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Master’s Degree Thesis

Environmental evaluation of plastic components with bio-fillers and comparison with conventional plastic composites in the automotive sector

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Summary

Plastic is one of the most widely used materials in the manufacturing of automobiles, second only to ferrous metals and alloys. The use of plastics in the automotive sector continues to increase, accounting for approximately 20% of a vehicle's total weight. Despite the advantages of engineered plastic composites in automotive manufacturing, their use significantly contributes to the vehicle's environmental impact, particularly during production. Additionally, the end-of-life treatment and recycling of plastics pose challenges due to the release of hazardous chemicals and the high costs associated with recycling in the automotive industry.

Natural fibers have emerged as a promising alternative to conventional plastic fillers. In this thesis, two commonly used natural fibers, kenaf and cellulose, were selected for a detailed environmental impact assessment. The study examines their integration into automotive composites, focusing on two case studies in which two automobile components (a tray and an engine beauty cover) made of plastics and reinforced with conventional fillers such as glass fibers are compared to their counterparts reinforced with kenaf and cellulose fibers. Moreover, these two natural fiber composites align with the composites required by Stellantis, with the kenaf-based component being part of a collaborative project between Politecnico di Torino and Stellantis.

The Life Cycle Assessment (LCA) methodology was applied using OpenLCA software and the Environmental Footprint and Ecoinvent databases. Specifically, the kenaf fiber-based tray was assessed from cradle to gate, while the cellulose fiber-based engine beauty cover was analyzed from cradle to grave. The study provides a comprehensive Life Cycle Inventory (LCI) detailing the materials used in component production. The Life Cycle Impact Assessment (LCIA) results reveal that the most significant reduction in environmental impact occurs in the global warming category for both natural fiber composites. Overall, the findings suggest that replacing conventional fillers with natural fibers in automotive manufacturing leads to a significant reduction, particularly in one of the main climate change impacts: Global Warming Potential (GWP). In addition to reducing environmental impacts, the use of natural fibers leads to lightweighting of vehicle components, which in turn contributes to lower fuel consumption over the vehicle's lifetime.

1. Introduction

The automotive industry is currently regarded as one of the most influential industries globally, where both manufacturers and consumers are seeking vehicles that are more sustainable, focusing on improved fuel efficiency and reduced environmental impact [1]. Since the automotive industry is the largest single manufacturing sector globally, the management practices, organizational structures, and responses to environmental pressures within this industry are significant not only on their own but also for their impact on many other business sectors [2].

In order to mitigate environmental footprint in automotive sector, sustainability is increasingly prioritized. Key environmental goals include reducing greenhouse gas emissions through the widespread adoption of electric and hybrid vehicles, which significantly reduce CO2 emissions compared to traditional internal combustion engines [3]. Additionally, the industry is implementing Life-Cycle Assessments (LCA) to evaluate and minimize environmental impacts from production to disposal [4] . The life-cycle perspective covers stages from design to production (including the supply chain), use, and finally disposal and recycling[2]. Cleaner production techniques, such as utilizing renewable energy sources in manufacturing plants and reducing water usage, are also being adopted [5]. Innovations in lightweight materials and advanced fuel-efficient technologies further contribute to emission reductions and overall vehicle efficiency. These efforts align with global sustainability standards and regulatory requirements, such as the European Union's CO2 targets for 2030, which aim for a 55% reduction in emissions for cars and a 50% reduction for vans [6], [7].

One promising approach is the replacement of conventional fillers in plastic components with natural fibers, which can reduce fossil resource dependency and improve end-of-life biodegradability. However, a comprehensive assessment is required to determine whether these materials provide real environmental benefits compared to traditional solutions. This thesis focuses on the LCA of automotive plastic components reinforced with natural fibers, specifically kenaf and cellulose fibers, as potential substitutes for conventional fillers.

The structure of this thesis is as follows:

- Chapters 1 and 2 review previous studies on bio-fillers in automotive plastic components, identifying potential alternatives to conventional fillers.
- Chapter 3 examines LCA studies on kenaf and cellulose fibers to establish life cycle inventory (LCI) data for components made from these materials.
- Chapter 4 details the LCA models developed for these bio-based components, including system boundaries, assumptions, and functional unit.
- Chapter 5 presents the results, comparing the environmental impact of components made from kenaf and cellulose fibers with their conventional counterparts. Additionally, the effect of lightweighting on fuel consumption is analyzed.
- Chapter 6 concludes with key findings, limitations, and recommendations for future research.

1.2. Thesis's Goal

This study aims to investigate whether the use and replacement of bio-fillers and natural fillers instead of conventional plastic materials in the automobile industry can reduce the environmental impacts of automobile production. In this research, the LCA tool is used to achieve the goal of comparing bio-fillers instead of conventional plastic fillers in the automotive industry. This thesis focuses on two bio-fillers: kenaf fiber, which is used in a tray as an automotive component, and cellulose fiber, which is incorporated into an engine beauty cover in Ford automobiles. These bio-fillers were selected based on a comprehensive literature review, which highlighted their potential applications in the automotive industry due to their mechanical properties, applicability in specific components, and environmental benefits. Their use is evaluated in terms of strength, feasibility, and potential impact reduction compared to conventional fillers.

The Global warming potential (GWP) environmental effects and various environmental indicators available in this tool, will be evaluated for both types of fillers, and the environmental advantages and disadvantages of using each of these fillers will be described, and finally they will be compared in order to analyze whether the new fillers for making automobile plastic parts can lead to a reduction in carbon footprint and other environmental impacts identified through the LCA. In the end, more sustainable fillers with fewer environmental impacts will be introduced in the automobile industry, taking into account the technical properties of these fillers in automotive industry.

1.3 Plastic component in Automotive industry

The global automotive plastics market, valued at USD 22.4 billion in 2023, is expected to grow to USD 57.15 billion by 2032, with a Compound Annual Growth Rate (CAGR) of 11% from 2021 to 2032. Key drivers of this growth include the potential for wider weight reduction, significant emission reductions, and advances in vehicle design and aesthetics [8].

Currently, huge amount of plastic and plastic composites is used in vehicles. The normal vehicle uses around 150 kg of plastics and plastic composites versus 1163 kg of iron and steel; right now, it is moving around 10-15 % of the total weight of the car (Fig. 1). Plastic and engineered polymer composites are the second most commonly used material after ferrous metals and alloys (cast iron, steel, nickel)[9]

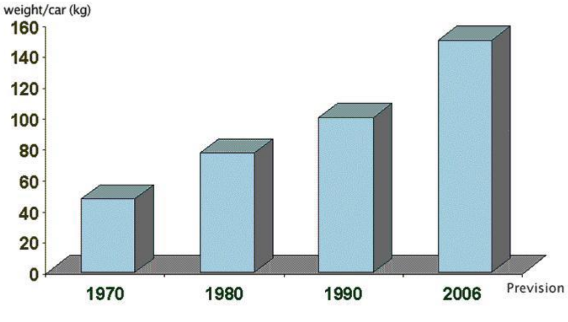

Fig. 1 use of plastics in automobiles [9]

To satisfy consumers and legislative demands for lighter, fuel-efficient automobiles, the automotive sector has begun to increase the use of lightweight polymers and composite materials in recent years. In certain cases, plastics are introduced to improve consumer comfort, and in other cases, they are utilized to replace heavier ferrous elements. These materials contribute to reducing the total weight of the vehicle as they are lightweight, durable, and easily moldable. This rising tendency is shown in (Fig. 2).

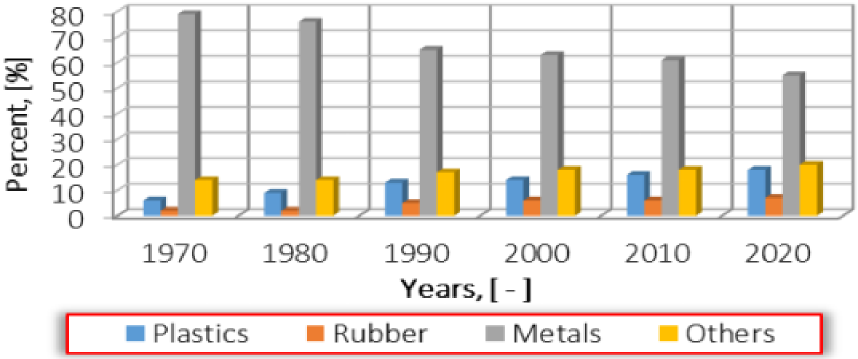

Fig. 2 Increase in plastic use in vehicle composition from 1970 to 2010 [10]

A typical vehicle comprises approximately 30,000 parts, with one-third of these being made from plastic. In total, around 39 different types of basic plastics and polymers are utilized in automobile manufacturing [11] The most common used plastics in various components of a car are shown as below (Fig. 3):

- Dashboard (PP, ABS, PC)
- Glass interlayer in windshield (PVB)
- Lighting (PC, PMMA, ABS, PBT)
- Bumper (PP, TPO, ABS, PC/PBT)
- Under the hood (PA, PP, PBT)
- Fuel systems (HDPE, PA, PBT, POM)
- Seating (PUR, PP, ABS, PA)
- Door handles (PA, ABS, PC/ABS)
- Wheelhouses and radiator support (Phthalic acid resin)
- Body panels (Epoxy, SMC, PPO/PPE alloys)
- Upholstery (PP, PVC, PUR)
- Interiors (PP, HDPE, ABS, PVC, PET) [11]

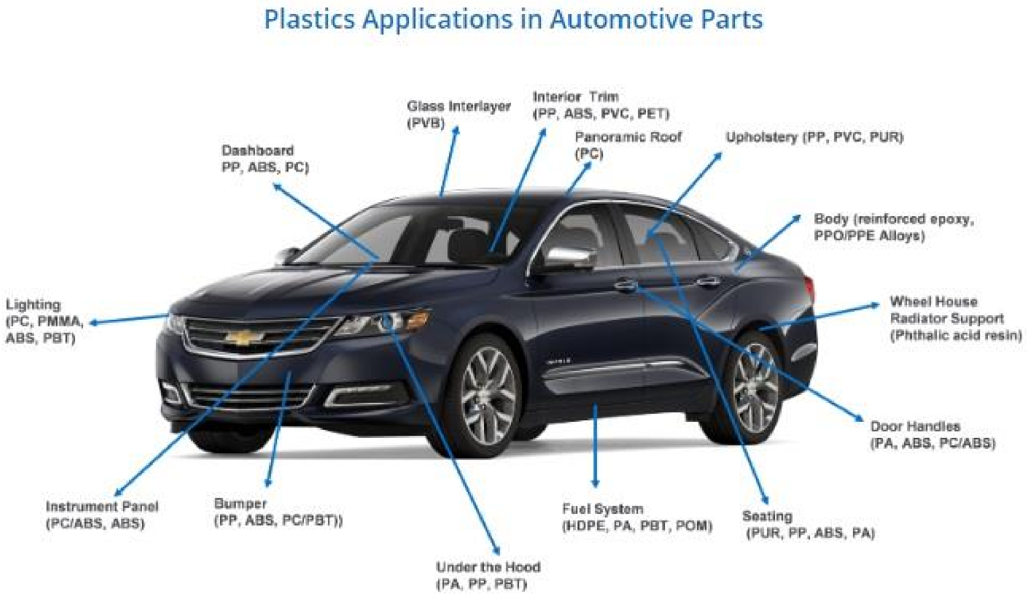

Fig. 3 Plastic applications in automotive components [11]

More detailed information on plastic and their applications will be found in Chapter 0.

1.3.1. Environmental challenges of plastic components

Plastics are widely used in automobiles and continue to have a great deal of potential for usage in automotive engineering. Plastics are extensively used in automobiles due to their versatility, ability to reduce weight, and ease of molding into complex shapes, allowing manufacturers to replace heavier materials [12], [13]. This substitution improves fuel efficiency and reduces greenhouse gas emissions. For instance, lightweight plastics can significantly lower vehicle weight, enhancing fuel economy and cutting CO2 emissions [14]. Fiber-reinforced plastics (FRPs) reduce component weight by 50–60% while maintaining performance standards. Another advantage of plastics is to be recyclable by being reheated into a liquid state [12].However, plastics, primarily produced from fossil fuels such as natural gas, pose significant environmental challenges due to their non-biodegradable nature. Once discarded, they persist in landfills and ecosystems, contributing to terrestrial and aquatic pollution [15]. Over time, plastics fragment into smaller particles, increasing their exposure to environmental factors and releasing various chemicals. These substances, which vary by plastic type, can negatively impact human health and the environment [16].

Recycling is another challenge for plastics. Only a small percentage of plastic waste is recycled, and recycled plastics often lack the properties needed for their original applications, making them less desirable than virgin plastics [17]. Although industries like automotive are increasingly exploring plastic recycling, it is often not cost-effective due to the infrastructure required. Multi-polymer or fiber-reinforced plastics further complicate recycling as separating materials is costly and complex [18]. Other end-of-life options, such as landfilling and incineration, pose significant environmental challenges. Landfills generate hazardous leachate, release greenhouse gases like methane, and occupy large areas, often rendering land unsuitable for future use [19]. Incineration, while capable of energy recovery, can emit particulates and greenhouse gases unless modern filters are used. Managing residual ash and slag remains problematic [20].

In conclusion, while plastics provide notable environmental advantages, such as weight reduction and energy savings, their end-of-life management presents significant challenges. Addressing these issues is critical for leveraging plastics' full potential in automotive applications.

2. Plastics and Fillers in Automotive Applications

This chapter focuses on plastics and fillers, their properties, and their applications in various automotive components. Section 2.1 introduces different types of plastics and their applications in various parts of a typical car. Section 2.2 discusses plastic fillers, their properties, and their role in composite materials. Section 2.3 provides a more detailed analysis of specific fillers and their applications in different types of plastics. Section 2.4 explores bio-based composites, including natural fibers and bioplastics, and their applications in automotive components. Finally, Section 2.5 presents an overall discussion summarizing the key points of the chapter.

2.1. Plastic

Plastic is frequently referred to as a generic term by consumers. Plastics are better defined as polymers, which are long molecules linked together by covalent bonds. Usually, plastic is divided into three groups: Thermoplastics, thermosets and rubber.

2.1.1. Thermoplastics

Thermoplastics made up almost 85% of the polymer production globally. There are two common types of thermoplastics:

1. Amorphous, which is processed above their glass-transition temperature (Tg), a temperature where the stiffness decreases significantly, therefore the polymer behaves as a liquid.

2. Crystalline, which is processed above their melting temperature (Tm).

Thermoplastics act like butter: they melt when heated and then harden back into a solid when cooled [21], [22] The most common types of thermoplastics include polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC), which account for above 70% of total production of thermoplastics. The thermoplastics are well-utilized in advanced technology areas due to their high Tg, or Tm [23].

2.1.2. Thermosets

Thermosets are usually low-viscosity liquids or low-molecular-weight solids, which are rigid and require cross-linking agents and fillers for curing and enhancing properties. Thermoset polymers are like an egg: they start as a liquid at room temperature, but when heated, they harden into a solid through a process called cross-linking. They are often combined with fillers and reinforcing fibers to reduce brittleness. The common types are unsaturated polyesters, phenolic resins, amino resins, urea/formaldehyde resins, polyurethanes, epoxy resins, and silicones [22], [23].

2.1.3. Rubber

Rubber, which is obtained from both natural sources and industrial methods, can stretch greatly and then return to its original shape once released. Rubbers can be either thermoplastic or thermoset [22] In automotive sector, up to 13 polymers may be utilized in a single automobile model (Table 1), but only three types of plastics account for approximately 66% of total plastics that make up an automobile: polypropylene (32%), polyurethane (17%), and PVC (16%).

Table 1. Plastics used in a typical car [9]

Component	Main Types of Plastics	Weight in Average Car (kg)
Bumpers	PS, ABS, PC/PBT	10.0
Seating	PUR, PP, PVC, ABS, PA	13.0
Dashboard	PP, ABS, SMA, PPE, PC	7.0
Fuel Systems	HDPE, POM, PA, PP, PBT	6.0
Body (incl. panels)	PP, PPE, UP	6.0
Under-bonnet Components	PA, PP, PBT	9.0
Interior Trim	PP, ABS, PET, POM, PVC	20.0
Electrical Components	PP, PE, PBT, PA, PVC	7.0
Exterior Trim	ABS, PA, PBT, POM, ASA, PP	4.0
Lighting	PC, PBT, ABS, PMMA, UP	5.0
Upholstery	PVC, PUR, PP, PE	8.0
Liquid Reservoirs	PP, PE, PA	1.0
Total	-	105.0

The properties and applications of the most common plastics in automobiles are mentioned in (Table 2). Materials such as polypropylene (PP), polyurethane (PUR), and polyvinyl chloride (PVC) are widely utilized in both interior and exterior automotive applications due to their exceptional chemical resistance, durability, and versatility. Moreover, polymers like polyamide (PA), polycarbonate (PC), and acrylic (PMMA) play essential roles in applications that demand mechanical stability, high transparency, and weather resistance. Polybutylene terephthalate (PBT) and polyethylene terephthalate (PET) are primarily employed in components that require thermal stability and chemical resistance, such as headlamp retainers and engine covers. Notably, Sheet Molding Compound (SMC) is recognized for its importance in structural parts like hoods and fenders, showcasing its mechanical strength and lightweight advantages. While polyamide (PA) is celebrated for its high abrasion resistance and low friction, its dimensional stability can be negatively impacted by moisture absorption, potentially leading to swelling and diminished performance over time. In contrast, materials like polybutylene terephthalate (PBT) and polyethylene terephthalate (PET) demonstrate excellent thermal and dimensional stability, making them more dependable for use in components such as fog lamp housings, door handles, and engine covers, where maintaining precise dimensions is vital for optimal functionality.

Table 2. Plastic Polymers uses in Automotive sections [9], [12], [23]

Polymer	Abbreviation	Uses in Automobile Section	Properties
Polypropylene	PP	Bumpers, battery boxes, cable insulation, petrol cans, indoor and outdoor carpets, carpet fibers	Extremely chemically resistant, almost completely impervious to water. Offers good UV resistance, especially in black color.
Polyurethane	PUR	Flexible foam seating, suspension bushings, cushions, hard plastic parts	High resiliency with flexible foam, rigid foam for insulation, durable elastomeric properties
Poly-vinyl-chloride	PVC	Instrument panels, sheathing of electrical cables, doors, pipes, waterproof clothes	Good resistance to chemicals and solvents. Offers good tensile strength and flexibility in some grades. Available in clear and colored forms.
Acrylonitrile-butadiene-styrene	ABS	Dashboards, covers	Durable thermoplastic with good resistance to weather, and some chemicals. Well-liked for vacuum-formed components
Polyamide	PA	Gears, bushes, cams, bearings, weatherproof coatings	Known as Nylon 6.6 or Nylon 6, has high abrasion resistance, low friction, and good chemical resistance. Absorbs water easily, which can affect dimensional stability.
Polystyrene	PS	Equipment housings, buttons, car fittings	Easy to manufacture, popular material but has poor resistance to UV light.
Polyethylene	PE	Auto bodies (glass reinforced), electrical insulation, packaging	Good chemical resistance, available in low-density (LDPE) and high-density (HDPE) forms. Can be manufactured in a range of densities, suitable for strength and aesthetic applications.
Polyoxymethylene	POM	Interior and exterior trims, fuel systems, tiny gears	High stiffness, rigidity, and excellent yield stability, even at low temperatures. Offers very good chemical and fuel resistance.
Polycarbonate	PC	Bumpers, headlamp lenses	Good weather and UV resistance, high transparency almost as good as acrylic.
Acrylic	PMMA	Windows, displays, screens	More transparent than glass, reasonable tensile strength with good UV and weather resistance. High optical quality and a wide color range.
Polybutylene terephthalate	PBT	Foglamp housings bezels, door handles, bumpers, carburetor components, locking system	Good chemical resistance, excellent electrical properties, tough material with good resistance to dynamic stress, thermal, and dimensional stability.
Polyethylene terephthalate	PET	Wiper arm housings, headlamp retainers, engine cover	Similar to PBT, with good thermal stability, excellent electrical properties, low water absorption, and excellent surface properties.

Polymer	Abbreviation	Uses in Automobile Section	Properties
Acrylonitrile styrene acrylate	ASA	Housings, interior parts, outdoor applications	Great toughness and rigidity, good chemical resistance, thermal stability, and outstanding resistance to weathering, aging, and yellowing. Offers a high gloss finish.
Thermoplastic Olefin	TPO	Bumper cover or fascia, body-colored fascias	Polypropylene polymer with rubber mixed in, good impact qualities, can be painted with an adhesion booster
Epoxy Resin	Epoxy	Hood (made from epoxy resin and glass fiber in resin transfer molding process)	Low viscosity resin with high mechanical properties, including tensile strength and modulus. Not used in exterior panels due to higher cost.
Sheet Molding Compound	SMC	Hoods, fenders, and doors (Corvette)	Combination of calcium carbonate, glass fiber, polyester resin, and additives. Offers good modulus and tensile strength.
Polyphenylene Oxide / Polyphenylene Ether Alloys	PPO/PPE Alloys	Under-the-hood components, battery systems, hydrogen fuel cell enclosures, interior trim	High thermal stability, mechanical strength, excellent electrical insulation, and chemical resistance.
Unsaturated Polyester	UP	Body panels, bumpers, structural parts	High strength-to-weight ratio, corrosion resistance, good durability
Styrene Maleic Anhydride	SMA	Instrument panels, interior trims, structural parts	High heat resistance, good dimensional stability, chemical resistance
Polymethyl Methacrylate	PMMA	Windows, sunroofs, headlight and taillight lenses	Transparent, lightweight, UV resistance, good impact resistance, weatherproof

2.2. Plastic Fillers

The term filler is generally referred to additives in polymer composites [23]At first, these additives were introduced to decrease the cost of thermoplastics, considering the increasing demand for this polymer. Fillers quickly rose to popularity due to their simplicity of incorporation into plastics and enormous possibilities for improving and differentiating products. These additions are critical for changing processability and important material qualities such as mechanical, thermal, optical, and electrical characteristics. As a result, they are more correctly described as "functional fillers." These little additions are critical tools for plastics formulators, each adding a distinct set of qualities to the basic polymer [24]. The term “filler” covers a broad spectrum of materials.

In this context, two major group exists: inorganic and organic. These two groups contain various substances shown in Table 3. Organic fillers are derived from natural plant sources, while inorganic fillers are sourced from minerals [25]. Ground Calcium Carbonate (GCC) is an inorganic filler commonly derived from limestone and chalk, both of which are fossil-based materials. It represents 34% of the market share, making it the leading inorganic filler utilized in plastics [26]. Talc, which is a hydrated magnesium silicate, effectively increases rigidity and impact resistance, particularly in polypropylene (PP). Its exceptional thermal stability, resulting from advanced milling techniques that enhance purity, makes talc an excellent choice for use in packaging materials [27]. Silicates, including mica, kaolin, and wollastonite, are employed to enhance the mechanical properties of plastics. Kaolin, obtained from kaolinite, is becoming increasingly favored for its effective coupling properties [28]. Glass fiber (GF) and natural fibers (NFs) such as sisal and flax are commonly used fibrous fillers that can modify the mechanical, electrical, and magnetic characteristics of composites [28]. The effectiveness of fiber-reinforced composites is influenced by both the type of fiber chosen and the bonding interface between the fiber and the matrix. However, the relatively excessive cost of these fibers can limit their application [29].

Table 3. Chemical families of fillers [26], [28]

Chemical family	Examples
Inorganic	
Oxides	Glass (Fibers, spheres, hollow spheres, flakes), SiO2, ZnO, Al2O3, Sb2O3 and MgO,
Hydroxides Salts	Mg (OH)2 and Al (OH)3 , CaCO3, CaSO4, BaSO4, hydrotalcite and phosphates
Silicates	Talc, kaolin, mica, montmorillonite, wollastonite, nano clays, asbestos and feldspar
Metals	Steel, Boron
Organics	
Carbon, graphite	Carbon fibers, Carbon nanotubes, carbon black, graphite fibers and flakes
Natural polymers	Cellulose fibers, Wood flour and fibers, starch, cotton, sisal and flax
Synthetic polymers	Polyester, aramid, polyamide and polyvinyl alcohol fibers

2.2.1. The principal properties of fillers for plastic

In the following parts key properties of principal fillers for plastic application is reviewed. These properties of fillers can vary widely depending on their application and the type of polymer. For thermoset and thermoplastic applications, the main considerations include the following aspects.

Cost

Fillers were initially used to reduce plastic production costs but are now valued for enhancing material properties, particularly in expensive polymers like polyamides and thermosets. Due to their higher density compared to polymers, fillers often increase production costs, especially for inexpensive thermoplastics, requiring more weight to replace polymer volume. However, they remain cost-effective when combined with existing additives or used in high-performance materials [30].

Chemical Composition

The chemical composition of fillers is less critical if they are inert, insoluble, non-toxic, and thermally stable, but impurities like soluble materials, hard grit (e.g., quartz), trace metals (e.g., iron and copper), color contaminants (e.g., humates and iron compounds), and hazardous substances (e.g., asbestos and crystalline silica) can affect performance [31]. Surface chemistry is key, as it influences adhesion to polymers and dispersibility, often requiring surface-active agents to enhance filler performance [32].

Specific Gravity (Density)

The introduction of fillers increases composite weight due to their higher density compared to polymers, benefiting applications like flooring, roofing, and soundproofing. However, in weight-sensitive uses like transportation, this added weight is undesirable, prompting the use of hollow glass or ceramic spheres for lightweight needs such as floatation aids [32], [33].

Hardness

The hardness of fillers, measured on the Mohs scale (ranging from talc at 1 to diamond at 10), impacts both processing and product performance. Hard fillers, such as glass fibers and quartz, enhance scratch and abrasion resistance but can accelerate wear on processing equipment, requiring harder metals [34], [35]. Common thermoplastic fillers have a hardness below 4, while soft fillers like calcium carbonate or talc may still cause wear due to hard impurities like quartz [24], [30].

Morphology

The size and shape of filler particles are crucial for both processing and final product properties, but they are difficult to measure due to their variety and changes during processing [36]. Filler particles can exist in three forms: primary particles, which are the smallest distinct units; aggregates, where primary particles bond tightly through processes like intergrowth or fusion; and agglomerates, which are looser groupings of aggregates held together by weaker forces. The differences between these terms are as below (Fig. 4). During processing, the size and shape of fillers can change, as seen with materials like hollow glass spheres, glass fibers, mica flakes, nano clays, and talc [31], [37].

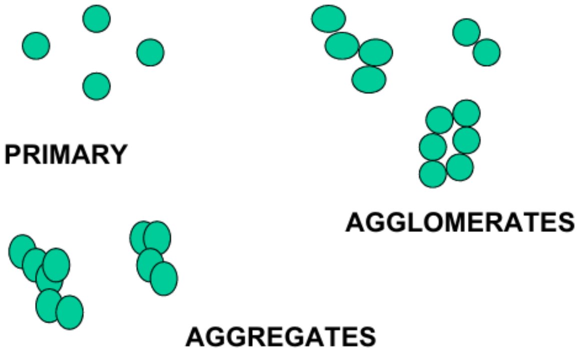

Fig. 4. The concept of primary particles, Agglomerates, and Aggregates [31]

Thermal Properties

The main thermal properties of particulate-filled polymer composites include specific heat, thermal conductivity, coefficient of thermal expansion, and thermal stability, which change with the amount of filler added. Specific heat capacity, adjusted for specific gravity, has little impact as most fillers have similar values to plastics. Thermal conductivity measures heat conduction, while thermal diffusivity indicates how heat moves through a material, with inorganic fillers providing better conductivity than polymers. Specialty fillers are used in high thermal conductivity applications, such as heat sinks, while organic fillers like wood flour have similar conductivities to polymers ([31], [37].

Electrical Properties

In electrical applications, filled polymers enhance conductivity or provide insulation, as in cable coatings. Conductivity and dielectric properties are key, with most fillers offering insulation and low conductivity. However, humidity can increase conductivity due to ionic impurities [31]. Specific fillers, like those for antistatic purposes or Electromagnetic Interference (EMI) shielding, are used for higher conductivity. Common conductive fillers include carbon black, metals, graphite, and doped zinc and tin oxides, while carbon and metal fibers are used for extremely high conductivity at low concentrations [38].

2.3. Principal filler types used in thermoplastics and thermoset

According to previous studies, some fillers have a wide range of uses in the world. Table 4 summarizes various fillers used in thermoplastics and thermosets, detailing their forms, sources, applications, and key characteristics. Calcium carbonates ($CaCO_3$), available in powder form from natural sources like chalk and limestone, are the most used filler due to their cost-effectiveness and ability to enhance stiffness in PVC and polyolefins. Talc, also a powder, is derived from hydrated magnesium silicate and is used in polyolefin composites, particularly in the automotive industry, where its platy structure increases stiffness, albeit at a higher cost than $CaCO_3$. Wood flour, made from wood scraps, serves as a sustainable filler in wood-polymer composites, though it has limitations like color change and low thermal stability. Aluminum hydroxide ($Al\ (OH)_3$) is utilized for its flame-retardant properties in various applications, while wollastonite, characterized by its needle-like crystals, enhances strength and thermal stability in thermoplastics and thermosets. Mica, available in powdered or flake form, is used in engineering thermoplastics for surface modification and stiffness but can be damaged during production. Finally, glass fiber, though more common in thermosets, enhances mechanical properties but presents processing challenges when used in thermoplastics.

Table 4. Principal fillers in plastic [39]

Filler	Forms	Sources	Application	comments
Calcium carbonates (CaCO3)	Powder	Chalk, limestone, marble	PVC, polyolefins, and thermoset resins.	Most common filler, cost-effective, improves stiffness
Talc	Powder (talcum powder)	Hydrated magnesium silicate,	Polyolefin composites, automotive industry.	Soft, platy structure, increases stiffness, more expensive than $CaCO_3$.
Wood flour	Powder	Wood scraps	wood-polymer composites (WPCs), especially with thermoplastics like polyethylene, polypropylene, and rigid PVC.	Sustainable, lower density than other fillers Limitation: color change, low thermal stability, high moisture absorption, and low durability during process.

Filler	Forms	Sources	Application	comments
Aluminum Hydroxide (Al(OH)3)	Powder, granules, crystalline	Bauxite, a rich aluminum ore	Flame retardant, solid surface, cables, aesthetic purposes in solid surface applications.	Releases water when heated, used in polyester resins, synthetic marble.
Wollastonite CaSiO3 (calcium metasilicate).	Needle-like crystals, powdered	Limestone or dolostone	Thermoplastics, thermosets, replaces short glass fibers in unsaturated polyesters.	Needle-like, improves strength and thermal stability, Low coefficient of thermal expansion (CTE). High dielectric strength, Hard enough for wear-resistant products.
Mica	Powder or flakes	Silicate minerals	Engineering thermoplastics and thermosets to increase stiffness, surface modification.	High purity, consistent color, high aspect ratio. Plates can be damaged during composite production.
Glass Fiber	Short/chopped fibers, continuous fibers, mats	Made by melting and spinning various glass compositions	Widely used thermosets, such as unsaturated polyester resins. Less used in thermoplastics due to processing issue	Enhance mechanical properties of thermoplastics and thermosets. , tough to process in thermoplastics.

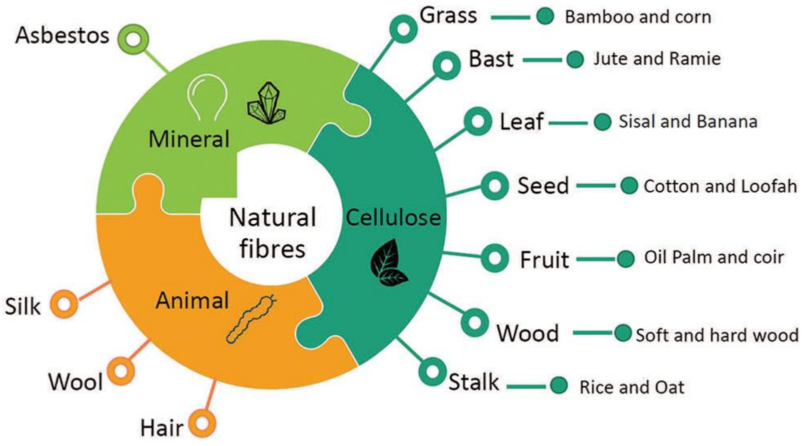

Fig. 5. Three main categories of natural fibers [39]

As shown in Fig. 5 natural fibers are classified into three main groups based on their origin: mineral, animal, and cellulose/lignocellulose fibers. Mineral fibers were once widely used in composites but have been banned in many countries due to serious health risks, such as their potential to be inhaled and cause cancer. Animal fibers, including silk and wool, generally have lower mechanical properties than plant-based fibers, with the exception of silk, which has high tensile strength but is expensive and primarily used in textiles. Among these categories, cellulose/lignocellulose fibers are the most commonly used in composites due to their relatively low cost and superior mechanical properties compared to other natural fibers. These fibers are derived from plants and can be further classified based on the specific plant part they originate from. Given their advantages, this study focuses exclusively on cellulose/lignocellulose fibers, excluding mineral and animal fibers [39].

As Table 3 shows another important source of organic fillers is plants, which generate natural fibers and are categorized as either primary or secondary based on their intended use. Primary plants are cultivated specifically for their fiber yield, whereas secondary plants produce fibers as a by-product. Examples of primary plants include jute, hemp, kenaf, and sisal, while secondary plants include pineapple, oil palm, and coir [40]. There is a growing trend to use biofibers as fillers and/or reinforcers in plastic composites. In recent years, their significance has markedly increased as they have been utilized to replace traditional fibrous fillers such as glass and carbon, due to their superior properties [41], [42]. This trend has been particularly prominent among European automobile manufacturers, who have extensively adopted these materials [43]. Table 5 lists the principal fibers utilized in commercial composites, which are now manufactured globally.

Table 5. Principal major fiber sources [44]

Fiber source	World production (103 ton)
Bamboo	30,000
Jute	2300
Kenaf	970
Flax	830
Sisal	378
Hemp	214
Coir	100
Ramie	100
Abaca	70
Sugar cane bagasse	75,000
Grass	700

2.4. Applications of bio-composites in automotive industry

In the previous sections, the principal fillers used in plastic components of automobiles were defined. In the following sections, key bio-composites relevant to automotive applications will be discussed. Among the various bio-composites used in the automotive sector, natural fiber-reinforced composites (NFRCs) have gained significant attention due to their sustainability and mechanical performance. Section 2.4.1 explores the role of natural fibers in automotive applications and their advantages. Section 2.4.2 focuses on bioplastics, a recently developed class of bio-composites in automotive applications, reviewing some of the most widely used bioplastics by major car manufacturers.

2.4.1. Natural fibers in automotive industry

The automotive industry has been utilizing bio-composites for a long time, and its interest in these materials is growing due to increasing concerns about sustainability and environmental impact. Global trends aimed at reducing CO2 emissions and improving fuel economy have heightened the significance of vehicle lightweighting. Utilizing fiber-reinforced composites provides substantial benefits, enabling automakers to produce lighter vehicle components that enhance performance and strength. A 50% reduction in weight can lead to a significant 40% energy saving and lower CO2 emissions [32]. Regarding the use, the construction industry is the largest user of these composites, integrating them into products such as flooring and decking. Since the 1990s, the automotive sector has played a crucial role in advancing Natural Fiber Reinforced Composites (NFRC) technology, enhancing both performance and awareness. NFRCs are preferred over synthetic fibers due to their reduced reliance on diminishing petrochemical resources and lower production of harmful by-products. The rising demand for environmentally friendly products has driven the increased production and use of NFRCs (Fig. 6) [45].

The classification of the natural fibers which is used in composites can be done based on the various source such as bast fibers (Jute, flax, hemp, and kenaf), leaf fibers (sisal, banana, PALF, and abaca), seed fibers (cotton, kapok, loofah, and milk), grass/reed fibers (bamboo, bagasse, and corn) and other fibers (coir, palm oil, hair, and wool) [46].

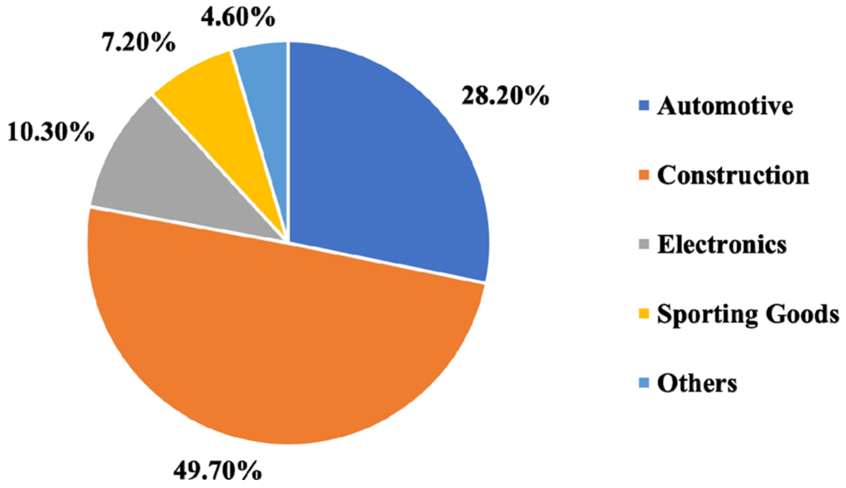

Fig. 6. Natural Fiber reinforced composites market [45]

In automotive composites, matrix material plays a role, both thermoplastic and thermoset matrices are employed alongside natural fibers (Fig. 7). The inherent low thermal stability of natural fibers restricts the selection of thermoplastic polymers to those with processing temperatures below 230°C, such as polyolefins, polyethylene, polypropylene, and ethylene propylene rubber. Among these, polypropylene is the most prevalently utilized thermoplastic matrix in the automotive sector. Conversely, epoxy resin is commonly used as a thermoset matrix with natural fibers. Polymers such as polyamides, polyester, and polycarbonates are unsuitable for use with natural fibers due to their requisite processing temperatures exceeding 250°C [47], [48]. The matrix material affects composite properties, with thermoplastics being favored for their recyclability and short production cycles. However, natural fibers have bonding issues with the matrix, which can be improved with treatments and coupling agents [48].

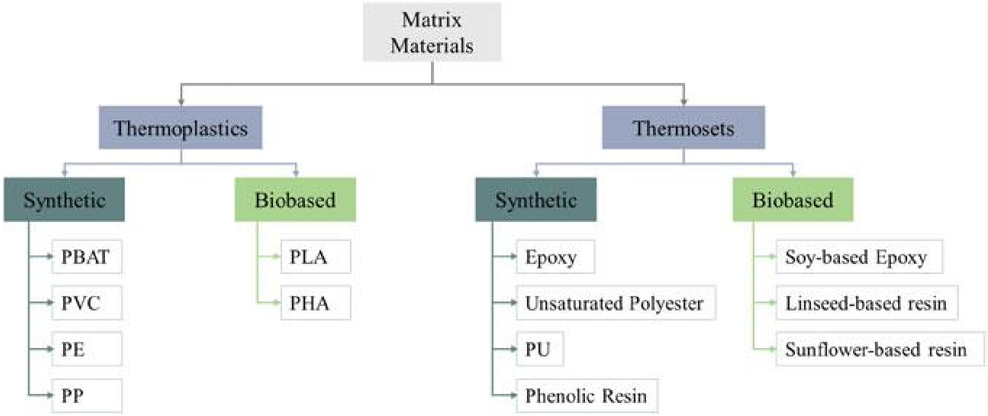

Fig. 7. Classification of matrix material [48]

Table 6 presents a comprehensive overview of the application of natural-fiber-reinforced polymer composites in the automotive industry. It highlights how various manufacturers incorporate natural fibers such as flax, hemp, sisal, jute, kenaf, and wood into different vehicle components, including door panels, seat backs, floor mats, and engine encapsulations. Ford and Mercedes-Benz stand out for their extensive use of natural fibers, with polypropylene, epoxy, and polylactic acid being among the common matrix materials.

Table 6. Applications of Natural-Fiber-Reinforced Polymer Composites in the Automotive Industry

Manufacturer	Part(s)	Fiber Type	Matrix	Reference
Audi	Seat back, Side and back door panel, Boot lining, Hat rack, Spare-tire lining	-	-	[49]
Citroen	Interior door paneling, Parcel shelves, Boot linings, Door panels, Mud guards	Recycled wood + Vegetable fibers	-	[49], [50]
BMW	Door panels, Headliner panel, Boot lining, Seat back, Noise insulation panels, Molded foot well lining, Soundproofing	Sisal, Wood fibers, Cotton, NF prepreg	Acrodur, -	[49], [50]

Manufacturer	Part(s)	Fiber Type	Matrix	Reference
Daimler-Benz (Mercedes-Benz)	Door panels, Windshield/dashboard, Business table, Pillar cover panel, Glove box, Instrument panel support, Insulation, Molding rod/apertures, Seat backrest panel, Trunk panel, Seat surface/backrest, Internal engine cover, Engine insulation, Sun visor, Bumper, Wheel box, Roof cover, Engine encapsulations, Parcel shelves, Rear trunk covers, Trim strip wood veneers, Rear panel shelves, Spare tire wheel covers	Flax, Sisal, Jute, Flax/Sisal, Abaca, Coconut, Wood, Cotton, Banana	Epoxy, Polyester, Polypropylene, -	[49], [73], [51] [50]
Ford	Front grill, Sliding door inserts, Floor trays, Door panels, B-pillar, Boot liner	Hemp, Wood	Polypropylene, -	[49] , [50] [52]
General Motors	Acoustic insulation, Ceiling liner, Seat backs, Cargo area floor, Door panels	Cotton, Hemp, Flax, Kenaf, Wood fibers	Polypropylene, -	[49] , [50] [52]
Honda	Cargo area, Floor area parts	Wood	-	[49] [51]
Lotus	Body panels, Spoiler, Seats, Interior carpets	-	-	[49]
Mazda	Door trims, Interior parts	Kenaf	Polypropylene	[51]
Mitsubishi	Floor mats, Indoor cladding, Seat back lining, Floor panel, Cargo area floor, Door panels, Instrument panels	Flax, Hemp/Cotton	Polylactic acid/nylon, -	[49] [51]
Mitsubishi + Fiat	Interior components	Bamboo	Polybutylene	[51]
Opel	Instrument panel, Headliner panel, Door panels, Pillar cover panel	-	-	[49]
Peugeot	Front and rear door panels	-	-	[49]
Rover	Insulation, Rear storage shelf/panel	-	-	[49]
Saturn	Package trays, Door panel	-	-	[49]

Manufacturer	Part(s)	Fiber Type	Matrix	Reference
Toyota	Door panels, Seat backs, Floor mats, Spare tire cover, Luggage compartment, Lexus package shelves	Kenaf, Bamboo	Polylactic acid, -	[49] [51] , [50] , [52]
Volkswagen	Door panels, Seat back, Boot-lid finish panel, Boot-liner, Door trim panel, Rear flap lining, Parcel trays	Flax, Sisal, Natural fibers	Polyurethane, -	[49] [51] [52]
Volvo	Dashboards, Ceilings, Seat padding, Natural foams, Cargo floor tray	Hemp/Jute	Rapeseed/Soy resin	[49] [51]

2.4.2. Bioplastics in automotive industry

The automotive industry frequently utilizes bioplastics, including natural fibers like soy and hemp, bio-polyamides (bio-PA) and their composites, DuPont Zytel (a blend of nylon resin materials), polylactic acid (PLA), and bio-based polypropylene (bio-PP) [53]. The properties and characteristics of the composite biodegradable material fulfill the increasingly stringent requirements of applications that a biodegradable polymer alone cannot meet [49]. The following subsections introduce some of the most commonly used bioplastics in the automotive industry. Additionally, tables at the end of this section summarize the most widely applied bioplastics and their components.

Polylactic acid (PLA)

Among bioplastics, polylactic acid (PLA) has gained significant attention due to its favorable mechanical properties and processability, making it a viable option for automotive applications. Derived from sugar or corn, PLA is a biopolymer with good melt processing properties, high tensile strength (55 MPa), and stiffness (3 GPa), which make it suitable for car interiors. [54]. However, it has limitations such as poor gas barrier performance, water permeability, low thermal stability, and low toughness [55]. To address these issues, techniques like plasticization, blending, and chemical modifications are employed. Plasticizers, constituting 20-30% by weight, lower the glass transition temperature (Tg) and improve mechanical properties, but plasticization alone is insufficient for automotive compatibility [56]. Enhancements like increased impact resistance and reduced water sensitivity are achieved through blending with low molecular weight compounds and adding impact modifiers [57].Currently, PLA is used in automotive components, including floor mats (Toyota Raum and Prius, 2003), canvas roofs and carpet mats (Ford Model U, 2003), and interior elements like seat fabrics, door trims, and ceiling components (Mazda Premacy Hydrogen RE) [58].Table 7 summarizes the various PLA materials and their applications within the automotive industry, highlighting their potential benefits and current utilization in automotive components.

Table 7. Commercial PLA Materials and their applications in the automotive industry [59], [60]

Type of PLA	Brand	Application	Comments
Standard commercial PLAs	-	Non-durable automotive uses like protective wrappings during vehicle manufacturing and transport	Currently lacks sufficient performance for durable automotive applications.
PLA fibers and fabrics	Ford, Toyota	- Canvas roof and carpet mats in Ford Model U - Floor mats in Toyota Raum and Prius cars	Used in interior applications due to the flexibility and strength of PLA fibers.
Biofront[1] stereocomplex PLA	Mazda	- Car seat fabric in Mazda Premacy Hydrogen RE Hybrid - Door trim and other interior components in Mazda Premacy Hydrogen RE Hybrid	Enhanced properties compared to standard PLA, making it suitable for automotive interiors.
PLA with Additives			
+ Talc as a nucleating agent	-	- Interior components: instrument panels, door panels, pillar covers, consoles, seat backs, and headliners. Under-the-hood components: air ducts and parts exposed to elevated temperatures. - Exterior parts (less common).	Used for parts requiring high rigidity and reduced moisture absorption.
+ Very fine-particle (0.05-micron) silica	-	- Potential use in interior components like dashboards and door panels	Still in the development stage.
PLA/Petrochemical Polymer Blends			
+ PE, PP	Toyota Motor	- Used for interior vehicle parts: scruff plates, cowl side trim, floor finish plate, toolbox.	
+ PC (GL-1401 alloy from Cheil Industries)	Samsung Group	- Suitable for durable applications, like cell phones.	Currently undergoing testing by General Motors and Ford.
+ Engineering thermoplastic resins + bio-polymers	-	- Automotive interior parts.	Combines bio-based and petrochemical polymers for enhanced properties.
+ Epoxy-based chain-extender	-	- Potential applications for structural automotive parts.	
PLA biobased			
+ stereocomplex -PLA nucleating agent + flexible ingredients + compatibilizer	Mazda	- Instrument panel and other interior components in Mazda Premacy Hydrogen RE Hybrid	Contains over 80% plant-derived content, combining thermal and shock resistance with an attractive finish.
Biocomposites			
+ Kenaf Fiber (chemically coupled)	Toyota	- Cover spare wheel on Toyota Prius and Toyota Raum.	Eco-Plastic PLA compounds designed for enhanced durability. Toyota plans to use Eco-Plastic in around 60% of interior components in the next-generation Prius hybrid.
Plantura[2] Biobased PLA	Plantura	- Air filter part, interior trim parts.	Includes 30% Woodfibre for enhanced strength.
Flax–PLLA Bio Composites	-	- Race car seat demonstrator.	High potential for structural automotive applications.

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[1] Biofront is a Trademarked name

[2] Trademark name

Bio-based polyamides

Another widely used bioplastic is bio-based polyamides (PAs) are thermoplastics derived from renewable resources like castor oil and sugarcane, offering excellent mechanical strength, toughness, and chemical resistance. They are produced using conventional thermoplastic techniques such as casting and injection molding [61]. Key bio-based PAs include PA 6,10, PA 10,10, PA 10,12 (developed by Evonik Industries AG), and PA 11 (developed by Arkema). These materials are used in automotive components like transmissions, fuel lines, turbo air ducts, and engine parts due to their low water absorption and high performance [62], [63]. PA 10,10, primarily from castor oil, is ideal for glass fiber-reinforced molding and exhibits a tensile strength of 55–59 MPa. Reinforcing bio-based PAs with cellulose nanofibers improves elasticity but increases brittleness [64]. Table 8 offers a comprehensive overview of the most notable current and emerging bio-based polyamides (PAs) for automotive applications, detailing their current and potential uses and some produces. From the listed PAs, PA 4,6 and PA 6,6 are potential automotive interests, still in the R&D state and showing promising results for future applications. Bio-based PA 5,10 has been developed by BASF Company. However, its high cost currently limits its application within the automotive industry [62], [65].

Table 8. Diverse commercial bio-based polyamides in automotive application [58], [62]

Bio-based polyamides	Current and Emerging Automotive Applications
PA 6	Under-the-hood components', engine and rocker valve covers, air injectors, automobile air intake manifolds • Structural components: front end modules • Exterior parts: door and tailgate handles, front-end grilles, exterior mirror housings, fuel caps and lids, wheel covers • Interior parts: driver side airbags, seat adjuster handles, pedals
PA 4,10	Engine covers, Air Injectors, Structural Modules, Door handles, Exterior grills, Air bags, Seat adjuster handles
PA 5,10	Accelerator pedal module, Cogwheel for steering angle sensors, cooling fans
PA 6,6	Under-the-hood: power-steering reservoir, engine and rocker cover, air intake manifold, radiator end tank, thermostat housing, shifter module, release handle chassis: shifter detent, air piston, carbon canister • Exterior parts: fan and shroud, headlamp bezels, mirror bracket, wheel covers, fuel filler door • Interior parts: seat levers & seat belt components, airbag bolts
PA 6,10	Housings and transmission components • Connectors, tubing and reservoirs in coolant circuits, wheel speed sensors fuel contact line • Air filter system
PA 12	Mono- and multilayer fuel lines, connectors • tank filler necks
PA 11	1. PA 11 resin: Flexible tubing, mono-wall fuel lines and multi-layer fuel lines, such in ESD-Flex conductive fuel-pump module for General Motor car models, fluid transfer lines (brake, cooling, clutch), friction parts, quick connectors, pneumatic brake noses 2. PA 11 fibers: Potential 'like vegetal' fiber reinforced-bioplastics for automotive applications. 3. PA Fine Powders as coatings for door handles, oil and fuel filters, engine blocks, wheels, coil springs, steering shafts, interior small parts, seat rails

Bio-based polyamides	Current and Emerging Automotive Applications
PA 10,10	Fuel lines and special cables, Tube air ducts, Cylinder head ducts, Engine mounts
PA 5,10	Charge air coolers, turbo air ducts, engine mounts, cylinder head covers, oil pans, transmission parts air filter housing (Daimler) • Accelerator pedal module, cogwheel for the steering angle sensor, cooling fan (Mercedes)
PA 4,6	Under-the-hood such as turbo diesel systems components

Bio-based Polyether-block-amides (PEBAs)

Another promising class of bio-based thermoplastics used in the automotive sector is Polyether-block-amides (PEBAs). (PEBAs) are thermoplastic elastomers with alternating hard and soft segments. The soft segments, made of polyether diols, provide flexibility across a wide temperature range, while the hard segments, composed of polyamides, form strong hydrogen bonds that act as cross-linking points. These bonds ensure high tensile strength, excellent abrasion resistance, and durability under heat and weathering. When heated, the hard phase melts, allowing PEBAs to be processed like conventional thermoplastics [60]. Derived from renewable feedstocks, bio-based PEBAs are offered by companies like Arkema and EMS-Grivory, with varying bio-content levels [66], [67] They replace traditional elastomers in demanding applications, including high-end automotive components, due to their superior chemical resistance and retention of mechanical properties under extreme conditions [60].

Polyurethanes (PU)

Polyurethanes (PU) are widely employed in automotive applications due to their durability and versatility. They are synthesized via polyaddition reactions involving isocyanates—such as toluene diisocyanate (TDI), methylene diphenyl isocyanate (MDI), and hexamethylene diisocyanate (HDI) and polyols derived from either petroleum-based or renewable resources [68]. While isocyanates are typically petroleum-derived, the polyol components can now come from renewable resources like sorbitol and isosorbide (starch-based), as well as vegetable oils such as soybean, castor, and sunflower oils [64], [69]. Succinic acid is also used to produce bio-based polyols, which improve foam morphology and mechanical properties [70]. Bio-based PUs are increasingly used in automotive applications for components like door panels, dashboards, and gearshifts due to their enhanced durability. With bio-content ranging from 10% to 60%, these PUs reduce vehicle CO2 emissions while maintaining performance comparable to petroleum-based alternatives [62]. Various bio-based polyols and their sources, including soybean, castor, and sunflower/rapeseed oils, are detailed in Table 9 for their application in PU foams for automotive use.

Table 9. Bio-Based polyurethane Materials and their automotive applications [60]

Raw Materials	Trade Name of PUR/Polyols	Type	Automotive Applications
Soybean oil	SoyOyl®[3]-based PUR foams, such as Baydur[4] polyurethanes	Flexible foams	• Seat-cushions and seat-backs in Ford Mustang, Expedition, Focus, Escape, Escape Hybrid, Mercury Mariner; • Soy-foam headliner in Ford Escape, Mercury Mariner
	BioFoam™ [5] based on BiOH™ polyols	Flexible foams	Seat-cushion and seat-backs in Ford Escape 2009
	Renuva™-based PUR foams	Flexible and rigid foams	• Automobile seats, arm and headrests, instrument panels, door panels, consoles, head liners, impact-absorbing foams, noise, vibration and harshness/under carpet foams, panels & bumper fascia
Soybean oil (cont.)	Agrol®-based PUR foams	Flexible foams	Head and arm rests for Toyota, Honda, Ford, and Chrysler vehicles
Castor oil	Lupranol® BALANCE50 based PUR foams	Flexible and rigid foams	Audi automobile seats, arm and head rests
Sunflower and/or rapeseed oil	Bio-based PUR foams	Flexible and rigid foams	Automobile seats
	Rubex Nawaro®	Flexible foams	Potential for automobile seats (Toyota)

Polyphthalamides (PPAs)

Polyphthalamides (PPAs) are semi-aromatic polyamides made from terephthalic or isophthalic acid. Their structure, which includes aromatic rings, gives them superior properties compared to traditional polyamides like PA 6 and PA 6,6, such as higher glass transition temperatures, increased melting points, and reduced moisture and solvent absorption [60]. These features enhance dimensional stability, solvent resistance, and mechanical performance at high temperatures, making PPAs suitable for automotive applications, especially in high-heat areas or components in contact with fuel or water. Bio-based PPAs, containing 50-70% renewable content, are used in parts like powertrain components, charge air ducts, and cooling system parts components [60], [66]. For example, Arkema's Rilsan®HT is used in the exhaust gas recirculation systems of Peugeot Citroen vehicles and in under-the-hood flexible tubes in Volkswagen cars [60]. Furthermore, leading automotive manufacturers are progressively integrating bioplastics and bio-based plastics into their production processes. Ford, for instance, incorporates eight sustainable materials—soy foam, wheat straw, kenaf fiber, cellulose, wood, coconut fiber, rice hull, and agave fibers from tequila industry waste—while setting a goal to eliminate single-use plastics by 2030 [[71], [72]. Toyota's long-term sustainability objectives for 2050 emphasize resource conservation, increased use of renewable and recycled materials, and advancements in eco-plastic technology, with ongoing initiatives in recycled plastic usage and end-of-life bumper recycling [73]. Similarly,

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[3] Registered trademark

[4] Registered trademark

[5] Trademark name

Audi is committed to developing a closed-loop system for recycling mixed automotive plastic waste to enhance resource efficiency [49].

2.5. Conclusion

In this chapter, we introduced the conventional and bio-fillers commonly used in the automotive industry and reviewed their applications in various vehicle components. We began by defining plastics, their classifications, and their properties relevant to automotive applications. We then examined plastic fillers, categorized into inorganic and organic types, which primarily serve to reduce costs while enhancing properties such as mechanical strength, thermal stability, optical characteristics, and electrical performance [24], [28]. Inorganic fillers—including talc, calcium carbonate, and glass fibers—are widely utilized due to their ability to improve stiffness, impact resistance, and heat resistance in plastics [26], [27], [29]. On the other hand, organic fillers, such as natural fibers and bioplastics, are increasingly attractive for composite applications due to their lower cost, low density, and potential contribution to biodegradability, making them particularly suitable for environmentally conscious applications [40]. Our review of previous studies indicates a growing trend in the use of natural fibers in the automotive sector. Among the various natural fibers employed, flax, hemp, kenaf, and sisal are the most widely adopted due to their favorable mechanical properties and availability. Flax is utilized in components by manufacturers such as Mercedes-Benz, General Motors, Mitsubishi, and Volkswagen. Hemp is commonly incorporated by Ford, General Motors, Mitsubishi, and Volvo, while kenaf is primarily used by General Motors, Mazda, and Toyota. Sisal is frequently employed in interior components by BMW, Mercedes-Benz, and Volkswagen. Additionally, wood fibers are extensively used for insulation, panels, and interior parts by manufacturers such as Citroën, BMW, Daimler-Benz, Ford, General Motors, and Honda [49], [51],[50]. In addition to natural fibers, bioplastics are another commonly used bio-based material in automotive applications, which is also explored in this review. Bioplastics, such as polylactic acid (PLA) and polyhydroxybutyrate (PHB), serve as matrix materials for both bio-fillers and natural fibers. Derived from renewable resources, bioplastics offer advantages such as a lower environmental impact and biodegradability when compared to conventional plastics [74]. By integrating natural fibers with biopolymers, it is possible to create fully biodegradable composites that help reduce environmental impacts throughout their life cycles [75].

Overall, the use of biomaterials in the automotive industry presents significant potential for reducing environmental impacts compared to conventional materials. Life Cycle Assessment (LCA) is one of the most effective methods for quantifying these environmental benefits across the entire life cycle of a product, process, or activity [26]. In conclusion, based on finding from review, we have chosen to develop LCA models for two of the most commonly used natural fibers, kenaf and cellulose fibers, which serve as reinforcements in automotive components, replacing conventional fillers like glass fiber. To implement the LCA, additional details are required, such as Life Cycle Inventory (LCI) data, the percentages of plastics and other chemicals, and the methods used to analyze the impact results for kenaf and cellulose fibers. These aspects will be addressed and discussed in the following chapters.

3. Kenaf and cellulose fibers in automotive: literature review

After a thorough review of previous studies, natural fibers have become a common trend in automotive plastic components to enhance properties and reduce environmental impacts. Among the natural fibers discussed in the previous chapter, kenaf and cellulose fibers emerge as two of the most promising alternatives to glass fiber for use in automotive interior parts. These two natural fibers have also been confirmed by Stellantis. It was necessary to find a case study involving a component that can be made with both traditional plastic and plastic with bio-fillers to evaluate their environmental impact. The two selected components are a tray and an engine beauty cover. The tray will be produced using its conventional plastic as well as a version reinforced with kenaf fibers. Similarly, the engine beauty cover will be made from conventional fiberglass and an alternative version incorporating cellulose fibers. The environmental impacts of these different components will be compared.

To study the environmental impacts of these natural fibers using the LCA tool, it is necessary to first understand the processes involved in obtaining these fibers from crops. These fibers are then used in composites, which are subsequently employed to manufacture car components. In this chapter, we first discuss the definitions and processes related to kenaf and cellulose fibers. We then review the LCA studies for each fiber to gather inventory data. Finally, a car component is selected to compare conventional components with those made from the new natural fiber-based materials, allowing us to assess the differences in environmental impacts.

3.1. Kenaf fiber

Kenaf fiber is a type of natural fiber known for its high tensile strength, making it highly suitable for composite applications across various fields. Biodegradation studies on Ecoflex/kenaf and PLA/kenaf biocomposites indicate that bast fibers like kenaf promote biodegradation due to their lignocellulosic structure [76]. Kenaf is recognized as one of the most superior organic cellulosic fibers, offering several advantageous physical and mechanical properties. It is two to three times more resistant to wear and abrasion than cotton, making it an ideal choice for various applications. Kenaf fibers effectively absorb moisture and provide excellent breathability. Their low elasticity means that fabrics made from kenaf retain their shape over time, reducing the likelihood of deformation [77]. Kenaf (*Hibiscus cannabinus* L., Malvaceae) is a warm-season annual fiber crop closely related to cotton (*Gossypium hirsutum* L., Malvaceae) and okra (*Abelmoschus esculentus* L., Malvaceae) that thrives across a significant portion of agricultural fields [78]. Kenaf is a fast-growing plant with a lifecycle of 90 to 125 days, during which it reaches a stem diameter of 1 to 2 mm and grows up to 80 cm in height. Its fibers are largely cellulose, found in both primary and secondary cell walls, with cellulose fibrils that measure around 0.2 to 0.25 μm in diameter. These fibers are bound in a layer with about 3% pectin and 14% hemicellulose, influencing their durability under heat and water exposure. Kenaf thrives in humid, temperate environments and is specifically cultivated for its fine, durable fibers. As an annual plant, kenaf can grow up to 100 cm and is harvested with fibers intact from top to bottom, as shown in Fig. 8. After harvesting, the stems undergo a process called retting, where exposure to water for about a week helps to break down the soft tissues [77]. Kenaf fiber retting is a crucial process for removing unwanted bark material from the fibers to prepare them for use in various applications [78]

Fig. 8. Kenaf plant [77]

In recent years, the use of kenaf fibers in the automotive industry has surged, highlighting their potential as a sustainable alternative to synthetic fibers. Research has shown that kenaf fiber reinforced with poly-L-lactic acid (PLLA) enhances mechanical properties and accelerates the crystallization of PLLA. Furthermore, studies have indicated that processing parameters significantly influence the mechanical properties of kenaf/polypropylene (PP) composites [77]. One of the key applications of kenaf in the automotive sector is in Sheet Molding Compounds (SMCs), which consist of molding resins, fibers, fillers, and various additives. Traditional SMC resins, typically composed of unsaturated polyester resins (UPR) and vinyl esters, are reinforced with short, chopped fiberglass or carbon fibers. Due to their morphology, tensile strength, and modulus, kenaf fibers present a viable and sustainable alternative to glass fibers in SMC formulations. Their incorporation in automotive composites not only offers comparable mechanical performance but also contributes to environmental sustainability by reducing reliance on synthetic reinforcements [79].

3.1.2. LCA literature on Kenaf Fiber

In this section, a review of the LCA of kenaf fiber across various industries is presented. Our LCA model will also be developed based on data collected from these previous studies. To facilitate a detailed analysis of prior findings, Table 10 summarizes the composites studied, the functional units, the environmental impact metrics measured, the LCA assessment methods and tools employed, and the key results obtained.

Jinwu Wang et al. conducted comparative life-cycle assessments of three types of fiber-reinforced sheet molding compounds (SMCs) utilizing kenaf fiber, glass fiber, and soy protein resin. Typically, automotive SMCs consist of unsaturated polyester and glass fibers; however, substituting these materials with kenaf fiber or soy protein may provide environmental advantages.

They synthesized a soy-based resin known as maleated acrylated epoxidized soy oil (MAESO) from refined soybean oil. The SMC1 composites were created using kenaf fiber and polyester resins, while the SMC2 composites combined kenaf fiber with a resin blend comprising 20% MAESO and 80% unsaturated polyester. Both composite types demonstrated favorable physical and mechanical properties, although neither reached the strength levels of glass fiber reinforced polyester SMCs. Data on energy and materials were collected from laboratory and literature sources, tracking each step in the supply chain for 1 kg of SMC, from raw inputs to intermediates and the final composite. Each component's energy demand, emissions, and byproducts were recorded. In this study, the functional unit was defined as the mass required to achieve equal stiffness and stability, which is critical for the durability of automotive interior parts. Their system boundary in Fig. 9 illustrates the full life cycle of the functional unit, including raw material production (with agricultural pre-chains), semi-finished part production, bus component manufacturing, use, and disposal. Processes common to all product systems were excluded from the comparative LCA. The scope includes raw material inputs, emissions from the production of all reagents and auxiliary materials, as well as energy extraction, conversion, and delivery. Finally, environmental assessment was performed using SimaPro software, with results showing clear ecological benefits from using soy-based resin and natural fiber instead of glass fiber in SMCs. The global warming potentials of kenaf fiber-reinforced SMC (SMC1) and kenaf soy resin-based SMC (SMC2) were 45% and 58%, respectively, of that for glass fiber-reinforced SMC [79].

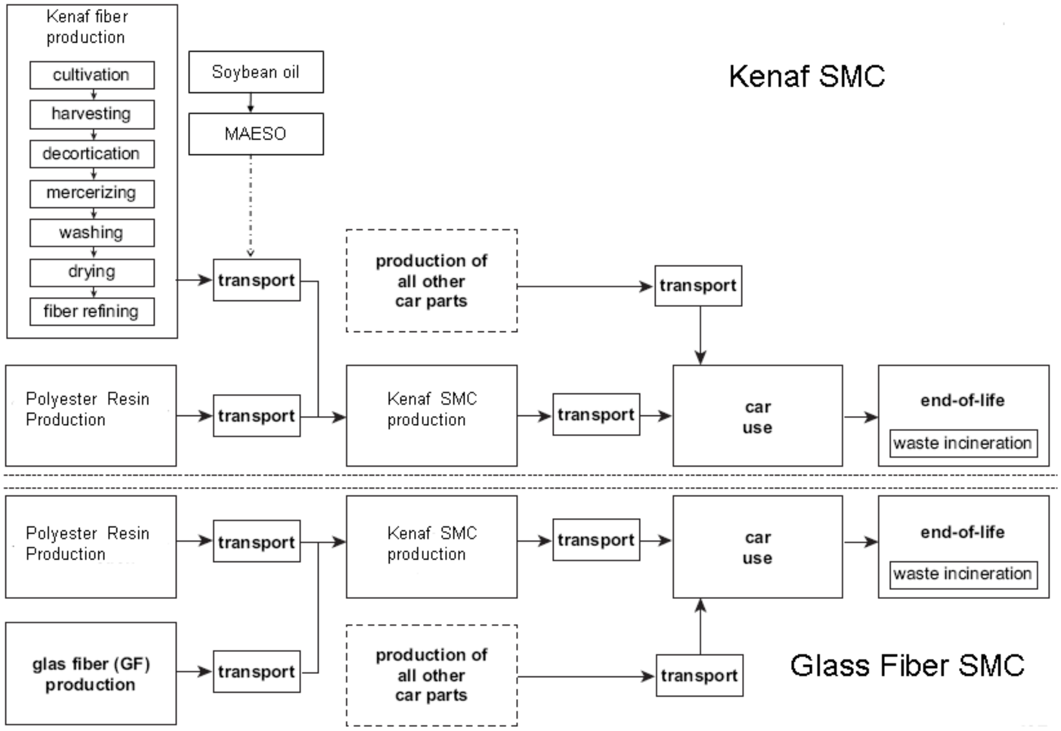

Fig. 9. Steps in the production of kenaf SMC and glass fiber SMC [79].

Wu et al. conducted a comparative life cycle assessment (LCA) to evaluate the environmental impacts of automotive components made from conventional glass fiber sheet molding compound (GF-SMC) versus zinc oxide (ZnO) and kenaf fiber reinforced unsaturated polyester composites. Using a cradle-to-grave approach and employing SimaPro LCA software, the study focused on the entire life cycle of the materials, utilizing Eco-indicator 99 as a single score to assess their environmental performance. The functional unit for the LCA was defined as 1 cubic meter (1 m^3) for both materials. The findings revealed a notable 9% reduction in energy consumption and a significant 33.2% decrease in overall environmental impact when employing kenaf/ZnO composites compared to GF-SMC. These results underscore the potential for more sustainable material choices in the automotive industry, supporting a shift towards eco-friendly manufacturing practices[80]. Result shows Natural Fiber Reinforced Biocomposites (NFRBCs) exhibit lower densities compared to conventional Glass Fiber Sheet Molding Compounds (GF-SMCs) due to the lightweight nature of natural fibers. The densities of NFRBCs range from 1159.4 kg/m^3 to 1510.3 kg/m^3, with the increase attributed to the incorporation of zinc oxide (ZnO) fillers, which enhance the physical properties of the composite. The addition of ZnO significantly influences the overall density, making it a key factor in the formulation. Furthermore, the resin content in NFRBCs is slightly higher than in GF-SMCs, likely because the natural fibers contain abundant hollow spots that can absorb more resin. This characteristic allows for a greater resin-to-fiber ratio in NFRBCs, contributing to their overall performance in automotive applications [80].

Kim et al. conducted a comparative life-cycle assessment (LCA) to evaluate the environmental impacts of automotive interior components made from two composite materials: kenaf fiber reinforced polyhydroxybutyrate composites and glass fiber reinforced polypropylene composites. Utilizing a cradle-to-grave approach, the study analyzed the entire life cycle of these products, with a functional unit defined as one automobile part made from fiber-reinforced composite, and reference flow is 1 kg of fiber reinforced composites. The assessment included two waste disposal scenarios—landfill and composting—and focused on the general form of the interior components, acknowledging their potential use in various applications. The study's system boundary covers all major processes in the lifecycle of composites, from biomass cultivation to waste management, excluding only the vehicle operation phase. This exclusion assumes that switching from glass fiber-reinforced composites to kenaf fiber-reinforced bio-composites does not create additional environmental impacts during vehicle use. As illustrated in Fig. 10, each component of the system boundary includes transportation where relevant. The boxes for corn and kenaf cultivation represent their respective growing processes, which involve the upstream production of fertilizers, agrochemicals, and fuel. Polypropylene and glass fiber production are included as cradle-to-gate processes, and the bio-composite part represents the injection molding step to create automotive components. Lastly, waste management processes account for all necessary steps to handle waste generated throughout the lifecycle of these composites [81].

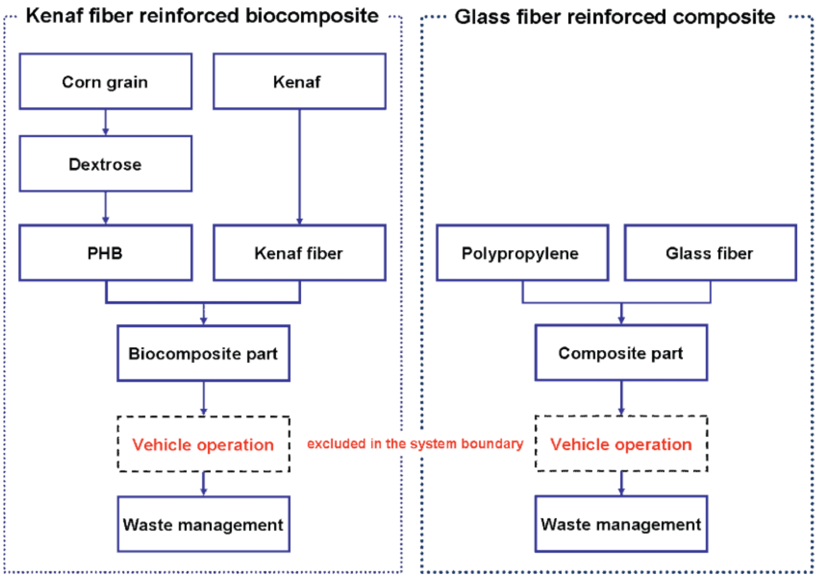

Fig. 10. System boundaries of kenaf and glass fiber reinforced composites [81]

The results indicated that kenaf composites outperformed glass fiber composites in terms of environmental performance, achieving reductions in nonrenewable energy consumption by 23% to 24% and greenhouse gas emissions by 6% to 16%. However, the kenaf composites did have a higher environmental impact regarding photochemical smog formation, acidification, and eutrophication, primarily due to nutrient losses during biomass production. Additionally, the study found that the composting scenario yielded fewer greenhouse gas emissions compared to landfill disposal, as some carbon from the kenaf composites is sequestered in the soil when compost is applied to the land [81].

Batouli et al. conducted research to evaluate the environmental performance of kenaf-fiber-reinforced polyurethane (PU) for use as insulation cores in structural insulated panels (SIPs) within the building sector. Due to the recent use of kenaf fiber as a replacement for PU in SIP insulation cores, they created and examined three composites made of rigid PU reinforced with 5%, 10%, and 15% kenaf core, alongside pure PU, all used as insulation cores in SIPs with kenaf-based structural boards. A life cycle assessment (LCA) was performed using SimaPro to assess the environmental impacts of these four SIPs at 10°C and 50°C. In this study, the SIP insulation core serves two main functions within buildings: structural support and thermal insulation. Structurally, the core must withstand shear forces to enhance the panel's stability and load-bearing capacity. Thermally, it provides insulation, helping regulate indoor temperatures by minimizing heat transfer. To support a meaningful environmental assessment and comparison, the functional unit chosen is the mass (kg) of insulating board required to achieve a thermal resistance (R-value) of 1 $m^2 \cdot K/W$ over an area of 1 m^2. This standardized approach facilitates the evaluation of the insulation core’s performance and environmental impact, aligning with similar studies and ensuring comparability of results. Results indicated that while kenaf has a lower environmental impact than PU, increasing kenaf content does not always reduce the overall environmental footprint. This is because the kenaf primarily fills voids previously occupied by air, which decreases porosity and increases the composite density without significantly enhancing thermal resistance [82].

Another study in the construction sector compares the environmental impact of Kenaf Fiber-Reinforced Cement (KFRC) wall panels to that of conventional Glass Fiber-Reinforced Cement (GFRC) wall panels. The scope of the research spans from cradle to grave, with the Life Cycle Assessment (LCA) beginning with raw materials and concluding with the disposal of the products at their end of life. In this study, the researchers utilized two distinct functional units. For structural performance, they defined the functional unit as the mass (in kg) of a 1 m x 1 m wall panel that can support a yield load of 1 kN, focusing on how each panel performs in terms of load-bearing capacity and stability. For thermal insulation, the functional unit was defined as the mass (in kg) of a 1 m^2 wall panel with a thermal resistance of 1 $m^2 \cdot K/W$, emphasizing the panel's effectiveness in heat insulation. These units allow for separate evaluations of each panel's environmental impact in supporting building structures and providing energy efficiency. The results indicate that GFRC panels outperformed KFRC panels across all categories for both structural and insulation functions. Notably, the Human Health (HH) cancer impact was significantly lower for KFRC, which exhibited only 42% of the HH cancer impact associated with GFRC for structural applications and 32% for insulation purposes [83].

Ardente et al. conducted a cradle-to-grave LCA of kenaf-fiber insulation boards, analyzing the environmental impact from kenaf cultivation through to the board's production. The manufacturing processes were based on operations in an Italian factory. The functional unit used in the study is defined as the mass of insulation board needed to achieve a thermal resistance of 1 $m^2 \cdot K/W$, indicating the amount of insulation material (in kilograms) required to provide effective heat resistance for a given area (1 m^2) over its lifetime. For this specific thermal resistance, the necessary insulation board mass is 1.52 kg. The production system is depicted in Fig. 11. For cultivation, kenaf is mainly grown in Italy, with some fiber sourced from other Mediterranean regions, particularly Morocco. Data on fertilizer and diesel usage were collected from a typical cultivation cycle in Italy, although water consumption during cultivation was not recorded. Transport within Italy relies on lorries, while international shipping uses cargo transport. The study excludes the installation and maintenance impacts of the insulation board but considers the energy savings and emissions reductions during its use phase. At the end of its life cycle, kenaf fibers are assumed to be incinerated, with CO_2 emissions from combustion not included. This is based on the rationale that the CO_2 released during incineration roughly equals the CO_2 absorbed by the plants during growth. Impact assessment results indicate that greenhouse gas (GHG) emissions are a key environmental factor in the board's life cycle, totaling approximately 3.17 kg CO_2 equivalent per functional unit. The largest portion of these emissions stems from the production of input materials, with polyester fibers accounting for about 39% of the total. Transport emissions contribute 23%, and the disposal phase adds another 25%, primarily from polyester fiber combustion [84].

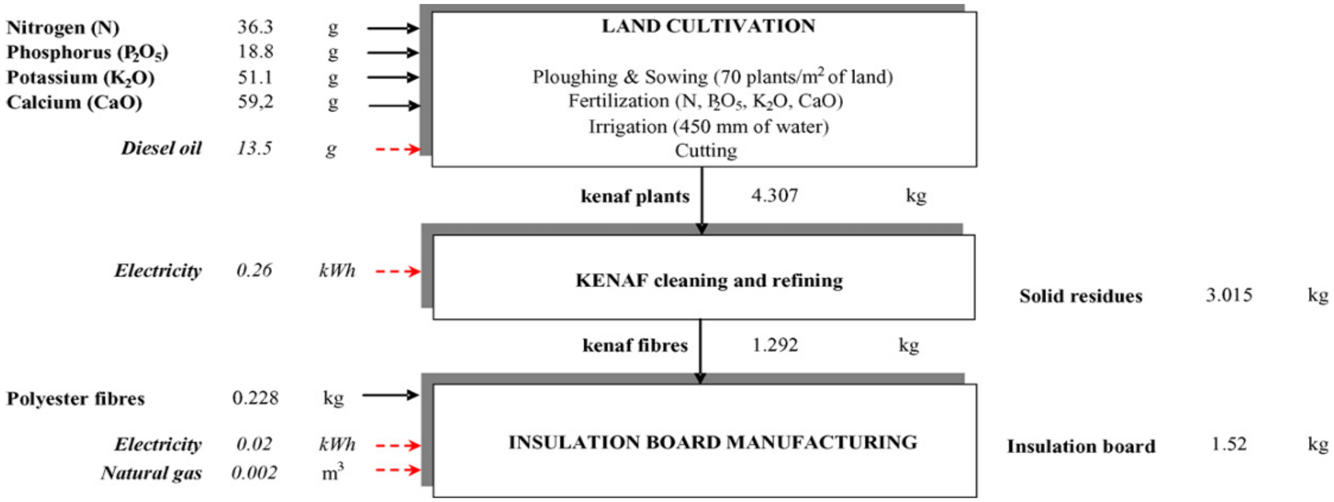

Fig. 11. Flow chart of the production system kenaf-fiber insulation boards [84]

In their study, Korol et al. conducted a comparative life cycle assessment (LCA) of plastic pallets made from various biocomposites and polypropylene-based composites, employing the ReCiPe Life Cycle Impact Assessment (LCIA) method. The materials examined included polypropylene (PP) composites reinforced with different fillers, specifically glass fibers (GF), cotton fibers (CF), jute fibers (JF), and kenaf fibers (KF), with filler proportions ranging from 10% to 30% by weight to achieve the necessary mechanical properties for the pallets. The analysis utilized SimaPro 8 software alongside the Ecoinvent database version 3.1. In this study, the functional unit (FU) was established as the manufacturing of one standard plastic pallet with a weight of 15 kg. This unit enabled the assessment and comparison of the environmental impacts associated with producing a single pallet crafted from different polypropylene composites that contained various types and proportions of fillers. The findings revealed that composites reinforced with cotton and glass fibers had the most significant environmental impacts among the materials tested, whereas the PP composite reinforced with kenaf fibers (PPKF) exhibited the least environmental impact. Additionally, the study innovatively utilized the results from the environmental assessment to quantify eco-efficiency. The researchers analyzed both environmental and cost efficiencies for each pallet, resulting in an eco-efficiency score that allowed for a ranked comparison of the different composites. This methodology helped identify materials and production methods that effectively balanced sustainability with cost considerations, aiding in more sustainable decision-making [85].

Table 10 summarizes various life cycle assessments (LCA) of kenaf fiber-reinforced composites, comparing their environmental impacts across different studies. It highlights key environmental impacts such as global warming potential (GWP), energy consumption, and human health effects. The results show that kenaf fiber composites generally offer environmental benefits, including reductions in GWP, nonrenewable energy consumption, and greenhouse gas emissions compared to traditional materials like fiberglass and other synthetic options. However, some studies observed higher impacts on photochemical smog, acidification, and eutrophication for kenaf composites.

Table 10. Summary of LCA Research on Kenaf Fiber-Reinforced Composites

Composites	Functional Unit	Environmental impact measured	Life cycle impact assessment method	LCA tool	LCA approach	Key findings	Reference
SMC reinforced with fiberglass, SMC reinforced with kenaf, SMC reinforced with kenaf and soy resin	1 kg for SMC reinforced with fiberglass, 0.63 kg for SMC reinforced with kenaf, 0.69 kg for SMC reinforced with kenaf and soy resin	GWP, acidification, ecotoxicity, water intake, ozone depletion, human health (cancer), smog	Eco-indicator 99 and Building for Environmental and Economic Sustainability (BEES)	SimaPro, Ecoinvent-	Cradle to gate	GWP reduction of 45% for SMC reinforced with kenaf and 58% for SMC reinforced with kenaf and soy resin compared to SMC reinforced with fiberglass	[79]
GF-SMC (Glass Fiber Sheet Molding Compound), zinc oxide and Kenaf (ZnO/Kenaf) fiber reinforced polyester composite	1 m³ for both material	Global warming Acidification HH, cancer HH noncancer HH criteria, air pollutants, Eutrophication, Ecotoxicity Smog, Natural resource depletion, Indoor air quality, Habitat alteration, Water intake, Ozone depletion	(BEES) and Eco-indicator 99	SimaPro,	Cradle-to-grave approach	ZnO/Kenaf composite showed a 9% reduction in energy consumption and a 33.2% decrease in environmental impact compared to GF-SMC. NFRBCs have lower density than GF-SMC, with ZnO fillers enhancing density and physical properties.	Wu et al., 2020
Kenaf fiber reinforced polyhydroxybutyrate (PHB) composites, Glass fiber reinforced polypropylene composites	One automotive interior part and the reference flow is 1 kg of fiber-reinforced composite	Nonrenewable energy consumption, Greenhouse gas emissions, Photochemical smog formation, Acidification, Eutrophication	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)	Not stated	Cradle-to-grave approach	Kenaf composites showed reductions in nonrenewable energy consumption by 23%-24% and greenhouse gas emissions by 6%-16% compared to glass fiber composites. However, kenaf composites had higher impacts in photochemical smog formation, acidification, and eutrophication. Composting scenario produced fewer GHG emissions than landfill due to carbon sequestration in soil.	[81]
Pure polyurethane (PU), PU reinforced with 5%, 10%, and	Mass (kg) of insulating board required	Global Energy Requirement (GER);	Not stated	SimaPro	Cradle to gate	While kenaf has a lower environmental impact than PU,	[84]

Composites	Functional Unit	Environmental impact measured	Life cycle impact assessment method	LCA tool	LCA approach	Key findings	Reference
15% kenaf core (for insulation cores in SIPs)	to achieve a thermal resistance of 1 m^2·K/W over an area of 1 m^2	Global Warming Potential (GWP); Photochemical Ozone Creation Potential (POCP); Nitrification Potential (NP); Acidification Potential (AP); Ozone Depletion Potential (ODP); Water Consumption; Waste Generation				increasing kenaf content does not consistently reduce the overall footprint due to decreased porosity and increased density, which do not significantly improve thermal resistance.	
Kenaf Fiber-Reinforced Cement (KFRC) vs. Glass Fiber-Reinforced Cement (GFRC)	For structural performance: mass (kg) of a 1 m x 1 m wall panel supporting a yield load of 1 kN; For thermal insulation: mass (kg) of a 1 m^2 wall panel with a thermal resistance of 1 m^2·K/W	Human health cancer, Human health non-cancer, Human health criteria air pollutants, Eutrophication, Ecotoxicity, Smog, Natural resource depletion, Indoor air quality, Habitat alteration, Ozone depletion.	BEES	SimaPro, Ecoinvent	Cradle-to-grave	GFRC panels outperformed KFRC in all categories. KFRC showed a significant reduction in Human Health cancer impact—42% of GFRC for structural use and 32% for insulation.	[83]
PP composites reinforced with glass fibers (GF), cotton fibers (CF), jute fibers (JF), and kenaf fibers (KF),	1 standard plastic pallet with 15 kg weight	Global warming potential (GWP), Acidification, Eutrophication, Ecotoxicity, Smog, Human health impacts, Water consumption, Natural resource depletion, Indoor air quality, Ozone depletion	ReCiPe 2016 midpoint	SimaPro 8, Ecoinvent 3.1	Cradle-to-gate	PPKF showed the least environmental impact compared to GF, CF, and JF composites. Cotton and glass fiber composites had the highest environmental impacts. Eco-efficiency was quantified and used to balance environmental and cost efficiencies for decision-making.	[85]
Kenaf-fiber-reinforced polyurethane (PU)	Mass (kg) of insulating board required to achieve a thermal resistance of 1 m^2·K/W over 1 m^2	Global warming potential (GWP), Acidification, Eutrophication, Ecotoxicity, Smog, Water consumption, and Natural resource depletion	BEES	SimaPro	Cradle-to-gate	Kenaf-reinforced PU composites exhibited a lower environmental impact than pure PU, but increasing kenaf content did not always reduce the environmental footprint.	[82].

3.2. Cellulose

Cellulose, the most abundant biodegradable polymer globally, is produced at a capacity of 10^{11}–10^{12} tons annually and has been widely utilized due to its desirable properties, including biodegradability and sustainability. It has traditionally been derived from plants like wood, hemp, cotton, and linen, as well as microorganisms such as fungi and bacteria, which offer variations in polymerization and purity. Since its discovery in 1838 by Payen, with a molecular formula of $C_6H_{10}O_5$, cellulose has been extensively used as a raw material for energy, construction, and manufacturing role in sustainable industries, with an estimated global commercialization value of $600 billion by 2020 [86]. Notably, nanocellulose, a derivative of cellulose, is expected to play a pivotal role in sustainable industries, with an estimated global commercialization value of $600 billion by 2020 [86]. Its structure, formed by D-anhydroglucopyranose units linked via glycosidic bonds, enables hydrogen bonding, significantly influencing its crystalline regions and physical properties. This feature also facilitates chemical modifications, leading to the creation of cellulose derivatives useful for manufacturing biopolymers across various industries[87], [88], [89]. With the increasing demand for low-carbon materials, cellulose is gaining attention as a replacement for fossil-based plastics in applications ranging from automotive components to thermal insulators, owing to its environmental benefits and vast industrial potential [90], [91].

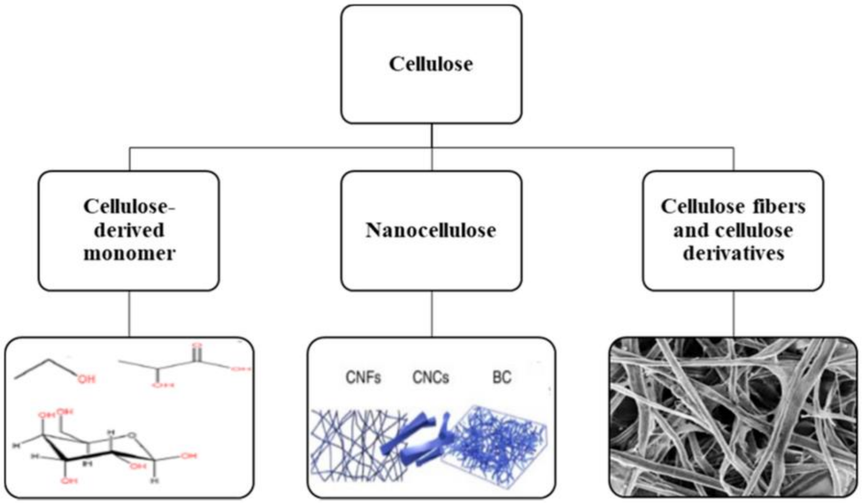

Fig. 12. A classification of different types of cellulose [92]

Fig. 12 illustrates these three forms of cellulose, with their respective products, properties, and applications detailed in the following sections.

Cellulose-derived monomers are produced by breaking cellulose into simpler molecules, primarily glucose, through processes like enzymatic or acid-catalyzed hydrolysis. The resulting glucose serves as a raw material for synthesizing various chemicals and monomers via catalytic or biotechnological methods. Common examples of these monomers include:Methanol, Ethanol, Lactic Acid (LA), Sorbitol, 5-Hydroxymethylfurfural (5-HMF), Levulinic Acid (LevA). These monomers can be transformed into eco-friendly polymers and copolymers, providing a sustainable alternative to traditional fossil-based materials. For example, lactic acid is used to manufacture polylactic acid (PLA), a widely recognized biodegradable polymer, while 5-HMF and LevA act as building blocks for bio-based resins and plastics [93].

Cellulose fibers and their derivatives are increasingly used in bio-composites and films, serving as fillers, matrices, or both. These fibers consist of multiple layers, including a primary and three secondary cell walls, which are made up of microfibril bundles about 10 µm in diameter [94]. The properties of cellulose fibers depend on factors such as the stru[95], [96]. Recently, all-cellulose composites have emerged, where the matrix and filler are both made from cellulose. These composites address issues of adhesion and interaction between the matrix and filler and have gained attention for their potential in biocomposites [97]. Cellulose in these materials can be in the form of fibers or nanocellulose [92].

Nanocellulose is a novel form of cellulose at the nanoscale that has gained significant attention in recent years due to its exceptional properties. It is known for its excellent mechanical properties, which make it a strong and stiff material, as well as its high aspect ratio, which refers to the ratio of length to diameter of the fibers. This high aspect ratio results in a large surface area, enhancing its potential for reinforcing other materials. Furthermore, nanocellulose is biodegradable, offering a sustainable alternative to synthetic materials [93]. Nanocellulose can be classified in two main ways: first, based on its size and appearance, which includes forms such as nanofibers and nanocrystals; and second, based on the methods used for its preparation and the raw materials, which include various processes like acid hydrolysis, enzymatic treatment, or mechanical processing. These unique characteristics make nanocellulose a promising material for various applications, especially in biocomposites and other environmentally friendly products [92]. Nanocellulose is categorized into three primary types based on the methods of preparation and the raw materials used. These categories include cellulose microfibrils (CMF), also known as cellulose nanofibrils (CNF), nanocrystalline cellulose (CNC), and bacterial nanocellulose (BNC). Cellulose microfibrils (CMF) or nanofibrils (CNF) are derived from plant fibers and are produced using chemical, mechanical, or a combination of treatments. These microfibrils are widely utilized due to their excellent mechanical and structural properties, making them suitable for various applications. Nanocrystalline cellulose (CNC), sometimes referred to as nanowhiskers, is produced through acid hydrolysis of cellulose from sources such as plants, animals, and bacterial resources. CNC is characterized by its crystalline structure and high mechanical strength, which are advantageous in applications requiring enhanced rigidity and stability. Bacterial nanocellulose (BNC) is synthesized by specific bacteria, resulting in a highly pure and mechanically robust material. BNC has diverse industrial and biomedical applications owing to its unique properties [92], [98]. Table 11, summarize the applications of the various types of nanocellulose.

Table 11. Summary of Nanocellulose Applications by Type

Nanocellulose Type	**Applications**
CNC	Food packaging, chemical sensors, biosensors, virus removal.
BNC	Wound healing, tissue engineering, fuel cells, ultrafiltration.
CNF/CMF	Air purification, fire retardants, piezoelectric sensors, electronic devices, lithium batteries.

3.2.1. LCA literature on cellulose fiber

Many studies have explored the use of cellulose fiber as a replacement material across various industries. In addition to cellulose fiber, many researchers have investigated different types of nanocellulose-based products to identify methods that can reduce environmental impacts. We provide a brief explanation for most of them and focus only on the main studies relevant to our case study.

Some studies have examined different feedstocks to determine which sources for cellulose have the lowest environmental burden [99], [100], [101]. Piccinno et al. (2018) applied a scale-up framework for life cycle assessment (LCA) to evaluate the environmental impact of nanocellulose production at an industrial scale [102][102]. Other studies have analyzed laboratory-scale methods for producing nanocellulose fibers [98], [103], [104]. Additionally, some research has focused on assessing the environmental impacts of recycled cellulose fibers in various industries, such as textiles, construction, and food packaging [105], [106], [107]. Hervy et al. (2015) evaluated the environmental impact of bacterial cellulose (BC)- and nanofibrillated cellulose (NFC)-reinforced epoxy composites using LCA [108]. Recently, researchers have developed new biobased composites to assess the mechanical and environmental efficiency of cellulose in composite materials [109]. Some studies have also focused on novel cellulose fibers, such as nanocrystalline cellulose (NCC), investigating its production processes and environmental performance [110].

In the following sections, we expand our review to include studies closely related to our work, some of which will serve as the basis for our case study in the next chapter.

Akhshik et al, applied Life Cycle Assessment (LCA) to compare a traditional car engine beauty cover with a bio-based alternative. The conventional material, a glass fiber-reinforced polyamide composite, was compared to a bio-based composed of cellulose and carbon fiber-reinforced polypropylene. The new bio-based engine cover is significantly lighter than the traditional material, reducing the component's weight by approximately 400 g. This composite was developed at the University of Toronto's Center for Bio-composites and Biomaterials. The study adopted a cradle-to-grave scope, beginning with the extraction of necessary raw materials, such as tree cultivation for natural fibers, the extraction and processing of natural gas, coal extraction, and the use of other energy sources, including renewable and nuclear power. The functional unit was defined as an engine beauty cover designed for a generic V6 engine in a Ford SUV or pickup truck. The cover enhances the engine's aesthetic appearance, provides heat insulation, and reduces noise emissions, with an expected lifespan of 25 years or 290,000 km, whichever occurs first. Results showed that both materials met manufacturer standards and were considered equivalent. However, the cellulose/carbon fiber composite outperformed the conventional material in most environmental impact categories, except for higher water and wood consumption. Concerns about eutrophication impacts from bio-based materials were mitigated in this case, as no fertilizers were used during the silviculture process [111].

Another article evaluates the environmental impacts of substituting traditional glass fiber composites with cellulose-fiber reinforced polypropylene for automotive components through a

Life Cycle Assessment (LCA) [112]. The study focused on a grill shutter housing component, assessing its production, use, and end-of-life stages. The proposed cellulose-fiber composite showed a 9.6% reduction in life cycle energy consumption and a 20.7% reduction in global warming potential (GWP) compared to the 30% glass fiber composite. Sensitivity analyses were also conducted to explore different scenarios, such as variations in vehicle lifetime and material sourcing. In line with the EPA's TRACI impact assessment method, biogenic carbon dioxide emissions from the combustion of woody biomass used in energy production were excluded from the analysis. The findings suggest that the use of cellulose-fiber composites offers significant environmental benefits, particularly in terms of energy and emissions reduction [112].

In another study by Hervy et al, the researchers evaluated the environmental impact of bacterial cellulose (BC)- and nano fibrillated cellulose (NFC)-reinforced epoxy composites using life cycle assessment (LCA). They compared these composites to neat polylactide (PLA) and glass fibre-reinforced polypropylene (GF/PP) composites as benchmark materials. The cradle-to-gate LCA showed that while BC- and NFC-reinforced composites had higher global warming potential (GWP) and abiotic depletion potential of fossil fuels (ADf) compared to PLA and GF/PP, their performance in terms of tensile modulus was superior. When considering the use phase and end-of-life impacts, the environmental profile of the nanocellulose-reinforced composites was similar to that of PLA and GF/PP. Additionally, the study's life cycle scenario analysis suggested that composites with over 60 vol.-% nanocellulose could have lower GWP and ADf than neat PLA, making high-nanocellulose-loaded composites more environmentally friendly than the best-performing commercial bio-derived polymers [108].

Table 12 provides an overview of LCA literature on cellulose fibers, comparing the functional units, environmental impacts, methods used in LCA models, LCA tools and approaches, and the key findings of each published study.

Table 12. Summary of LCA Literature on Cellulose Fibers and Their Composites

Composites	Functional Unit	Environmental impact measured	Life cycle impact assessment method	LCA tool	LCA approach	Key findings	Reference
Nano-Fibrillated Cellulose (NFC) from manure-derived digestate and Kraft pulp	1 kg of NFC	Global Warming Potential (GWP), fossil resource scarcity, freshwater eutrophication, human toxicity, terrestrial acidification (TAP), terrestrial ecotoxicity	ReCiPe 2016 Midpoint (H)	openLCA version 1.9	Cradle-to-gate analysis	Manure-derived NFC reduces impacts by 45%. GWP: manure NFC 4.41 kg CO_2 eq./kg, wood NFC 9.74 kg CO_2 eq./kg. Pulp-to-NFC step is a hotspot.	[99]
Nanocellulose from four lab-scale fabrication methods	10 g of dry nanocellulose	Environmental footprint of production methods	Eco-Indicator 99	SimaPro databases	Cradle-to-gate analysis	TEMPO oxidation is the most sustainable method. Sonication has higher mechanical treatment impacts. Nanocellulose has a	[98]

Composites	Functional Unit	Environmental impact measured	Life cycle impact assessment method	LCA tool	LCA approach	Key findings	Reference
						lower impact than carbon nanotubes.	
Traditional car engine beauty cover vs. bio-based bio-based	Engine beauty cover for a V6 engine in a Ford SUV or pickup truck	Environmental impact comparison of materials	US EPA TRACI 2.1	openLCA, SimaPro, Gabi, GREET, NREL	Cradle-to-grave analysis	The bio-based composite outperforms the conventional material in most impact categories. It has higher water and wood consumption. Both materials meet manufacturer standards.	[113]
Cellulose nanowhiskers from unripe coconut fibers (EUC) and white cotton fibers (EC)	1 gram of nanowhiskers	Energy and water consumption, liquid effluent emissions, climate change, water depletion, eutrophication, human toxicity	ReCiPe method	SimaPro, Ecoinvent V2 database	Cradle-to-gate analysis	EC system has a lower environmental footprint than EUC system. EC requires less energy and water and emits fewer pollutants.	[100]
Cellulose nanocrystals (CNCs) from unripe coconut fibers	1 gram of CNC	Water and energy consumption, use of chlorine-based chemicals, yield, environmental impacts	ReCiPe method	SimaPro, Ecoinvent V2 database	Cradle-to-gate analysis	High-power ultrasound extraction method has the lowest environmental impacts. Using lignin as a power source does not differ significantly from its use as a chemical byproduct.	[101]
Cellulose-fiber reinforced polypropylene vs. glass fiber composites for automotive components	Grill shutter housing component	Life cycle energy consumption, global warming potential (GWP)	EPA's TRACI	SimaPro, Ecoinvent V2 database	Cradle-to-grave analysis	Cellulose-fiber composite reduces energy consumption by 9.6% and GWP by 20.7% compared to glass fiber composite.	[112]
Alternative methods for producing cellulose nanocrystals (CNCs)	1 gram of CNC	Environmental impacts of different CNC production methods	ReCiPe 2016 (H), CED (Cumulative Energy Demand)	SimaPro v9.0	Cradle-to-gate analysis	Some green methods have higher impacts, but deep eutectic solvent and enzymatic hydrolysis show lower endpoint impacts.	[103]
Nanocrystalline cellulose (NCC) production process	1 kg of dry NCC	Global warming, fossil fuel depletion, water consumption, human toxicity	ReCiPe 2016	GaBi (Ecoinvent database)	Cradle-to-gate analysis	Diethylene glycol and electricity are key contributors to environmental impacts. Water consumption from raw materials like cotton fibers is significant.	[110]

Composites	Functional Unit	Environmental impact measured	Life cycle impact assessment method	LCA tool	LCA approach	Key findings	Reference
Chemically recycled cellulose carbamate fiber	1 kg of cellulose carbamate fiber	Climate impact, water scarcity, cumulative energy demand, land use, freshwater consumption	IPCC 2021 GWP 100, SimaPro version 1.04	SimaPro	Cradle-to-gate analysis	Major impacts come from electricity and sodium hydroxide. Recycled fibers have lower to middle range impacts compared to primary fibers.	[106]
CNC/PDMS bio-based membrane	1 m² of CNC-PDMS membrane	Global warming potential, ozone depletion, smog, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory, ecotoxicity, fossil fuel depletion	TRACI 2.1, ReCiPe 2016	SimaPro 9.3	Cradle-to-gate analysis	12% reduction in global warming potential compared to PDMS. CNC addition reduces environmental impacts with similar costs.	[114].
ELT (End-of-Life Tires)-reinforced HMA	1 m² of HMA (Hot Mix Asphalt) for motorway construction	Cumulative Energy Demand (CED), Global Warming Potential (GWP), ReCiPe indicators	ReCiPe, CED, GWP	GaBi Professional (2016)	Cradle-to-gate analysis	ELT fiber-reinforced mixture showed 25% reduction in impacts and 70% improvement in fatigue resistance.	[105]
Salt-CNC Composite	1 MJ of energy stored (for salts & composites), 1 kg (for CNC)	Global warming, ozone depletion, fossil fuel depletion, and other 10 impact categories	TRACI II	SimaPro v8.3	Cradle-to-gate	CNC production accounted for over 50% of the impact. Scaling up reduced mixing and sonication impacts; drying remained high-impact. Magnesium sulfate, zinc sulfate, and calcium chloride were favorable.	[115].
nanofibril (CNF) films (flexible routes)	2 grams of dry CNF film	Embodied energy, global warming potential (GWP), water usage	Not mentioned	Ecoinvent database v.3.9.1	Cradle-to-gate	CNF films showed 15%-20% higher impacts than PET but can improve with scaling and cradle-to-cradle cycles.	[104]
CNF films (spray-deposited)	Equivalent mass of material required to achieve the same level of performance based on specific tensile stiffness (E/ρ) as 1 kg of NFC-reinforced	Energy demand, waste management, global warming potential (GWP)	CML 2001	GaBi v6	Cradle-to-gate	Spray deposition and drying processes require high energy. Optimized scenarios can reduce impacts 2-5 times versus synthetic packaging.	[108]

Composites	Functional Unit	Environmental impact measured	Life cycle impact assessment method	LCA tool	LCA approach	Key findings	Reference
	epoxy composite						
Cellulose nanocrystals (CNCs) from sugarcane biorefineries	1 kg of CNCs	GWP, abiotic depletion	Not mentioned	SimaPro	Cradle-to-gate	Producing 7.73 tons of CNCs daily results in 23.6 tons CO2 eq. GWP. Sulfuric acid and ethanol identified as key contributors to impacts.	[116]
PLA-P and cellulose paper composite straws	1 straw	GWP, ecological footprint	ReCiPe 2016 midpoint (H) approach	SimaPro 9.0	Cradle-to-gate	PLA-P straws bonded through dip molding improve water resistance and strength. 35-40% degraded in soil/compost in 4 months. Reduced ecological footprint.	[109]
Nanocellulose Production Pathway	1 kg of spun yarn	Multiple categories: global warming, toxicity, etc.	ReCiPe 2016 midpoint and endpoint methods	OpenLCA v1.4.1	Cradle-to-gate	Industrial-scale production reduced environmental impact per kg by up to 6.5 times compared to lab scale.	[102].
Cellulose micro- and nanofibers (CNFs)	1 kg of CNFs produced from bleached hardwood kraft pulp	Global Warming Potential, Acidification Potential, Nutrient Enrichment, Photochemical Ozone Formation, Primary Energy Consumption, Use of Agricultural Land	Product Environmental Footprint (PEF) methodology	GaBi Ecoinvent	Cradle-to-gate	Mechanical and TEMPO-mediated oxidation routes have lower environmental impacts than the enzymatic route. TEMPO-mediated oxidation enables selective production of specific CNFs.	[117]

4. LCA of bio-fillers for Automotive applications

4.1. LCA of kenaf in SMCs

As previously discussed, this study focuses on kenaf fiber as a potential substitute for glass fiber, a conventional reinforcement material. The objective of this study is to conduct a Life Cycle Assessment (LCA) to estimate environmental impacts of sheet molding compounds (SMCs) reinforced with kenaf fiber, a natural fiber, and glass fiber, a conventional reinforcement material. To achieve this goal, three datasets are utilized to model the production of fibers, resins, and ultimately the SMCs. To achieve this, the following methodology was applied:

1. Modeling the production of Unsaturated Polyester Resin (UPR): The resin matrix, common to both kenaf and glass fiber-reinforced SMCs, was modeled to establish a baseline.

Inventory data for UPR production were derived from a comparable published work by Jinwu Wang (2013), which provided Life Cycle Assessment (LCA) data for kenaf fiber-reinforced composites produced on a laboratory scale.

2. Developing a new kenaf fiber Life Cycle Assessment (LCA) Model: Since the existing Ecoinvent dataset primarily reflects global and Indian conditions, a new LCA model was tailored for kenaf fiber production in Italy. This model was based on data from Ardente et al. (2008), ensuring alignment with Italian and European agricultural and processing practices [84].

3. Integrating the kenaf fiber Dataset into SMC production: The developed inventory, representing Italian and European conditions, was incorporated for the production process of kenaf fiber-reinforced SMCs [79]. Consistent with [79] approach, catalysts and additives were excluded from the analysis. Their contribution, representing less than 1% of the total material composition, was deemed negligible in terms of environmental impact. Fig. 13, summarize system boundaries of this LCA study. The system boundary for the production of kenaf SMC and conventional glass fiber SMC encompasses raw material extraction, manufacturing, and transportation between these stages. This approach, known as cradle-to-gate*,* ensures a comprehensive evaluation of the environmental impacts associated with both conventional and bio-based fillers, aligning with the study's goal and scope.

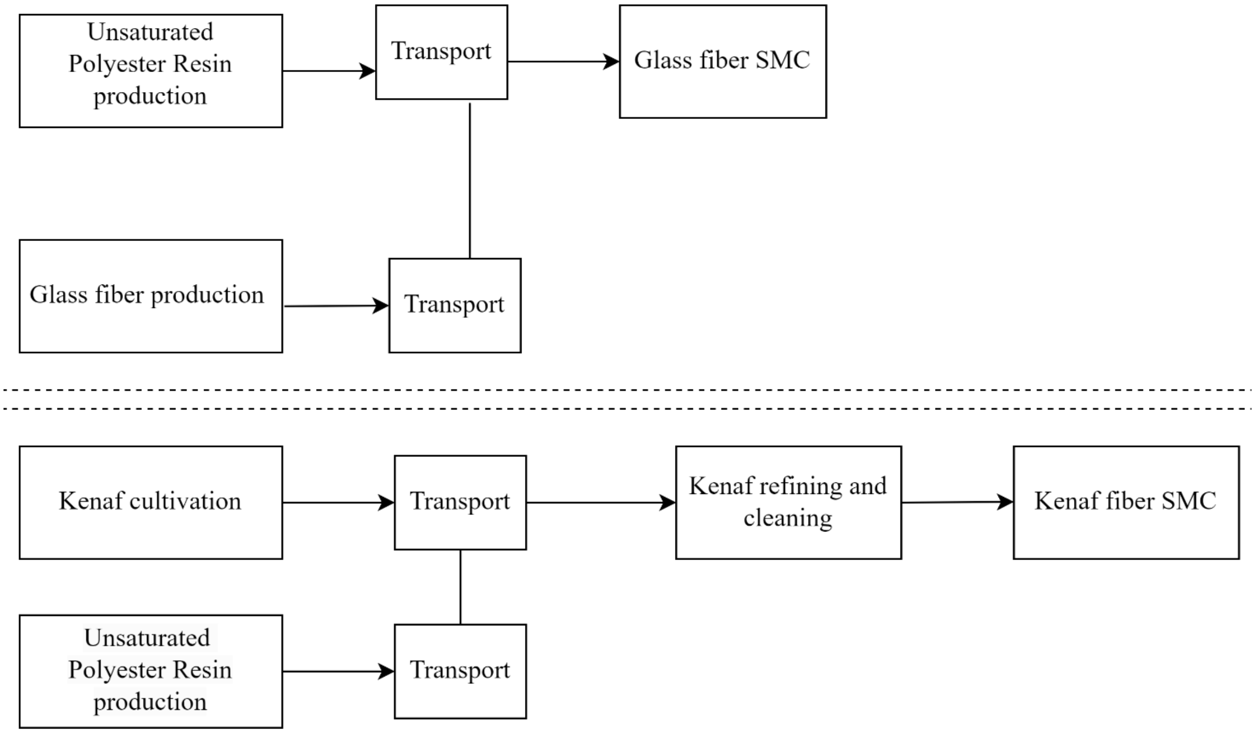

Fig. 13. System boundary for kenaf SMC and glass fiber SMC for this study

4.1.1. Standard Unsaturated Polyester Resin Production

The unsaturated polyester resin (UPR) can have different formulations and production processes. In the study by [79], a formulation provided by a chemistry company in the U.S. was presented, but energy inputs were not included. Wang (2013) claims that all gaps in formulations and energy materials were gathered from laboratory experiments and literature [79]. This assumption is referred to as the Standard Unsaturated Polyester Resin Production. The term "standard" means that the UPR formulation offered in their study can be assumed to be representative of all UPR resins available in the marketplace. The production of UPR begins with a reaction that requires heat. The mixture is heated to 190°C and kept at that temperature or 15-18 hours to ensure the substances in the resin are completely mixed and reacted. During this process, water is produced as a byproduct. This water is removed by a condenser system and recycled back into the reactor to increase efficiency. Once the resin reaches the desired molecular weight, it is cooled and transferred to a separate tank, where it is diluted with styrene to stabilize the resin and achieve the desired market mixture. Water usage in the process is about 0.01 gallons per pound of resin and is mainly used for cooling purposes [79].

Inventory data of UPR production were gathered from a comparable published study [79]. That study provided LCA data for kenaf fiber-reinforced composites based on laboratory-scale synthesis. Information on unsaturated polyester resin and glass and kenaf fiber SMC were referred US, which has been adapted to consider a generic production in Europe and specially Italy. Additionally, LCA data related to the production of raw materials were retrieved from the Ecoinvent 3.9.1database. We assumed catalysts and additives were excluded from the analysis, as their contribution represents less than 1% of the total material composition and their environmental impact is considered negligible [79]. The system boundary is cradle to gate with the functional unit defined as 1 kg of unsaturated polyester resin dissolved in styrene. Table 13 presents the life-cycle inventory for 1 kg of unsaturated polyester resin dissolved in styrene, derived from engineering data, process chemistry [79]. Then, this unsaturated polyester resin will be used in the production of two types of fiber-reinforced sheet molding compounds (SMCs): one reinforced with kenaf fiber and the other with glass fiber. The primary modification from [79] is the transportation data, which were sourced from the Italian study by [84], instead of U.S. data in the original paper. All transportation is assumed to be carried out using lorries with a maximum capacity, covering an average distance of 200 km.

Table 13. Materials and energy input and output of 1 kg unsaturated polyester resin (UPR) dissolved in styrene [79]

Flow [Unit of measure]	Quantity	Reference dataset
Inputs		
Propylene glycol [kg]	0.29	market for propylene glycol, liquid | propylene glycol, liquid | Cutoff, U – RER
Maleic anhydride [kg]	0.19	market for maleic anhydride | maleic anhydride | Cutoff, U – GLO
Styrene [kg]	0.35	market for styrene | styrene | Cutoff, U – GLO
Diethylene glycol [kg]	0.031 kg	market for diethylene glycol | diethylene glycol | Cutoff, U – GLO
Hydroquinone [kg]	0.0002	market for hydroquinone | hydroquinone | Cutoff, U – GLO
Water [m^3]	0.01593	
Cooling water [m^3]	0.106	

Flow [Unit of measure]	Quantity	Reference dataset
Electricity [MJ]	0.379	electricity voltage transformation from medium to low voltage | electricity, low voltage | Cutoff, U – IT
Natural gas [m^3]	0.063	market for natural gas, low pressure | natural gas, low pressure | Cutoff, U – RoW
Transport, freight, light commercial vehicle [kg*km]	1*200	transport, freight, lorry 7.5-16 metric ton, EURO3 – RER
Output		
UPR [kg]	1	

4.1.2. Glass and kenaf fibers SMC

This section outlines the inventory and LCA models for SMC composites reinforced with kenaf and glass fibers. First, the inventory of kenaf fiber, and then kenaf fiber SMC are collected. After that the inventory data for glass fiber SMC, which is the conventional composite is gathered. The functional unit is also 1 kg for each composite and the system boundary follows a cradle to gate approach.

4.1.2.1. Kenaf fiber SMC

In this section, we develop the LCA inventory for kenaf fiber production and then for the kenaf fiber-reinforced SMC. As previously noted, the kenaf fiber dataset in Ecoinvent is not specific to Italy nor representative of Europe. Therefore, the kenaf cultivation and refining processes are modeled according to the system boundary outlined in Fig. 14.

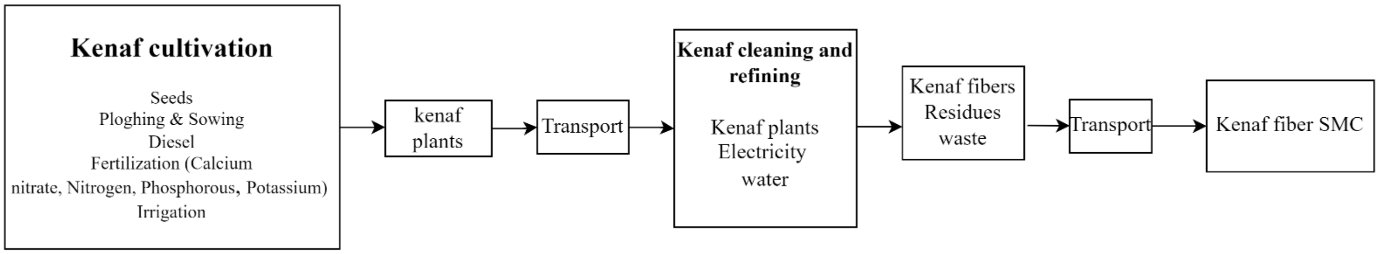

Fig. 14. Flow chart of the production system kenaf-fiber [84]

According to the literature, production of kenaf plants takes place mainly in Italy, also a portion of kenaf plants is typically imported from foreign countries, particularly Morocco [84]. As an Italian based scenario, we consider the case where all kenaf plants are cultivated and refined within Italy. This approach reduces the transportation distance for raw materials, by eliminating the need for international transport. For this scenario, we utilized data from [84]. The goal of this LCA model is to evaluate the environmental impacts of kenaf fiber cultivated and refined by an Italian firm. The analysis of kenaf fiber excludes the end-of-life phase of the composites (disposal or recycling), focusing instead on a cradle-to-gate approach. The functional unit is defined based on [84], which was 1.29 kg of kenaf fiber. The kenaf fiber produced in this study will be used as reinforcement in SMC (Sheet Molding Compound) and compared with the kenaf fiber available in the Ecoinvent 3.9.1 database. First, the inventory data for land cultivation are entered as shown in the Table14., the output from this step is used as an input for the subsequent process of kenaf refining and cleaning. Most of the inventory data was obtained from the paper by [84], which provided information for 1 m^2 of land. However, data for ploughing, seeds, and pesticides were estimated using the Ecoinvent 3.9.1 database, referencing kenaf cultivation practices in India.

Table14. Kenaf cultivation inventory data

Flow [Unit of measure]	Quantity	Reference dataset
Input		
Calcium nitrate [g]	59.2	market for calcium nitrate | calcium nitrate | Cutoff, U - RER
Diesel [MJ]	0.578	market for diesel, burned in agricultural machinery | diesel, burned in agricultural machinery | Cutoff, U - GLO
Nitrogen [g]	36.3	market for inorganic nitrogen fertiliser, as N | inorganic nitrogen fertiliser, as N | Cutoff, U - IT
Phosphorous [g]	18.8	market for inorganic phosphorus fertiliser, as P2O5 | inorganic phosphorus fertiliser, as P2O5 | Cutoff, U - IT
Potassium [g]	51.1	market for inorganic potassium fertiliser, as K2O | inorganic potassium fertiliser, as K2O | Cutoff, U - IT
Irrigation [m3]	0.252	market for irrigation | irrigation | Cutoff, U - RoW
Seed [kg]	0.00215	market for linseed seed, at farm | linseed seed, at farm | Cutoff, U - GLO
Pesticide [kg]	0.0002	market for pesticide, unspecified | pesticide, unspecified | Cutoff, U - GLO
Ploghing [s]	3.96	Ploughing, with 5 or 6 soc plough, processing - RoW
Transport, freight, light commercial vehicle [kg*km]	4.307*200	transport, freight, lorry 7.5-16 metric ton, EURO3 - RER
Output		
Kenaf Italy [kg]	4.307	

As shown in Fig. 14, once cultivation is complete, the kenaf plants undergo a retting process to remove the non-useful parts. This process produces high-quality kenaf fiber suitable for use in our kenaf SMC composites.

Table15 presents the inventory data for the refining and cleaning phase. The kenaf plants produced in the previous stage are used as input in this phase for cleaning and refinement.

Table15. Inventory list for kenaf refining and cleaning

Flow [Unit of measure]	Quantity	Reference dataset
Input		
Electricity [kWh]	0.26	electricity voltage transformation from medium to low voltage | electricity, low voltage | Cutoff, U - IT
Kenaf plants Italy [kg]	4.307	market for fibre, kenaf | fibre, kenaf | Cutoff, U - GLO
Water [m3]	0.49	
Transport, freight, light commercial vehicle [kg*km]	1.292*200	transport, freight, lorry 7.5-16 metric ton, EURO3 - RER
Output		
Kenaf fiber [kg]	1.292	
Solid residues [kg]	0.6	
Waste [kg]	2.41	

After refining, two products are produced: kenaf fiber (the main product) and vegetable solid residues (a byproduct) as shown in Fig. 13. As a result, allocation is required in this section to calculate the environmental impacts. The kenaf fibers are the primary output and are directed to industrial sector, while the residues are by-products used in the production of refuse-derived fuels (RDF). Although the total solid residue account for the largest mass fraction (70%) of the total treated material, it has a low economic value. Only about 20% of the residues have an economic value[84], the by-product, and the remaining is considered waste. To assess the economic value, the prices of the product and byproduct are required. While prices may vary on online platforms, we relied on the values provided by [118] for accuracy. The value of kenaf fiber is approximately €0.50 per kg, while the economically valuable residues are valued at €0.12 per kg [118]. We assumed that 4.307 kg of kenaf plants yield 1.29 kg of qualified fiber, valued at €0.50 per kg, and 0.6 kg of residues with a market value of €0.12 per kg. The remaining 2.41 kg is considered waste. The results show that while the residues represent a higher mass percentage (70%), their economic value is much lower, assigning them a secondary role. Therefore, the economic allocation is as follows:

- **Kenaf fiber (Italy)**: 1.29 kg → 85%
- **Residues (only 20% of residues has economic value)**: 0.60 kg → 15%

These percentages represent the shares by which the environmental impacts are allocated between the two outputs. Since the fibers are the primary product, they bear the majority of the environmental burden. As a result, environmental impacts are more accurately allocated using the economic criterion, which considers both the mass and the relative market value of the co-products (kenaf fibers and residues). Regarding the transport along phases, the transport occurred by lorry and average transport distance for this scenario is 200 km. In detail, lorry with maximum capacity of $16*10^3$ kg is assumed.

Once the kenaf fiber is produced, it is further processed into kenaf fiber-reinforced sheet molding compounds (SMC) for automotive applications. The fabrication of Kenaf SMC composite involved using a sheet molding compound (SMC) process with unsaturated polyester resin mixed with kenaf fibers at 38 wt%. The LCA of kenaf fiber itself was mentioned in the previous section. Table16, shows the formulation of kenaf SMC based on the [79]. Background datasets used are from Ecoinvent database. Catalysts and additives were omitted from the analysis because their contribution was estimated to account for less than 1% of the total material composition, and their environmental impact was deemed insignificant [79].

Table16. Kenaf sheet molding compound inventory [79]

Flow [Unit of measure]	Quantity	Reference dataset
Input		
Standard UPR[6] Resin [g]	605	Standard UPR Resin, Refer to Table 1
Electricity [MJ]	0.601	electricity voltage transformation from medium to low voltage | electricity, low voltage | Cutoff, U - IT
Kenaf fiber [g]	380	Kenaf fiber Italy, Refer to table 3 and 4
Output		
Kenaf SMC [kg]	1	

4.1.2.2. Glass Fiber SMC

Glass fiber-reinforced SMCs, a type of conventional composite, were also modelled from [79] to compare the environmental performance of this traditional composite with that of the new SMC reinforced with kenaf fibers. A summary of the formulation and inventory data of the standard glass fiber reinforced SMC is available in Table 17 based on [79].

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[6] Unsaturated Polyester Resins

Table 17. Glass fiber sheet molding compound Inventory [79]

Flow [Unit of measure]	Quantity	Reference dataset
Input		
Standard UPR Resin [g]	323	Table 13
Electricity [MJ]	0.379	electricity voltage transformation from medium to low voltage | electricity, low voltage | Cutoff, U - IT
Glass fiber [g]	500	market for glass fibre | glass fibre | Cutoff, U – PER (Europe)
Electricity [MJ]	0.379	electricity voltage transformation from medium to low voltage | electricity, low voltage | Cutoff, U - IT
Calcium carbonate (Filler) [g]	161	market for calcium carbonate, precipitated | calcium carbonate, precipitated | Cutoff, U – RER (Europe)
Transport, freight, light commercial vehicle [kg*km]	1*200	transport, freight, lorry 7.5-16 metric ton, EURO3 - RER
Output		
Glass fiber SMC [kg]	1	

4.2. Kenaf fiber for automotive applications: LCA Case study on hooked-type multifunctional steering wheel tray

In order to estimate the environmental impacts of kenaf fiber, thorough literature review, a component was identified that highlights the application of kenaf composite materials in the automotive sector. The selected part is, a hooked multifunctional steering wheel tray, available from various brands as a car accessory, can be easily transformed into a basic work desk by attaching it to the steering wheel. The component features a hanging design that does not require lower section support, ensuring it does not interfere with the driver's leg movements. It is lightweight yet sturdy enough to hold items like a laptop. A similar version of this component includes a cup holder. Made from acrylonitrile butadiene styrene (ABS), it weighs approximately 600 g and measures 420 mm in length, 28 mm in width, and 1.5 mm in thickness. Fig. 15 illustrates an example of the hooked multifunctional steering wheel tray [119].

Fig. 15.Example of a hooked-type multifunctional steering wheel tray [119]

In this LCA, the hooked-type multifunctional steering wheel tray is manufactured using ABS reinforced with natural fiber composites (NFC), specifically kenaf fiber in this case. This approach incorporates plant fiber as a filler to reduce the reliance on petroleum-based ABS thermoplastic matrix. A review of the literature suggests that adding up to 40 wt% of particulate plant fibers as filler in natural fiber-reinforced thermoplastic composites can provide structural strength comparable to pure thermoplastic materials [119]. Accordingly, this kenaf-reinforced tray will be compared to its 100% ABS counterpart. Table 18 indicates the properties of the hooked-type multifactional steering wheel tray used for this case study.

Table 18.The hooked-type multifunctional steering wheel tray [119]

Type of Material Used	**Pure virgin ABS**	**Kenaf reinforced ABS composites**
Formulation	100% ABS	40 wt% kenaf, 60 wt% ABS
Product Weight	600 g	600 g
Material Weight	ABS: 600 g	Kenaf: 240 g; ABS: 360 g

4.2.1. Goal and scope definition

The goal of this study is to assess the environmental impact of the hooked-type multifunctional steering wheel tray using the ReCiPe 2016 midpoint method, comparing the conventional ABS material with the substitution of the new kenaf-reinforced ABS composite. The system boundaries of this study involve a cradle to gate approach, including raw material extraction up to the gate stage. Fig. 16 shows overall system boundaries in the LCA of implemented hooked-type multifunctional steering wheel tray. Regarding functional unit, it is defined as a hooked-type multifunctional steering wheel tray with a total mass of 600 g.

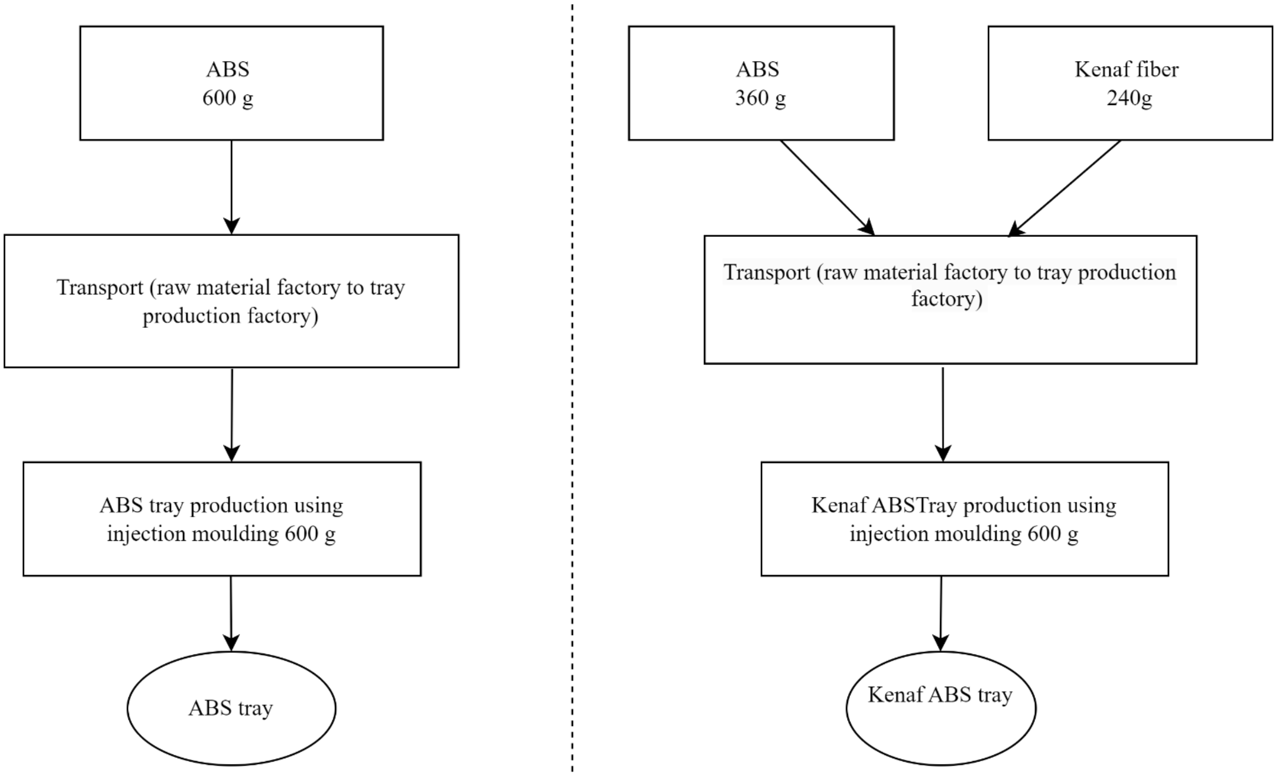

Fig. 16. System boundaries involved in the LCA of a hooked-type multifunctional steering wheel tray [119]

4.2.2. Data and Life Cycle Inventory (LCI)

The Life Cycle Inventory data for this component and all assumptions are made base on [119] book chapter and Ecoinvent database. The transport of raw materials from the factory to the tray production facility is assumed to cover a distance of 100 km, utilizing a small truck [119]. Table 19 and Table 20 respectively present the inventory lists used for the components made of ABS and those made of ABS reinforced with kenaf fiber.

Table 19. Inventory data for the production of hooked-type multifunctional steering wheel tray made of ABS [119]

Flow [Unit of measure]	Quantity	Reference dataset
Input		
Acrylonitrile Butadiene Styrene (ABS) [g]	600	acrylonitrile-butadiene-styrene copolymer production | acrylonitrile-butadiene-styrene copolymer | Cutoff, U - RER
Injection molding [g]	600	injection moulding | injection moulding | Cutoff, U - RER
Transport, freight, light commercial vehicle [kg*km]	0.6*100	transport, freight, light commercial vehicle - Europe without Switzerland
Output		
ABS [g]	600	

Table 20. Inventory data for the production of hooked-type multifunctional steering wheel tray made of Kenaf reinforced ABS [119]

Flow [Unit of measure]	Quantity	Reference dataset
Input		
Acrylonitrile Butadiene Styrene (ABS) [g]	360	acrylonitrile-butadiene-styrene copolymer production | acrylonitrile-butadiene-styrene copolymer | Cutoff, U - RER
Injection molding [g]	600	injection moulding | injection moulding | Cutoff, U - RER
Kenaf fiber [g]	240	Kenaf fiber Italy, Refer to table 3 and 4
Transport, freight, light commercial vehicle [kg*km]	0.6*100	transport, freight, light commercial vehicle - Europe without Switzerland
Output		
Kenaf ABS [g]	600	

4.3. LCA of cellulose and Cellulose nanofibers (CNF)

As mentioned earlier, another fiber with the potential to replace conventional fillers, such as glass fiber, is cellulose fiber. Since cellulose fiber is available in the Ecoinvent database, we have only reconstructed the Cellulose nanofibers (CNF) using one of the laboratory methods from the study by Li et al. (2013) [98]. This Cellulose nanofibers (CNF) from TEMPO-oxidation (chemical modification) and homogenization (mechanical disintegration), following the process described by Li et al. (2013) [98] which was reviewed in our literature review for cellulose fiber. Any modification to the inventory data from [98] inventory data are detailed in the Table 21. Additionally, all inventory data used are based on European dataset from Eocoinvent database. Then, this modelled fiber will be used in a scenario in the following section for our selected automotive component. Based on this explanation, our inventory data is presented in Table 21.

Table 21. Inventory for Cellulose nanofibers (CNF) [98]

Flow [unit of measure]	Quantity	Ecoinvent dataset	Notes
Inputs			
Kraft pulp [kg]	4	Sulfate pulp, unbleached {RER}| market for sulfate pulp, unbleached | Cut-off, S	-
NaClO [kg]	12.853	Sodium hypochlorite, without water, in 15% solution state {RER}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, S	-
NaBr [kg]	0.135	Sodium chloride, powder {RER}| sodium chloride production, powder | Cut-off, S	NaBr not available in Ecoinvent, replaced by NaCl in line with [98]
NaOH [kg]	0.8	Sodium hydroxide, without water, in 50% solution state {RER}| market for sodium hydroxide, without water, in 50% solution state | Cut-off, S	-
Ethanol [kg]	25	Ethanol, without water, in 99.7% solution state, from fermentation {GLO}| market for ethanol, without water, in 99.7% solution state, from fermentation | Cut-off, S	-
Water [kg]	550	Water, deionised {Europe without Switzerland} | market for water, deionised | Cut-off, S	-
Transport [tkm]	0,8	Transport, freight, lorry 7.5-16 metric ton, EURO4 {RER}| market for transport, freight, lorry 7.5-16 metric ton, EURO4 | Cut-off, S	Assumed 200 km of raw material transport [120]
Electricity [kWh]	5,5	Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, S	Cable blender
Electricity [kWh]	1,1	Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, S	Syringe pump
Electricity [kWh]	7	Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, S	Centrifuge washer
Electricity [kWh]	96	Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, S	Homogenizer
Outputs			
CNF [kg]	1		-
spent solvent mixture [kg]	25	market for spent solvent mixture | spent solvent mixture | Cutoff, U - Europe without Switzerland	

4.4. Cellulose fibers for automotive applications: LCA case study on an engine beauty cover

After an extensive review of the literature on the life cycle assessment (LCA) of cellulose fibers and their applications, a specific component was selected as a case study to evaluate the environmental impacts of this natural fiber. The chosen component is an engine beauty cover designed for a generic V6 engine, typically used in Ford SUVs or pickup trucks [111]. In this section, three different LCA models are developed to assess the environmental impact of the selected component:

- The first model represents the conventional design, where the engine beauty cover is made using traditional plastic materials. The inventory data for this model is sourced from [111].

- The second model introduces a bio-based alternative, in which the conventional material is partially replaced with cellulose fiber. The inventory data for this model is also based on the study by [111].

- The third model explores a Cellulose nanofibers (CNF)-based scenario, where Cellulose nanofibers (CNF) replace cellulose fibers in the bio-based engine beauty cover. The inventory data for Cellulose nanofibers (CNF) is derived from [98], as detailed in Section 4.3.1. To ensure consistency in the comparison, the Cellulose nanofibers (CNF) is substituted based on equivalent fiber weight, maintaining the same reinforcement ratio as in Model 2.

Based on this explanation, the material compositions for these three components are presented in Table 22.

4.4.1. Goal and scope

The objective of this study is to evaluate and compare the environmental impacts generated during the production phase and end-of-life stage of the current glass fiber-reinforced engine beauty cover with its bio-based cellulose/Nano-cellulose alternative.

Table 22 shows presents the material composition for three different engine beauty covers used in this study. It includes the weight (in grams) of materials for the conventional engine beauty cover (reinforced with glass fiber) and two bio-based versions—one using cellulose fiber and the other using nano-cellulose fiber. All compositions include up to 5% proprietary materials, which are not publicly available (and excluded from calculations) but meet the necessary manufacturing requirements.

Table 22. Material composition for three engine beauty covers used in this study [111]

Components	Materials	Weight (g)
Conventional Engine Beauty Cover	Glass fiber	132
	Mica minerals	264
	Polyamide	925
Bio-based Engine Beauty Cover (Cellulose fiber)	Cellulose fiber	207
	Carbon Fiber	103
	polypropylene	695
Bio-based Engine Beauty Cover (Cellulose nanofibers (CNF))	Nano-Cellulose fiber	207
	Carbon Fiber	103
	polypropylene	695

4.4.1.2. System boundaries

This research adopts a cradle-to-grave approach, encompassing the entire lifecycle of the component, from the extraction of raw materials to its end-of-life in landfill disposal. Fig. 17 and Fig. 18 illustrate the system boundaries and life cycle processes for both bio-based and conventional engine covers.

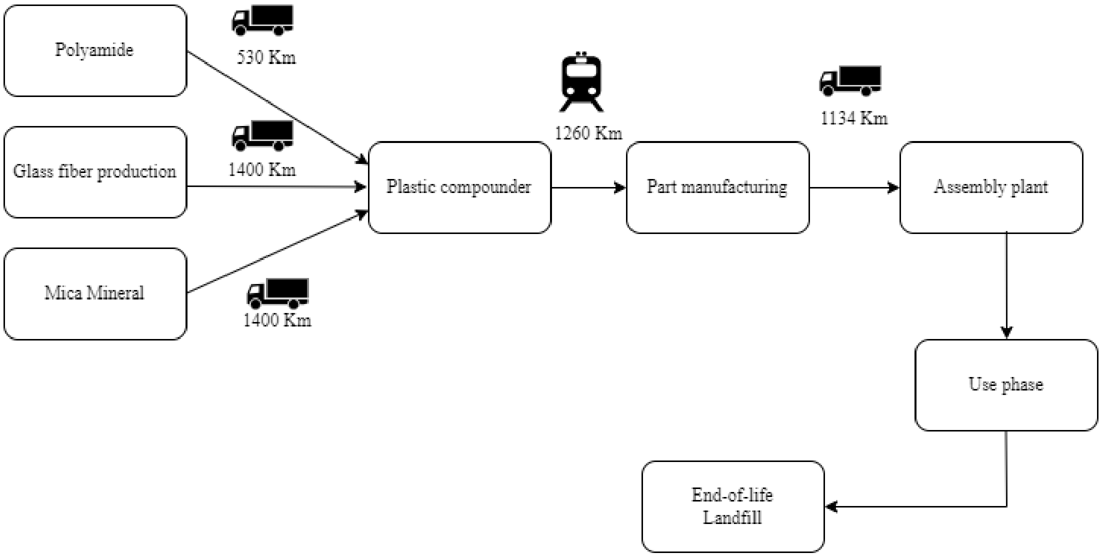

Fig. 17. System boundary and processes in life cycle of conventional engine cover based on [111], with modifications

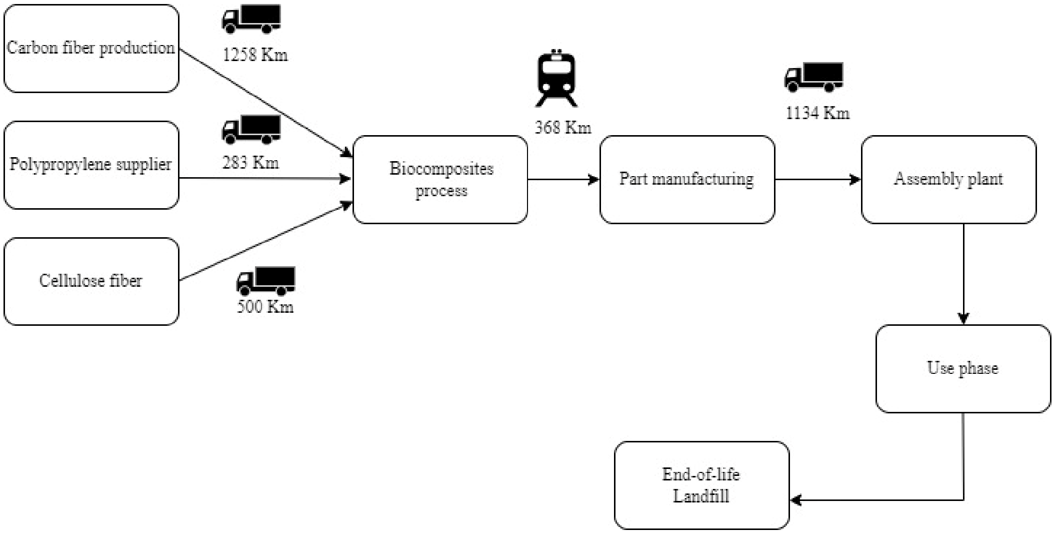

Fig. 18. System boundary and process in the life cycle of bio-based fiber reinforced engine cover from [111], with modification

4.4.1.3. Functional unit

The functional unit for this study is an engine beauty cover designed for a generic V6 engine in a Ford SUV or pickup truck. Its purposes are to enhance cosmetic appeal, isolate engine heat, and reduce noise. The functional unit (FU) of this study is a fixed volume of 957.98 cm^3, representing one engine beauty cover, which can be either bio-based or glass fiber-based. These components are manufactured via injection molding and designed to last over 290,000 km or 25 years. Since the material composition differs for each type, the corresponding reference flows in mass are 1.322 kg for the conventional engine beauty cover and 1.005 kg for the bio-based engine beauty covers, which includes both cellulose and cellulose nanofiber (CNF) composites. These values are derived based on the mass balance approach, ensuring consistency between input and output flows

At the end of its lifecycle, the part will be sent to a landfill. The total volume of the cover is 957.98 cm^3, with fiber content calculated by weight. A unit with 30 wt% (glass fiber and mica) is assumed to have comparable performance to one with 30 wt% (cellulose/Cellulose nanofibers (CNF) (Table 22).

4.4.1.4. Life cycle inventory (LCI)

This study considers only processes that contribute more than 1% to the total system flows of mass, primary energy, and environmental pollutants. In the product use phase, fuel consumption is calculated based on the article by [108]. For the end-of-life stage, this LCA follows only the landfill scenario, as it is the most common disposal method for plastic composite parts in Europe [121]. All transport were based on real-world average distances rather than estimated values [111]. Additionally, both covers contain up to 5% proprietary additives; however, these additives were excluded from the LCA calculations [111]. To build the inventory, both primary and secondary data were used. All secondary data were sourced from the Ecoinvent 3.9.1 database in OpenLCA. Cardboard manufacturing, packaging, and recycling were not considered, as the majority of automobile manufacturers recycle their cardboard. Reuse was also excluded because it falls below the 1% threshold criterion. As mentioned earlier, all logistics data are based on real-world average mileage, with transportation primarily carried out by truck. The only exception is the transport to the part manufacturer, which is done by train for both bio-based and conventional components, as shown in Fig. 17 and Fig. 18.

The inventory data are presented in a Table 23 for the production of conventional engine beauty cover based on the work of [111]. However, we adapted the data for Italy and Europe based on Ecoinvent dataset to create a more realistic model that aligns with our geographical scope.

Table 23. Inventory for conventional engine beauty cover [111]

Flow [Unit of measure]	**Quantity**	**Reference dataset**	**Note**
Input			
Glass fiber [kg]	0.132	glass fiber production | glass fibre | Cutoff, U – RER	
Mica [kg]	0.264	kaolin production | kaolin | Cutoff, U – RER	Kaolin was selected as a replacement material, with data sourced from the openLCA Nexus database [122]
Polyamide 6.6 [kg]	0.925	Polyamide 6.6 fibres (PA 6.6), production mix, at plant, from adipic acid and hexamethylene diamine (HMDA), PA 6.6 granulate without additives – EU-27	
Injection moulding [kg]	1.322	injection moulding | injection moulding | Cutoff, U – RER	
Electricity [Kwh]	0.203	market for electricity, low voltage | electricity, low voltage | Cutoff, U – IT	
Transport [kg*km]	1260*1.322	transport, freight train | transport, freight train | Cutoff, U – IT	Compound Transport
Transport [kg*km]	1134*1.322	transport, freight, lorry 7.5-16 metric ton, EURO3 – RER	Part Transport to assembly
Transport [kg*km]	1400*0.132	transport, freight, lorry 7.5-16 metric ton, EURO3 – RER	Glass fiber Transport
Transport [kg*km]	530*0.925	transport, freight, lorry 7.5-16 metric ton, EURO3 – RER	Polyamide transport
Transport [kg*km]	1400*0.264	transport, freight, lorry 7.5-16 metric ton, EURO3 – RER	Mineral Transport
Output			
Current Engine beauty [cm3]	957.98		

The inventory data for the bio-based engine beauty cover using cellulose fiber is primarily sourced from [111]. However, some data could not be found in the Ecoinvent database. In addition to adapting the data to reflect Italy and Europe-specific conditions, additional data was obtained from other datasets, as indicated in the Table 24.

Table 24. Inventory for bio-based engine beauty cover made with cellulose fiber [111]

Flow [Unit of measure]	Quantity	Reference dataset	Note
Input			
Cellulose fiber [kg]	0.207	cellulose fibre production | cellulose fibre | Cutoff, U – RoW	
Polypropylene [kg]	0.695	Polypropylene granulate (PP), production mix, at plant – RER	ELCD[7] dataset [123]
Carbon fiber	0.103	Carbon fibre production, production mix, at plant, technology mix, 100% active substance – GLO	Environmental Footprint (EF) secondary data [124]
Injection moulding [kg]	1.005	injection moulding | injection moulding | Cutoff, U – RER	
Electricity	0.168	market for electricity, low voltage | electricity, low voltage | Cutoff, U – IT	
Transport [kg*km]	368*1.005	transport, freight train | transport, freight train | Cutoff, U – IT	Bio-composite Transport
Transport [kg*km]	0.103*1258	transport, freight, lorry 7.5-16 metric ton, EURO3 – RER	Carbon fiber transport
Transport [kg*km]	0.695*283	transport, freight, lorry 7.5-16 metric ton, EURO3 – RER	Polypropylene transport
Transport [kg*km]	0.207*500	transport, freight, lorry 7.5-16 metric ton, EURO3 – RER	Cellulose fiber transport
Transport [kg*km]	1134*1.005	transport, freight, lorry 7.5-16 metric ton, EURO3 – RER	Part transport to assembly
Output			
Bio-based Engine beauty [cm3]	957.98		

The third LCI corresponds to a new scenario introduced in our study to assess the environmental impacts contributions of Cellulose nanofibers (CNF), as developed by Li et al. (2013) [98], in our engine beauty cover component. The inventory table for this scenario follows the same structure as the previous tables, with the only modification being the replacement of cellulose fiber with Cellulose nanofibers (CNF), as specified in Table 25. The inventory data for Cellulose nanofibers (CNF) was presented in Table 21.

Table 25. Inventory for bio-based engine beauty cover made with Cellulose nanofibers (CNF)

Flow [Unit of measure]	Quantity	Reference dataset	Note
Input			
Nano-Cellulose fiber [kg]	0.207	Nanocellulose	Cellulose nanofibers (CNF) refer to Table 21
Polypropylene [kg]	0.695	Polypropylene granulate (PP), production mix, at plant – RER	ELCD[8] dataset [123]
Carbon fiber	0.103	Carbon fibre production, production mix, at plant,	Environmental Footprint (EF) secondary data [124]

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[7] European Reference Life Cycle Database

[8] European Reference Life Cycle Database

Flow [Unit of measure]	Quantity	Reference dataset	Note
		technology mix, 100% active substance – GLO	
Injection moulding [kg]	1.005	injection moulding | injection moulding | Cutoff, U – RER	
Electricity	0.168	market for electricity, low voltage electricity, low voltage | Cutoff, U – IT	
Transport [kg*km]	368*1.005	transport, freight train | transport, freight train | Cutoff, U – IT	Bio-composite Transport
Transport [kg*km]	0.103*1258	transport, freight, lorry 7.5-16 metric ton, EURO3 – RER	Carbon fiber transport
Transport [kg*km]	0.695*283	transport, freight, lorry 7.5-16 metric ton, EURO3 – RER	Polypropylene transport
Transport [kg*km]	0.207*500	transport, freight, lorry 7.5-16 metric ton, EURO3 – RER	Cellulose fiber transport
Transport [kg*km]	1134*1.005	transport, freight, lorry 7.5-16 metric ton, EURO3 – RER	Part transport to assembly
Output			
Bio-based Engine beauty [cm3]	957.98		

To model the use phase, we used the assumptions from the published paper by Hervy et al. (2015) [108]. To evaluate the environmental impact during the use phase of a car's polymer and composite parts, they provided a formula that links fuel consumption to the weight of the car parts. The formula calculates the fuel economy of a part based on its weight relative to the total weight of the car:

$$\text{Fuel economy of the panel} = \frac{(\text{Weight of the panel})}{(\text{Weight of the car})} \times \text{Fuel economy of the car} \times c$$

However, the impact on fuel consumption is not solely dependent on weight—other factors, such as aerodynamics, are also important. Therefore, a factor "c" was introduced to account for this. It was set to 0.5, meaning a 10% weight reduction in the car leads to a 5% reduction in fuel consumption, based on a study of Peugeot-Citroën cars [108].

Finally, we estimated the use phase inventory inputs based on the car type in [111] which is Ford SUVs or pickup trucks [111], by assuming an average car weighs 3800 kg, drives 290,000 km, and has a fuel consumption of 10 liters per 100 km [111]. Our component weighs 1.005 kg, so the fuel consumption of our component over the car's lifetime is 3.834 liters. For the current beauty engine cover, which is 1.322 kg, the amount is 4.87 liters. Table 26 shows the data we have used in our model.

Table 26. Data used in use phase in both bio-based and current engine beauty cover

Flow [Unit of measure]	Quantity	Reference dataset	Note
Diesel [kg]	4.03	market for diesel | diesel | Cutoff, U – Europe without Switzerland	The fuel consumption over lifetime for current engine beauty cover
Diesel [kg]	3.22	market for diesel | diesel | Cutoff, U – Europe without Switzerland	The fuel consumption over lifetime for bi-based engine beauty cover

In our LCA model, we also considered the **end-of-life** management for our component. To identify an appropriate approach, we surveyed previous studies and found a report by the European Plastics Recyclers Association, which indicated that less than 15% of polymer waste from the automotive sector is recycled, with more than 60% being landfilled. The remaining portion is incinerated for energy recovery [121]. Additionally, in the study by Akhshik et al. (2017), recycling fiber-reinforced composites was found to be unfeasible due to economic and technical barriers. Specifically, the high costs of recycling, the complexity of the processes, the lack of established methods for incineration, and challenges in dismantling these materials make landfilling the most likely scenario [111]. Therefore, for the end-of-life phase, we assumed that our plastic parts end up in landfills at the end of their service life, and recycling and energy recovery were excluded from our model. In this phase, secondary data was used to model landfilling. We selected data from Ecoinvent, primarily relying on available datasets for the landfilling of plastics. The following Table 27 and Table 28 show the inputs and outputs associated with the EOL phase of conventional and biobased engine beauty cover.

Table 27. Inventory for landfill of conventional engine beauty cover

Flow	Unit	Amount	Reference dataset	Note
Input				
Engine beauty covers current	kg	1.322		Based on Table 23
Transport to the landfill	Kg*km	0.09	market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U – RER	
Output				
EoL conventional cover	kg	1.322	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U – IT	Waste

Table 28. Inventory for landfill of bio-based engine beauty cover

Flow	Unit	Amount	Reference dataset	Note
Input				
Engine beauty covers bio-based	kg	1.005		Based on Table 24
Transport to the landfill	Kg*km	0.06	market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U – RER	
Output				
End-of-Life Biobased cover	kg	1.005	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U – IT	Waste

5. Life Cycle Impact Assessment of the case study analyses

To assess the environmental impacts of kenaf and cellulose fibers, two natural fibers used in this study, OpenLCA software and the Ecoinvent 3.9.1 database were utilized to conduct a comprehensive Life Cycle Impact Assessment (LCIA). The analysis was first performed for fiber production, followed by an evaluation of the overall environmental and health impacts of both materials when used in a car, comparing natural fibers with conventional fillers. This approach ensures a holistic comparison of the environmental impacts of traditional and innovative materials in the automotive industry. To achieve this, we applied recognized LCIA methodologies commonly used in similar studies on automotive components: ReCiPe Midpoint (H) and TRACI 2.1.

The ReCiPe Midpoint (H) method provides a detailed assessment across 18 environmental categories, including climate change, ozone depletion, human toxicity, terrestrial acidification, marine eutrophication, and water use [125]. By covering a broad range of impact categories, ReCiPe Midpoint (H) ensures a comprehensive evaluation of both fiber production and their integration into vehicle components, enabling a more thorough comparison between bio-based and conventional materials.

Finally, we used the TRACI 2.1 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) methodology to summarize the impacts of each natural fiber and its components in a car. TRACI 2.1, developed by the U.S. Environmental Protection Agency (EPA), is particularly useful in a North American context, where it offers region-specific impact categories such as:

- Ozone Depletion,
- Smog Formation,
- Human Health Impacts (via air pollutants),
- Eutrophication, and
- Fossil Fuel Depletion.

TRACI recommends using high-quality data whenever possible to reduce uncertainties in both data and modeling. As an impact assessment tool, it does not address the selection of inventory data sources. Instead, its primary focus is on the characterization of impact categories [126].

5.1. Kenaf and glass fiber SMC case studies

To summarize the kenaf section, we first produced the LCA of unsaturated polyester resin (UPR) as the resin matrix. Then, kenaf fiber was obtained through cultivation and refinement, leading to the final processed fiber (see Fig. 13 Fig. 14). This kenaf fiber replaced glass fiber in our sheet molding compound (SMC) composites, as required by Stellantis for use in the automotive industry. Additionally, we molded an LCA-based car component in two versions: one made entirely of plastic and another incorporating kenaf fiber as a replacement. This allowed us to compare the environmental impact through real case studies. In the following sections we mention the results for each stage. The ReCiPe 2016 Midpoint (H) method was selected for this study due to its comprehensive approach to assessing and comparing environmental impacts across multiple categories. This method transforms the extensive list of life cycle inventory results into a set of indicator scores that quantify the relative impacts. For unsaturated polyester resin and kenaf fiber process

Table 29 shows the results of producing 1 kg of SMC reinforced with kenaf and glass fiber using the ReCiPe 2016 Midpoint (H) method.

Table 29. Impact categories results of 1 Kg of glass and kenaf fiber SMC.

Impact category	Reference unit	Glass fiber SMC	Kenaf fiber SMC
Fine particulate matter formation	kg PM2.5 eq	0,004251	0,003105
Fossil resource scarcity	kg oil eq	0,913177	1,038435
Freshwater ecotoxicity	kg 1,4-DCB	0,092128	0,075548
Freshwater eutrophication	kg P eq	0,000765	0,000672
Global warming	kg CO2 eq	2,565888	2,189729
Human carcinogenic toxicity	kg 1,4-DCB	0,15075	0,119967
Human non-carcinogenic toxicity	kg 1,4-DCB	3,343644	1,691907
Ionizing radiation	kBq Co-60 eq	0,201287	0,158551
Land use	m2a crop eq	0,032016	0,02708
Marine ecotoxicity	kg 1,4-DCB	0,124615	0,099606
Marine eutrophication	kg N eq	7,48E-05	6,92E-05
Mineral resource scarcity	kg Cu eq	0,008611	0,005666
Ozone formation, Human health	kg NOx eq	0,008156	0,006275
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,008759	0,007285
Stratospheric ozone depletion	kg CFC11 eq	2,23E-06	1,13E-06
Terrestrial acidification	kg SO2 eq	0,00958	0,006584
Terrestrial ecotoxicity	kg 1,4-DCB	9,578184	3,997577
Water consumption	m3	0,039879	0,121792

The following comparison can be made between glass fiber and kenaf fiber SMC (see Table 29):

In all impact categories, kenaf fiber-based Sheet Molding Compound (SMC) outperforms fiberglass SMC, demonstrating superior environmental performance. For instance, in terms of fine particulate matter formation, kenaf fiber produces 27% less impact (0.003105 kg PM2.5 eq compared to 0.004251 kg PM2.5 eq for fiberglass). Similarly, for global warming, kenaf fiber results in 14.7% lower CO2 eq emissions (2.19 kg CO2 eq vs. 2.57 kg CO2 eq for fiberglass). The comparison also reveals kenaf's significant advantages in human carcinogenic toxicity (20.5% less) and marine ecotoxicity (20% less). Water consumption, however, is a notable exception where kenaf fiber has a higher value, consuming 0.1218 m³ compared to fiberglass's 0.0399 m³. This represents a 3.05 times higher water usage for kenaf fiber SMC, though the other environmental benefits largely outweigh this difference. Overall, kenaf fiber proves to be a more environmentally friendly option across most impact categories, despite the higher water consumption. This finding is consistent with previous work by [79], which also highlighted the environmental benefits of kenaf fiber over fiberglass. Overall, the kenaf-based composite presents environmental benefits by reducing emissions, toxicity, and resource depletion, making it a promising alternative to conventional glass fiber SMC in automotive applications.

Fig. 19 shows global warming indicator of 1 kg of glass fiber SMC, visualized in a Sankey diagram with a 10% of cut-off. illustrates Sankey diagram to produce 1 kg of glass fiber SMC. As it is clear the main contributor to climate change is glass fiber production, which accounts for 48.54% of the total impact, followed by UPR resin production.

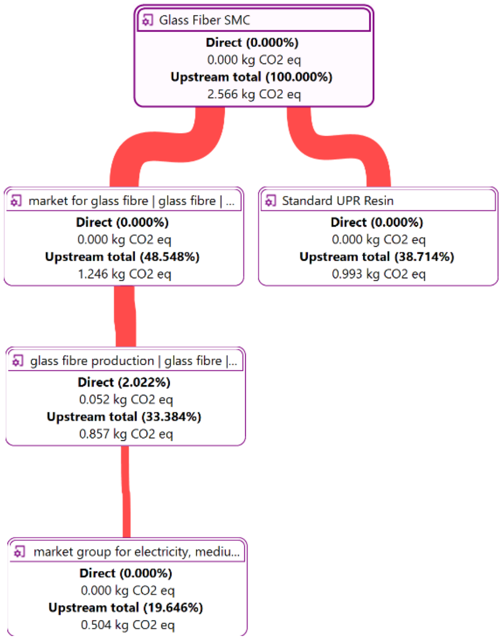


Fig. 19. Global warming indicator of 1 kg of glass fiber SMC, visualized in a Sankey diagram with a 10% of cut-off

Fig. 20 shows global warming indicator of 1 kg of kenaf fiber SMC, visualized in a Sankey diagram with a 10% of cut-off. As it is illustrated in figure, the main impacts are associated with UPR resin production (84.7% of total impact), one of the key ingredients in the kenaf fiber-reinforced SMC.

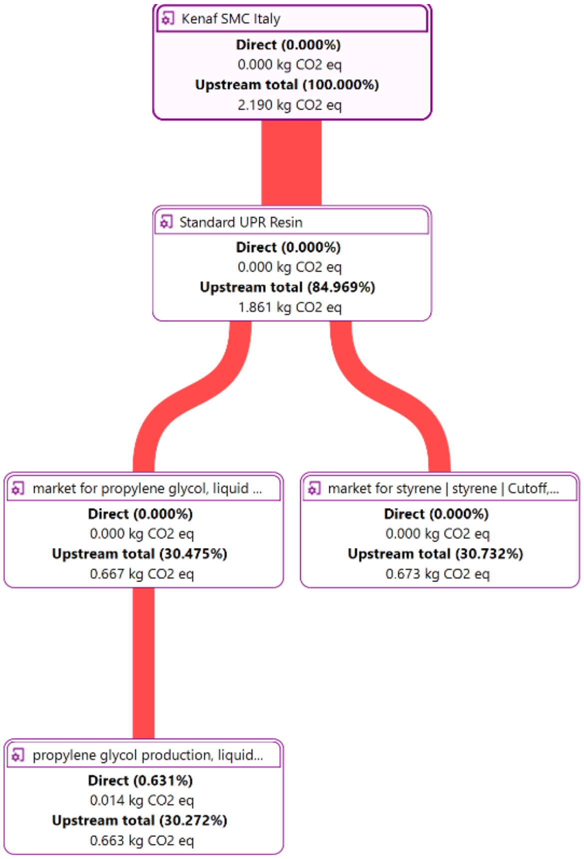


Fig. 20 Global warming indicator of 1 kg of kenaf fiber SMC, visualized in a Sankey diagram with a 10% of cut-off

5.1.1 Comparison of car components made from Acrylonitrile-Butadiene- Styrene (ABS) and Kenaf reinforced composite

The goal of this part is to assess the environmental impact of the hooked-type multifunctional steering wheel tray which was made based on Table 20 ,using the ReCiPe 2016 midpoint (H) method, comparing the conventional Acrylonitrile-Butadiene-Styrene (ABS) material with the new kenaf-reinforced ABS composite. On the other hand, when 40% of ABS is replaced with kenaf fiber, the total impact on climate change decreases to 2.549 kg CO_2 eq., compared to 3.524 kg CO_2 eq. for the 100% ABS tray, as shown Fig. 21 and Fig. 22 respectively. The term ABS existing in the figure means the current tray which is made of ABS only without any kenaf fiber.

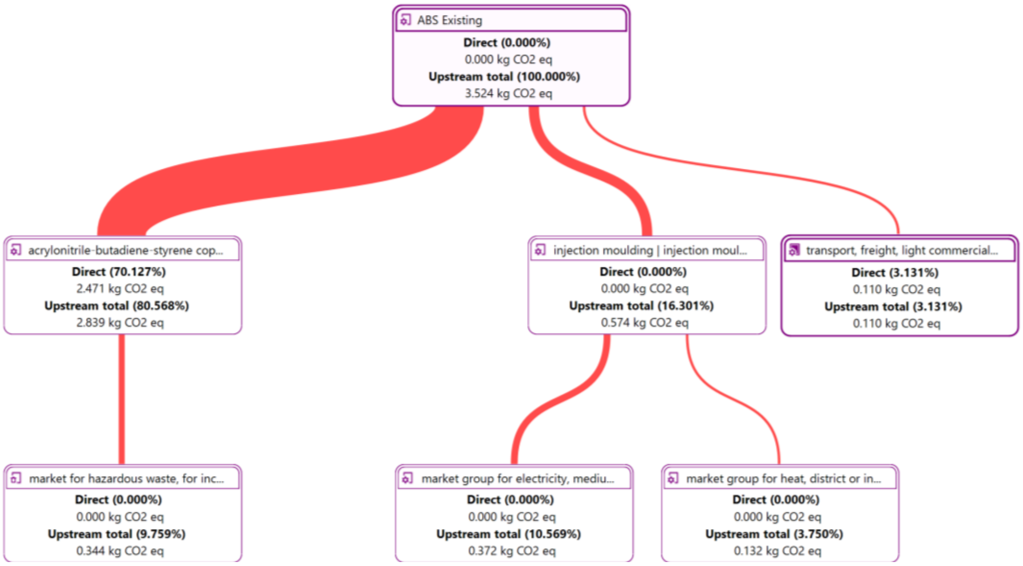


Fig. 21 shows the global warming Sankey diagram for the tray made entirely of ABS. ABS production is the primary contributor to the carbon footprint of the tray, accounting for 70.12% of the global warming indicator, equaling 2.471 kg CO_2 eq. The contribution of transport is negligible compared to ABS production and injection molding.

ABS production contributes 66% of total impact (corresponding to an absolute value of 1.704 kg CO2 eq.), while the 40% weight of kenaf fiber resulted in only 0.159 kg CO2 eq. This improvement proves the potential of kenaf fibers to lower dependence on non-renewable resources and improve sustainability of automotive sector. On the other hand, when 40% of ABS is replaced with kenaf fiber, the total impact on climate change decreases to 2.549 kg CO_2 eq., compared to 3.524 kg CO_2 eq. for the 100% ABS tray, as shown Fig. 21 and Fig. 22 respectively. The term ABS existing in the figure means the current tray which is made of ABS only without any kenaf fiber.

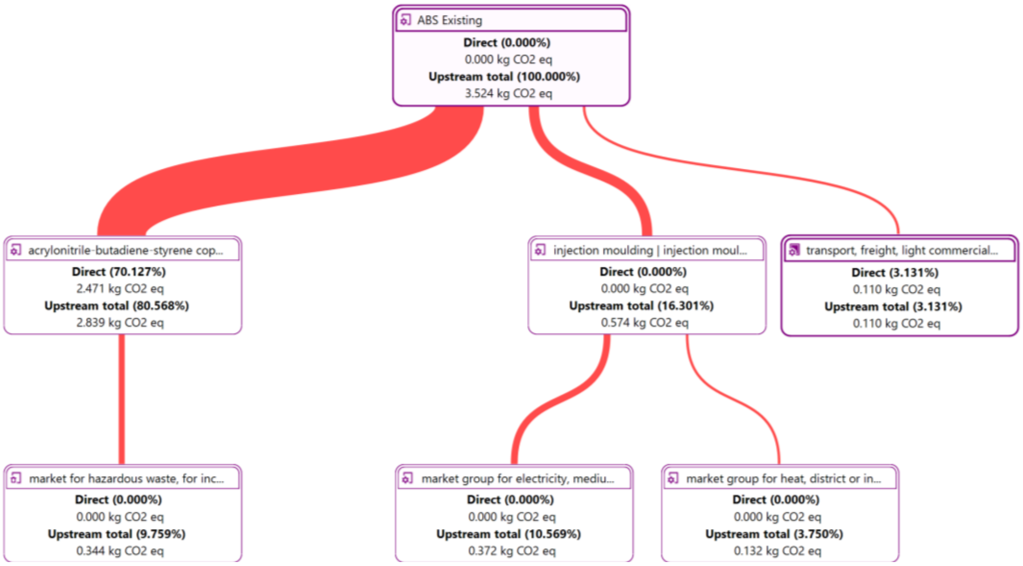


Fig. 21. Global warming indicator of 1 ABS tray visualized in Sankey diagram, cut-off 7%

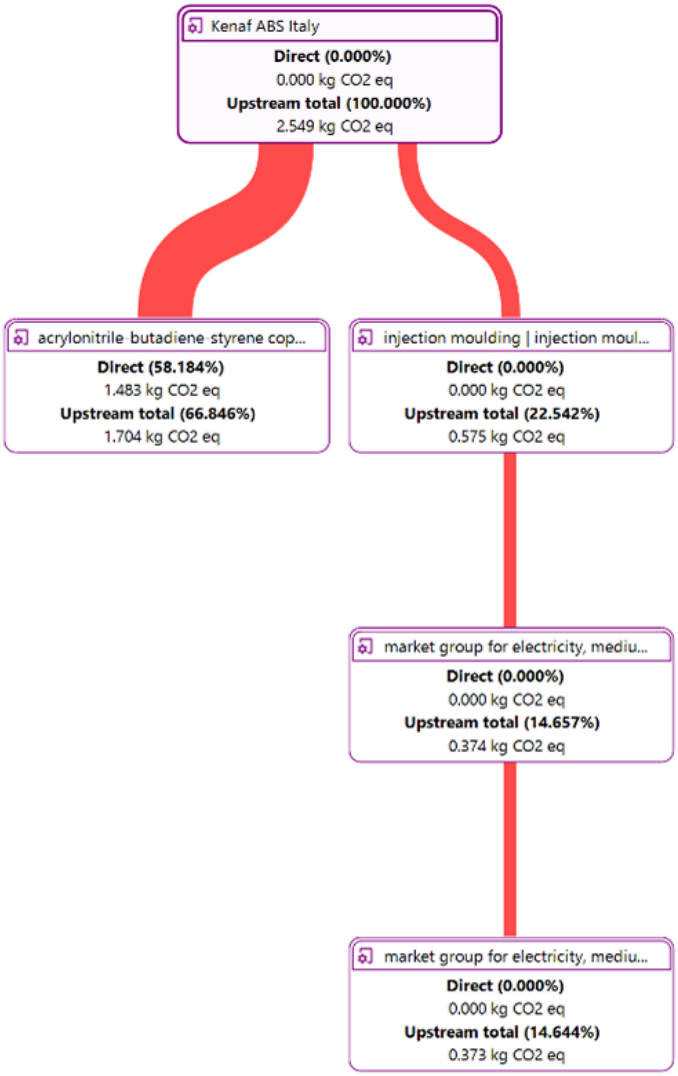


Fig. 22. Sankey diagram for kenaf ABS tray, cut-off 7%

When comparing the environmental impacts of the Kenaf ABS composite and the existing ABS in automotive applications, several key differences emerge across various impact categories (See Table 30, Fig. 23). In terms of fossil resource scarcity, Kenaf ABS also shows better performance, requiring 1.04 kg oil eq, which is 30.2% lower than the 1.49 kg oil eq required by the existing ABS. However, when assessing human carcinogenic toxicity, the Kenaf ABS component has a slightly lower value of 0.11 kg 1,4-DCB, compared to 0.14 kg 1,4-DCB for the traditional ABS, showing a 21.4% reduction in toxicity. Other categories such as freshwater eutrophication and marine ecotoxicity show marginal differences, with the Kenaf ABS composite performing slightly better in both. Although Kenaf ABS demonstrates improved performance in several key environmental areas, it still presents 10.8% higher land use (0.041 m^2a crop eq) compared to the existing ABS (0.037 m^2a crop eq). This suggests that while kenaf fibers offer sustainability benefits in many respects, they may still contribute to land use pressures.

Table 30. Impact analysis of a tray made from ABS and Kenaf fiber

Impact category	Reference unit	Kenaf ABS	ABS existing
Fine particulate matter formation	kg PM2.5 eq	0,002435	0,003053
Fossil resource scarcity	kg oil eq	1,042121	1,485965
Freshwater ecotoxicity	kg 1,4-DCB	0,043865	0,043035
Freshwater eutrophication	kg P eq	0,000533	0,000568
Global warming	kg CO2 eq	2,548628	3,524264
Human carcinogenic toxicity	kg 1,4-DCB	0,111075	0,139648
Human non-carcinogenic toxicity	kg 1,4-DCB	1,199878	1,173633
Ionizing radiation	kBq Co-60 eq	0,206853	0,201437
Land use	m2a crop eq	0,041369	0,036764
Marine ecotoxicity	kg 1,4-DCB	0,059578	0,058697
Marine eutrophication	kg N eq	9,27E-05	0,000114
Mineral resource scarcity	kg Cu eq	0,004115	0,003236
Ozone formation, Human health	kg NOx eq	0,004666	0,005674
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,004953	0,006089
Stratospheric ozone depletion	kg CFC11 eq	5,91E-07	4,43E-07
Terrestrial acidification	kg SO2 eq	0,006694	0,008543
Terrestrial ecotoxicity	kg 1,4-DCB	2,301186	1,686315
Water consumption	m3	0,073951	0,045198

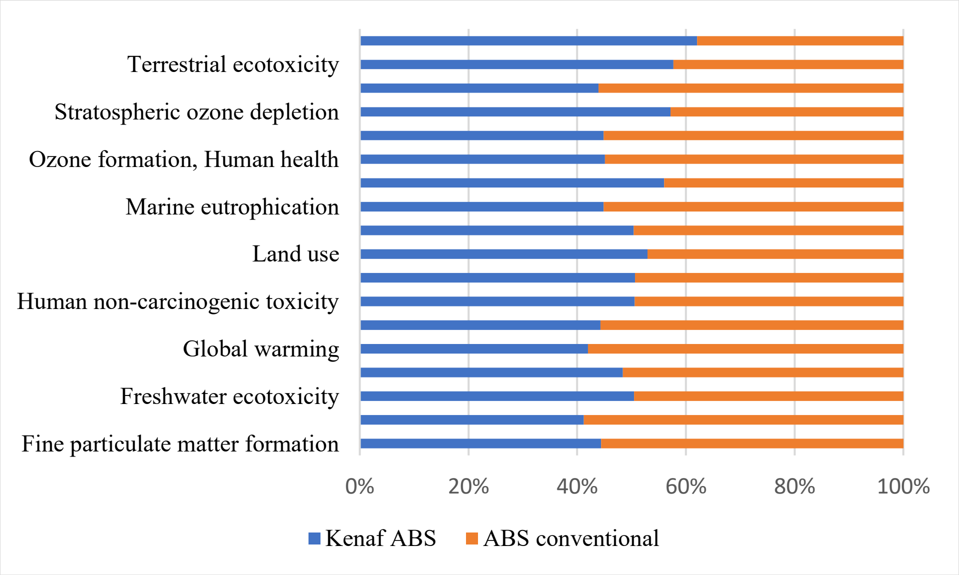


Fig. 23. Impact analysis of a tray made from ABS and Kenaf fiber

The Fig. 23 illustrates the relative contributions of Kenaf ABS and conventional ABS across various environmental impact categories. Notably, Kenaf ABS shows lower impacts in critical categories such as global warming, fossil resource scarcity, and particulate matter formation, indicating its potential for sustainability improvements. However, some categories, such as terrestrial ecotoxicity and water consumption, exhibit higher values for Kenaf ABS.

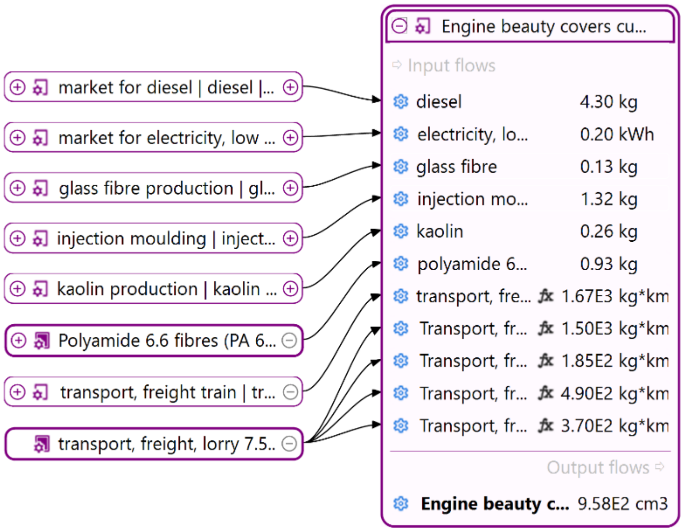
Overall, the Kenaf-ABS composite appears to offer significant environmental advantages in all impact categories except for two: land use and water consumption. These two categories indicate that while kenaf fibers provide environmental benefits in many areas, they require more land and water resources compared to traditional ABS material.

5.3. Cellulose and Cellulose nanofibers (CNF) case study

In this section, we analyze the results for our selected automotive component based on three LCA models previously developed: (1) the current or conventional engine beauty cover, (2) a bio-based engine beauty cover incorporating cellulose fiber [111], and (3) an engine beauty cover made with CNF as a new scenario in our study. For this part we used TRACI 2.1 as the paper by [111].

5.3.1. Conventional engine beauty cover results

Fig. 24 illustrates the model graph for production and use phase of an engine beauty cover made from conventional materials without the use of natural fibers based on Table 23.



diesel	4.30 kg
electricity, lo...	0.20 kWh
glass fibre	0.13 kg
injection mo...	1.32 kg
kaolin	0.26 kg
polyamide 6...	0.93 kg
transport, fre...	1.67E3 kg*km
Transport, fr...	1.50E3 kg*km
Transport, fr...	1.85E2 kg*km
Transport, fr...	4.90E2 kg*km
Transport, fr...	3.70E2 kg*km
Engine beauty c...	9.58E2 cm3

Fig. 24. Model graph of current or conventional engine beauty cover

Table 31 shows the results for the production, use phase, and EOL of an engine beauty cover with a volume of 957.98 cm³, made from conventional materials, using TRACI 2.1.

Table 31. Results for an engine beauty cover made from conventional materials

Impact category	Reference unit	Result
Acidification	kg SO2 eq	0,066946
Carcinogenics	Comparative Toxic Unit for humans (CTUh)	3,13E-07
Ecotoxicity	Comparative Toxic Unit for ecosystems (CTUe)	92,16255
Eutrophication	kg N eq	0,027114
Fossil fuel depletion	MJ surplus	58,47834
Global warming	kg CO2 eq	16,02825
Non carcinogenics	CTUh	1,62E-06
Ozone depletion	kg CFC-11 eq	4,68E-06
Respiratory effects	kg PM2.5 eq	0,005274
Smog	kg O3 eq	0,740472

5.3.2. Bio-Based Engine Beauty Cover results – Cellulose-Based

After calculating the impacts of the conventional engine beauty cover, we performed the LCIA of its bio-based counterpart, also with a volume of 957.98 cm³ and 1.005 kg weight, but this time using cellulose fiber in the inventory based on Table 24. Fig. 25 presents the model graph of this engine beauty cover for the production and use phases.

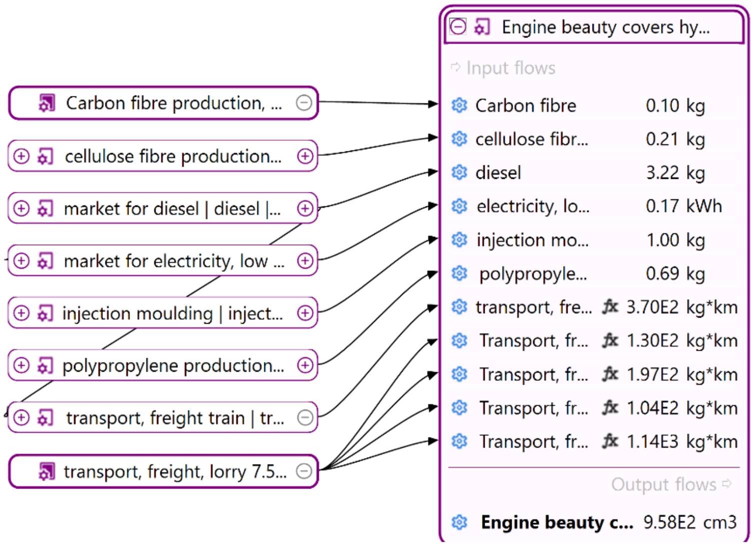


Fig. 25. Model graph of a bio-based engine beauty cover made with cellulose fiber

Table 32 shows the results for the production, use phase, and EOL of an engine beauty cover made from cellulose with a volume of 957.98 cm³.

Table 32. Results for an engine beauty cover made from cellulose fiber

Impact category	Reference unit	Result
Acidification	kg SO2 eq	0,025851
Carcinogenics	CTUh	3,7E-07
Ecotoxicity	CTUe	78,17028
Eutrophication	kg N eq	0,019662
Fossil fuel depletion	MJ surplus	34,40656
Global warming	kg CO2 eq	5,32038
Non carcinogenics	CTUh	1,23E-06
Ozone depletion	kg CFC-11 eq	3,01E-06
Respiratory effects	kg PM2.5 eq	0,00267
Smog	kg O3 eq	0,310339

5.3.3. Results of Bio-based or Bio-Based Engine Beauty Cover – CNF-Based

To evaluate the environmental impact of cellulose nanofibrils (CNF) as a substitute for conventional fillers in the automotive industry, we replaced cellulose fiber with CNF in our bio-based engine beauty cover (see Table 25). Fig. 26 presents the model representation of the CNF-based engine beauty cover, with a volume of 957.98 cm³ and 1.005 kg weight, covering both the production and use phase.

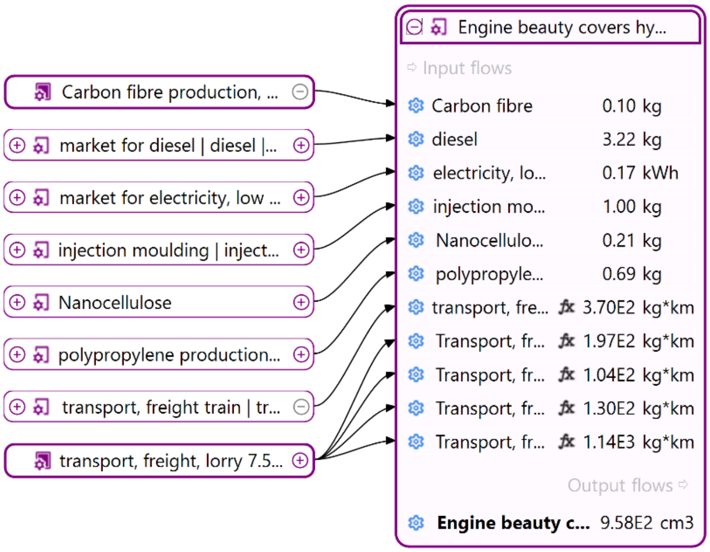


Fig. 26. Model graph of a bio-based engine beauty cover made with CNF

Table 33 shows the results for the production, use phase, and EOL of an engine beauty cover made from CNF with a volume of 957.98 cm³.

Table 33. Results for an engine beauty cover made from CNF

Impact category	Reference unit	Result
Acidification	kg SO2 eq	0,157303
Carcinogenics	CTUh	2,54E-06
Ecotoxicity	CTUe	666,3229
Eutrophication	kg N eq	0,12702
Fossil fuel depletion	MJ surplus	62,5507
Global warming	kg CO2 eq	26,55132
Non carcinogenics	CTUh	1,4E-05
Ozone depletion	kg CFC-11 eq	9,07E-06
Respiratory effects	kg PM2.5 eq	0,024235
Smog	kg O3 eq	1,66049

5.3.4. Comparison of LCA Results from Three Engine Beauty Cover Models

Here, we compare the results of three LCA models developed in our study: (1) the conventional engine beauty cover, (2) a bio-based engine beauty cover incorporating cellulose fiber, and (3) an engine beauty cover made with cellulose nanofibrils (CNF) as a new scenario. Fig. 27 illustrates the environmental impacts—ecotoxicity, fossil fuel depletion, global warming, and smog—assessed using the TRACI 2.1 method from production to EOL stage. CNF-based engine beauty covers show the highest values across these categories, with ecotoxicity at 666.32 CTUe, fossil fuel depletion at 62.55 MJ surplus, and smog at 1.66 kg O3 eq, indicating a greater environmental burden compared to their conventional counterpart. However, the cellulose-based engine beauty cover demonstrates the lowest global warming potential at 5.32 kg CO2 eq, making it the most environmentally favorable option among the three.

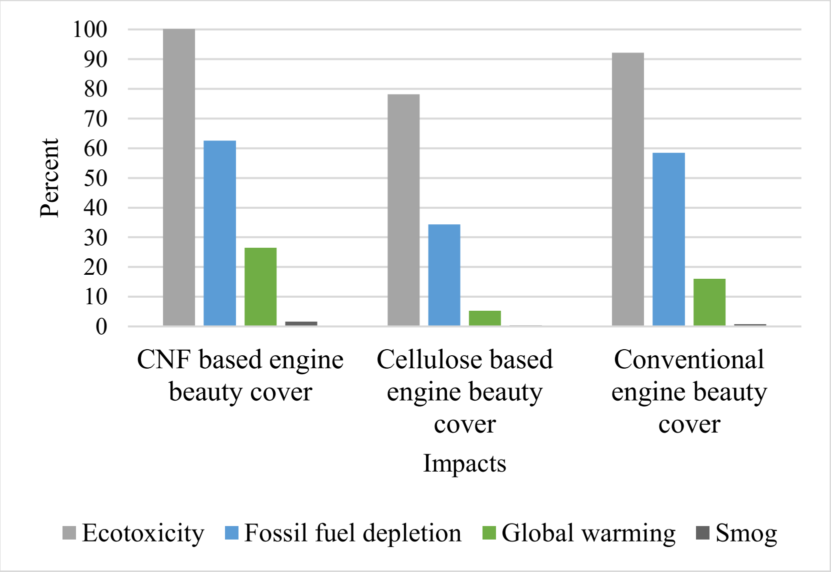


Fig. 27. Environmental Impacts of engine beauty covers made from conventional, cellulose-based, and CNF materials

Because of significant environmental impacts of the CNF-based engine beauty cover, we present a Fig. 28 illustrating the contribution analysis of CNF different production stages, providing a clearer understanding of the impact categories and identifying the processes with the greatest environmental effects. As shown in Fig. 28, the production phase of CNF has a particularly significant impact. As mentioned in Table 21.

Table 21, we use inventory data from Li et al., 2013 [98]. Upon reviewing their results, they also emphasize the importance of understanding the environmental impacts of nanocellulose production, especially with its expected growth. Understanding the rapid expansion of nanocellulose production, it is crucial to identify and address potential environmental risks early [98]. We highlighted the global warming impact in the CNF production process in Fig. 29 by presenting a Sankey diagram focused on global warming. The diagram shows that the highest contribution to global warming comes from the electricity used in CNF production, followed by two other materials involved in the process.

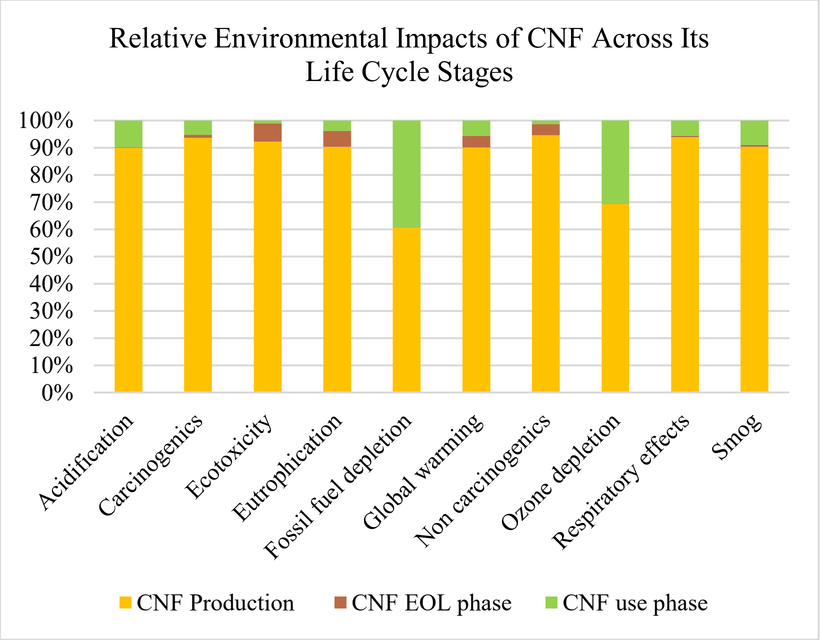


Fig. 28. Relative Environmental Impacts of CNF Across Its Life Cycle Stages

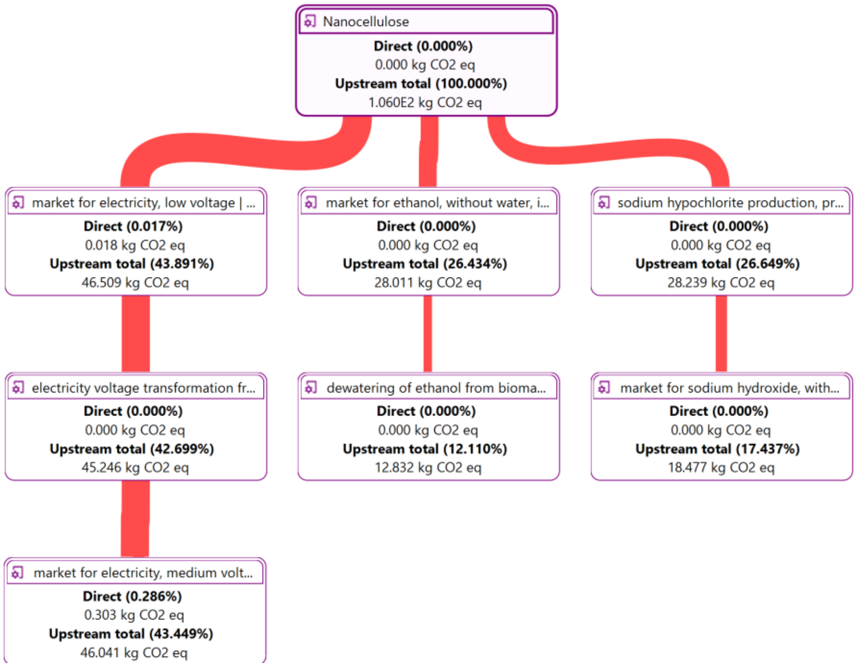


Fig. 29. Sankey diagram of CNF production, highlighting global warming impact (cut-off: 7%).

Fig. 30 presents the Sankey diagrams for the all stages from cradle to grave of an engine beauty cover made from current materials. The main contributors to climate change are the production and use phases, which account for more than 90% of global warming, while less than 10% comes from the landfilling of the conventional engine beauty cover.

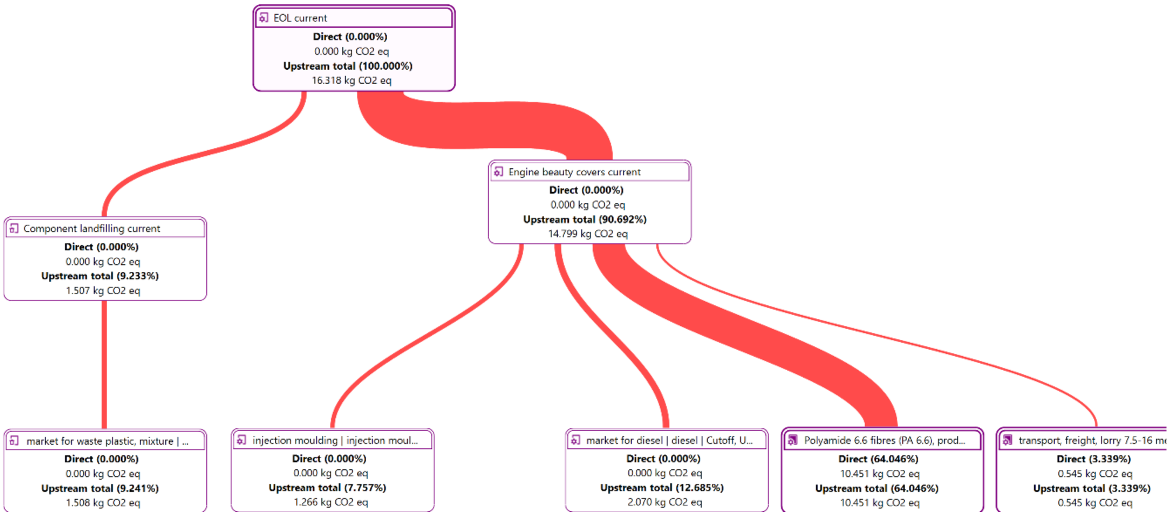


Fig. 30. Sankey diagram of conventional engine beauty cover for all stages cradle to grave, with emphasis on climate change indicator, cut-off 7%.

Fig. 31 shows the Sankey diagram for an engine beauty cover made from cellulose fiber, illustrating the production and use phases. The main impacts are associated with PP, a component of the cellulose-based engine beauty cover (31.48%), and diesel from the use phase (35.57%).

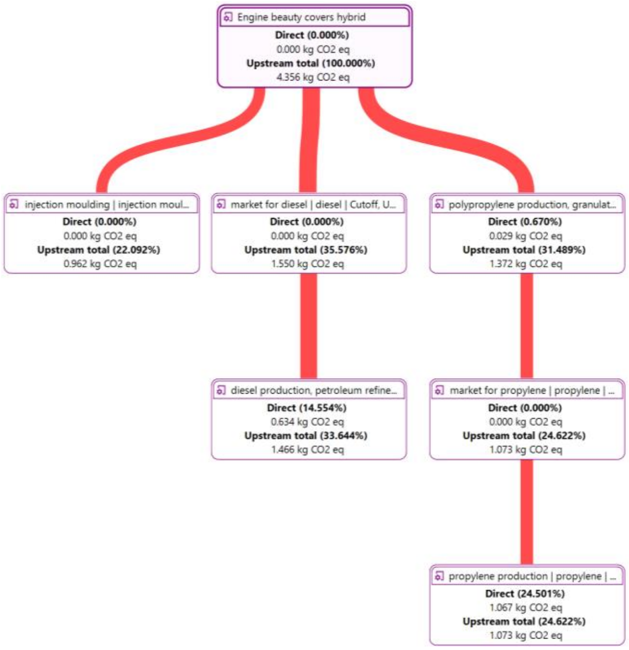


Fig. 31. Sankey diagram of cellulose-based engine beauty cover production and use stage, with emphasis on climate change indicator, cut-off 7%.

Table 34. Impacts of both the bio-based and current engine beauty cover based on TRACI 2.1

Impact category	Reference unit	Conventional engine beauty cover	Cellulose fiber-based engine beauty cover
Acidification	kg SO2 eq	0,066946	0,025851
Carcinogenic	Comparative Toxic Unit for humans (CTUh)	3,13E-07	3,70E-07
Ecotoxicity	Comparative Toxic Unit for ecosystems (CTUe)	92,16255	78,17028
Eutrophication	kg N eq	0,027114	0,019662
Fossil fuel depletion	MJ surplus	58,47834	34,40656
Global warming	kg CO2 eq	16,02825	5,32038
Non carcinogenic	CTUh	1,62E-06	1,23E-06
Ozone depletion	kg CFC-11 eq	4,68E-06	3,01E-06
Respiratory effects	kg PM2.5 eq	0,005274	0,00267
Smog	kg O3 eq	0,740472	0,310339

When comparing our results (see Table 34) with those of [111] Akhshik et al. (2017), differences in impact values across categories are expected, as our inventory was adapted for Europe and Italy, while their study was conducted in Canada. Despite these variations, the overall trends remain comparable. In global warming potential, a key impact category, their study reported 20.3 kg CO_2 eq for the conventional engine beauty cover, whereas our findings indicate 16.02 kg CO_2 eq. For the cellulose-based component, their result was 8.76 kg CO_2 eq, while our study found 5.32 kg CO_2 eq. Although the absolute values differ, the percentage reduction in global warming potential is approximately 60% in both studies, further supporting the environmental benefits of cellulose-based materials.

Overall, all TRACI indicators show better results for the cellulose fiber-based materials compared to the current materials, except for Carcinogenics (See Table 34). This result aligns with the work of Akhshik et al. (2017) [111]. The slight difference in Carcinogenics impacts is due to the PA production process used in our current model, which includes the reuse of materials in PA production. In acidification, the cellulose-based cover is 2.59 times lower. For ecotoxicity, the cellulose-based cover is 1.18 times lower. While some studies, such as [127], have indicated that biomaterials exhibit relatively high eutrophication potential, the cellulose fibers examined in this study are not derived from agricultural sources. As a result, their production does not involve the use of fertilizers, thereby minimizing their contribution to eutrophication, which is 1.38 times lower in this study compared to conventional materials. In terms of fossil fuel depletion, the cellulose-based cover is 1.7 times lower, and in global warming, it is 3.01 times lower. The non-carcinogenics impact is 1.32 times lower for the cellulose-based cover, while in ozone depletion, it is 1.56 times lower. In respiratory effects, the cellulose-based cover is 1.98 times lower, and for smog, it is 2.38 times lower. Regarding water consumption of the current materials is 1.18 times higher than that of the cellulose fiber-based alternative. These results highlight the significant environmental benefits of using cellulose-based materials, particularly in reducing global warming potential, fossil fuel depletion, and other harmful impacts.

As discussed earlier, replacing conventional materials with natural fibers in automobiles leads to weight reduction, which ultimately decreases fuel consumption. In the Fig. 32, we analyzed the fuel consumption of our cellulose/CNF based engine beauty cover with its conventional counterparts over a total lifetime of 290,000 km. The results clearly demonstrate a reduction in fuel consumption when transitioning from conventional materials to a cellulose-based component.

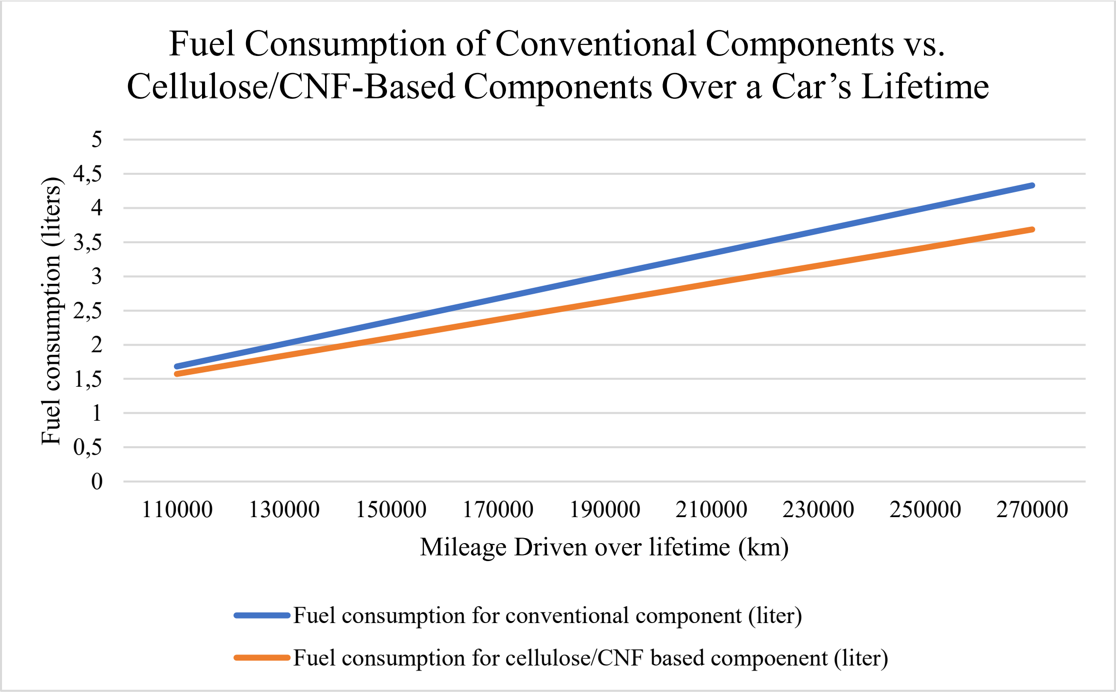


Fig. 32. Fuel Consumption of Conventional Components vs. Cellulose-Based Components Over a Car's Lifetime

6. Conclusion

This thesis looks at the environmental performance of two natural fibers, kenaf and cellulose, as potential replacements for conventional fillers in automotive components, focusing on their life cycle assessments (LCAs). We first built the LCA model for the fibers and then applied them to automotive components, comparing them with traditional components made from conventional fillers like glass fibers. The components included a tray made with kenaf fiber and an engine beauty cover made with cellulose fiber and cellulose nanofibers (CNF). The LCA results, especially for the engine beauty cover, showed that using bio-fillers significantly reduces global warming potential and other environmental impacts compared to conventional materials. Another key finding was the reduction in weight when using natural fibers in composites, which ultimately lowers fuel consumption, such as diesel, during the vehicle's use phase. For the engine beauty cover, we saw a 20.08% reduction in fuel use.

One important discovery was related to the use of cellulose nanofibers (CNF) for the engine beauty cover. Although CNF, derived from plant fibers, is gaining attention for its improved properties from chemical and mechanical treatments, the component made with CNF actually had the highest environmental impacts compared to both conventional and cellulose fiber-based engine covers. The main contributor to these impacts was the production phase of CNF, particularly the high electricity usage and certain materials involved in its production. Future studies should focus on improving the production process of CNF, with particular attention to reducing energy consumption and exploring alternative, more sustainable production methods. This could include investigating renewable energy sources for CNF production or optimizing chemical treatments to lower their environmental footprint.

While this study highlights the environmental benefits of bio-based composites, it also reveals some challenges, particularly in terms of increased land use and water consumption. As shown in Table 30, the LCA of the tray made with kenaf fibers showed an increase in both water and land use, mainly due to the agricultural phase of growing kenaf. Further research could explore ways to mitigate these impacts, such as through more efficient agricultural practices, optimizing water usage, or even exploring alternative bio-based fillers that could offer reduced environmental impacts during cultivation

Another challenge we faced in this study was modeling the end-of-life (EoL) scenarios for the components. We used a cradle-to-gate approach for the kenaf-based component and a cradle-to-grave approach for the cellulose-based component. However, accurately predicting the EoL pathways for these materials was quite complex. Recycling efficiency and disposal methods can vary a lot depending on factors like regional policies, the technology available, and local infrastructure. These differences added some uncertainty to our analysis. This challenge emphasizes the need for more research to better understand how these bio-based composites behave at the end of their life.

Finally, it is essential to consider all impact categories in an LCA and take a comprehensive approach before making decisions. While bio-based materials show great potential for the future of automotive manufacturing, further research is needed, especially as many factories strive to reduce the environmental impact of their products throughout their entire life cycle.

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