador with 35% market share. | 57 |
| Bamboo     | Grows within many unique climates, from jungles to mountainsides. Supported best with soils possessing high moisture content and good water-holding capabilities. Snowfall should be avoided, and annual rainfall should be more than 1000 mm. | Almost all bamboo production takes place throughout the Asia-Pacific region. The largest producers of bamboo are China, India, and Brazil. | 58,59 |
| Flax       | High relative humidity with temperatures ideally in the 18°C–20°C range. Optimum soil conditions include fertile soils with loose aggregate structure for air access and a pH of 6.5–6.9. | Popular areas of cultivation include France, Canada, Argentina, India, USA, Ukraine, Kazakhstan, Egypt, and the Czech Republic. | 74,85 |
| Hemp       | Grows between 5.6°C and 27.5°C, with 14°C being optimal for growth. Requires 4–5 months free of frost to produce harvestable crops. Optimum yields require 500–700 mm of precipitation. Ideal soil pH is suggested to be 6.0 | Adapted to grow in various regions worldwide, including temperate, tropical, and sub-tropical zones. Most hemp production is located within Canada, China, and the European Union (EU). France, the Netherlands, and Romania are the biggest producers in the EU. | 56 |
| Jute       | Hot, humid climate during wet summer seasons. 24°C–27°C is ideal with annual pre-monsoon rainfall of 1000–2000 mm at sowing time. | Equatorial, tropical, and subtropical zones. Cultivated in India, Bangladesh, China, Vietnam, Myanmar, Thailand, and Brazil. | 71 |
| Kenaf      | Production fits well around the world with high ecological adaptability. Requires soil temperature of about 15°C for germination and growth. | Can be cultivated between 30°S and 45°N. Typical production regions include India, China, and Pakistan. | 73 |
| Ramie      | Humid climates with moderate temperature. Relative humidity of 25% with temperatures of 20°C–31°C are optimal. Requires uniformly distributed rainfall of 1500–3000 mm annually. | Most production occurs in China. Also cultivated in India, Indonesia, Korea, Taiwan, Brazil, Japan, and the Philippines. | 72 |
| Sisal      | Grows in tropical or subtropical countries in well-drained soil anywhere between sea level and frost line. Requires a moist atmosphere with high temperature. Sisal feeds on lime, magnesia, potash, and phosphoric acid. | Presumed to be native to Central America. Most production occurs in Brazil and Tanzania, though China and Kenya are also major cultivators. | 60,61 |
measurements. The errors in CSA calculations associated with conventional measurements were found to scale with larger diameter measurements, thus providing a plausible explanation for the inverse relationship between fiber strength and modulus and fiber diameter found in literature. Separate studies have also shown relationships between clamping length during testing, fiber length, and mechanical properties. Since fiber breakage is expected to occur at the weakest point of the fiber, longer fibers have a higher probability of having a weak section within them, consequently reducing their strength and strain to failure. For similar reasons, clamping length exhibits an inversely proportional relationship with fiber strength as larger clamping lengths introduce more defects that weaken the fiber.66

**Local fibers and usability**

Natural fiber selection for natural composites depends heavily on geographic availability. Flax fibers are popular within Europe, whereas jute, kenaf, hemp, ramie, and sisal fibers are favored in Asia. In New Zealand, Harakeke fibers (commonly known as New Zealand flax) are being considered for structural applications by virtue of their high mechanical properties and local availability.69 Industrial chains connected to natural fibers impart considerable influence upon global economies, and vice-versa. World natural fiber production is estimated to be 33 million tonnes with a total farm value of US$60 billion in 2013. In the European Union (EU), approximately 10,000 companies from 14 countries are involved in planting, harvesting, scutching, spinning, weaving, knitting, finishing, and trading to produce finished fabrics made from linen (flax). Rapid growth in Brazil following the end of the Second World War propelled the country into becoming the largest producer and exporter of sisal today. Hemp production takes place predominantly in China, Canada, and the EU, with their main fiber usage being channeled toward specialty pulp and paper, insulation material, and biocomposites for automotive applications. India and Bangladesh account for 97% of worldwide jute and kenaf production in 2013/14, with their labor-intensive cultivation and processing requirements providing a livelihood and food security for many families across Asia. National laws requiring jute usage in packaging material prompted India to become the largest consumers of jute as well. When considering the full value chain of jute including agriculture, marketing, transportation, and manufacturing, 25 million people in Bangladesh (or about one-fifth of its population) are dependent on jute. Overall, a reasonable estimate of total employment in natural fiber industries is about 300 million people globally, roughly 4% of the world population.88 Even with the importance of natural fibers in the global economy, plants containing usable fibers often see many other uses as well.

Typically, only a small fraction of a plant is fit for fiber production, with the rest being used for industrial, medicinal, and culinary applications.75–79,89,90 Only 4% by weight of sisal fibers are extracted from sisal leaves, with the remaining weight being attributed to plant cuticle, dry matter, and water.75 Ramie plants produce even lower fiber yields between 2% and 4% by weight of the plant, with jute plant fiber yields falling between 4% and 6%.89,90 However, other parts of these plants can still be utilized as

| Fiber   | Tensile strength (MPa) | Young’s modulus (GPa) | Failure strain (%) | Density (g/cm³) | References |
|---------|------------------------|-----------------------|-------------------|-----------------|------------|
| Abaca   | 400–813                | 12–33.6               | 2.9               | 1.5             | 54,68      |
| Bagasse | 96.24–290              | 8.5–17                | 4.03              | 1.25            | 54,68      |
| Bamboo  | 140–230                | 11–17                 | 1.3               | 0.6–1.1         | 54,68      |
| Flax    | 345–1500               | 27.6–100              | 1.2–3.2           | 1.5             | 54,66,68   |
| Hemp    | 550–900                | 68.9–70               | 1.6–4             | 1.47–1.48       | 54,66,68   |
| Jute    | 200–800                | 13–55                 | 1.16–3            | 1.3–1.49        | 54,55,66,68|
| Kenaf   | 930                    | 53                    | 1.6               | 1.45            | 54,68      |
| Sisal   | 511–710                | 9.4–22                | 2–3               | 1.34–1.5        | 54,68      |
| Ramie   | 400–938                | 24.5–128              | 2.5–3.8           | 1.5             | 54,68      |
| Oil palm| 206–248                | 3.2–3.567             | 4–25              | 0.7–1.55        | 54,68      |
| Pineapple| 170–1627              | 1.44–82               | 2.4–14.5          | 0.8–1.6         | 54,68      |
| Coir    | 130–1150               | 4–62                  | 15–40             | 1.2             | 54,66,68   |
| Curaua  | 500–1150               | 11.8                  | 3.7–4.3           | 1.4             | 68         |
| E-glass | 3400                   | 73                    | 4.4–4.8           | 2.55            | 86,87      |
| Aramid  | 3000–3600              | 60–179                | 1.9–4.4           | 1.44            | 86,87      |
| Carbon  | 3400–4800              | 240–425              | 0.8–2.0           | 1.78            | 86,87      |

*Ultra-high modulus carbon fiber.

*Ultra-high tenacity carbon fiber.
by-products for a variety of other purposes, thereby reducing waste. Oil extracted from kenaf seeds are known to have extensive medicinal uses. Furthermore, kenaf seed oil has found industrial usage as an alternative to mineral oils for lubricant applications resulting from its inexpensive, renewable nature. Bamboo leaves possess medicinal properties as well, with bamboo shoots having culinary value as sources of high protein, vitamins, and minerals. Hemp is a versatile crop with multiple industrial uses. Other than fiber usage from the stalk of the plant, hemp leaves are used to create pulps and building materials including insulation, cement, and stucco. Oils, isolates, and distillates are extracted from hemp flowers for medicinal and recreational purposes. Moreover, hempseed oil is an ingredient in hygiene products such as soaps and lotions, as well as in industrial products including paints, solvents, and printing inks.

In pursuit of a domestic source of natural fiber, hemp is a commercial crop of interest in Alberta, Canada. As a short season crop which thrives in long hours of sunshine, hemp is well suited toward Alberta’s geo-climatic conditions. Well-developed fibrous root systems grant hemp better resiliency against dry conditions in the Canadian Prairies than most crops, although the plant is not as compatible with saturated soils by the same token. In Canada, the optimum time of sowing is mid- to late-May, as the risk of hard frost has passed by this time. In recent years, overall hemp production acreage has trended upwards for both Alberta and Canada as a whole, with these trends largely driven by the hemp grain market. Alberta’s share of Canadian hemp production area rose from 2% in 1998 to 32% in 2011. High versatility regarding plant part utilization allows for the generation of multiple revenue streams corresponding to each part of the hemp plant. Increasing demand exists for hemp protein in both human and pet food markets, with growing demand for food markets for certified organic hemp production. High mechanical properties make hemp fibers a viable product within biocomposites in the aerospace, automotive, and packaging industries. Additionally, textile, paper, and building markets express interest in hemp fibers for applications with virtue of its durable, anti-microbial, acoustic, and aesthetic properties. The Albertan government collaborates with the hemp fiber industry “to advance product development and commercialization as well as facilitate supply chain development.” Efforts by the government to meet this end include investment in a fiber processing pilot plant for the decortication of hemp stalk in 2009. Prior to 2018, harvesting of hemp chaff (flowers, leaves, and stems) was forbidden as these parts contained bioactives, primarily cannabidiol (CBD), which were restricted by regulations. Changes in these regulations brought about by the Cannabis Act authorized bioactive extraction from the chaff by licensed processors, thereby triggering a market surge by allowing for the creation of cosmetics, natural health products, and pharmaceuticals with bioactive ingredients. Favorable geo-climatic conditions for growth, a high degree of usability and increasing market demand have propelled hemp to become a strong contender for natural fiber cultivation in Alberta.

A comparative cradle-to-manufacture LCA study conducted by La Rosa et al. on hemp and glass fibers demonstrates the disparities between the two materials’ environmental impacts. The functional unit in the study was defined as an eco-sandwich panel made of natural material including a cork core sandwiched by bio-based epoxy resin reinforced with hemp mats. For comparison, a traditional sandwich composite consisting of a polyurethane core with petroleum-based epoxy resin and glass fiber reinforcement was also studied. By using data for energy, materials, processes, and transportation from European sources, 11 different impact categories were created to compare the environmental effects of 1 kg of hemp mat and glass fiber production. Some common categories used include global warming, eutrophication, and acidification potential, though other rarer categories such as human toxicity and terrestrial ecotoxicity potential were also used. All impact categories were considerably higher for the glass fiber s, except for land occupation since hemp production required over 20 times as much land usage. Typically, renewable materials score worse than petrochemical polymers in the ecotoxicity and eutrophication categories, though the choice of using organic hemp grown without fertilization and pesticides in the LCA reduced these impacts for the hemp mats.

Alongside hemp, flax is another available crop in Alberta with encouraging prospects for cultivation and use. Geo-climatic conditions including a narrow temperate climate band across Western Canada with long hours of daylight in the summer and low to freezing temperatures in the fall are suitable for flax cultivation in northern Alberta. Sensitivity to spring frosts requires flax seeding to be delayed until the risk of frost is reduced. The flax industry contributes about $300 million annually to the Canadian economy, though only 9% of Canadian flax production occurs in Alberta. Flax production and acreage have expanded in Alberta as markets have shifted from Europe to China, with China being the largest export market. Flax cultivars are selected for either fiber (flax fiber) or oil (oilseed flax) production, with most flax cultivated in North America being grown for the oil. Locations of production between these two types of flax differ, as fiber flax is adapted to wet fall climates which aid in postharvest fiber processing. Until recently, straw was considered an impediment for oilseed production and was burned. However, uses for industrial fibers in composites, paper and nonwoven fiber have increased whole plant utilization potential. Considerable interest has been shown toward
flaxseed oil as a functional food ingredient with many health benefits. In industrial applications, flaxseed oil (often referred to as linseed oil) is used extensively to produce paints, printer ink, varnishes, and linoleum flooring.\textsuperscript{81,82} Multipurpose utilization across several industries, increasing foreign market demand and desirable climate conditions in Alberta highlight the feasibility of flax as a local source of natural fiber within the province.

To highlight the significance of material production location on environmental impacts, Deng and Tian\textsuperscript{92} conducted a consequential LCA (CLCA) study on flax fiber reinforced composites. The focus of the CLCA was on the “marginal environmental impact changes due to a shift from glass fibers to flax fibers for composite reinforcement from a macro-economic perspective,” with the functional unit for both types of fibers being interior car panels with equal stiffness serving a driving distance of 200,000 km. Unlike using a regular LCA, the CLCA used here addresses environmental impact changes associated with marginal production, use, and disposal changes, while also incorporating the global flax fiber market in the analysis. Since most fiber flax production occurs in China and France, flax supply ratios of 70% and 30% were used for each country, respectively, based on global market data. Using this supply mix, environmental impacts such as climate change, fossil depletion, and many others, were found to be higher in the production and end-of-life stages of the flax composite when compared to the glass composite. The high impact of the flax composite was attributed to inferior flax cultivars producing lower flax yield efficiencies in China compared to France, as well as China’s heavy dependence on coal as a source for electricity. Inclusion of the use phase benefits of the flax composites negated many of its production and end-of-life impacts, with positive environmental impacts being observed in 10 of the 17 environmental impact categories when compared to the glass composites for a full life cycle. Further, consideration of an alternate scenario where 100% of flax fibers were sourced from France resulted in significant impact reductions in most of the impact categories. Accordingly, geographic location can have substantial effects on environmental impacts for products in their production and end-of-life stages, thereby entailing its careful reflection within LCA studies.

**Fiber material cost**

An attractive feature of natural fibers in engineering applications are their relatively low costs in comparison to synthetic fibers. In many cases, natural fibers meet engineering design criteria while still being inexpensive. Although synthetic fibers tend to have superior mechanical properties when density is not accounted for, the specific strength and modulus of natural fibers are comparable to those of synthetic ones.\textsuperscript{62} Table 3 shows the average prices of some natural and synthetic fibers.

| Fiber       | Price (US$/kg) |
|-------------|----------------|
| Wood        | 0.3–0.6        |
| Flax        | 2.1–4.2        |
| Hemp        | 1.0–2.1        |
| Jute        | 0.4–1.5        |
| Coir        | 0.3–0.5        |
| Cotton      | 2.1–4.2        |
| Sisal       | 0.6–0.7        |
| Kenaf       | 0.3–0.5        |
| Bamboo      | 0.5            |
| Wool        | 1.6–2.4        |
| Feather     | 1.1–2.0        |
| Silk        | 2.6–40.0       |
| Glass       | 2.0            |
| Carbon      | 22.0–27.0      |

Both natural and glass fiber price variations depend heavily on sources of geographic area.\textsuperscript{67} Low densities found in natural fibers correspond to lower transportation costs, thereby reducing the cost of natural fibers.\textsuperscript{63} Use-phase cost savings of natural fibers emerge in the automobile industry through weight reductions of composite parts, allowing for higher fuel efficiency.\textsuperscript{31} Reduced energy demands are required for natural fiber production as well.\textsuperscript{65} Lower costs of natural fibers imply lower costs for composites reinforced with natural fibers instead of synthetic fibers, meaning the overall cost of the composite can be reduced by varying the amount of natural fiber loading if the cost of the fiber and matrix material differ.\textsuperscript{63} On the contrary, implementing natural fibers as a substitute for glass fibers was a costly alternative within the European automotive industry in 2002. Retooling injection moulding processes within the industry already geared toward glass fibers would have been expensive, so glass fibers remained the standard.\textsuperscript{64} Thus, although their raw material costs may be lower, other costs of production must also be considered for a more complete approach in bolstering the cost-efficiency of natural fibers within industrial settings.

**Biopolymer matrices**

As an alternative to petroleum-derived synthetic polymers, biopolymers made of renewable resources have garnered increased interest recently from scientific and industrial fields.\textsuperscript{83} Environmental concerns related to petrochemical plastics including global warming, limited fossil fuel availability, low biodegradability, and accelerated landfill deposits have shifted research interests toward biopolymers to mitigate these effects.\textsuperscript{50} Two different criteria are
used in in defining the term “biopolymer”: the source of the raw materials and the polymer’s biodegradability. From this definition, biodegradable polymers made from renewable resources (biobased), non-biodegradable polymers made from sustainable crude polymers (biobased), and biodegradable polymers made from fossil fuels all classify as biopolymers. Biobased biopolymers are produced either by biological systems (plants, animals, and microorganisms) or by chemical synthesis of natural starting materials such as starch, sugar, and corn. Further, natural polymers can be divided into three main classes based on their structure: polysaccharides, polynucleotides, and polypeptides. Most bio-based biopolymers today are sourced from first-generation feedstock, including edible biomass (starch, sugar, plant oils, etc.) as well as non-consumable sources like natural rubber. Cellulose, a polysaccharide found in plant cell walls, is the most abundant biopolymer in the world. Plants produce over $10^{11}$ tons of cellulose annually, though other living organisms like bacteria and fungi can produce cellulose as well. Starch is another abundant plant-based biopolymer, stored in plants as an energy reserve. As a natural carbohydrate polymer, starch can be extracted from many diverse sources in nature, including rice, wheat, potato, and corn. Biopolymer matrices sourced from renewable materials like soy, starch, and cellulosic plastics can be used in biocomposite applications. Polylactic acid (PLA) is a common biopolymer produced by the polymerization of lactic acid from renewable resources such as corn starch or sugar canes. Collagen is the most abundant animal-based biopolymer, with its most important sources being pig skin, bovine hide, and pork and cattle bones. Polylactic acid (PLA) is a common biopolymer produced by the polymerization of lactic acid from renewable resources such as corn starch or sugar canes. Biopolymers such as cellulose, collagen, polyethylene, and starch are a family of microbially produced biopolymers mainly synthesized from renewable materials through fermentation. Polylactide (PCL), a synthetic polymer, is easily biodegraded by enzymes and fungi despite its fossil fuel-based origins. Different types of biopolymers provide a variety of attributes useful for industrial applications. Selection criteria for biopolymers vary drastically between different industrial applications. Biopolymer characteristics to consider include pH, density, refractive index, diffusion coefficients, melting temperature, rheological properties, fracture toughness, durability, and many others. For example, polysaccharides such as chitosan are chosen to coat fruits and vegetables owing to their low toxicity, high biodegradability, antifungal, antioxidant, and film-forming capabilities. Regarding composite materials, high biodegradability, and weather resistance enables PLA to be a suitable green matrix material. Composites based on biopolymers like hyaluronic acid have been used in medical applications for drug delivery, as they possess excellent biocompatibility, biodegradability, and nontoxicity characteristics. In the automotive industry, Mitsubishi Motors used PLA and polybutylene succinate (PBS) reinforced with bamboo fiber to prepare high strength car floor mats. For composite durability, composites manufactured with hydrophilic biopolymers like cellulose and starch absorbed more moisture compared to composites prepared with hydrophobic biopolymers like PHB and PHBV (both types of PHAs). On account of the different benefits and attributes available across their numerous varieties, biopolymer matrices for composites should primarily be chosen based on application-specific criteria.

Conclusion

From the findings of this review, green composites have proven to be a viable alternative to synthetic composites in many applications. Low production costs, widespread availability, reduced environmental impacts, and high specific strength and stiffness are just a few benefits of green composites over traditional glass, carbon, Kevlar, and other man-made composites. As an analytical tool, LCA can aid in quantifying the environmental impacts of a product through its production, use, and end-of-life phases. LCAs can be applied/used on a variety of products from different areas and industries, meaning guidelines for conducting LCAs are unable to outline the procedure for conducting every step of the analysis. However, ISO has established general protocols to complete an LCA. When analyzing the short- and long-term economic costs and benefits of a product or system, an LCC study should be employed. Like LCA, LCC is a broad analysis tool without concrete steps for how to conduct all analyses, though it instead aims to integrate the costs that a product or system incurs throughout its life cycle into the decision-making process in early stages of development. Both LCA and LCC studies should be utilized when determining the economic and environmental impacts of the use or advancement of green composites.

Use phase durability of green composites should ideally be included within LCA studies but is rarely done so in practice due to limited knowledge of material deterioration processes. Regardless, four different mechanisms were identified in compromising the mechanical properties of green composites: moisture absorption, UV exposure, biodegradation, and temperature and weather effects. The hydrophilic nature of natural fibers encourages moisture absorption, thereby causing swelling of the fibers and compromising the structural integrity of the composite. UV exposure weakens composites by breaking covalent bonds within polymer matrices and promoting photo-oxidation at the polymer’s surface. Biodegradation occurs when microorganisms break down organic polymers via enzymatic reactions, though biodegradation is often viewed favorably as a means of environmentally friendly end-of-life disposal. Combinations of these three mechanisms are studied in both natural and accelerated weathering studies, with added temperature effects amplifying moisture induced degradation.
When choosing natural fibers as reinforcement in green composites, their cultivation conditions and locality, mechanical properties, usability, and cost are some parameters to consider. Different fibers have varying requirements for optimal temperatures, rainfall, and soil conditions. Geographic availability of certain fiber types can also limit which fibers can be utilized in a specific region. Knowledge of the mechanical properties of natural fibers may help in choosing the right type of fiber for a particular application, though considerable variance exists in reported mechanical properties of natural fibers due to inconsistent testing methods and measurements between studies in literature. Ideally, natural fibers should be sourced from plants with usable by-products from its non-fiber counterparts to minimize plant waste. Costs of different types of natural fibers vary, though most are significantly cheaper than their traditional synthetic alternatives. Within Alberta and Canada, hemp and flax are viable crops for fiber cultivation due to Alberta’s suitable climate conditions, market demands from multiple products and channels and from recent relaxation of hemp cultivation regulations. Biopolymer matrices within green composites are another feasible substitute to synthetic polymers to support sustainable development. Considering the wide range of biopolymers available with each possessing unique characteristics, their selection criteria for green composites are heavily dependent on usage requirements such as weather and moisture resistance, biocompatibility, biodegradability, and many others.

Although extensive research has been conducted regarding the durability, life cycle analyses, and mechanical properties of green composites, work from these categories as they relate to green braided composites are sparse. Unlusoy and Melenka94 demonstrated the effects of braiding angle, void content, and void distribution on the flexural properties of cellulose-based braided composites. Rajesh and Pitchaiamani95 discovered that braided architectures of jute-based composites have enhanced mechanical properties when compared to the conventional woven fabric architecture. Bruni-Bossio et al.96 studied the significance of braid angle, resin type, and curing method on the porosity of braided green composites. Further studies into green composite mechanical properties should investigate the effects of varying several composite parameters including linear yarn density, a wide range of braiding angles, fiber volume fraction, and different fiber-matrix compositions for proper composite characterisation. Little to no information is available for life cycle analyses of green braided composites. LCA and LCC studies must be performed on these composites to assess their ability to meet environmental impact and cost constraints, especially in contrast to synthetic composites with traditional structures. Durability considerations must also be included within these analyses to estimate environmental impacts with greater accuracy. Weathering studies should be conducted on green braided composites to predict their use-phase durability and longevity alongside biodegradation tests to develop procedures for end-of-life disposal.

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