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Characterization and life cycle assessment of alkali treated abaca fibers: the effect of reusing sodium hydroxide

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ABSTRACT

The increasing demand for natural fibers, driven by their advantageous attributes such as low density, sustainability, and high specific strength, has promoted the adoption of sustainable alternatives in composites. Although alkali treatments are known to improve fiber properties, they entail challenges regarding NaOH consumption and environmental impact, making it necessary to explore cleaner production strategies. This study evaluated the effects of implementing a circular economy approach through the recirculation of an NaOH solution on the treatment of abaca fibers. The fiber properties were assessed using thermogravimetric analysis (TGA), scanning electron microscopy (SEM), and tensile strength testing, along with an evaluation of the carbon footprint through a life cycle assessment. New life cycle inventories were developed to reflect the NaOH recirculation process. Comparative analyses were conducted using polypropylene fibers. The findings indicate that the recirculation of the NaOH solution remains effective for up to eight cycles, producing consistent TGA, SEM, and tensile strength results while achieving a 25 % reduction in the carbon footprint compared to conventional treatment. Additionally, this study highlights the environmental advantages of abaca over synthetic fibers, with increased tensile strength (8–46 %) and carbon footprint reduction (55–86 %) compared to polypropylene fibers. These results highlight the potential of abaca fibers to contribute to the circular economy, enhance resource efficiency, and mitigate climate change.

1. Introduction

The application of natural fibers has brought benefits to various industries, and their use has been growing [1]. Natural fibers possess key properties such as low density, sustainability, high availability in nature, cost-effectiveness, reduced dependence on non-renewable energy/material sources, and relatively high specific strength [2]. Natural fibers are essential for the production of comfortable and breathable garments in the textile industry [3]. Natural fibers are used in the automotive and aerospace industries to develop lighter and biodegradable components [4]. They are used in the fabrication of composites and reinforcement of construction materials [5–8], offering the additional benefit of potentially reducing the carbon footprint of cement composites [9]. These examples reflect the growing interest in the use of natural fibers as sustainable alternatives in various industrial applications.

Natural fibers are compared to polymer fibers because both address key challenges regarding traditional cementitious matrices, considering that concrete has low tensile strength and poor energy dissipation capacity, which makes it prone to cracking [10]; among polymer fibers, polypropylene (PP) is particularly valued in the concrete industry owing to its ease of processing and cost-effectiveness [11].

Natural fiber treatments significantly contribute to improving their intrinsic properties and expanding their versatility in various industrial applications. These treatments primarily aim to improve the adhesion and compatibility between natural fibers and polymeric matrices in composite materials [12,13]. Despite these advantages, many challenges arise concerning the use of natural fibers in applications, such as poor dispersion in the matrix and, most critically, the low durability of fibers in the matrix [14]. Hence, two strategies have been developed regarding whether to modify the matrix [15] or fiber by applying different treatments [14,16].

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Notation

NaOH	Sodium hydroxide.
TGA	Thermogravimetric analysis.
DTG	Derivate thermogravimetric analysis.
SEM	Scanning electron microscope.
LCA	Life cycle assessment.
LCI	Life cycle inventory.
LCIA	Life cycle impact assessment.
GWP	Global warming potential.
kg CO_2 eq.	Kilograms of carbon dioxide equivalents.
T0	No treatment cycle performed.
T1	Single-use of NaOH solution
T2-T10	Reuse of NaOH solution, from second use to tenth use.
CT	Conventional treatment with a single use of NaOH solution.
RT	Reuse of NaOH solution per 8 cycles of recirculation
NAF	Natural abaca fiber.
TAF-CT	Treated abaca fiber - conventional treatment.
TAF-RT	Treated abaca fiber - reuse treatment.
PPF	Polypropylene fiber.
ANOVA	Analysis of variance.
n	number of samples per treatment.
P	*P*-value.
ISO	International Standards Organization.
ASTM	American Society for Testing and Materials.
PCR	Product category rules.
ESPAC	Ecuadorian survey of surface and continuous agricultural production.
INAMHI	Ecuadorian Institute of Meteorology and Hydrology
CH_4	Methane.
N_2O	Nitrous oxide.
IPCC	Intergovernmental Panel on Climate Change.
$Frac_{LEACH}$	Partitioning factor for the fraction of fertiliser and manure nitrogen applied to soil that is lost through leaching and runoff.
CO	Colombia.
EC	Ecuador.
IN	India.
PE	Peru.
US	United States.
GLO	Global.
RoW	Rest of world.

Among the treatments intended for composite applications, alkaline treatment is notable, in which the fibers are subjected to a sodium hydroxide (NaOH) solution to modify their surface and enhance adhesion with polymeric matrices [17,18]. Additionally, treatments with silane coupling agents aim to establish chemical bonds between the fibers and resins to optimize the load transfer and improve the mechanical properties of the composite [15,19]. Other treatments, such as thermal, enzymatic, and peroxide treatments, have also been used to adjust the characteristics and compatibility of natural fibers with matrices. These treatments enable the production of natural fiber-reinforced composites with specific properties tailored to diverse applications [20].

Table 1
Sodium hydroxide consumption per 1 kg of natural fiber in the reviewed literature.

Fiber	Fiber: Solution ratio[a]	Alkaline treatment (%)														Ref.
		1	2	3	4	5	6	7	8	9	10	12	15	20	50	
		Sodium hydroxide (kg)														
Abaca	1:28	-	-	0.83	-	-	-	-	-	-	-	-	-	-	-	[30]
Abaca	1:33	-	0.65	-	-	-	-	-	-	-	-	-	-	-	-	[28]
Abaca	1:30	0.30	-	-	-	1.43	-	-	-	-	-	-	-	-	-	[22]
Abaca	1:15	-	-	-	-	0.71	-	-	-	-	1.36	-	1.96	2.50	-	[36]
Alfa	1:15	0.15	-	0.44	-	0.71	-	0.98	-	-	-	-	-	-	-	[37]
Bagasse	1:20	0.20	-	0.58	-	0.95	-	-	-	-	-	-	-	-	-	[33]
Bamboo	1:20	-	0.39	-	-	-	1.13	-	-	-	1.82	-	-	-	-	[24]
Bamboo	1:15	-	-	-	-	-	-	-	-	-	1.36	-	1.96	2.50	5.00	[23]
Banana	1:15	0.15	-	-	-	-	-	-	-	-	-	-	-	-	-	[38]
Coir	1:23	-	-	-	-	1.11	-	-	-	-	-	-	-	-	-	[26]
Mauritius hemp (*Furcraea foetida*)	1:20	-	-	0.58	-	-	1.13	-	-	1.65	-	2.14	2.61	-	-	[29]
Hemp	1:6	-	-	-	-	-	-	-	-	-	0.55	-	-	-	-	[25]
Hemp	1:15	-	-	-	-	0.71	-	-	-	-	-	-	-	-	-	[39]
Hemp	1:55	-	-	-	-	-	-	-	-	-	5.00	-	-	-	-	[40]
Hemp	1:20	-	-	-	-	0.95	-	-	-	-	-	-	-	-	-	[41]
Hemp, Flax	1:40	-	-	1.17	-	1.90	-	-	2.96	-	3.64	4.29	5.22	6.67	-	[42]
Jute	1:15	-	-	-	-	0.71	-	-	-	-	-	-	-	-	-	[34]
Jute	1:15	-	-	-	-	0.71	-	-	-	-	-	-	-	-	-	[43, 44]
Kenaf	1:20	-	-	-	-	0.95	-	-	-	-	-	-	-	-	-	[35]
Palm (*Phoenix sp.*)	1:20	-	-	-	-	0.95	-	-	-	-	1.82	-	2.61	3.33	-	[31, 45]
Doum palm	1:20	0.20	0.39	0.58	0.77	-	1.13	-	1.48	-	-	-	-	-	-	[46]
Royal palm	1:25	-	-	-	-	1.19	-	-	-	-	-	-	-	-	-	[47]
Pineapple, ramie, sansevieria	1:100	-	1.96	-	-	-	-	-	-	-	-	-	-	-	-	[48]
Sisal	1:25	-	0.49	-	-	-	-	-	-	-	-	-	-	-	-	[49]
Sisal	1:20	-	-	-	-	-	-	-	-	-	1.82	-	-	-	-	[50]

[a] By mass
No reported: -

1.1. NaOH consumption in the alkali treatment of natural fibers

Alkaline treatment or mercerization is one of the most widely used chemical treatments for natural fibers [21]. This treatment has been shown to be effective for fibers from coconut, sisal, jute, banana, bagasse, flax, oil palm, and abaca [17]. This process usually involves immersing the fibers in alkaline solutions, typically NaOH, at solution concentrations ranging from 1–50 % [22,23]; the treatment can be conducted at room temperature or elevated temperatures [24,25], with exposure times varying from 30 min to 72 h [26,27]. Subsequently, the mercerized fibers are washed with water to remove any residual alkaline content and then neutralized to prevent further degradation [28,29]. Finally, the fibers are dried at room temperature [30,31] or at temperatures ranging from 50 to 105°C [18,32], for varying periods of time, typically between 6 and 72 h [33,34].

However, this procedure can lead to a significant consumption of NaOH, which not only affects production costs but also raises environmental concerns [35]. The quantity of NaOH required per kilogram of natural fiber depends on the solution concentration and fiber type. For example, low-concentration NaOH solutions (1 %) consume 0.15–0.20 kg of NaOH per kg of natural fiber. At common concentrations (3–5 %), NaOH consumption ranges between 0.44 and 1.90 kg of NaOH per kg of natural fiber, while at high concentrations of NaOH (10–50 %), up to 6.67 kg of NaOH per kg of natural fiber may be required. This consumption also depends on the type of natural fiber and fiber solution ratio, as shown in Table 1.

Consequently, the main environmental challenge of alkaline treatment of natural fibers is the production of sodium hydroxide (NaOH) through electrolysis, which is an energy-intensive process [35]. This has a significant environmental impact on the treatment processes. Additionally, when fibers are removed from the alkaline bath, the generation of wastewater adds environmental concerns in terms of the treatment itself and the disposal of effluents [51]. Together, these factors create the need for more sustainable practices in the alkaline treatment of natural fibers.

Several studies have focused on the reuse of NaOH solution from the natural fiber surface treatment process as part of a circular economic strategy. This approach aims to reduce both NaOH consumption and wastewater generation [50,52–54]. A 40 % NaOH solution effectively removed lignin from empty palm fruit bunch fibers, and the solution was reusable for multiple lignin extractions [52]. A recent study explored the reuse of NaOH solution in the treatment of Spanish broom fibers with 15 % NaOH. They concluded that the maceration effect reduced the lignin content in the fibers, and the same alkali solution could be used for at least five preparations [53].

Reusing NaOH solutions in different applications has proven to be effective in enhancing material properties and offering some environmental benefits. In one approach, sisal fibers treated with 10 % NaOH and incorporated into alkali-activated slag-based composites demonstrated improved flexural and compressive strengths with reduced electrical conductivity and density using the residual NaOH solution as an activator [50]. Another method involves residual bagasse fibers for use in the production of fiber-reinforced biocomposite pellets, where a NaOH recovery process allows for the recycling of up to 61 % of the NaOH used, although the reduction in carbon footprint is 1 % [54].

For these reasons, circularity measures, such as reducing chemical consumption and wastewater generation, can be implemented to mitigate the environmental impacts associated with the production of treated natural fibers. Several researchers have proposed the use of life cycle assessments (LCA) to assess the effectiveness of cleaner production methods and circular economy alternatives. [55–57].

According to the FAO [58], abaca fiber ranks as the sixth most produced natural fiber worldwide, with an annual production of 107 kt in 2022, ahead of jute, flax, hemp, kenaf, and sisal. Abaca plays a crucial role in the production of paper, monetary paper, textiles, ropes, packaging, and in the automotive industry because of its strength and durability [59,60]. It shows promising results in construction applications in the reinforcement of cement composites, where it enhances tensile strength, crack resistance, and durability [61,62]. Despite their significant industrial importance, the environmental impact of abaca fibers remains underexplored compared to that of other fibers such as jute, flax, hemp, and kenaf [63–67]. Therefore, it is essential to generate a detailed life cycle inventory and environmental profile for abaca to better understand and quantify its environmental implications across various applications.

The objectives of this research are (i) to study the effect of recirculation and reuse of NaOH solution for the treatment of natural fibers and analyze its influence on the properties of abaca fibers, (ii) to generate life cycle inventories for the treatment process of natural abaca fibers with NaOH solution, (iii) to quantify the carbon footprint of the NaOH treatment process for abaca fibers and the proposed recirculation and reuse of residual NaOH solution as a circular economy scenario using a life cycle perspective, and (iv) to evaluate the carbon footprint results in the context of polypropylene fibers as a conventional synthetic alternative.

2. Materials

2.1. Abaca fibers

Abaca natural fibers obtained from the Manila hemp plant (*Musa textilis*) are known for their strength, durability, and versatility [68]. Their water resistance and ability to withstand biological degradation make them particularly suitable for applications that require robustness and longevity [61,69]. In the construction industry, when applied to cement-based composites, they act as a reinforcement, improving the tensile and flexural strength [70,71] and potentially serving as a replacement for synthetic fibers. The abaca fibers used in this study were cultivated in Ecuador, the second-largest exporter of abaca worldwide [58].

2.2. Abaca NaOH treated fiber

Alkaline treatment of the natural abaca fibers was performed as described by Alcivar-Bastidas et al. [30]. This involved preparing a 3 % NaOH solution in distilled water and immersing the natural fibers in a fiber:solution ratio of 1:28 by mass for 4 h. Subsequently, the fibers were removed from the solution and washed with tap water until the rinse water became clear. Finally, the fibers were dried in an oven at 85 ± 1 °C for 24 h, after which they were stored and packaged at room temperature. The materials and quantities used are listed in Table 2. Natural abaca fibers and abaca fibers treated with 3 % NaOH have a length of 30 mm, which is the optimal size for application in masonry mortar cement composites [30].

2.3. Polypropylene fiber

Polypropylene fibers are synthetic fibers manufactured by the extrusion of polypropylene. These fibers act as reinforcements to improve the mechanical properties of cement-based composites [72,73].

Table 2
Material quantities for abaca fiber alkali treatment with 3 % NaOH solution.

Material	Weight (g)
Input	
Deionized water (solution)	1000
NaOH	30
Abaca natural fiber	36.1
Tap water (wash water)	4326
Output	
Abaca treated fiber	28.7

In this study, the polypropylene fibers were made of 100 % virgin material. The fibers were made according to the ASTM C1116 standard [74], for which the specifications were as follows: 19 mm length, 0.03–0.05 mm diameter, tensile strength between 300–350 MPa, 910 kg/m^3 density, and high resistance to alkalinity [75].

3. Methods

3.1. Reuse of NaOH solution in alkali treatment of abaca fiber on a laboratory scale

As part of the circular economy initiative, a scheme for the recirculation and reuse of the NaOH solution is proposed, as shown in Fig. 1, where the solution is reused after fiber immersion. An experimental testing framework was defined, and treatment 1 (T1) was initiated, as described in Section 2.2.

Subsequently, the residual NaOH solution became the initial solution for the second cycle of treatment (T2), maintaining the material proportions shown in Table 2, a fiber:solution ratio of 1:28, and a fiber:wash water ratio of 1:120 by mass. This procedure was repeated until the maximum number of treatments with the same solution was achieved.

3.1.1. Titration Method for measuring NaOH solution concentration

The standard Titration Method described in the Standard Methods for the Examination of Water and Wastewater was used to determine the NaOH solution concentration in all samples, as described in Section 2320 B. Titration Method [76].

The method involves titrating the sample with standard sulfuric acid (H_2SO_4) and chemical indicators (phenolphthalein). The volume of acid used was recorded, and the alkalinity was calculated using a formula that accounts for the volume of acid, its normality, and sample size. The result was expressed in milligrams per liter as calcium carbonate ($CaCO_3$), providing a reliable measure of the water's buffering capacity. Finally, a known solution of NaOH was measured and compared to the $CaCO_3$, and a conversion factor was used to determine the concentration of NaOH in percentage (%).

3.2. Fiber properties tests

3.2.1. Thermogravimetry/derivative thermogravimetry analysis (TGA/DTG)

Thermogravimetric analysis was conducted on untreated and treated abaca fibers. This was performed by comparing the rate of weight loss and decomposition temperature to observe changes in the fiber mass. This test indicated the thermal decomposition, moisture content, and thermal stability of the fibers. The analysis was developed with the use of SDT Q600 Simultaneous Thermal Analyzer equipment, under a ramp rate of 15°C/minute from room temperature to 104°C and 50°C/minute from 104°C to 1000°C. This test was performed as described in the studies by Alcivar-Bastidas et al. [30], Shahril et al. [29], Fu et al. [77], and Kathirselvam et al. [78]. The effectiveness of thermal treatments on natural fibers, such as the removal of lignin and hemicellulose, has been observed [79–81].

3.2.2. Scanning electron microscope (SEM)

To analyze the morphology of the fibers, an SEM test was performed using a FEI Inspect® scanning electron microscope, and the recommendations from similar studies by Wei et al., [82,83] were followed. This test visually provides the surface roughness, porosity, and fiber wall structure, allowing an examination of the removal of substances such as impurities, wax, hemicellulose, lignin, and fatty acids due to alkaline treatment [29,38].

3.2.3. Tensile test

The tensile test used to determine the tensile strength of untreated abaca fibers and alkaline-treated fibers with different treatment cycles was performed according to Cai et al., [84,85] and Alcivar-Bastidas et al. [30]. This involved placing a fiber in a sample holder, which was secured with epoxy at the bottom. It was then subjected to tension at a velocity of 1 mm/min using a universal testing machine Shimadzu AGS-X with a load cell of 500 N. The tensile strength at breaking point was obtained from the testing machine, and the diameter was obtained by the SEM test described above using Motic Images Plus 3.0. Also, an analysis of variance (ANOVA) was performed, with $\alpha=0.05$ and 30 samples ($n=30$) for each scenario. This analysis was performed to determine if there were significant differences in tensile strength between the treatments [86]. It is considered essential to statistically evaluate the behavior of the natural abaca fiber (NAF), single-use of NaOH solution (T1) samples and the solution reuse treatments, with the main purpose of determining the extent to which the use and recycling processes remained effective.

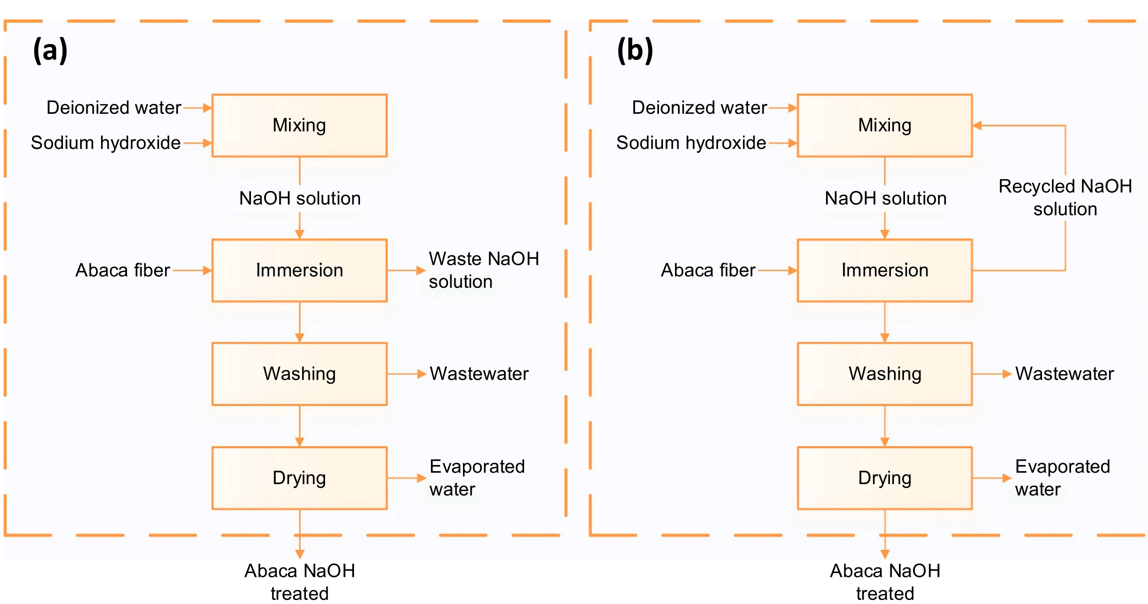

Fig. 1. Flow chart of alkaline treatment of abaca fiber. (a) Conventional treatment. (b) Proposal for recirculation and reuse of NaOH solution.

3.3. Life cycle assessment

Life Cycle Assessment (LCA) is a methodology used to evaluate the environmental impacts associated with a product's life cycle, from raw material extraction through production, use, disposal, and recycling [87]. By conducting LCA, it is possible to identify areas where improvements can be made to reduce the environmental footprint of products or processes. ISO 14040 and ISO 14044 are LCA standards that provide the principles and framework for conducting LCA studies [88, 89]. This framework includes (i) defining the goal and scope and establishing objectives and boundaries; (ii) conducting a life cycle inventory (LCI) and collecting data on inputs and outputs; (iii) performing a life cycle impact assessment (LCIA) and evaluating environmental impacts; and (iv) interpretation and drawing conclusions for decision-making and improvement.

3.3.1. Goal and scope definition

The natural abaca fiber and alkali-treated abaca fiber within this study are considered for use in cement-based composites, in accordance with ASTM C1116 [74], as an alternative to polypropylene fibers; therefore, they are defined as construction products. A cradle-to-gate scope is defined according to Product Category Rules (PCR) for construction products in EN 15804:2012 [90]. These include A1, raw material supply, A2, transport, and A3, manufacturing.

Abaca is produced globally, with the Philippines being the leading producer, accounting for 63.56 % of abaca production, followed by Ecuador at 34.50 %, and other countries at 1.94 % [58]. In this study, the processes of abaca cultivation, abaca fiber production, and alkaline-treated abaca fiber production were associated with the geographic scope of Ecuador. The polypropylene fiber was associated with the geographical scope of the US, which is the origin of the fibers according to the manufacturer.

3.3.1.1. System boundaries. Four systems are studied:

(i) Natural abaca fiber (NAF) production (Fig. 2. a): The system covers two phases: abaca and fiber production. Abaca production involves seedling production, growth until the seedlings are transplanted into the crop, and forming groups of stems that grow from the base (Fig. 3. a). The abaca plant matures within a period of 18–24 months and can be harvested thrice a year [91]. Harvesting involves cutting the stems approximately 10 cm from the ground with an outward beveled cut to prevent the plant from rotting [60]. After cutting, the leaves are removed and the harvested pseudostems are grouped. Tuxiying then begins, which involves cutting the pseudostem until it reaches the central zone (tuxy) containing the biomass to be transformed into a fiber [92].

(ii) In the second phase of fiber production, the tuxies are stripped using a mechanism consisting of a diesel engine, pulleys, and blades (Fig. 3.b). Finally, the fibers are dried in the sun for 1–3 days (Fig. 3.c).

(iii) Treated abaca fiber – conventional treatment (TAF-CT) production (Fig. 2.b): This system covers natural abaca fiber production plus conventional 3 % alkali treatment as described in Section 2.2.

(iv) Treated abaca fiber – reuse treatment (TAF-RT) production (Fig. 2.b): This system is a variant of TAF-CT. This includes NAF production plus 3 % alkaline treatment with recirculation of the NaOH solution, as proposed in Section 3.1.

(v) Polypropylene fiber (PPF) production (Fig. 2.c): This process begins with the input of polypropylene granulates, which are produced through the polymerization of propylene monomers [93]. This product serves as the primary raw material for the fiber manufacturing process. Electricity is crucial for powering extrusion, spinning, and other machinery involved in converting polypropylene into fibers [94].

The functional unit was 1 kg of fiber, with four different scenarios depending on the system boundaries: 1 kg of natural abaca fiber, 1 kg of abaca fiber treated with a 3 % NaOH solution, 1 kg of abaca fiber treated with a reused 3 % NaOH solution, and 1 kg of polypropylene fiber (Table A.1 in Appendix A).

3.3.2. Life Cycle Inventory

3.3.2.1. Natural abaca fiber production. The Ecoinvent LCI calculation tool for crop production [95] was used to model the life cycle inventory (LCI) of abaca production. It employs various models to calculate emissions from field activities, land transformation and occupation, irrigation, and carbon uptake by plants [96]. This tool requires agricultural and meteorological inputs from the plantation sites.

The agricultural input was obtained from the Ecuadorian Survey of Surface and Continuous Agricultural Production (ESPAC 2022) [97]. This survey used the multiple frame sampling methodology, and for abaca production, a sample of farms that represented 24.35 % of the total abaca fiber produced was considered [98]. An expansion factor was then applied to obtain the total results for all items surveyed for all abaca fibers produced in Ecuador [99]. The information surveyed included planted and harvested areas, harvested tons, use of irrigation, and the quantity and type of fertilizers and pesticides [97]. According to the ESPAC survey, there are seven types of abaca plantations that vary according to the use of fertilizers and pesticides, depending on the organic or inorganic origin of these substances. The predominant plantation does not involve the use of fertilizers or pesticides, representing 54.93 % of the Ecuadorian abaca harvest [98]. Owing to its representativeness, the current study was limited to modeling this type of plantation.

Meteorological data were obtained from the Ecuadorian National Institute of Meteorology and Hydrology [100]. The selected meteorological station is located in the province of Santo Domingo, which accounts for 90 % of Ecuadorian abaca production [98].

To generate inventories of biomass and organic waste, the average biomass distribution in the abaca plant (Fig. 4. a) was obtained from Cortez et al. [101]: leaves (16.36 %), pseudo-stem waste (63.79 %), and tuxy (19.85 %). Seven farms in Santo Domingo-Ecuador were visited, from which it was evident that organic residues such as leaves, pseudo-stem waste, and stripping waste were left in the plantation. According to farmers, this is a common practice in Ecuador. The biomass serves as a nutrient source for new plants [102,103]. Owing to the absence of anaerobic conditions, CH_4 emissions were not generated [104]. In this study, the waste biomass was considered to remain within the system; this approach has been used in studies of other plantations under similar conditions [101,103,104].

To model the inventories of energy in biomass and carbon dioxide uptake by biomass for abaca production, the Ecoinvent LCI calculation tool for crop production requires a reference crop. In this study, banana (*Musa* spp.) was selected as the base crop because of its close botanical relationship with abaca (*Musa textilis*), as both belong to the *Musaceae* family [107,108]. Additionally, they are cultivated in the same region in Ecuador [105] and exhibit similar biomass distribution patterns (Fig. 4); in the case of banana, the main product is the fruit, while for abaca is the tuxy. As the biomass distribution is a critical input for the Ecoinvent LCI calculation tool [96], this similarity in biomass distribution makes banana an appropriate reference crop.

Dinitrogen monoxide (N_2O) from the crop residues for abaca production was calculated using the IPCC Guidelines [109], yield from ESPAC 2022 [97], biomass distribution from Cortez et al. [101], and moisture and nitrogen content from Armecin et al. [110,111]. Indirect N_2O emissions from leaching and runoff were estimated using IPCC Guidelines [109]. The leaching-runoff factor was calculated according

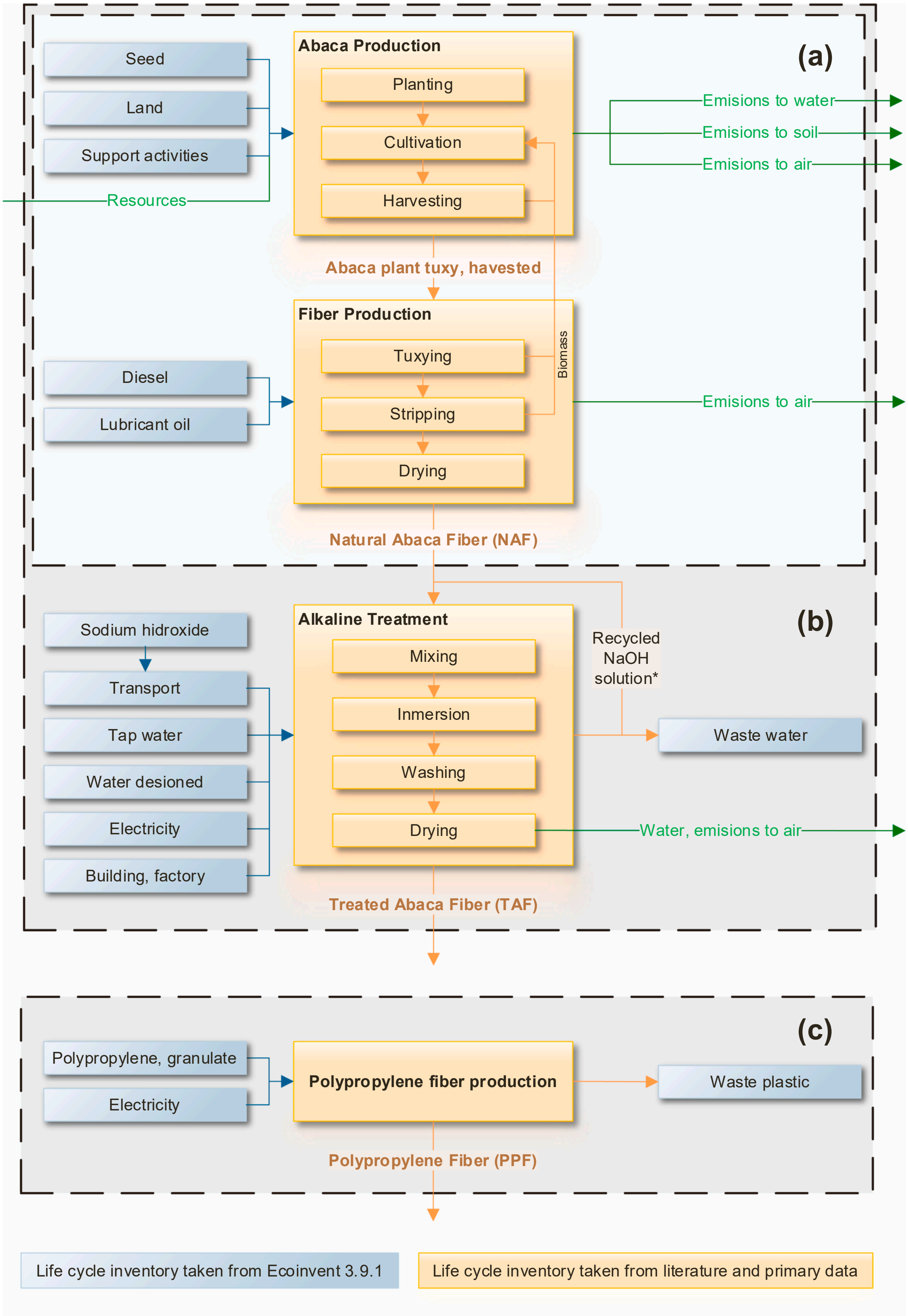

Fig. 2. Cradle-to-gate system boundary for the production of (a) abaca fiber, (b) abaca fiber treated and (c) polypropylene fiber. * Included in reuse case study.

Fig. 3. Abaca fiber production stages in Santo Domingo-Ecuador: (a) group of abaca trees, (b) stripping process, and (c) drying process.

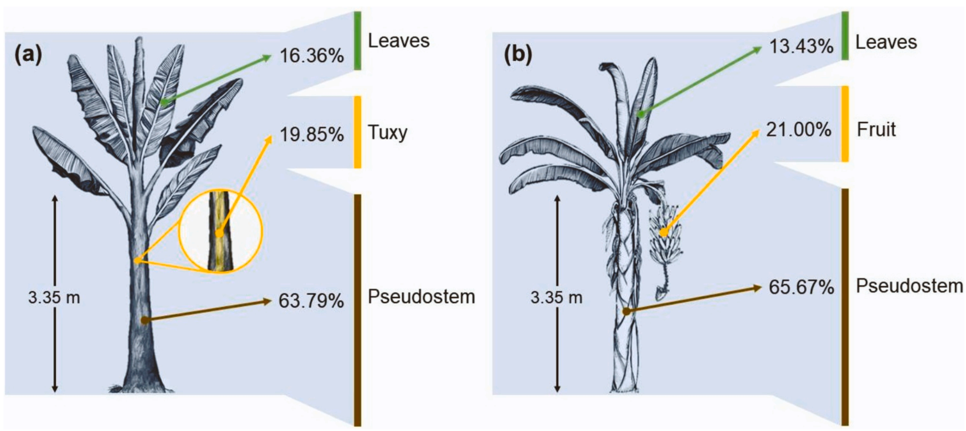

Fig. 4. Average distribution of biomass of (a) abaca plant (*Musa textilis*) [92,101] and (b) banana plant (*Musa* spp.) [105,106].

to Franke et al. [112] and replaced $Frac_{LEACH}$ in the IPCC calculations. This approach was used in a previous carbon footprint study of bananas in Ecuador [104].

Finally, the inventory of fuel and lubricant consumption for the fiber stripping and drying process was collected from the seven farms visited. The fuel was transformed into energy units using the factors for Ecuadorian diesel (density: 850 kg/m^3; heat capacity: 40.8 MJ/kg) [113].

3.3.2.2. Treated abaca fiber production. The inventory of raw materials for the abaca alkaline treatment fiber process using a 3 % NaOH solution and the proposal for recirculation and reuse of the NaOH solution were taken from the results provided in this study, in Section 2.2 and Section 4.1, respectively. Facilities and energy inventories for the alkaline treatment fiber process were taken from the "mercerizing process, textile – IN" detailed in Ecoinvent 3.9.1 [114] and Faist Emmenegger et al. [67]. This process was adapted to Ecuadorian electricity, and the LCA process of Ramirez et al., [115,116] was used. The NaOH supplier closest to Guayaquil is located in Callao, Peru [117]. Sodium hydroxide and sodium chloride from Ecoinvent 3.9.1 were adapted for Peruvian electricity.

3.3.2.3. Polypropylene fiber production. The life cycle inventory of raw materials for polypropylene fiber production was obtained from studies by Yin et al. [93] and Van den Heede et al. [94]. Processes for polypropylene granulate production, electricity, and waste treatment were obtained from Ecoinvent 3.9.1 [114].

The main parameters and assumptions of this study are summarized in Table A.1 in Appendix A.

3.3.3. Life Cycle Impact Assessment

The methodology used for LCIA was the ReCiPe Midpoint (H) version 1.13 [118]. The impact category of global warming potential (GWP100), also known as the carbon footprint, was selected because it is considered the most critical indicator of climate change [119]. OpenLCA 2.1.1 [120] was used for LCA calculations.

4. Results and discussion

4.1. Reuse of NaOH solution in alkali treatment of abaca fiber on a laboratory scale

Table 3 shows the experimental results of reusing NaOH solution in the alkaline treatment of natural abaca fibers. Following the methodology described in Section 3.1, by maintaining the same proportions of fiber:solution and fiber:wash water materials, each washing cycle preserved a similar behavior as the conventional treatment of a single-use NaOH solution (T1).

The 10 reuse cycles resulted in a loss of sodium hydroxide solution owing to the treatment process (fiber washing and evaporation), ranging from 26.61 % to 30.16 %. As a consequence of alkaline treatment,

Table 3
Experimental inventory of materials in 10 cycles of NaOH solution reuse for alkaline treatment.

Cycle	Initial NaOH solution (g)	Abaca fiber (g)	Washing water (g)	Wet fiber (g)	Dry treated fiber (g)	Final NaOH solution (g)	NaOH in final solution (%)
T0	-	-	-	-	-	-	2.98
T1	1030	36.1	4326.0	333.59	28.70	719.34	2.96
T2	719.34	25.2	3021.2	243.92	20.04	512.59	2.95
T3	512.59	17.9	2152.9	162.89	13.83	370.29	2.93
T4	370.29	13.0	1555.2	106.74	10.05	271.77	2.91
T5	271.77	9.5	1141.4	85.05	7.37	196.38	2.89
T6	196.38	6.9	824.8	59.66	5.52	142.56	2.88
T7	142.56	5.0	598.7	44.80	3.99	103.38	2.86
T8	103.38	3.6	434.2	31.64	2.92	74.78	2.47
T9	74.78	2.6	314.1	23.85	2.07	52.57	0.84
T10	52.57	1.8	220.8	16.79	1.52	36.91	0.31

natural fibers experience mass reduction owing to the removal of impurities, and wax, hemicellulose, and lignin are removed [121–123]. This behavior was observed in T1, with a mass reduction of 20.5 %; from T2 to T9, similar values between 18.9 % and 20.4 % were obtained. T10 exhibited the lowest mass loss of 15.6 %.

Washing cycles were stopped at T10 because the solution was lost. Initially, there was a certain amount of solution, considering the 1:28 fiber:solution ratio; however, as the washing cycles continued, the solution was lost, which resulted in inadequate fiber treatment solution for washing cycle T11. After 10 cycles of NaOH reuse, there was a 70.11 % reduction in NaOH consumption per kilogram of treated abaca fibers.

The titration test was performed on all samples from T0 to T10, as shown in Table 3, where the initial solution concentration in T0 was 2.98 % and the NaOH concentration in T10 was 0.31 %. The initial value of 2.98 % can be attributed to the manual procedure of dissolving NaOH in the solution. After applying the first procedure of using and recycling the water solution, the NaOH concentration in T1 was measured to be 2.96 %, which closely resembled the initial concentration of T0. Between T2 and T4, the NaOH concentration showed a slight decrease, ranging from 2.95 % to 2.91 %, indicating that the recycling process effectively maintained the concentration at levels similar to those at T0.

From T5 to T7, the average NaOH concentration stabilized at 2.88 %, which remained within an acceptable range, suggesting that the washing and recycling procedures were still effective. It is important to mention that at T8, the NaOH concentration decreased to 2.47 %, representing 17 % of the initial concentration, which could be due to the impurities retained throughout the washing and recycling processes. Between T8, T9, and T10, sharp changes occurred: the value for T9 decreased to 0.84 %, and T10 decreased to 0.31 %. The NaOH concentration further decreased, indicating a substantial loss of NaOH, which could affect the chemical processes required to modify the properties of the natural fibers.

This noticeable reduction in NaOH concentration between T9 and T10 was likely due to the cumulative effects of washing and recycling. This reduction may result in insufficient removal of impurities such as hemicellulose, cellulose, and pectin, which are crucial for the proper adhesion of the fiber to the matrix. The significant decrease in the concentration between T8 and T9, by approximately 1.63 % (55 % of

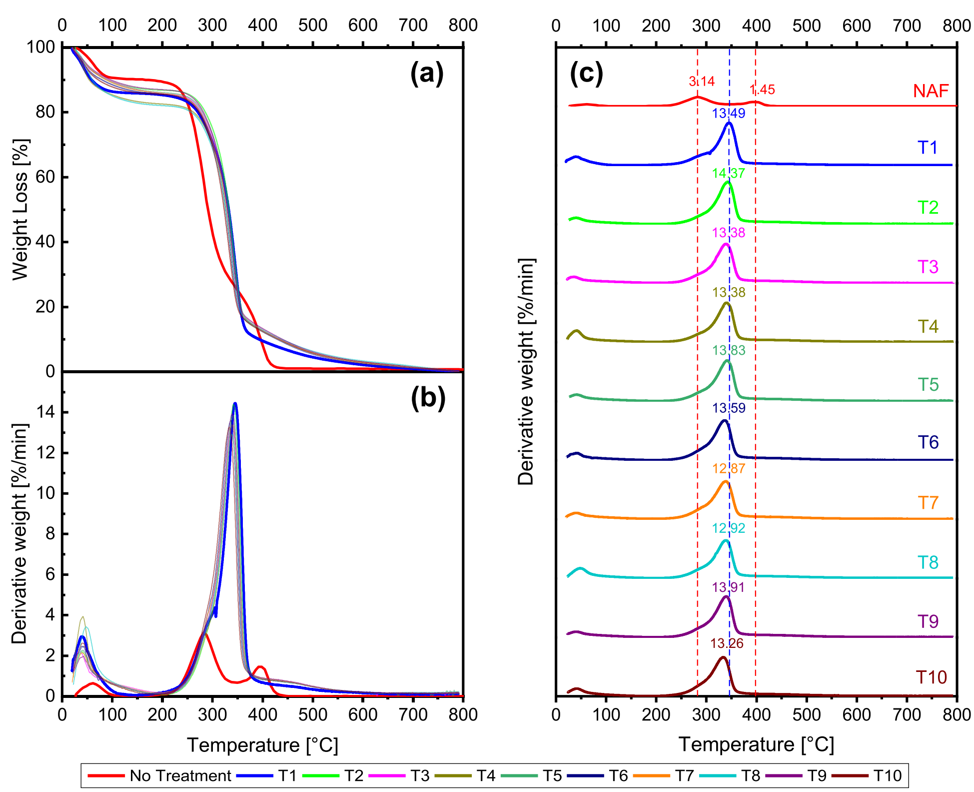

Fig. 5. Thermogravimetric analysis (a) and derivative thermogravimetric analysis (b–c) of natural abaca fiber (NAF) and treated abaca fiber (T) in 10 cycles of NaOH solution reuse (1–10).

the total alkali concentration), may represent a critical threshold at which the effectiveness of the treatment diminishes, potentially compromising the overall outcome.

4.2. Influence of the reuse of NaOH solution on the abaca fiber properties

4.2.1. Thermogravimetry/Derivative Thermogravimetry Analysis (TGA/DTG)

Thermogravimetric analysis was performed to investigate the effect of different cycles of washing and reusing NaOH solution on the composition of the fiber in terms of thermal stability. Fig. 5.a shows the curves of all ten samples subjected to different washing and reuse cycles, including the natural fiber without treatment, described as natural abaca fiber (NAF) in Fig. 5. b. The DTG curve of the NAF fiber shows an initial peak at 60°C (mass loss around 4 %), which corresponds to the vaporization of absorbed water [124]. After this peak, there are two more peaks at 280°C and 400°C; according to Shahril et al. [29], between 200°C and 300°C, the expulsion of hemicellulose lignin and an insignificant amount of cellulose from the fiber occurs. Between 300°C and 410°C, eliminations of cellulosic components led to mass loss and implied the omission of lignin and wax [78].

Fig. 5.c shows the DTG curves of samples T1–T10, where all samples show similarities in their behavior and two main peaks are visible between 40°C and 340°C.

Sample T1 experiences a mass loss of 3 % at 38°C owing to vaporization of absorbed water and approximately 60 % mass loss at 335°C owing to elimination of hemicellulose and cellulosic components, with lignin being eliminated from the samples [125]. During the process of using the recycle solution, the same water solution of 3 % NaOH was used to determine the process efficiency by the non-cellulosic material

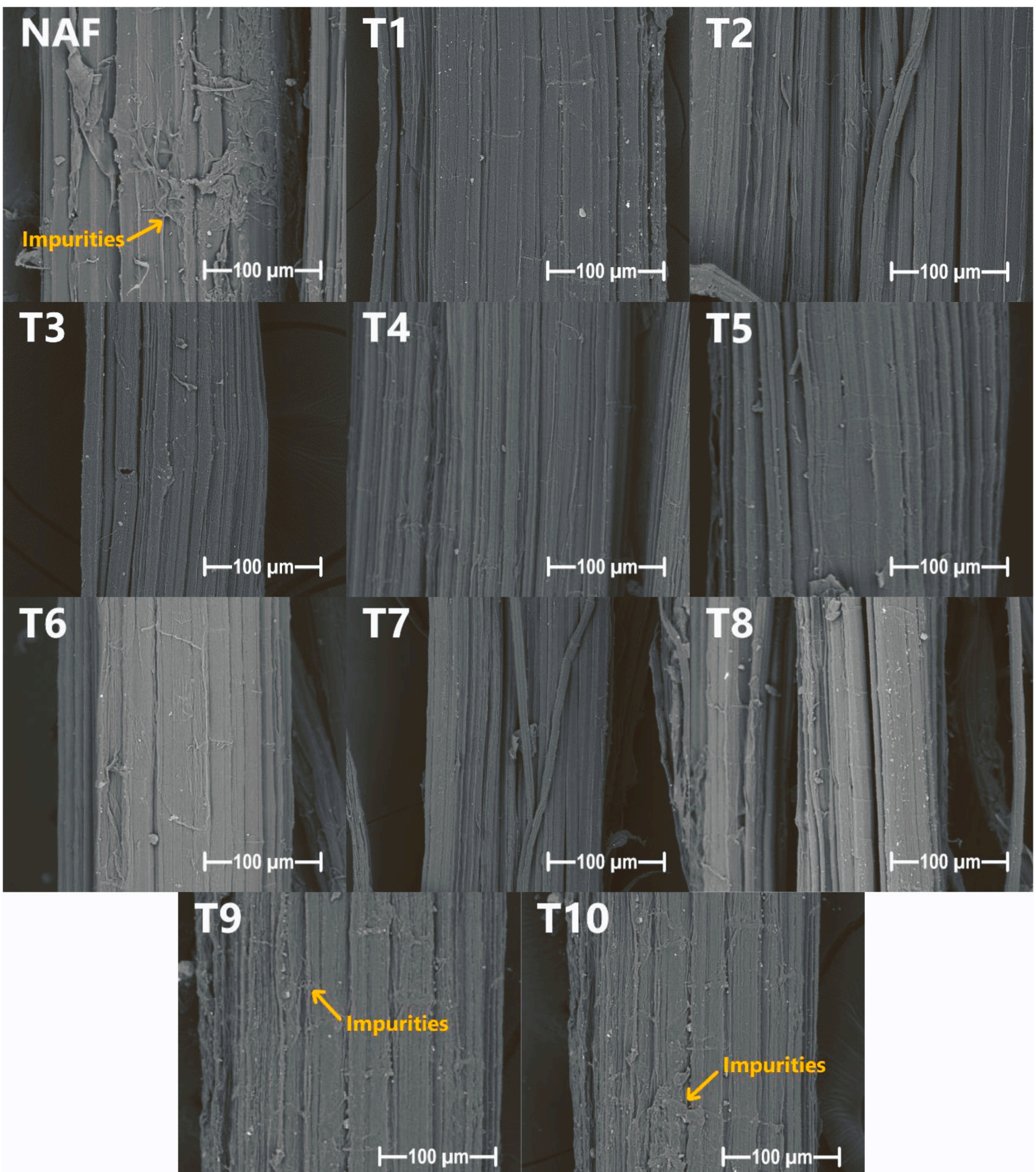

Fig. 6. Scanning electron microscope (SEM) results of natural abaca fiber (NAF) and treated abaca fiber (T) in 10 cycles of NaOH solution reuse (1–10).

residue content in the cellulosic fibers after the process. The main difference among samples T2, T3, T4, T5, T6, T7, and T8 occurs within 300–400℃, which is the interval corresponding to the fraction of hemicellulose and cellulose, where an evident peak is formed for all treated samples. This corresponds to a loss in mass of a 60 %. Samples T9 and T10 experience similar behavior, with a mass loss of 5 % at 42℃, and a mass loss of 65 % at 340℃, corresponding to the elimination of hemicellulose and cellulose. Comparing the treated and untreated samples, it is evident that hemicellulose and cellulose were lost in all samples with different mass losses., Lignin was still present at 400℃ in the untreated samples, while in the treated samples, it was lost. For all samples, the washing and reusing solution of NaOH eliminated the amorphous cellulose, hemicellulose, and lignin proportion in the fiber, and the heat flow required by the fiber sample to decompose was comparatively higher in the alkali-treated fibers than in the untreated samples [77]. In addition, there was no significant variation among the treated samples with respect to mass loss and temperature of occurrence, suggesting that the same alkali solution could be used for at least 10 preparations.

4.2.2. *Scanning Electron Microscope (SEM)*

In Fig. 6, SEM analysis of samples at 100 μm shows the behavior of untreated and treated samples using the washing and reusing NaOH solution. Visual techniques were used to perform the analyses. The visualization of the specimens was performed by the measurement of the reflected electrons from the surface of examined samples. As observed in the figure, NAF samples present impurities and undesirable globular protrusions at irregular intervals, while treated samples from T1–T8 do not. It is known that alkali treatment improves the surface roughness by removing the hydroxyl coat (OH-), no cellulosic materials, and wax from the surface of the fiber; by removing the hydroxyl coat, the fiber becomes more hydrophobic and reduces the water absorption [84].

Treated samples T1, T2, T3, T4, T5, T6, and T7 do not show impurities or globular protrusions; hence, the alkali treatment with washing and reusing NaOH appears effective in removing undesirable residues from the surface [121]. In addition, fibrillation and breakdown of the fiber bundle into elementary fibers are visible in these samples, which may occur because pectin, lignin, hemicellulose, and cellulose are removed from the abaca fibers during alkali treatment [85].

Up to sample T8, the surface roughness of the natural fiber increased with the disintegration of the hemicellulose and lignin structure, which increased the contact between the real surface area and the environment; hence, it improved the adhesive interface between the fibers and the matrix [126]. T8 shows a few impurities on its surface, but they can be considered negligible because the fibers are not bundled and are still separated into elementary fibers. However, T8 represents a turning point where the process of using and recycling the solution could be considered effective.

In contrast, sample T9 exhibited elementary fibers and the presence of impurities. It could be said that at this point, washing and reusing the NaOH solution was no longer effective. Up to T8, the samples showed the same pattern; however, a transition regarding the efficacy of the procedure began at T9. Samples T9 and T10 contained impurities, dust, and wax that were not cleaned during the process. Again, the fibers were bonded to the fiber bundle, decreasing the interfacial adhesion [36].

Through SEM, it can be seen that samples NAF, T9, and T10 show similarities; even if alkali treatment was applied to all samples, including T9 and T10, the recycled water treatment was only effective up to sample T8, where minor impurities were observed. These results show that for T9 and T10, the natural fibers did not react with the treatment, showing impurities, and they seem to bond. Hence, the effectiveness of the alkali treatment through washing and recycling NaOH solution was lost at T9. Thus, from T1 to T8, the behavior was similar, and the alkali treatment of the washing and recycling technique was effective up to this point.

4.2.3. *Tensile strength*

The samples subjected to tensile stress are shown in Fig. 7. It is seen that NAF reached a 342.92±30.23 MPa tensile strength, which is similar to the result obtained by Valášek et al. [121], with 326±38 MPa; even if both abaca fibers are from different countries, Ecuador and Philippines, respectively, the results are alike. After applying the alkali treatment, a consistent increase in the tensile strength was observed from T1 to T10 compared to that of the untreated natural abaca fiber (NAF). This suggests that alkali treatment, which involves using and recycling water, initially enhances the strength of the fibers. To evaluate the statistical significance of these improvements, an ANOVA analysis was conducted on the tensile strength results across the samples.

Alkali treatment of natural fibers is known to improve the mechanical properties of the fibers themselves and their composites [33,61,85]. However, the effect of alkali treatment on abaca fibers can vary depending on the concentration of the NaOH solution, exposure of the samples to this solution, and the time and temperature of the drying cycle.

For instance, Cai et al. [84], use concentration percentages of 5 %, 10 %, and 15 %, but with different dipping and drying time, results vary; in the first scenario with 30 min dipping time and 2 h drying at 80℃, tensile strength increased by 12 %, 11 %, and 11 %, respectively. In the second scenario, with 2 h dipping time and 2 h drying at 80℃, tensile strength just increased by 8 % with a 5 % concentration, and with 10 % and 15 % concentration, it decreased by 5 % and 6.5 %, respectively [127]. Liu et al. [128], used a 3 % concentration solution, dipping time of 90 min, and 40 min drying at 75℃, and observed a tensile strength increase of 5.35 %. In this research, using 3 % concentration, a dipping time of 4 h, and 24 h drying at 85℃, in the conventional alkaline treatment (T1), tensile strength increased 38 %, from 342.92 MPa to 473.32 MPa ($P < 0.001$).

In this study, washing and recycling NaOH solution on the samples may have affected the tensile strength. T2 increased by 35 % compared to NAF ($P < 0.001$).

Samples T1–T8 showed an increase of over 34 % compared to NAF. The ANOVA analysis yielded a *P*-value (P) greater than 0.05 ($P = 0.156$), indicating that the tensile strength results for these samples are statistically comparable, meaning that any observed differences in strength are not significant enough to be considered meaningful. Essentially, the alkali treatment was consistently effective across these samples (T1–T8), enhancing the fiber strength in a statistically similar manner. Although there were some variations compared to T1 in the tensile strengths of T3 ($P = 0.457$), T5 ($P = 0.878$), T6 ($P = 0.587$), and T8 ($P = 0.683$), these differences were within a range that did not affect the overall statistical comparability; therefore, alkaline treatment remained effective until T8.

However, a critical turning point was identified between T8 and T9. In sample T9, the tensile strength increased as well, but this increase was

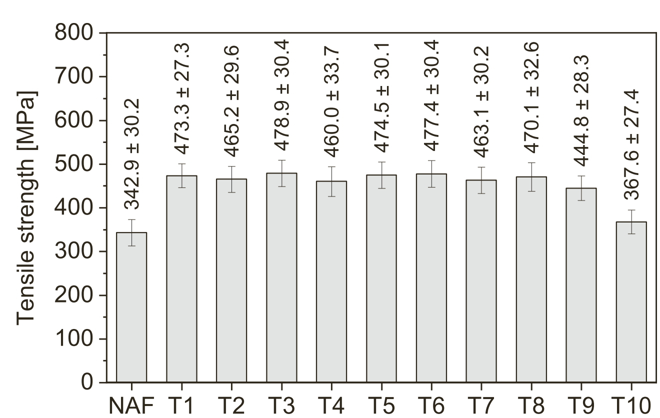

Fig. 7. Tensile strength results of natural abaca fiber (NAF) and treated abaca fiber (T) in 10 cycles of NaOH solution reuse (1–10). Values are mean ± standard deviation (n = 30).

29 % compared to NAF, which differs from the previous samples ($P < 0.001$), and the ANOVA analysis between these two samples showed a P-value of less than 0.05, indicating that the results for T9 are not statistically comparable to those for T8. This suggests that the treatment process, particularly the recycling of the alkali solution, began to lose its effectiveness after the eighth cycle. The tensile strength of T9, although still higher than that of the untreated NAF, showed a significant decrease with respect to the earlier trend of improvement. This marked reduction in effectiveness is further reinforced with sample T10, which still shows a low increase in tensile strength of 7 %, with values of 367.56 MPa compared to 342.92 MPa for NAF. The ANOVA results ($P < 0.001$) confirmed that T8, T9, and T10 are statistically different. This suggests that although the treatment still contributes to some enhancement of the fiber strength, this enhancement is no longer consistent.

Moreover, although the tensile strength of T9 represents a 29.72 % increase compared to that of NAF and T10 shows a 7 % increase, the ANOVA analysis indicates that these increases are not statistically comparable to those of the earlier samples (T1–T8). This research identified T8 as the critical turning point for the effectiveness of alkali treatment in reinforcing abaca fiber tensile strength. Beyond this point, the process of using and recycling the alkali solution no longer yielded statistically significant improvements. Despite some tensile strength improvement, the diminishing returns observed at T9 and T10 suggest that the treatment process should be limited to eight cycles for optimal effectiveness.

4.3. Life cycle assessment

4.3.1. Life cycle inventory

Table A.2 in Appendix A shows the results of the Ecoinvent LCI calculation tool for crop production applied to the abaca production. This tool assesses biogenic interactions such as energy in biomass, carbon dioxide uptake by biomass, and land use. It also includes activities such as establishing orchards, planting, and trellis system. In outputs, the tool calculates inventories of emissions to soil, water, and air.

In this study, where the scope was limited to calculating the GWP100, emissions to the air were critical. The only air emission calculated by the tool, due to the nature of the cultivation (without fertilizers and pesticides), was N_2O, and was replaced by the results calculated using the IPCC for N_2O from crop residues and leaching/runoff at 2.64E-05 and 3.19E-06 kg N_2O per kg of harvested abaca plant tuxy, respectively. The total N_2O is 2.96E-05 kg N_2O per kg of harvested abaca plant tuxy, which also represents 0.48 kg N_2O ha^{-1}, lower than other studies reported for banana crops of 1.35–1.6 kg N_2O ha^{-1} for unfertilized soils [129–131].

Carbon dioxide, in air, captured during abaca plants growth is 0.34 kg per kg of harvested abaca plant tuxy, similar to that obtained by adapting the studies of Cortez et al. [101] and Armecin et al. [110], which reported 0.34 kg of organic carbon per kg of harvested abaca plant tuxy. According to the results of ESPAC 2022 [97], the fiber production of abaca per hectare in this study is 1.3 tons, similar to yield values for Ecuador of 1.2–1.3 tons per hectare from FAO [58], higher than the range of 0.5–1 ton reported in other studies [51,101].

In fiber production, tuxy is stripped using the mechanism shown in Fig. 3.b, which involves diesel operation at a consumption rate of 0.02 liters of diesel per kg of dry fiber according to the farmers' survey. This value differs from Göltenboth et al. [92], who reported higher consumption values ranging from 0.05 to 0.08 liters of diesel per kg of dry fiber. In terms of energy, the stripping mechanism uses 0.6936 MJ/kg of dry fiber (Table 4), which is close to the reported range by González-García et al. [132], of 1.2–1.49 MJ/kg of dry fiber for the scutching of hemp/flax fiber using electricity.

Table 5 shows a comparison between all inventories: one cycle (T1) of conventional alkali treatment of abaca fibers (CT) and the option of treatment with the reuse of NaOH solution (RT) in eight washing cycles (T1–T8). The RT proposal generated a 70 % reduction in NaOH and deionized water consumption, as well as the same reduction in NaOH transportation. Wastewater generation was reduced by 14 %. There was a slight increase of 0.88 % in wash water consumption. In both cases, the reduction in the mass of abaca fibers after treatment remained at an average of 20.5 %, similar to that observed in other studies [84,85].

The inventories for polypropylene fiber (PPF) production are listed in Table 6. Electricity was the only input added to the inventory of Polypropylene and granulates to produce PPF. It requires 1.515 kWh per kg of PPF, which is similar to other values reported in LCA and environmental product declarations (EPDs) of micro and macro fibers, reporting energy consumption values between 1.51 and 4.73 kWh per kg of PPF [133–136].

Table 4
Input and output flows of abaca fiber production.

Flow	Process/Category	Amount	Unit	Data Source
Input				
Abaca plant tuxy, harvested	This Study	12.17	kg	[101]
Diesel, burned in agricultural machinery	Market for diesel, burned in agricultural machinery | APOS, U - GLO	0.6936	MJ	This study
Lubricating oil	Market for lubricating oil | APOS, U - RoW	0.002	kg	This study
Output				
Fiber, abaca	This Study	1	kg	This study
Water	Emission to air/low population density	6.51E−03	m^3	[101]

GLO: Global, RoW: Rest-of-World

Table 5
Input and output flows of abaca alkali treated fiber production.

Process/Category	Unit	CT	RT	Data Source
Input				
Market for building, hall | APOS, U - GLO	m^2	1.56E−05	1.56E−05	[67,114]
Electricity, at supply, 2018 mix - EC	kWh	1.55	1.55	[67, 114–116]
Fiber, abaca	kg	1.26	1.26	This study
Chlor-alkali electrolysis, membrane cell | sodium hydroxide, without water, in 50 % solution state | APOS, U - PE[a]	kg	1.05	0.325	This study
Market for tap water | APOS, U - CO	kg	150.73	152.07	This study
Market for water, deionised | APOS, U - RoW[b]	kg	33.8	10.50	This study
Market for transport, freight, sea, bulk carrier for dry goods | APOS, U - GLO[c]	tkm	1.34	0.414	This study
Output				
Fiber, abaca treated	kg	1	1	This study
Direct disposal of wastewater from textile production | APOS, U - GLO	kg	0.165	0.142	This study
Water, emission to air/low population density	m^3	1.06E−02	1.06E−02	This study

CT: Conventional alkali treatment (one cycle)
RT: Reuse of NaOH solution per eight cycles of recirculation
EC: Ecuador, PE: Peru, CO: Colombia, GLO: Global, RoW: Rest-of-World
[a] Sodium hydroxide and sodium chloride production are adapted with Peru's electricity.
[b] 50 % sodium hydroxide solution state water was considered and removed from the flow.
[c] Sodium hydroxide transport.

Table 6
Input and output flows of polypropylene fiber production.

Flow	Process/Category	Amount	Unit	Data Source
Input				
Electricity, medium voltage	Market group for electricity, medium voltage | APOS, U - US	1.517	kWh	[93,94]
Polypropylene, granulate	Market for polypropylene, granulate | APOS, U - GLO	1.05	kg	[93,94]
Output				
Polypropylene fiber	This Study	1	kg	This Study
Waste plastic, mixture	Market group for waste plastic, mixture | APOS, U - RER	0.05	kg	[93,94]

GLO: Global, US: United States, RER: Europe

4.3.2. Life Cycle Impact Assessment

Different processes of natural, treated, and synthetic fiber production were classified and compared. Fig. 8 shows the main process contribution results in terms of the carbon footprint.

The carbon footprint of natural abaca fiber (NAF) production was 0.47 kg CO_2 eq./kg fiber (Fig. 8.a), similar to the global warming potential (GWP) results of 0.4–1.9 kg CO_2 eq./kg of fiber analyzing flax, hemp, and jute from other studies [137]. The most significant contributing process was abaca production with 79 % of GWP (Fig. 8. b).

Conventional alkaline treatment increased the carbon footprint of NAF, and the GWP of treated abaca fiber – conventional treatment (TAF-CT) production was 1.48 kg CO_2 eq./kg fiber, 3 times higher than that of NAF, with the highest contributing process being sodium hydroxide production at 35 %, followed by abaca production at 32 %. Conventional alkaline treatment (sodium hydroxide, electricity, and other processes from the alkali treatment) represented 60 % of the GWP of TAF-CT. Abaca fiber production in TAF-CT increased by 26 % compared to the abaca plant harvest in NAF, and in terms of CO_2, it increased by 0.09 kg CO_2 eq./kg fiber owing to the mass reduction in the natural fiber during the alkaline treatment.

The process of reusing the sodium hydroxide solution in the treated abaca fiber – reuse treatment (TAF-RT) is 1.11 kg CO_2 eq./kg of fiber, a reduction in the carbon footprint of 0.37 kg CO_2 eq./kg fiber, or a 24.86 % reduction compared with TAF-CT. The process with the greatest reduction in the GWP was NaOH production (25 %). This is mainly due to the reduction in NaOH consumption from 1.05 to 0.32 kg of NaOH/kg of fiber. The consumption of the other flows was reduced by reusing the NaOH solution; however, their influence on the final GWP did not exceed 0.52 %.

Polypropylene fiber (PPF) production has a carbon footprint of 3.30 kg CO_2 eq./kg fiber. The process with the highest contribution to GWP was the production of granulated polypropylene (76 %), followed by the use of electricity in synthetic fiber production (22 %). The treatment of polypropylene waste from this process accounts for 2 % of the total.

When comparing the carbon footprint of PPF with that of the other fibers, PPF had the highest environmental impact. In contrast to abaca fibers, the GWP of NAF is 86 % lower than that of PPF. TAF-CT has a 55 % lower carbon footprint than PPF, indicating that although the treatment increases the environmental impact compared to NAF, it remains considerably lower than that of PPF. On the other hand, TAF-RT presented a 66 % lower carbon footprint than PPF, highlighting the advantage of reusing NaOH solution in GWP over both PPF and TAF-CT; nevertheless, the TAF-RT GWP was still higher than that of NAF.

However, to improve the GWP analysis, other properties, such as strengths, should be considered. When comparing the results of the carbon footprint and tensile strength (Fig. 9), NAF has a lower tensile strength than the traditional natural fibers reviewed in other studies (flax, jute, and kenaf) [67,114,138]; however, natural abaca fibers still have a lower carbon footprint. With the application of alkali treatment, the tensile strength performance of abaca fibers improved while maintaining a carbon footprint similar to that of other natural fibers. In terms of GWP/tensile strength between abaca and PPF, TAF-RT has one of the highest tensile strengths with one of the lowest carbon footprints, making TAF-RT a sustainable option to be evaluated as a replacement for PPF in concrete where abaca is available. Natural fibers are competitive alternatives in terms of mechanical performance and environmental sustainability compared to synthetic alternatives such as PPF for use in concrete. PPF had the lowest tensile strength and the highest carbon footprint.

4.4. Limitations and recommendations for further research

The LCA results for agricultural products such as natural fibers are influenced by the use of fertilizers and pesticides [132]. Although the global use of these products in abaca is negligible [51], 45.07 % of the crops in Ecuador use chemical and organic fertilizers and pesticides. Therefore, it is recommended that the LCA calculations of these products

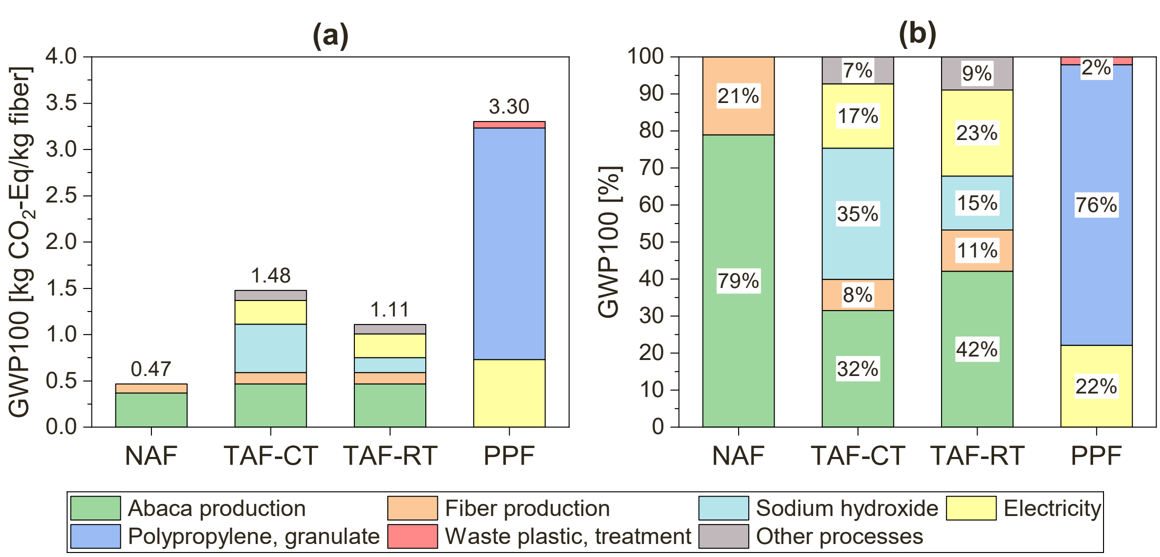

Fig. 8. (a) Characterization results and (b) contribution analysis in Global Warming Potential (GWP) for natural abaca fiber (NAF) production, treated abaca fiber – conventional treatment (TAF-CT) production, treated abaca fiber – reuse treatment (TAF-RT) production, and polypropylene fiber (PPF) production.

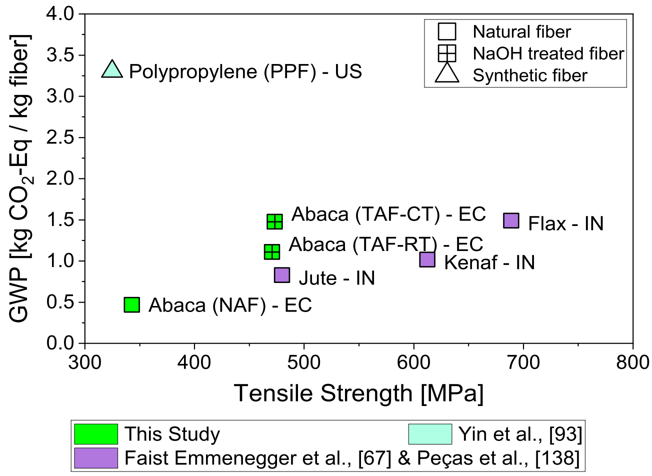

Fig. 9. Global warming potential results of fibers in literature [67,93,138] and this study. NAF: natural abaca fiber, TAF-CT: treated abaca fiber – conventional treatment (1 cycle), TAF-RT: treated abaca fiber – reuse treatment (reuse of NaOH solution per 8 cycles of recirculation), PPF: polypropylene fiber, EC: Ecuador, US: United States, IN: India.

be enhanced in future studies.

The production of abaca fibers generates substantial residual biomass [51]. A limitation of LCA studies on agricultural products is the decomposition conditions of biomass. This study was based on the aerobic decomposition of biomass as a common condition; however, the possibility of anaerobic conditions should be analyzed in future studies.

The Ecoinvent LCI calculation tool for crop production was used to generate an inventory of the tuxy harvest of the abaca plant. One limitation of using this model is the selection of information from existing crops. In this study, banana was used as the base crop for abaca. The inventory of this study could be improved by investigating the properties of abaca cultivation in terms of carbon capture and content. However, the LCA results were not affected by capture because the methodology used in this study did not consider captured carbon in the GWP impact calculation.

The process of using and recycling NaOH solution has been applied to abaca fibers only with the aim of determining the effectiveness of the solution in treating the fiber. It is recommended that this methodology be applied to other natural fibers, such as jute, kenaf, and hemp.

This study compared the physical and environmental properties of abaca fibers, focusing on TGA, SEM, tensile strength, and LCA. It is recommended to conduct a study on the influence of these fibers and measure their cost and environmental impact when applied to cement composites, such as mortar and concrete.

5. Conclusions

This study investigated the impact of the recirculation and reuse of NaOH solution on the alkaline treatment of natural abaca fibers, including its effect on fiber properties and carbon footprint. The following conclusions are drawn from the experimental findings:

- The TGA analysis revealed consistent internal composition across samples T1 to T10, with similar temperatures for vaporization of absorbed water (40°C) and an average mass loss of 4 %. Notably, hemicellulose, cellulose, and lignin were lost at 340°C, resulting in equivalent behavior among samples treated with recirculated NaOH solution.
- SEM observations showed uniform structures without impurities in samples T1–T7, forming elementary fibers by removing pectin, lignin, hemicellulose, and cellulose. However, at T8, minor protrusions appeared insignificant, as the fibers remained elementary. By T9 and T10, the impurities became more visible and elementary fibers bonded, indicating the diminished effectiveness of the alkali treatment.
- Despite these variations, all the samples exhibited increased tensile strength. Up to T8, the increase was greater than 34 %, demonstrating the efficacy of 3 % NaOH recirculation and reuse. Beyond T8, the tensile strength improvements were slightly reduced, with increases of 29 % and 7 %, respectively, compared to the NAF samples. Sample T8 suffered a reduction of 2 % compared to T1, which is still acceptable and in the range of comparison. However, the T9 experiments showed a decrease of 6 % compared to T1, while T10 suffered the highest decrease of 21 % compared to T1. At this point, the variation between all samples indicated that there was a turning point between T8 and T9. Relying on conservativity, this research concludes that T8 is the turning point, and up to this cycle of using and recycling the alkali treatment could be considered effective.
- In terms of titration, the results showed that up to T8, the NaOH concentration was relatively stable, maintaining its effectiveness in the recycling process. However, between T8 and T9, the critical turning point occurs, significantly dropping the concentration, thereby diminishing treatment efficacy. This result is related to those obtained in SEM and tensile tests, where impurities start to appear at T8 and the tensile strength starts decreasing.
- Recirculation and reuse of the 3 % NaOH solution were effective up to Treatment 8, with consistent TGA results, SEM showing elementary fibers and no impurities up to T8, and nearly uniform tensile strength enhancement up to this point.
- By utilizing the Ecoinvent LCI calculation tool for crop production, key insights were gained regarding the inventory of abaca cultivation and fiber treatment. Emissions to the air, water, soil, and land associated with abaca cultivation were quantified, providing data for understanding the environmental impacts of abaca production. Additionally, a comparison of the treatment options highlighted the potential benefits of reusing the NaOH solution, presenting a substantial reduction in resource consumption and wastewater generation.
- Carbon footprint results show the environmental advantages of natural fibers, particularly abaca, over synthetic alternatives, with notable reductions in carbon footprint and higher tensile strength, especially with the proposed recirculation and reuse treatment (TAF-RT). The implementation of circular economy principles through the reuse of NaOH solution demonstrates not only environmental benefits but also resource efficiency. The reductions in NaOH consumption, wastewater generation, and overall environmental impact emphasize the potential for sustainable practices in industrial processes.

CRediT authorship contribution statement

Maria Jose Martinez-Echevarria: Writing – review & editing, Supervision, Conceptualization. **Angel D. Ramirez:** Writing – review & editing, Supervision. **Daniel M. Petroche:** Writing – review & editing, Visualization, Investigation. **Stefany Alcivar-Bastidas:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Table A1
Summary of main parameters and assumptions in this study.

Phase	Parameters and assumptions
Agricultural phase	– Geographical scope: Ecuador. – LCI models by Ecoinvent LCI calculation tool for crop production. – Base crop: Banana. – Agricultural inputs: ESPAC 2022 [97]. – Limited to modeling without fertilizers and without pesticide plantation. – Meteorological data: INAMHI 2017 [100]. – Biomass distribution: Cortez et al., [101]. – Moisture and nitrogen content: Armecin et al., [110,111]. – Waste management: Organic residues are left in the plantation. Waste biomass remains within the system in anaerobic conditions, CH_4 emissions are not generated by waste biomass [104]. – N_2O emissions: IPCC Guidelines [109] and Franke et al., [112].
Alkali treatment	– Geographical scope: Ecuador. – Electricity: Ecuador [115,116]. – Facilities and energy consumption: Ecoinvent 3.9.1 (IN), adapted with Ecuadorian electricity. – Sodium hydroxide and sodium chloride production: Callao, Peru [117] and Ecoinvent 3.9.1 (US), adapted with Peruvian electricity. – Changes in NaOH and wastewater inventories due to the reuse of NaOH solution.
Polypropylene fiber production	– Geographical scope: United States. – Polypropylene granulate: Ecoinvent 3.9.1 (US). – Electricity and waste treatment inventories: Yin et al., [93] and Van den Heede et al., [94].

IN: India, US: United States

Table A2
Input and output flows of abaca production (tuxy). Data Source: Ecoinvent LCI calculation tool for crop production [95] using ESPAC data input [98]

Flow	Process/Category	Amount	Unit
Input			
Carbon dioxide, in air	Resource/in air	0.34	kg
Energy, gross calorific value, in biomass	Resource/biotic	3.96	MJ
Establishing orchard	Market for establishing orchard | APOS, U - GLO	2.89E−03	Item(s)
Fruit tree seedling, for planting	Market for fruit tree seedling, for planting | APOS, U - GLO	2.89E−03	Item(s)
Land use change, perennial crop	Market for land use change, perennial crop | APOS, U - EC	3.06E−06	ha
Occupation, permanent crop, non-irrigated	Resource/land	0.61	m2*a
Planting tree	Market for planting tree | APOS, U - GLO	2.89E−03	Item(s)
Transformation, from permanent crop, non-irrigated	Resource/land	3.06E−02	m2
Transformation, to permanent crop, non-irrigated	Resource/land	3.06E−02	m2
Trellis system, wooden poles, soft wood, tar impregnated	Market for trellis system, wooden poles, soft wood, tar impregnated | APOS, U - GLO	6.11E−05	ha
Output			
Abaca plant tuxy, harvested	This Study	1	kg
Cadmium	Emission to soil/agricultural	−2.86E−08	kg
Cadmium, ion	Emission to water/ground water	2.74E−10	kg
Cadmium, ion	Emission to water/surface water	6.50E−09	kg
Chromium	Emission to soil/agricultural	−8.40E−07	kg
Chromium, ion	Emission to water/ground water	1.22E−07	kg
Chromium, ion	Emission to water/surface water	6.00E−07	kg
Copper	Emission to soil/agricultural	−7.47E−06	kg
Copper ion	Emission to water/ground water	1.44E−07	kg
Copper, ion	Emission to water/surface water	6.06E−06	kg
Dinitrogen monoxide	Emission to air/low population density	2.96E−05	kg
Lead	Emission to soil/agricultural	−2.34E−07	kg
Lead	Emission to water/ground water	7.16E−10	kg
Lead	Emission to water/surface water	1.15E−07	kg
Mercury	Emission to soil/agricultural	−1.48E−08	kg
Mercury	Emission to water/ground water	2.82E−11	kg
Mercury	Emission to water/surface water	6.47E−09	kg
Nickel	Emission to soil/agricultural	−9.02E−07	kg
Nickel, ion	Emission to water/surface water	6.79E−07	kg
Nitrate	Emission to water/ground water	1.17E−02	kg

(continued on next page)

Table A2 (*continued*)

Flow	Process/Category	Amount	Unit
Phosphate	Emission to water/ground water	1.12E−05	kg
Phosphate	Emission to water/surface water	4.68E−05	kg
Phosphorus	Emission to water/surface water	4.85E−04	kg
Zinc	Emission to soil/agricultural	−1.04E−05	kg
Zinc, ion	Emission to water/ground water	3.96E−07	kg
Zinc, ion	Emission to water/surface water	3.25E−06	kg

GLO: Global, EC: Ecuador

Table S1

. Life cycle inventories of abaca production (tuxy) from Ecoinvent LCI calculation tool for crop production [95] using ESPAC data input [98]

Flow	Process/Category	Amount	Unit
Input			
Carbon dioxide, in air	Resource/in air	0.34	kg
Energy, gross calorific value, in biomass	Resource/biotic	3.96	MJ
Establishing orchard	Market for establishing orchard | APOS, U - GLO	2.89E-03	Item(s)
Fruit tree seedling, for planting	Market for fruit tree seedling, for planting | APOS, U - GLO	2.89E-03	Item(s)
Land use change, perennial crop	Market for land use change, perennial crop | APOS, U - EC	3.06E-06	ha
Occupation, permanent crop, non-irrigated	Resource/land	0.61	m2*a
Planting tree	Market for planting tree | APOS, U - GLO	2.89E-03	Item(s)
Transformation, from permanent crop, non-irrigated	Resource/land	3.06E-02	m2
Transformation, to permanent crop, non-irrigated	Resource/land	3.06E-02	m2
Trellis system, wooden poles, soft wood, tar impregnated	Market for trellis system, wooden poles, soft wood, tar impregnated | APOS, U - GLO	6.11E-05	ha
Output			
Abaca plant tuxy, harvested	This Study	1	kg
Cadmium	Emission to soil/agricultural	-2.86E-08	kg
Cadmium, ion	Emission to water/ground water	2.74E-10	kg
Cadmium, ion	Emission to water/surface water	6.50E-09	kg
Chromium	Emission to soil/agricultural	-8.40E-07	kg
Chromium, ion	Emission to water/ground water	1.22E-07	kg
Chromium, ion	Emission to water/surface water	6.00E-07	kg
Copper	Emission to soil/agricultural	-7.47E-06	kg
Copper ion	Emission to water/ground water	1.44E-07	kg
Copper, ion	Emission to water/surface water	6.06E-06	kg
Dinitrogen monoxide	Emission to air/low population density	2.96E-05	kg
Lead	Emission to soil/agricultural	-2.34E-07	kg
Lead	Emission to water/ground water	7.16E-10	kg
Lead	Emission to water/surface water	1.15E-07	kg
Mercury	Emission to soil/agricultural	-1.48E-08	kg
Mercury	Emission to water/ground water	2.82E-11	kg
Mercury	Emission to water/surface water	6.47E-09	kg
Nickel	Emission to soil/agricultural	-9.02E-07	kg
Nickel, ion	Emission to water/surface water	6.79E-07	kg
Nitrate	Emission to water/ground water	1.17E-02	kg
Phosphate	Emission to water/ground water	1.12E-05	kg
Phosphate	Emission to water/surface water	4.68E-05	kg
Phosphorus	Emission to water/surface water	4.85E-04	kg
Zinc	Emission to soil/agricultural	-1.04E-05	kg
Zinc, ion	Emission to water/ground water	3.96E-07	kg
Zinc, ion	Emission to water/surface water	3.25E-06	kg

GLO: Global, EC: Ecuador

Table S2

. Life cycle inventories of abaca fiber production

Flow	Process/Category	Amount	Unit	Reference
Input				
Abaca plant tuxy, harvested	This Study	12.17	kg	[101]
Diesel, burned in agricultural machinery	Market for diesel, burned in agricultural machinery | APOS, U - GLO	0.6936	MJ	This study
Lubricating oil	Market for lubricating oil | APOS, U - RoW	0.002	kg	This study
Output				
Fiber, abaca	This Study	1	kg	This study
Water	Emission to air/low population density	6.51E-03	m^3	[101]

GLO: Global, RoW: Rest-of-World

Table S3
. Life cycle inventories of abaca alkali treated fiber production for 3% NaOH solution

Flow	Process/Category	Amount	Unit	Reference
Input				
Building, hall	Market for building, hall | APOS, U - GLO	1.56E-05	m^2	[67,114]
Electricity, low voltage	Electricity, at supply, 2018 mix - EC	1.55	kWh	[67,114-116]
Fiber, abaca	This Study	1.26	kg	This study
Sodium hydroxide, without water, in 50% solution state	Chlor-alkali electrolysis, membrane cell | APOS, U - PE [a]	1.05	kg	This study
Tap water	Market for tap water | APOS, U - CO	150.73	kg	This study
Water, deionized [b]	Market for water, deionised | APOS, U - RoW	33.8	kg	This study
Transport, sea [c]	Market for transport, freight, sea, bulk carrier for dry goods | APOS, U - GLO	1.34	tkm	This study
Output				
Fiber, abaca treated	This Study	1	kg	This study
Wastewater from textile production	Direct disposal of wastewater from textile production | APOS, U - GLO	0.165	kg	This study
Water	Emission to air/low population density	1.06E-02	m^3	This study

[a]Sodium hydroxide and sodium chloride production are adapted with Peru's electricity.
[b]50% sodium hydroxide solution state water is considered and removed from this flow.
[c]Sodium hydroxide transport.
CT: Conventional alkali treatment (1 cycle), RT: Reuse of NaOH solution per 8 cycles of recirculation
EC: Ecuador, PE: Peru, CO: Colombia
GLO: Global, RoW: Rest-of-World

Table S4
. Life cycle inventories of abaca alkali treated fiber production for 3% NaOH solution and reuse of solution (9 cycles).

Flow	Process/Category	Amount	Unit	Reference
Input				
Building, hall	Market for building, hall | APOS, U - GLO	1.56E-05	m^2	[67,114]
Electricity, low voltage	Electricity, at supply, 2018 mix - EC	1.55	kWh	[67,114-116]
Fiber, abaca	This Study	1.26	kg	This study
Sodium hydroxide, without water, in 50% solution state	Chlor-alkali electrolysis, membrane cell | APOS, U - PE [a]	0.325	kg	This study
Tap water	Market for tap water | APOS, U - CO	152.07	kg	This study
Water, deionized [b]	Market for water, deionised | APOS, U - RoW	10.50	kg	This study
Transport, sea [c]	Market for transport, freight, sea, bulk carrier for dry goods | APOS, U - GLO	0.414	tkm	This study
Output				
Fiber, abaca treated	This Study	1	kg	This study
Wastewater from textile production	Direct disposal of wastewater from textile production | APOS, U - GLO	0.142	kg	This study
Water	Emission to air/low population density	1.06E-02	m^3	This study

[a] Sodium hydroxide and sodium chloride production are adapted with Peru's electricity.
[b] 50% sodium hydroxide solution state water is considered and removed from this flow.
[c] Sodium hydroxide transport.
CT: Conventional NaOH treatment (1 cycle), RT: Reuse of NaOH solution per 8 cycles of recirculation
EC: Ecuador, PE: Peru, CO: Colombia
GLO: Global, RoW: Rest-of-World

Table S5
. Life cycle inventories of polypropylene fiber production

Flow	Process/Category	Amount	Unit	Reference
Input				
Electricity, medium voltage	Market group for electricity, medium voltage | APOS, U - US	1.517	kWh	[93,94]
Polypropylene, granulate	Market for polypropylene, granulate | APOS, U - GLO	1.05	kg	[93,94]
Output				
Polypropylene fiber	This Study	1	kg	This Study
Waste plastic, mixture	Market group for waste plastic, mixture | APOS, U - RER	0.05	kg	[93,94]

GLO: Global, US: United States
RER: Europe

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