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Coir ropes as a low-tech circular alternative to synthetic ropes in French Polynesia pearl farming

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ABSTRACT

Local coir rope production utilises waste from copra cultivation and could provide a natural alternative to synthetic ropes in French Polynesia's pearl farming industry. This research aimed to enhance the understanding of coir rope production for pearl farming in the region. Initially, the mechanical properties of coconut fibres were analysed, as well as the construction of ropes made from these fibres. To determine the impact of retting on the mechanical properties of ropes and to assess the relevance of this process, ropes with different retting times in seawater and/or freshwater were tested. A life cycle analysis was also conducted to compare the benefits of locally producing a coir fibre rope versus importing a commercial HDPE rope. Results showed that retting did not significantly affect rope mechanical properties, this polluting process could then be avoided. However, the braiding processwe used to make the ropes was proven to influence both mechanical properties and water resistance. It should then be optimised to have coir ropes with higher strength and mechanical properties retention in water, which would also improve their environmental performance, and make them suitable for use as ropes in pearl farming in French Polynesia.

1. Introduction

French Polynesia (FP) is an overseas collectivity of France comprising over a hundred islands in the South Pacific Ocean, located thousands of kilometres away from major continental landmasses. The archipelago's economy is based on tourism and pearl farming, the latter accounting for more than half of export-related revenues (Mao Che, 2024). Like other aquaculture systems, pearl farming is highly dependent on synthetic materials, such as collectors, buoys, and ropes, which are suspended in the water column across the lagoons and primarily made from polyethylene or polypropylene (Goulais et al., 2024). However, these synthetic gears can be lost due to various causes, such as storms or conflicts with other boats. Andréfouët et al. (2014) surveyed a pearl-growing lagoon and found a significant amount of synthetic waste both inside and outside of the concessions, with ropes being the most common waste. Lost synthetic gears such as ropes or lines are known to physically harm ecosystems (Galgani et al., 2021; Valderrama Ballesteros et al., 2018) and represent a danger for local species such as sharks (Ward-Paige and Worm, 2017) and manta rays (Carpentier et al., 2019). After a certain amount of time, which varies depending on the formulation of the polymer, the lost gears break down into particles smaller than 5 mm, known as secondary microplastics (Andrady, 2011). Microplastics have been found in various species in the lagoons of FP, including fish (Forrest and Hindell, 2018; Garnier et al., 2019), corals (Connors, 2017), and oysters (Gardon et al., 2021). Microplastics are known to affect pearl oyster physiology and pearl biomineralisation (Gardon et al., 2021; 2020a; 2024; 2020b; 2018; Goulais et al., 2024; Han et al., 2022), which, along with causing environmental stress, puts the economy of the archipelagos at risk.

Biodegradable synthetic ropes have been developed to replace conventional plastics and avoid environmental pollution by undergoing faster and more complete degradation at sea than currently used plastics (Le Gué et al., 2023). However, while these polymers could reduce the by-catch caused by lost gear, little is known about their assimilation and mineralisation in the marine environment (Paul-Pont et al., 2023), and microplastics coming from biodegradable polymers could potentially impact the biomineralisation of the pearl before biodegradation. Furthermore, Zimmermann et al. (2020) showed that common bioplastics could be toxic if used with the same additives as conventional plastics, which could also impact oysters during use (Gardon et al.,

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2020a).

Some of the ropes used in pearl farming have a short service life, allowing the use of natural-based ropes, which are usually not considered as a result of their shorter lifetimes compared to synthetic polymers. Coconut (*Cocos nucifera*) is a crucial resource in French Polynesia, with copra oil production being a significant source of income for the islands (Mao Che, 2024). Copra production requires only the endosperm of the coconut, as shown in Fig. 1. Coconut husks, comprising endocarp, mesocarp and exocarp, are usually discarded and burnt. The mesocarp of the coconut contains fibres that can be extracted from the spongy matrix, called pith, in which it is naturally found (Van Dam et al., 2006). The coconut husk must be dried to extract the fibres from the mesocarp. Extraction can be done mechanically once the husk is dry, or after a retting period, which involves immersing the husk in seawater or freshwater. During this process, microbial activity breaks down the non-cellulosic components of the husks, such as lignin and pectin, which helps to separate the fibres from the rest of the husk material. Industrial retting is known to cause environmental impacts such as chemical pollution, marine hypoxia, plankton biodiversity loss (Nandan, 1997; Remani et al., 1989), and is even known to affect groundwater in certain regions of India (Jessy Mol, 2017). After the fibres are extracted from the husk, they can be braided into coir ropes, offering a low-tech natural and circular replacement for synthetic ropes used in pearl farming. Pith is also known for its wide application range in agriculture and represents a valuable by-product (Reddy, 2019).

This study aimed to explore the key factors in coconut fibre rope production for use in pearl farming activities in FP. The mechanical properties of coconut fibres and their use in rope production were first analysed. To assess the relevance of this potentially polluting process, the impact of retting on the mechanical properties of the rope was then studied. Finally, a life cycle assessment was conducted to evaluate the advantages of locally manufacturing a coir fibre rope compared to importing a commercial high-density polyehtylene (HDPE) rope.

2. Materials and methods

2.1. Materials

Coir rope samples were produced locally using coconut husks retrieved from copra producers around the islands. Coconut husks were first retted for several soak times in freshwater and/or seawater to study the impact of retting on rope properties. Table 1 presents the different immersion times that were tested. The coir rope used as a reference (ref.) is the rope that has not been subjected to any retting process. After retting, husks were dried for 2 weeks and crushed in a semi-mechanised defibrator to separate the mesocarp fibres from the pith. The mixture was then passed through a sieve shaker to remove the short fibres and the remaining pith. After being retrieved, the fibres were dried for two hours and manually sorted to remove any potential exocarp residue that could obstruct the braiding process. The fibres were then passed through a mechanical comb and mechanically braided, guided by a flax thread.

Table 1
Retting immersion times for ref. ropes.

Freshwater [weeks]	Seawater [weeks]
0	0, 4, 8, 12
1	1, 2, 3
4	8, 12, 16, 24
12	0, 12

Different ropes and fibres were also examined to understand how construction affects mechanical properties. Two hand-braided ropes were tested, one from the Marquesas Islands made primarily for artistic craftsmanship (Ma.) and one from Tubuai Island made for functional craftsmanship (Tu.). An industrially produced twisted rope from India (In.) was also tested. Table 2 provides further details on the construction of the different ropes used in this study which are shown in Fig. 2.

A synthetic HDPE rope with a 4 mm diameter was also evaluated to compare coir ropes with a commercial synthetic benchmark. This synthetic rope featured a braided outer covering encasing a woven core, both constructed from HDPE monofilaments with a 0.27 mm diameter. The rope's linear density was 5.0 g/m.

2.2. Scanning electron microscope (SEM)

Surface observations of coir fibre specimens were made using Scanning Electron Microscopy (SEM). Before examination, the samples were coated with a very thin layer of 60% gold and 40% palladium alloy to make the surfaces conductive and avoid surface charging.

2.3. Length distribution analysis

To analyse the length distribution of the fibres within each rope, the following protocol was followed:

1. cutting a 50 cm sample from the rope,
2. unbraiding the sample,
3. measuring the length of each fibre.

Table 2
Details of the various coconut ropes used.

Reference	ref.	In.	Ma.	Tu.
Source	Tahiti	India	Marquesas Islands	Tubuai Island
Process	machine-twisted	machine-twisted	hand-braided	hand-braided
Retting [weeks]	variable	0	1	7
Linear mass [g/m]	6.50	11.2	6.03	5.79

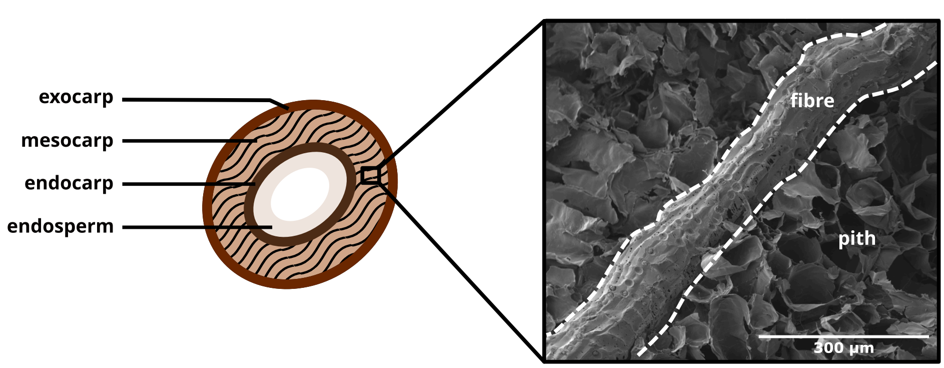

Fig. 1. Schematic view of the coconut structure alongside SEM observation of the mesocarp structure.

Fig. 2. Observations of the different ropes used in the study.

A Python algorithm based on the skeleton method (Lee et al., 1994; Zhang and Suen, 1984) implemented in the Scikit-Image library (Walt et al., 2014) was developed to measure several fibre samples at the same time using a scanner. Each fibre was detected and its central line was measured. This approach enabled the consistent measurement of numerous samples, a task unachievable through conventional visual techniques. It was also possible to gain insight into the diameter distribution by dividing the fibre's surface area along its length by the calculated length.

2.4. Water sorption

Dynamic Vapour Sorption (DVS) equipment was used for water sorption analysis. Testing was made at 25°C on individual fibres that were first dried for 4 h. The humidity levels were then set in increments of 10%, each level lasting 4 h. The apparatus continuously monitored changes in sample mass during the sorption or desorption of water vapour over time. Water uptake was then calculated as the difference in mass between the dry sample and the sample stabilised at each stage. The uptake of water at RH = 100% was measured by weighing the samples before and after 12 h of immersion in distilled water. Soaking was performed in a room maintained at 21°C. Five samples were tested for DVS and water saturation tests.

2.5. Mechanical testing

Mechanical testing was carried out on a 10 kN capacity tensile test machine, in a room maintained at 21 °C with a relative humidity of 50%. A 50 N load cell was used for testing the fibres and a 500 N load cell for testing the ropes. These load cells were chosen according to the sample breaking strengths to ensure high resolution and more accurate measurement of their tensile properties. The fibres were tested using pneumatic clamps and the ropes were tested by winding them around two pins with a diameter of 50 mm. Two markers were attached to the sample and measured with a digital camera to provide the strain of the samples. Wet samples were soaked in tap water for at least 12 h before testing.

2.6. Life cycle analysis (LCA)

A life cycle analysis has been performed to evaluate the impact of the production of the coir fibre rope ref. and to compare it to the importation of a braided HDPE rope. Both braids were compared using the Ecoinvent 3.5 database and data from industrial contacts implemented in the OpenLCA software. Fig. 3 shows the stages studied for each braid.

HDPE is obtained by polymerising ethylene (C_2H_4) produced by cracking petroleum at high temperature (Kniel et al., 1980). The granules obtained are then extruded in the form of monofilaments. These two processes were modelled using data from the Ecoinvent 3.5 database, for production in China. The final rope is obtained by braiding these monofilaments using a machine. The electricity consumption of an industrial braiding machine for producing 1 kg of braid was obtained from an industrial contact. To account for the import of HDPE braid from China to French Polynesia, transport by container ship over a distance of 10,000 km has been assumed and implemented in the model using the Ecoinvent 3.5 dataset.

Coconut husks were sourced directly from the archipelagos and a scenario without retting was evaluated. Fibre extraction and rope twisting were the only mechanised operations considered for life cycle analysis. The energy requirement to produce 200 m of rope was measured at 400 Wh for both steps, and the energy for producing 1 kg of rope is then 308 Wh, as given by the linear mass of the ref. rope. The FP electricity mix showed in Table 3 was modelled using the Polynesian

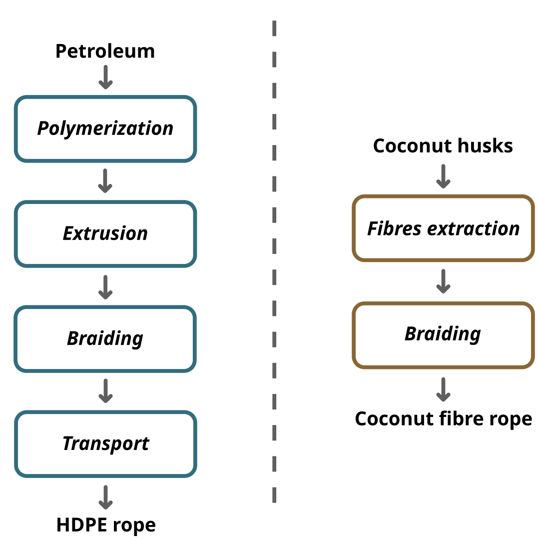

Fig. 3. Stages in the production of HDPE braid and coir braid.

Table 3
FP's electricity mix (de l'Énergie, 2022).

	fossil	wind	hydraulic	solar	total
Production [GWh]	481.9	0.08	142.3	47.4	671.7
Production [%]	71.8	0.01	21.2	7.1	100

Observatory for Energy report for 2021 (de l'Énergie, 2022) and the Ecoinvent 3.5 dataset. The model did not consider importation since the braid was produced locally.

In pearl cultivation, pearls are grown on chaplets that are immersed in water. For this study, a typical chaplet that is 2 m long and holds a load of 100 N was considered. The primary purpose of the ropes used in this process is to securely hold these chaplets. Therefore, the functional unit selected for this analysis is the quantity of rope, measured in grams, required to support a chaplet of this size and weight. This determination is based on data obtained from wet mechanical testing of the ropes, ensuring that the selected functional unit accurately reflects the rope's capability to perform its intended function. The breaking strengths for the ref. and HDPE ropes were 0.020 $N.tex^{-1}$ and 0.27 $N.tex^{-1}$, respectively. As a result, the amount of rope required to support the chaplet was 7.14 g for the ref. rope and 0.74 g for the HDPE rope.

Impacts were calculated using the ReCiPe 2016 midpoint method (Huijbregts et al., 2016) to compare the environmental impacts of both ropes.

3. Result and discussion

3.1. Fibre analysis

3.1.1. SEM observations

The surface of each fibre was observed to assess whether the origin of the coconut influenced the fibre topology. Fig. 4a shows the topologies observed. No significant differences were observed despite the geographical dispersion and different retting processes of the samples studied. On all fibres, pores showing tylosis were observed, an example of tylosis is shown on Fig. 4b. These tyloses block the exchanges between the fibre and its environment under stress or in the presence of a pathogen (Agrios, 2005). Fig. 5 shows the cross-sectional view of an individual fibre of the ref. rope and highlights its structure made of elementary fibres. Elementary fibres are defined by a lumen, a hollow core, surrounded by multiple cell walls (Mohanty et al., 2005). Coconut fibres comprise lignin, hemicellulose, and crystalline cellulose arranged in a helix (Tran et al., 2015). Cellulose that makes up the secondary wall of the cell and its helical arrangement are particularly visible in Fig. 5a.

3.1.2. Water sorption

Natural fibres, such as coir, are hydrophilic due to their chemical composition rich in polar -OH bonds (Bismarck et al., 2001). Since the application studied here involves the ropes being immersed in water, the absorption of water by the coir fibres was evaluated. Fig. 6 presents the water sorption curve obtained from the DVS tests. For a relative humidity of 90%, the fibres absorbed an average of 18 ± 2% of their weight in water, which is consistent with the values found by Hill et al. (2009) who conducted tests at the same temperature. However, despite tests conducted at a lower temperature for samples immersed in distilled water, water uptake reached a significantly higher amount of 77 ± 18%, which also complies with the literature (Mittal and Chaudhary, 2018). Given that the tests were performed at 21°C, the water absorption at saturation point at 25°C is expected to be even more significant than the values observed. The variation in absorption rate observed between a relative humidity of 90% and 100% can be attributed to the lumen of the elementary fibres. This void contains free water that the material has not absorbed, but is still measured during weighing.

3.1.3. Mechanical testing

Water sorption is known to influence the mechanical properties of natural fibres (Baley et al., 2005; Martinelli et al., 2024), ref. coir fibres were tested before and after saturation in distilled water. Fig. 7 shows the specific load versus strain curves that were obtained for samples in 50% of RH and samples saturated with water (100% RH). Table 4 summarises the mechanical properties obtained from the tests. While no significant difference was observed in tensile strength, water saturation caused a plasticising effect that increased elongation at break by 28% while reducing the specific modulus by 22%. These results indicate that water has no significant impact on the tensile strength of the coir fibres. Fig. 8 presents fractographic images obtained after tensile testing of a dry sample. A flat surface, characteristic of tensile failure, is then observed. During the loading process, the weakening of lignin and hemicellulose caused the tensile fracture, leading to the failure of the walls within cells, as well as the delamination of the cells between each other (Silva et al., 2008).

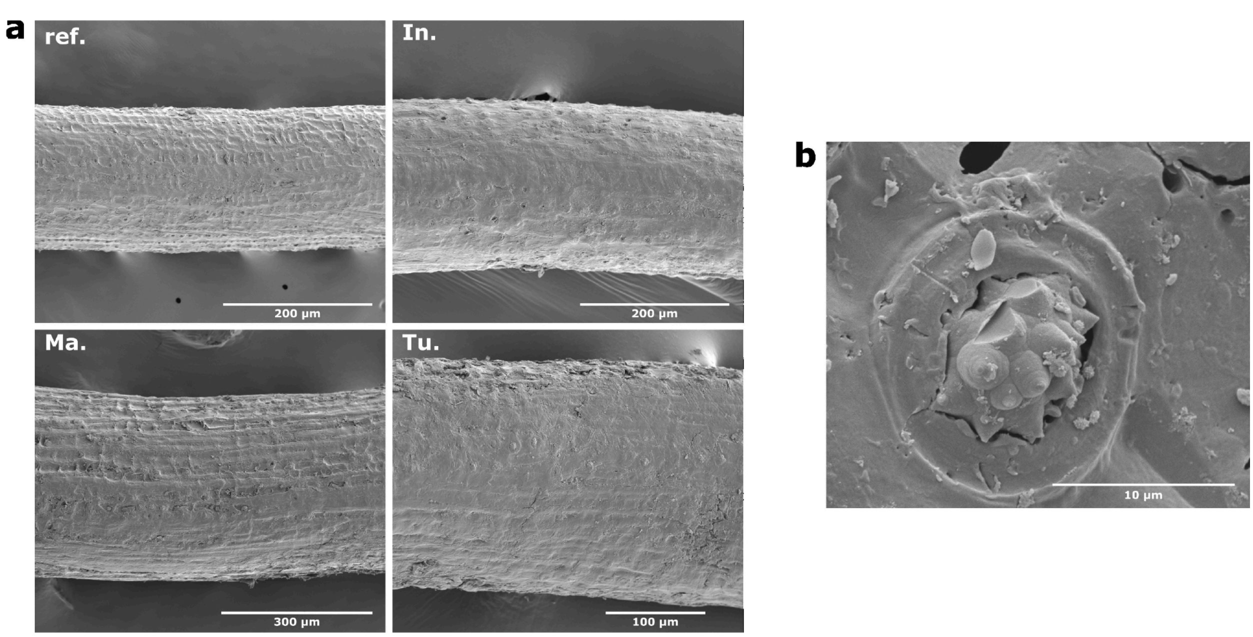

Fig. 4. Surface observations of the different fibres at the initial state.

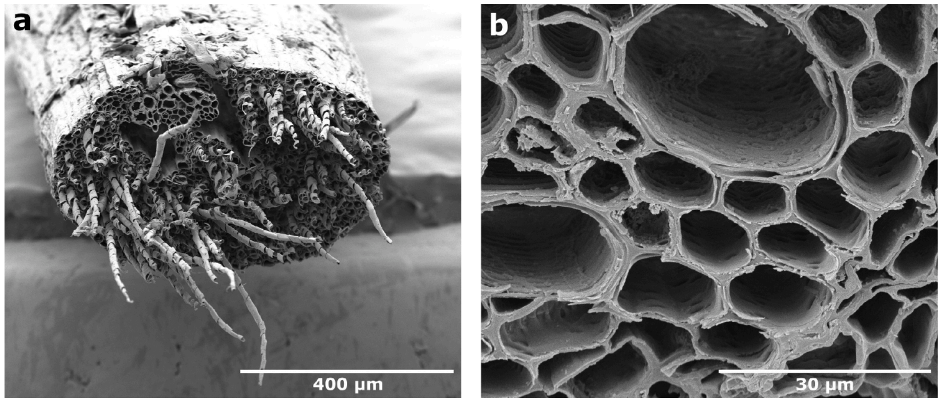

Fig. 5. Cross-sections observations of coir fibres (ref.).

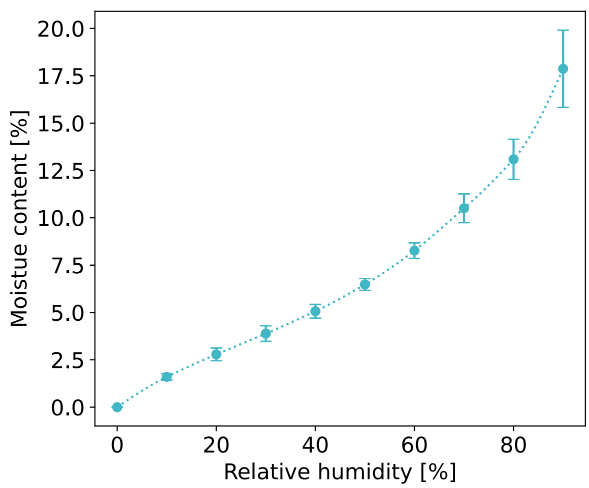

Fig. 6. Water sorption curves of coir fibres (ref.) at 25°C.

Strength values obtained for coir fibres are 0.08 ± 0.008 N.tex^{-1}. These values are significantly lower than those of a synthetic HDPE monofilament, which can reach a specific breaking load of 0.4 N.tex^{-1} (Le Gué et al., 2023). Therefore, it is crucial to optimise the manufacturing of coir ropes to avoid amplifying this difference when moving from the fibre scale to the rope scale.

3.2. *Rope testing*

3.2.1. *Length distribution*

The tension within a rope must be distributed along its length to support a load. The fibres comprising a synthetic rope are continuous from end to end, allowing a good distribution of tension. The length of coconut fibres is limited to the size of the coconut from which they originate (between 10 and 40 cm). The coconut rope then performs mechanically due to the interlocking of the fibres. The way a rope is braided significantly affects its mechanical properties. The role of fibre length is also important: the longer a fibre, the more it can interact with others, thus better distributing the applied tension. The distribution of the length of the fibre in each of the ropes was analysed to correlate with the rope-making method, the length of the fibre and the mechanical

Table 4
Mechanical properties of coconut fibres before and after water saturation.

	50% RH	100% RH
Strain [%]	8.5 ± 3.8	11.9 ± 5.6
Specific load [N.tex^{-1}]	0.080 ± 0.008	0.075 ± 0.0195
Specific modulus [N.tex^{-1}]	3.3 ± 0.3	2.6 ± 0.4

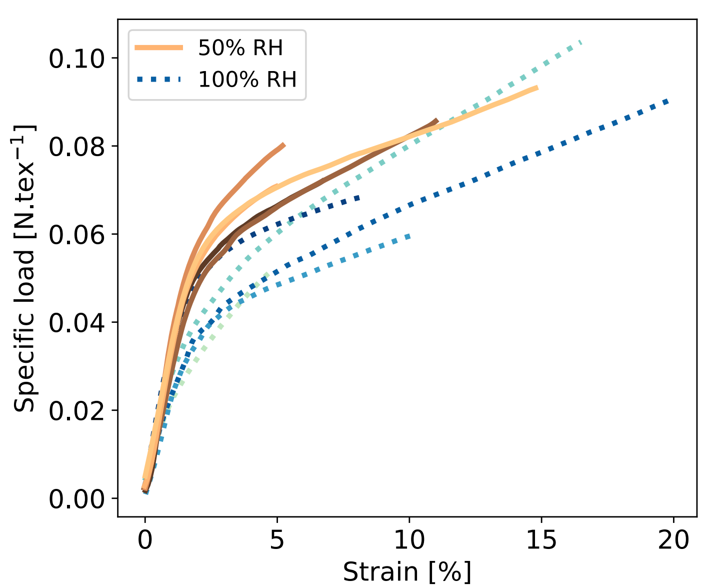

Fig. 7. Specific load versus strain curves for coconut fibres at 50% and 100% RH.

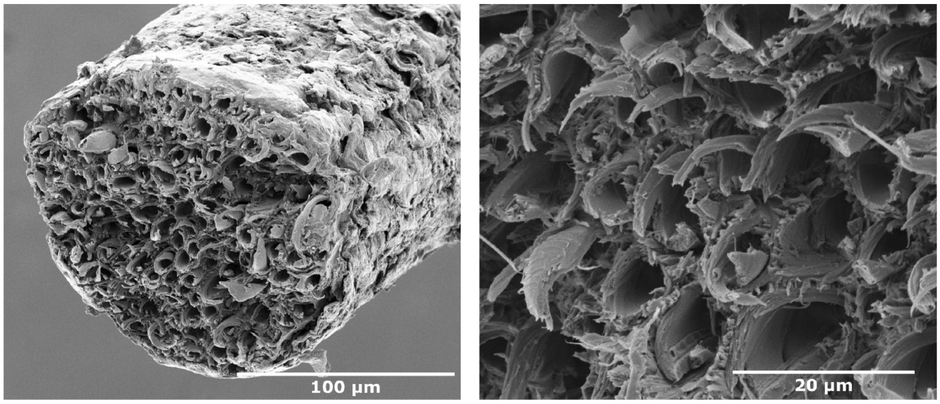

Fig. 8. Cross-section observation of a coconut fibre after failure.

properties.

Fig. 9 illustrates the distribution of lengths and diameters within each studied rope, with each point corresponding to a measurement on a fibre. Table 5 presents the average lengths and diameters derived from these measurements. The measured lengths ranged from 10 mm to 350 mm, which are typical values for coconut fibre lengths (Kulkarni et al., 1981; Lekha, 2004). The ropes from the Marquesas Islands and Tubuai Island exhibited, on average, longer fibres compared to the ropes from Tahiti and India, with fibres exceeding 40 cm in some cases. This difference can be attributed to differences in rope manufacturing processes, where hand-made ropes, such as Ma. and Tu., underwent a selection process to utilise the longest fibres, facilitating the braiding process. On the contrary, ropes such as ref. and In. are machine-made, resulting in a higher proportion of shorter fibres, as machines do not distinguish between lengths. Additionally, machines tend to be less careful, causing damaged fibres within the rope that are not typically seen in handmade ropes. Furthermore, Ma. and Tu. ropes are made from larger coconuts that are specifically grown for their fibres, while ref. ropes are produced from by-products of copra cultivation, where the size of the coconut is not a determining factor.

The measured diameters ranged from 0.2 mm to 1.2 mm, which is consistent with the values found in the literature (Rajan and Abraham, 2007). However, it is important to interpret the diameter results with caution, because the scanner's precision has limitations, especially when it comes to accurately describing the longitudinal section of the smallest fibres. As a result, the analysis may not accurately represent the smallest fibres.

3.2.2. Mechanical testing

The ropes were then mechanically tested to investigate the role of fibre length on their tensile mechanical performance. The tests were carried out in tension on dry samples and after saturation in water. Fig. 10 illustrates the tensile curves for dry conditions (solid line, shades of brown) and when saturated in seawater (dotted line, shades of blue) for the various ropes studied.

Table 5
Average length [mm] and diameter [mm] of the ropes studied.

	Mean length	Mean diameter
ref.	80	0.6
In.	84	0.5
Ma.	137	0.5
Tu.	178	0.5

A similar behaviour was observed for the different ropes, with variations in rupture. The rupture of ref. and In. ropes was gradual and could involve only one of the two strands composing the rope, indicating poor stress distribution within the section. Irregular twisting, as visible for these two ropes in Fig. 2, can lead to strands with locally different properties in the rope, where a strand that elongates less may end up bearing excess load and breaking. For Ma. and Tu. ropes, rupture occurred abruptly for all strands, indicating a good balance of stresses within the rope section, attributed to homogeneous braiding as seen in Fig. 2.

Fig. 11 presents the various mechanical properties obtained in bar form to compare dry and wet states, as well as different ropes among themselves. These results highlight the importance of the braiding step in obtaining suitable coconut ropes for pearl farming. Indeed, the average specific strength of ref. fibres was 0.08 $N.tex^{-1}$, while the rope had a strength three times lower at 0.028 $N.tex^{-1}$. Braiding also induced greater flexibility, with strain at failure doubling after twisting, and a modulus reduced by a factor of 20. The failure properties of the In. rope were similar to those found for the ref. rope, which is consistent with the length of the fibres and their similar construction. Ma. rope appears to have better mechanical rupture properties than Tu., without necessarily having the longest fibres, indicating that the quality of rope braiding

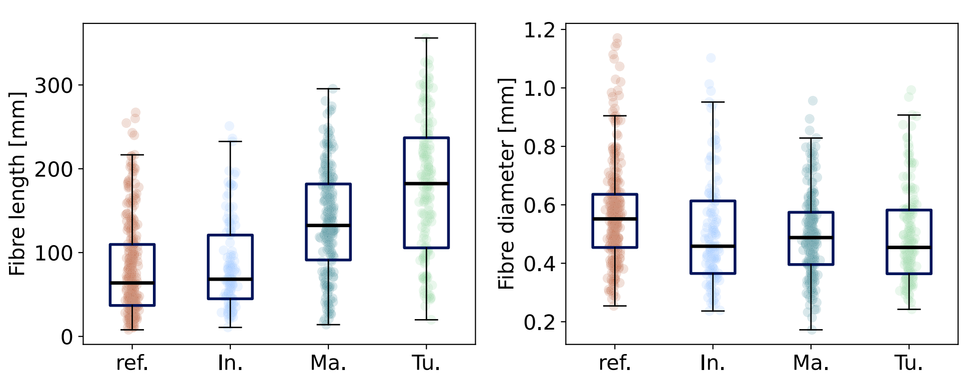

Fig. 9. Length and diameter distributions for all tested ropes.

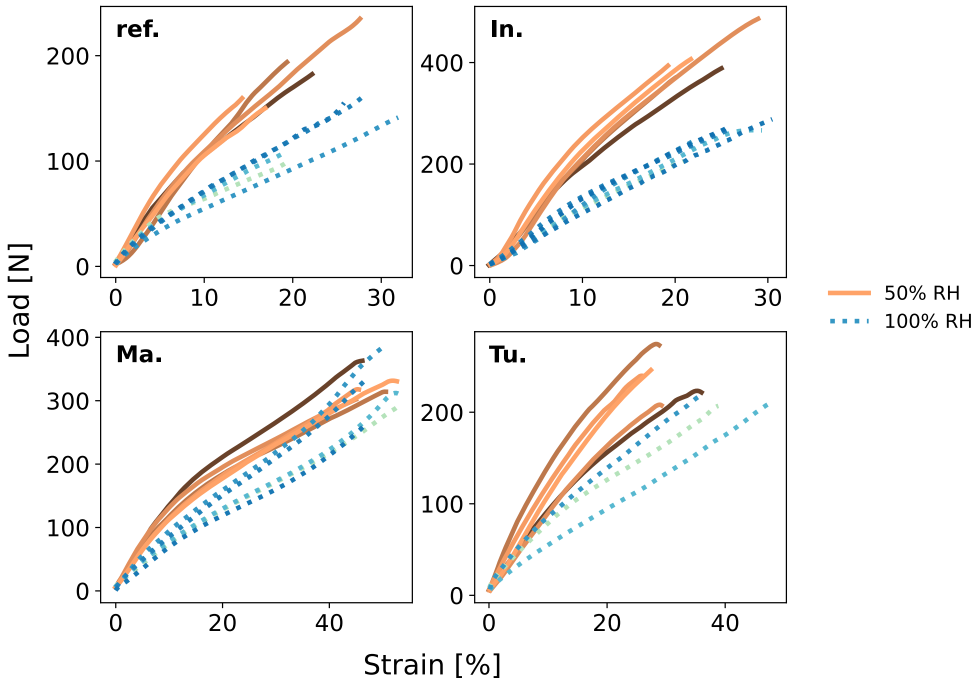

Fig. 10. Load versus strain curves for the different ropes at 50% and 100% RH.

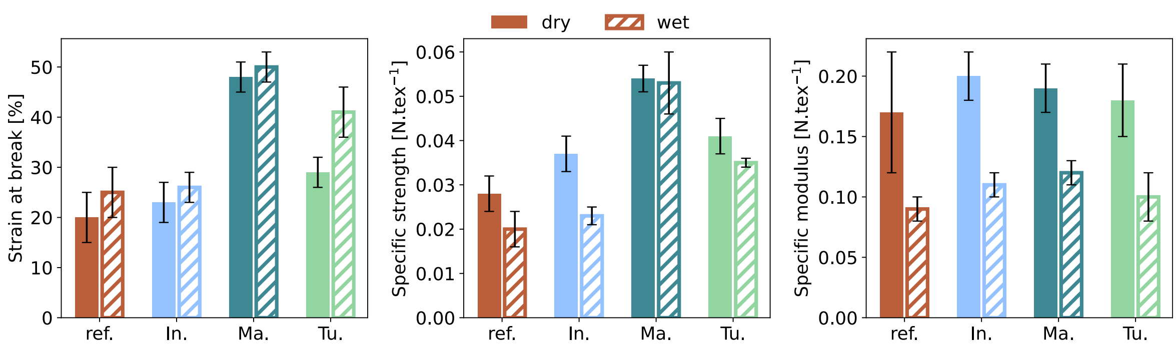

Fig. 11. Comparison of the mechanical properties of tested ropes.

plays a more significant role than fibre length. Despite the difference in the mechanical properties of the ropes, the moduli were similar. This suggests that the construction and braiding quality have a low influence on the final modulus of the rope. ref. and In. were the ropes most impacted by water saturation. Since the absorption of water did not notably impact the tensile strength of individual fibres, it can be asserted that the alteration in mechanical properties was due to the presence of free water in the ropes. The presence of water between the fibres may act as a lubricant, making it easier for the fibres to slide over each other, which accentuates the heterogeneity of the loading in the section and increases the elongation. This resulted in a higher strain at break, as seen in Fig. 11, and a lower load at break for both machine-twisted ropes. Ma. rope was the least affected by water saturation, with no significant loss of load at break and no significant increase in strain at break. With a looser and more irregular braiding, the second manually crafted rope exhibited a greater sensitivity to tensile load after saturation. This suggests that the braiding not only influences the characteristics of the rope but also aids in preserving it when the rope is immersed in water. When tested wet, the ropes had a similar loss of modulus, indicating that water saturation affects them similarly and braiding has a low impact on stiffness retention.

According to these findings, coir ropes can be utilized in pearl farming operations for tasks that involve bearing low loads. However, it is important to consider the reduction in mechanical properties caused by water and to optimize the braiding process to enhance both strength and strength retention when submerged.

3.2.3. *Retting influence*

The influence of retting on the mechanical properties of ropes was studied in addition to braiding. Fibres were soaked in freshwater and/or seawater for different immersion times, as described in Table 1. After the process of retting, each batch was twisted separately, and mechanical testing was carried out to obtain mechanical properties depending on the duration of retting. This is depicted in Fig. 12, where each panel represents a particular property on the y-axis. The x-axis for each panel denotes the retting time in seawater (t_w), while each curve in a panel represents the retting time in freshwater. As the seawater retting was conducted after freshwater retting, Fig. 12 provides the possible trajectories for each property depending on the two retting media. The grey area on each panel represents the dispersion for the non-retted rope for better visualisation. For the strain at break, the load at break and the modulus, measured values were close to or within the initial scatter, with no distinctive trends. This suggests that the different retting of the husks after the different treatments did not influence the mechanical properties of the manufactured ropes significantly. Based on these findings, it appears that retting, a process known to cause pollution, may

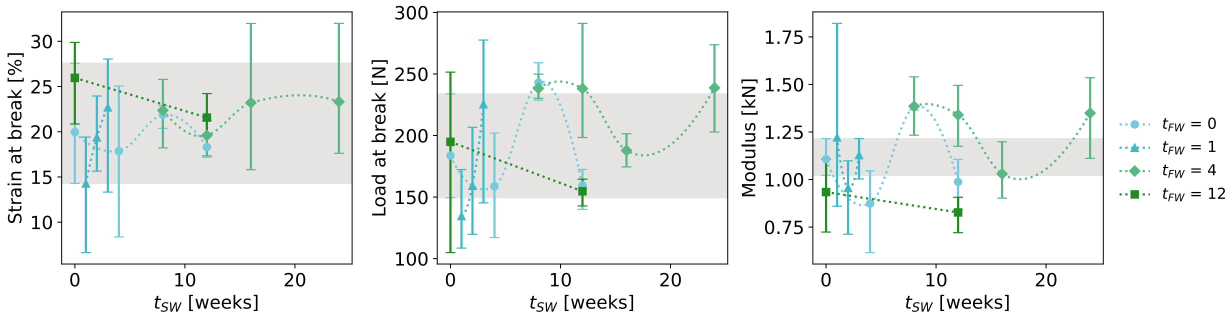

Fig. 12. Change in mechanical properties with retting in seawater and freshwater for ref. ropes.

not be necessary.

3.3. Life cycle analysis

After evaluating the mechanical characteristics of the ropes, a life cycle assessment was carried out to contrast the environmental effects of locally manufactured coir ropes with those of imported HDPE braid. This assessment used a functional unit based on the material needed to create a 2-meter rope strong enough to support a pearl chaplet. Table 6 outlines the environmental impacts of each braid based on the functional unit of supporting a 10 kg pearl chaplet. The outcomes are illustrated in Fig. 13 using a histogram to facilitate understanding. The top value is normalised to 100%, and all other values are shown as percentages of this peak value.

The HDPE rope appeared to have more impact across 10 categories, including water consumption, mineral and fossil resource scarcity, marine and freshwater ecotoxicity, human carcinogenic and non-carcinogenic toxicity, freshwater eutrophication, emission of ionising radiation, and land use. The manufacturing process of the coir rope, mentioned herein as ref., exhibits a greater impact across seven categories: terrestrial toxicity and acidification, stratospheric ozone depletion, creation of human and terrestrial toxic ozone, marine eutrophication, and formation of fine particulate matter. It is important to note that both braids demonstrated equivalent global warming potentials. To identify the relationship between the life cycle stages of the braids and their environmental impacts, the environmental profiles of the braids were plotted. Fig. 14 presents, for each impact category, the different contributions of each stage involved in obtaining the HDPE braid.

HDPE polymerisation and extrusion appear to be the most polluting stages of its life cycle, with a significant contribution from the transport

Table 6
Impacts for obtaining coir and HDPE braids.

Impact category	ref.	HDPE	unit
Fine particulate matter formation	4.30E-06	2.54E-06	kg PM2.5 eq
Fossil resource scarcity	5.99E-04	1.31E-03	kg oil eq
Freshwater ecotoxicity	4.13E-06	1.75E-05	kg 1,4-DCB
Freshwater eutrophication	2.98E-08	2.63E-07	kg P eq
Global warming	2.09E-03	2.09E-03	kg CO_2 eq
Human carcinogenic toxicity	1.07E-05	5.34E-05	kg 1,4-DCB
Human non-carcinogenic toxicity	1.47E-04	4.40E-04	kg 1,4-DCB
Ionizing radiation	2.16E-05	8.84E-05	kBq Co-60 eq
Land use	9.71E-07	4.03E-06	m^2a crop eq
Marine ecotoxicity	1.12E-05	2.43E-05	kg 1,4-DCB
Marine eutrophication	6.00E-08	2.78E-08	kg N eq
Mineral resource scarcity	6.74E-07	1.22E-06	kg Cu eq
Ozone formation, Human health	6.88E-06	4.60E-06	kg NO_x eq
Ozone formation, Terrestrial ecosystems	6.95E-06	4.98E-06	kg NO_x eq
Stratospheric ozone depletion	1.52E-09	2.28E-10	kg CFC11 eq
Terrestrial acidification	1.37E-05	6.54E-06	kg SO_2 eq
Terrestrial ecotoxicity	7.47E-03	1.36E-03	kg 1,4-DCB
Water consumption	2.49E-05	2.65E-05	m^3

of the braid to French Polynesia. These results confirm that the petroleum-based nature of HDPE monofilaments is problematic. However, the extrusion process, which is common for both petroleum-based and bio-based plastics, also poses an environmental issue. Using natural fibres, such as coconut fibres, could help avoid these two problems, and the local manufacturing of fibres also eliminates the need for transportation, another source of pollution. Furthermore, a scenario without this process was investigated as retting did not affect the mechanical properties. The environmental impact of making the coconut fibre braid is then determined by the energy consumed during the extraction and braiding of the fibres, which is directly related to the energy source. The environmental profile of the Polynesian electricity mix provided in Table 3 was modelled to study the contribution of the different energy sources to the impact categories. Fig. 15 shows the impact contributions of the energy sources within the Polynesian electricity mix used to produce the ropes. It can be seen that energy from fossil resources is the main contributor to all impact categories except water consumption, which is mainly from hydraulic energy. The environmental impact categories in which coir braid production exceeds that of HDPE braid are primarily driven by the consumption of fossil resources during manufacturing. Moreover, the inferior mechanical properties of the coir rope when immersed, compared to the strength of HDPE rope, necessitate using 13 times more material to achieve equivalent performance. This substantial increase in material usage consequently amplifies the environmental impact by the same factor. Mechanical testing of the Ma. rope demonstrates that an enhanced braiding process can significantly improve both the mechanical properties and strength retention of the rope when immersed in water. By optimising the braiding process to achieve better stress distribution and reduce defects, the overall properties of the rope can be enhanced. As a result, less material would be required to achieve the same load-bearing capacity as synthetic ropes, leading to a notable reduction in environmental impact. Another approach to mitigating the environmental impact of rope production is to enhance the production process itself. This could involve reducing energy consumption by refining operational parameters, such as optimising sieve times or increasing braiding speeds. By improving these aspects of the production process, energy efficiency can be enhanced, leading to a reduction in the overall environmental impact.

However, although global LCA databases such as Ecoinvent allow good first estimation of environmental impacts, their generalised data may not always align with the specific conditions of remote archipelagos such as French Polynesia. This misalignment can lead to inaccurate assessments of environmental impacts, highlighting the need for region-specific data and models to ensure more accurate and relevant LCA results. Similarly, while tensile testing is an effective method for estimating the suitability of a rope for a specific application, the utilisation of ropes submerged in lagoons for pearl farming introduces a multitude of complex stressors, including wave action, current dynamics and animal interactions. Additionally, creep resulting from constant loading and the accumulation of biofouling may also contribute to increased stress on the ropes. Furthermore, conducting in-situ ageing tests on coir ropes is essential to determine whether the fibres maintain sufficient

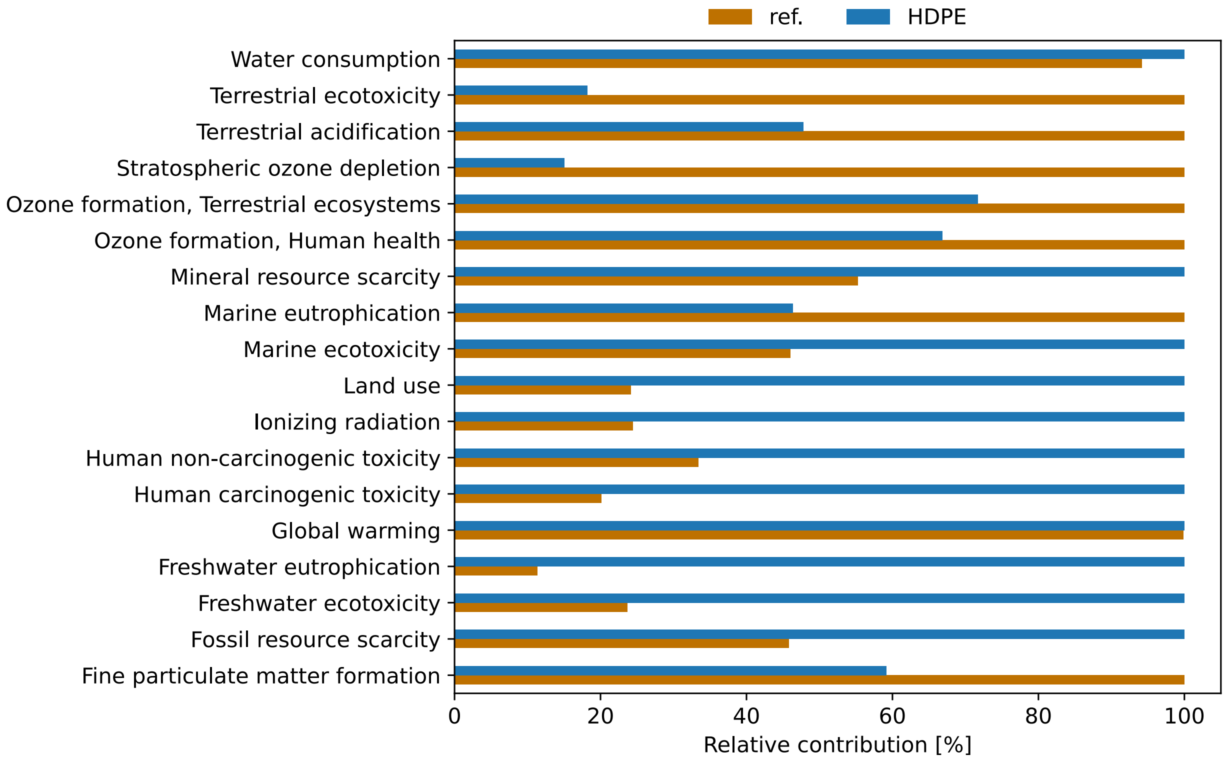

Fig. 13. Relative contributions of the HDPE and coconut fibre ropes for each impact category.

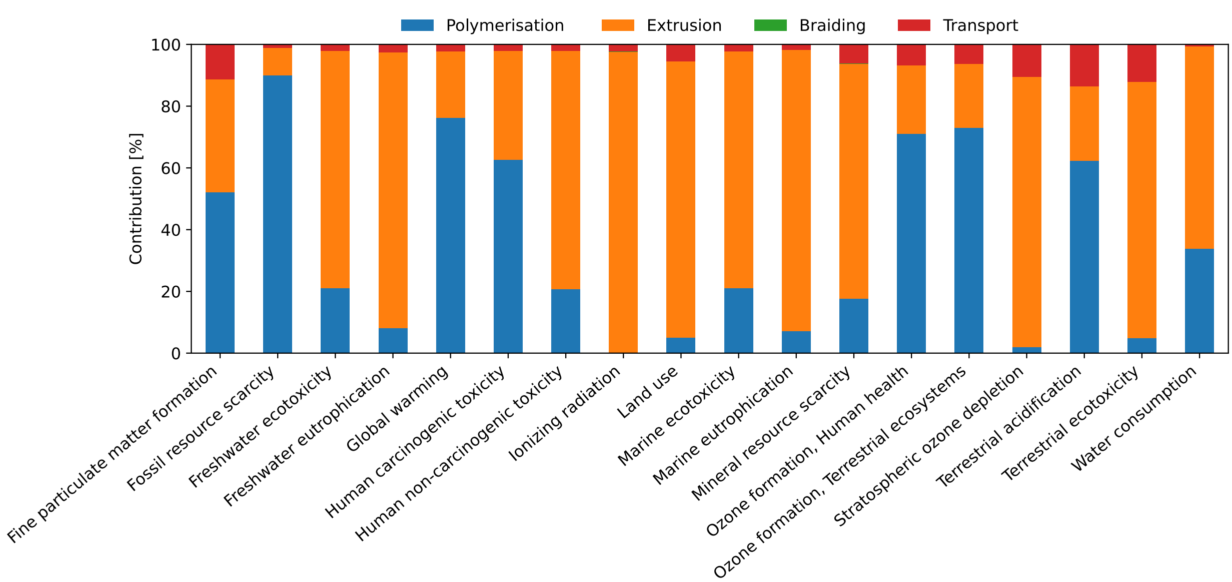

Fig. 14. Impact categories and contributions of HDPE braid production stages.

strength over the necessary period for pearl cultivation. If the fibres do not retain adequate strength, it is crucial to estimate the required dimensions or modifications to the ropes to counteract degradation and ensure their effectiveness throughout the pearl growth process.

Finally, it is important to note that this analysis only includes the production and transport phases of the braids, excluding their use and end-of-life, which are currently not available in the literature. These results do not question the use of coconut fibres to avoid plastic pollution but provide insight to enhance the ecological benefits of their production.

4. Conclusion

The mechanical properties of the individual coir fibres were evaluated under dry and water-saturated conditions. The results indicated that water had little effect on the mechanical properties of the fibres. However, the water effect caused a decrease in mechanical properties for the machine-twisted ropes, indicating that the braiding process plays an important role in both mechanical properties and strength retention once immersed. The influence of retting was also evaluated to better understand the role of this process on the mechanical properties of the coir ropes. Given that the mechanical characteristics remained largely unchanged after the various retting procedures, it seems that this step is

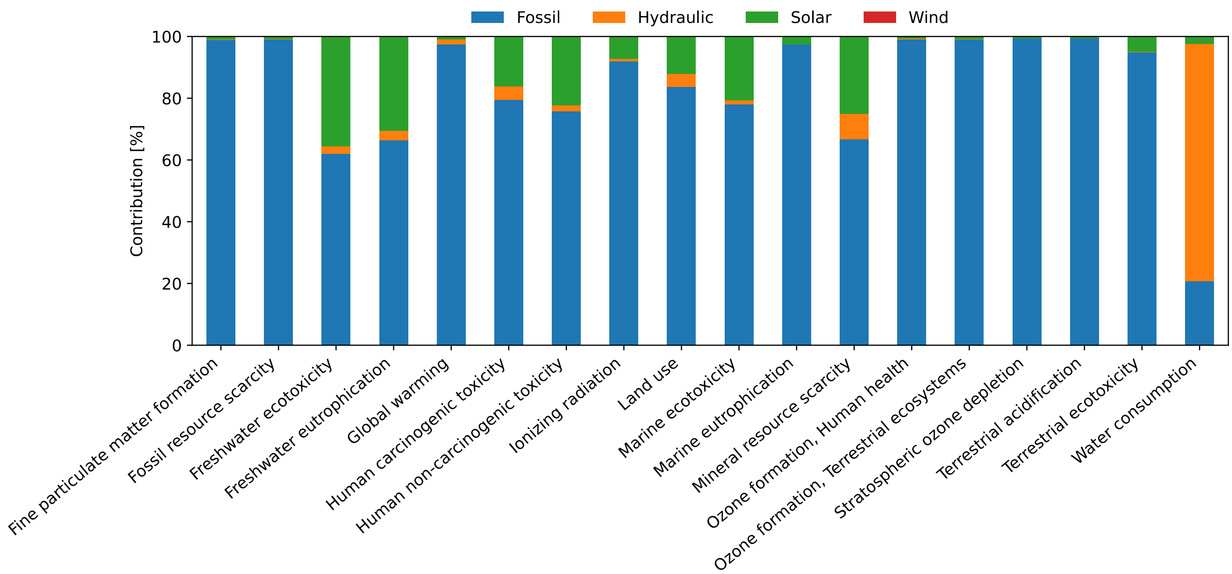

Fig. 15. Impact categories and contributions of French Polynesian electricity mix.

not essential, providing an opportunity to prevent the environmental pollution associated with it. While the production of coconut fibre ropes presented a significantly lower impact on various environmental categories, its lower mechanical properties required a greater amount of material to withstand the same load as HDPE ropes. Consequently, the environmental performance of coir rope production was comparable to that of HDPE braid production and import. These findings underline the importance of improving coir rope production as a safer alternative to synthetic fibres, which currently pollute French Polynesia's lagoons. By replacing synthetic ropes with coir, the pearl farming industry can significantly reduce environmental contamination, thereby contributing to the preservation of the lagoons and the protection of marine species.

CRediT authorship contribution statement

Louis Le Gué: Writing – original draft, Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Peter Davies:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Formal analysis, Data curation, Conceptualization, Software. **Mael Arhant:** Writing – review & editing, Supervision, Investigation, Formal analysis, Conceptualization. **Benoit Vincent:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Benoit Parnaudeau:** Resources, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors received materials from Polyacht and Benoit Parnaudeau is an employee of Polyacht. However, these affiliations did not influence the design, interpretation, or reporting of the findings.

Data availability

Data will be made available on request.

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