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Characteristics of alkaline-modified coconut fibre via microwave-assisted extraction in cementitious composites

Siti Nursyazwani Shahizam[1], Mohd Samsudin Abdul Hamid[2*], Noor Husna Mohammad Nor[3], Endah Kanti Pangestuti[4], Arief Kusbiantoro[5], Anggy Rio Pratama[6]

[12]*Civil Engineering Studies, Universiti Teknologi MARA, Pulau Pinang Branch, MALAYSIA.*
[3]*Chemical Engineering Studies, Universiti Teknologi MARA, Pulau Pinang Branch, MALAYSIA.*
[45]*Program Studi Teknik Sipil, Universitas Negeri Semarang, INDONESIA.*
[6]*PT. Pratama Jaya Reka, Kota Semarang, Jawa Tengah, INDONESIA.*

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ABSTRACT

Coconut fibre, a lignocellulosic by-product of *Cocos nucifera L*, is recognised as a sustainable strength-enhancing material in cementitious composites. Untreated fibres, however, exhibit poor interfacial bonding due to surface impurities and limited reactivity. This study examines the effects of NaOH treatment at concentrations of 2, 3.5, and 5 per cent on the microstructural, elemental composition, and functional groups of coconut fibre. SEM analysis revealed progressive morphological refinement as the NaOH concentration increased. SEM observations revealed that untreated coconut fibres possessed rough surfaces covered with non-cellulosic components, which can hinder effective fibre–matrix bonding. Progressive surface modification was observed as NaOH concentration increased, with NaOH-treated fibres exhibiting enhanced surface roughness and porosity, and the removal of surface impurities. EDX confirmed carbon (C) and oxygen (O) as dominant elements. The C-O ratio increased after treatment due to the removal of hydrophobic impurities and greater exposure of cellulose hydroxyl groups. FTIR spectra revealed a broad O-H stretching band around 3400 cm^{-1}, indicating hydroxyl groups associated with cellulose and the partial removal of hemicellulose, lignin, and surface impurities after treatment. Among the conditions examined, coconut fibre treated with 5% NaOH displayed the most favourable surface characteristics, suggesting a strong potential to improve the fibre-matrix interaction within cementitious composites. These results indicate that alkaline-treated coconut fibre can serve as an effective reinforcement material for the development of sustainable fibre-reinforced concrete.

[2*] Corresponding author. *E-mail address*: samsudin85@uitm.edu.my

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1. INTRODUCTION

Coconut fibre has been shown to have huge potential as a sustainable, strength-enhancing material due to its wide availability, low density, durability, and favourable lignocellulosic composition [1-3]. The use of coconut fibre obtained from agricultural waste was found to support life cycle practices by enhancing waste commercialisation and producing optimal environmental impacts [4-6]. Through this approach, an abundant agricultural by-product is found to transform material functions into suitable forms for engineering applications [6]. Nevertheless, the composition of non-cellulosic constituents, surface impurities, and relatively low surface reactivity in coconut fibre has limited effective interfacial bonding and reduced the overall performance of composite materials [7]. Alkaline treatment using sodium hydroxide (NaOH) has been reported as an effective technique for modifying fibre surface characteristics, yet variations in treatment concentration and processing conditions influence the resulting physical, microstructural, and chemical properties of the fibres [8]. Accordingly, this study conducts a comprehensive and systematic investigation into the effects of sodium hydroxide (NaOH) treatment on coconut fibre, focusing on the development of fibre surface characteristics, microstructural changes, and the identification of key functional chemical groups that influence fibre reactivity and interfacial behaviour within composite material systems. By providing comparative analysis across different alkaline concentrations, this research aims to enhance understanding of fibre-modification mechanisms and to examine the effective utilisation of treated coconut fibre in sustainable concrete composites. Furthermore, the study applied NaOH treatment, which was integrated with microwave irradiation, to accelerate the fibre modification process. Microwave-assisted treatment enables rapid, volumetric heating through mechanisms such as dipolar polarisation and ionic conduction, thereby promoting a more uniform distribution of energy throughout the fibre structure [9-10]. In comparison with conventional thermal soaking methods, microwave irradiation significantly shortened the treatment time and reduced energy consumption while simultaneously improving the efficiency of removing non-cellulosic components.

Coconut fibre is widely described in the previous study as a natural lignocellulosic fibre extracted from the husk (mesocarp) of *Cocos nucifera L.*, a waste produced in tropical countries such as India, Sri Lanka, Indonesia, Brazil, and Malaysia [11-12]. Furthermore, this material is known as a renewable, low-cost, and biodegradable resource that is frequently highlighted for its environmental impact benefits and its suitability for sustainable and composite construction materials in applications [13-14]. Previous studies also emphasised that fibres have widespread availability and accessibility, making them utilised in engineering applications while providing additional economic opportunities for communities involved in coconut production [11-12]. The component in coconut structure known as coir fibre is also known for its relatively high durability among natural plant fibres, mainly due to its naturally high lignin content, which enhances its strength and resistance in structural applications. Previous studies consistently report that coconut fibre possesses low density, making it particularly advantageous for lightweight composite materials [13-14]. The physical characteristics of coir fibre vary in terms of fibre length and coarseness, and it is generally classified into two main categories: brown and white fibres. Brown fibres, sourced from mature coconut husks, tend to offer enhanced strength and rigidity, whereas white fibres, derived from immature husks, are finer and more elastic, resulting in varied performance outcomes in composite and structural applications [12]. Low density is often highlighted as an important advantage, contributing to an improved toughness-to-weight ratio in both cement-based and polymer-based composite materials [11,14]. Beyond their reinforcing capability, coconut fibres are also able to improve the thermal and acoustic insulation performance of composite systems and geotextile applications [1,13].

Other than that, a variety of analytical techniques have been employed to examine the microstructure of coconut fibre across multiple length scales to ensure its characteristics. Scanning Electron Microscopy (SEM) is commonly used to characterise the surface morphology and topographical features of the fibre, including surface roughness, grooves, pores, and impurities [2, 4, 15-19]. SEM produces high-resolution images that enable detailed observation and evaluation of the fibre's surface condition. In microstructural

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studies of coconut fibre, it often demonstrates an irregular and heterogeneous surface morphology, a trait widely associated with natural plant fibres [3, 15-17]. The fibre surface generally exhibits longitudinal grooves, ridges, and uneven textures, reflecting the arrangement of cellulose microfibrils along the fibre axis [12]. The presence of these surface features facilitates a mechanical interlocking between the fibre and the surrounding matrix to enhance composite strength [20]. The presence of non-cellulosic components, such as lignin, hemicellulose, waxes and surface impurities, is commonly observed on the fibre surface [4, 15, 21-24]. These substances form a natural layer that partially covers the cellulose microfibrils, thereby limiting the exposure of reactive hydroxyl groups [3, 22]. Consequently, untreated coconut fibres generally exhibit lower surface reactivity and weaker interfacial bonding compared with chemically treated fibres [1]. Microvoids and pores were found to be observed within the fibre structure, illustrating the characteristic cellular structure of coconut fibre. These pores are responsible for the fibre's high-water uptake and adversely affect its dimensional stability when used in composite systems, including concrete [25].

Coconut fibre, known as lignocellulosic material, is composed primarily of cellulose, hemicellulose, lignin and small amounts of waxes and pectin. The chemical composition of these constituents features multiple reactive functional groups, including hydroxyl (-OH), carbonyl (C=O), carboxyl (-COOH), and lignin-associated aromatic groups [2, 4, 15, 18, 21-22, 26-27]. These reactive functional groups play an important role in determining the fibre's chemical reactivity, hydrophilicity, and interfacial bonding potential within composite systems [4]. A thorough understanding of these functional groups and their behaviour is essential for optimising chemical treatments, improving interfacial adhesion, and enhancing the mechanical performance of fibre-reinforced composites. The identification and characterisation of functional groups in coconut fibre are typically performed using spectroscopic and chemical analytical techniques. Fourier Transform Infrared Spectroscopy (FTIR) is frequently applied to characterise the vibrational behaviour of functional groups in materials. FTIR analysis characterises vibrational transitions induced by infrared absorption, with characteristic peaks reflecting bond vibrations within the fibre surface. In studies of coconut fibre, FTIR analyses often show shifts in peak positions, changes in peak intensity, or the disappearance of specific absorption bands related to lignin and hemicellulose, indicating chemical or structural modifications in the fibre following treatment [4].

Therefore, in this study, the objectives are to identify the effect of sodium hydroxide (NaOH) treatment on the physical and surface characteristics of coconut fibre, to examine the microstructural properties of coconut fibre for application in composite concrete and to determine the functional chemical groups present in coconut fibre for its suitability for composite concrete applications.

2. MATERIALS AND METHODS

2.1 Materials and Chemicals

Raw coconut fibres were locally sourced from Kampung Bandar, Weng, Baling, Kedah, Malaysia. The fibres were extracted from mature coconut husks through a manual mechanical decortication process. Dried husks were manually beaten and crushed using hand tools to loosen the fibrous bundles from the surrounding pith and non-fibrous materials, as shown in Fig.1(a), after which the fibres were separated from the husk matrix [3, 28]. Then, the fibres were washed with clean water to remove surface impurities and dust particles [28], and subsequently oven-dried at 45 °C for 6 hours to ensure the removal of residual moisture before undergoing chemical treatment and characterisation as shown in Fig. 1(b) [29]. Dried fibres were stored in a clean, dry environment until further use. For each treatment condition, 10 g of oven-dried coconut fibre was used. Sodium hydroxide (NaOH) pellets (molecular weight 40.00 g/mol, Merck KGaA) were used as the alkaline reagent. Distilled water was used throughout the experimental procedures.

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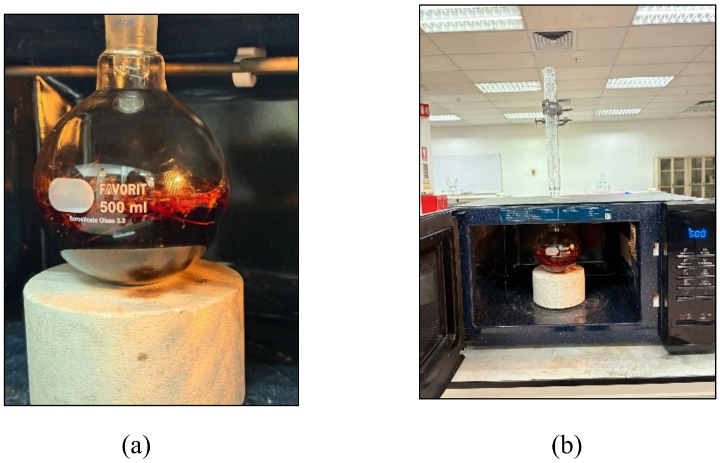
Fig. 1. Preparation of coconut fibre (a) Raw coconut fibre after wash; (b) Drying process using oven

2.2 Microwave-Assisted Alkaline Treatment of Coconut Fibre

NaOH solutions with concentrations of 2.0%, 3.5%, and 5.0% (w/v) were prepared using distilled water. For each treatment, 10 g of dried fibre was immersed in the respective NaOH solution in a 250 mL borosilicate flask, as shown in Fig. 2(a). The flask was subjected to microwave irradiation at 800 W for 5 minutes to facilitate rapid alkaline modification. Following treatment, the fibres were thoroughly rinsed with distilled water to remove residual alkaline and dissolved organic constituents. Rinsing continued until a neutral pH of approximately 7 was achieved [30]. The treated fibres were then air-dried at room temperature in a clean, dust-free environment for 24 to 28 hours, as shown in Fig. 2(b). Four fibre conditions were prepared for analysis: untreated, 2%, 3.5%, and 5% NaOH-treated samples.



(a) (b)

Fig. 2. Alkaline treatment process of coconut fibre (a) Immersive process using NaOH; (b) Heating process using microwave oven

2.3 Scanning Electron Microscopy (SEM) with Energy Dispersive Spectroscopy (EDX)

Four coconut fibre samples, which are untreated, 2% NaOH-treated, 3.5% NaOH-treated, and 5.0% NaOH-treated, were prepared for combined scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) analysis to investigate surface morphological changes induced by alkaline treatment and to determine elemental composition [2, 4, 15-19]. Each fibre sample was cut into segments approximately 5-10 mm in length. Individual fibres were mounted on aluminium stubs using conductive carbon adhesive tape. Owing to the non-conductive nature of coconut fibres, a thin gold coating was applied using a sputter coater to minimise charging effects during SEM observation. SEM analysis was performed using a Phenom World scanning electron microscope operated at an accelerating voltage of 10-15 kV. Imaging began at low magnifications (100×-500×) to identify representative areas, followed by higher

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magnifications (1000×-5000×) to investigate surface details. Surface roughness and structural alterations resulting from NaOH treatment were closely examined. EDX analysis was carried out on selected areas of each fibre to determine elemental composition, with emphasis on carbon (C) and oxygen (O). Changes in elemental distribution were assessed to evaluate the chemical modifications induced by the alkaline treatment.

2.4 Fourier Transform Infrared Spectroscopy (FTIR)

Four coconut fibre samples were analysed using FTIR to assess the chemical changes resulting from alkaline treatment. to analysis, each fibre sample was ground into a fine powder using a laboratory grinder to prepare it for examination. FTIR analysis was carried out using an Attenuated Total Reflectance (ATR) accessory attached to a PerkinElmer Spectrum FTIR spectrometer. The powdered fibre samples were placed directly onto the ATR crystal. Spectra were recorded over a wavenumber range of 4000 to 400 cm^{-1} at a resolution of 4 cm^{-1} with 32 scans per sample to ensure adequate signal quality. During analysis, infrared radiation interacted with the fibre samples, and specific chemical bonds absorbed energy at characteristic frequencies corresponding to their vibrational modes. The resulting spectra were processed using instrument software and presented as absorbance versus wavenumber plots. Each absorption band in the spectrum represents a distinct functional group or molecular vibration, enabling the identification of chemical components such as cellulose, hemicellulose, and lignin, as well as changes in functional groups resulting from NaOH treatment.

3. RESULTS AND DISCUSSION

3.1 Surface Morphology of Coconut Fibre

In this study, the fibre surface appears rough, flaky, and irregular, with substantial amounts of non-cellulosic constituents such as hemicellulose, lignin, and waxes loosely adhering to the fibre wall, along with remnants of parenchyma (pith) cells present as cellular debris and fragmented tissues on the fibre surface for the untreated fibre, as shown in Fig.3 and agreed by [2, 4, 12, 24]. These components form flaky fragments and surface debris that cover much of the fibre exterior, resulting in a compact yet chemically impure outer layer. [2, 15]. Such a surface coating acts as a barrier to effective interfacial bonding between the fibre and the cementitious matrix, often leading to weak fibre-matrix adhesion [31]. In addition, the presence of hydrophilic non-cellulosic materials promotes moisture absorption, thereby reducing the dimensional stability of the fibre [3, 25]. No significant surface alteration is observed, indicating that the natural chemical constituents and surface impurities remain intact [2]. As NaOH concentration increased (2%, 3.5%, and 5%), SEM revealed progressive changes, as shown in Figs. 4-6. The treated fibre surface becomes noticeably rough, porous, and uneven. The absence of the squamous surface layer corresponds to progressive surface etching and cavity development [2]. Under alkaline conditions, the amorphous phases within the fibre are preferentially attacked, generating globular pits (cavities) and nested pores distributed along the fibre surface [2, 4]. These nested pores are characterised by smaller cavities embedded within larger ones, which is attributed to the non-uniform etching of the fibre's amorphous regions. This selective degradation results in a porous structure comprising both macro-scale cavities and micro-scale pits. In addition, as the NaOH concentration increases, the tylosis-like structures are unveiled in the pit regions, with occasional protruded tylosis observed extending towards the fibre surface, indicating enhanced opening of internal pore pathways that facilitate matrix penetration and anchorage [4, 22, 32]. Surface cleanliness of the image shown has notably improved, as waxy layers and residual impurities have been effectively eliminated from the coir fibre, thereby exposing the underlying cellulose fibrils. The removal of surface waxes and non-cellulosic constituents exposes cellulose hydroxyl (-OH) groups, enhancing the fibre's chemical reactivity with the surrounding matrix of the material [12].

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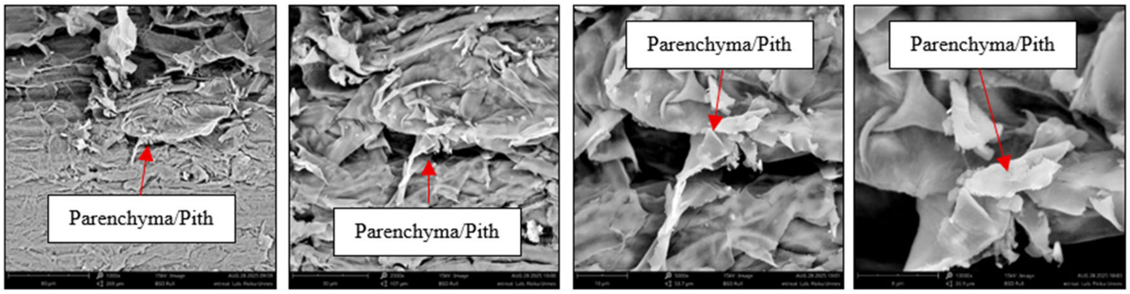
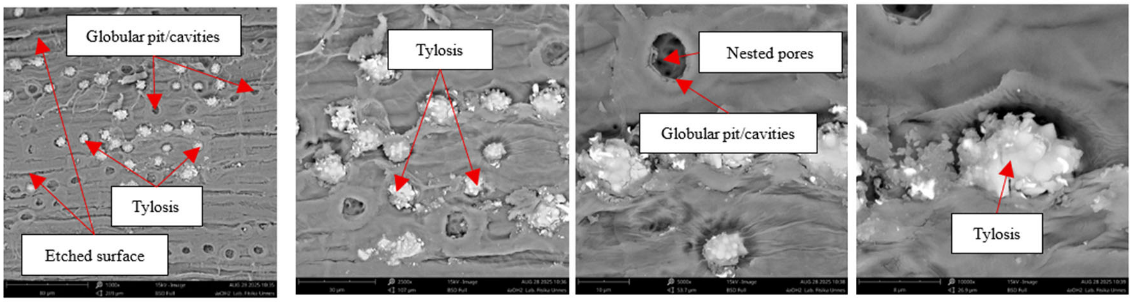


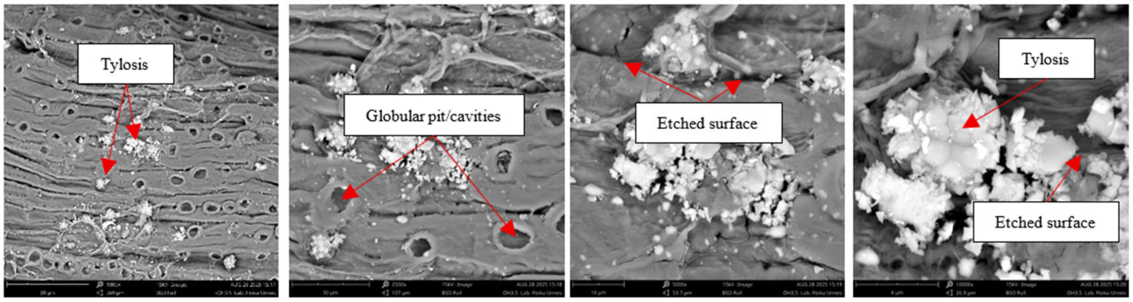
(a) (b) (c) (d)

Fig. 3. Microstructural mage of untreated coconut fibre (a) 1000×; (b) 2500×; (c) 5000×; (d) 10000×



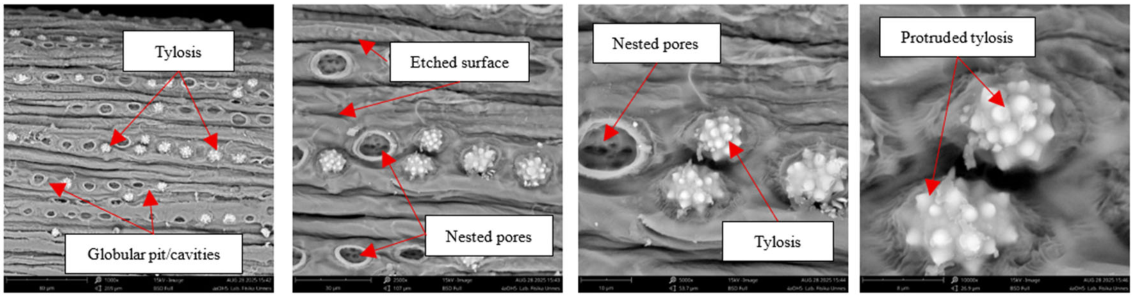
(a) (b) (c) (d)

Fig. 4. Microstructural image of 2% NaOH treated coconut fibre (a) 1000×; (b) 2500×; (c) 5000×; (d) 10000×



(a) (b) (c) (d)

Fig. 5. Microstructural image of 3.5% NaOH treated coconut fibre (a) 1000×; (b) 2500×; (c) 5000×; (d) 10000×



(a) (b) (c) (d)

Fig. 6. Microstructural image of 5% NaOH treated coconut fibre (a) 1000×; (b) 2500×; (c) 5000×; (d) 10000×

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A comparison of untreated and 5% NaOH-treated coconut fibres reveals marked morphological changes. In untreated fibres, the surface was covered with waxes and amorphous deposits, and it displayed poor adhesion to cementitious or polymer matrices. Therefore, it was found that the surface coatings restricted both wettability and mechanical interlocking [25, 33]. Previous studies agree this on coir fibres, where the alkaline treatment modifies its fibre surface by cleaning and roughening it, promoting improved interfacial bonding with epoxy or cementitious matrices and enhancing the mechanical performance of fibre-reinforced composites [21, 34-36]. In contrast, the 5% NaOH-treated fibres showed pronounced porosity and well-defined surface grooves corresponding to the orientation of cellulose microfibrils, demonstrating extensive removal of hemicellulose and lignin. Findings of a cleaner, roughened surface provide increased contact and anchoring sites for hydration products or matrix resin, and it improves interfacial adhesion and efficient stress transfer within the composite material [31].

Lower NaOH concentrations (2% and 3.5%) were found to modify the fibre surface with minimal effect, with values less than 5%. At a 2% NaOH concentration, partial removal of non-cellulosic components was observed, leading to modest increases in surface roughness and porosity, with residual amorphous regions remaining that can produce minimal hindrance to effective matrix bonding. Treatment at 3.5% resulted in more pronounced surface degradation, though it was less uniform than that observed at 5%. Similar trends have been reported for other natural fibres, such as abaca and coir, where incremental increases in alkaline concentration enhance surface roughness and interfacial performance, although the optimal concentration depends on fibre type and treatment duration [25]. Since the 2% and 3.5% treatments expose less cellulose and generate fewer anchoring sites, their ability to improve composite performance is relatively limited compared to the 5% treatment.

Based on SEM analysis, the fibres indicate that the 5% NaOH-treated coconut fibre exhibits enhanced surface characteristics, emphasising its strong potential for application in composite concrete. Improvement in roughness and porosity provides mechanical interlocking sites for cement hydration products to bind. Furthermore, exposed cellulose hydroxyl groups that form stronger chemical interactions with the matrix. Previous studies on alkaline-treated coir and related fibres demonstrate that treatment improves tensile and flexural strength of fibre-reinforced composites due to better interfacial bonding [22, 33]. By integrating coir fibre into concrete, the resulting material exhibits captivating morphological features: crack bridging, energy dissipation, and toughness. On top of this, it was found that reducing microcracking ultimately led to enhanced mechanical performance and durability in sustainable fibre-reinforced concrete systems [37].

The EDX analysis showed that carbon (C) and oxygen (O) remain the dominant elements in both untreated (Fig. 7) and NaOH-treated (Fig. 8) fibres, indicating that the fundamental lignocellulosic structure is preserved after chemical treatment, as the high carbon and oxygen contents reflect the fibre's organic nature and correspond to the primary constituents of cellulose, hemicellulose, and lignin that form the bulk of natural plant fibres and agreed by previous study. [2, 19, 26]. It was found that NaOH treatment increases the oxygen-to-carbon (O/C) ratio by removing hydrophobic surface impurities such as fats, waxes, and lignin. Furthermore, it enhances cellulose exposure and improves the fibre's hydrophilicity. [12]. The high oxygen content is largely attributed to the numerous hydroxyl (-OH) groups present in cellulose. [38]. Trace amounts of inorganic elements, such as calcium (Ca), magnesium (Mg), potassium (K), aluminium (Al), and silicon (Si), were also detected at low levels, reflecting the natural mineral content of the fibre [2, 19, 26]. Following NaOH treatment, additional elements such as silicon (Si), sodium (Na), and nitrogen (N) were observed, with the sodium originating from the NaOH solution and some ions remaining adsorbed on the fibre surface [26].

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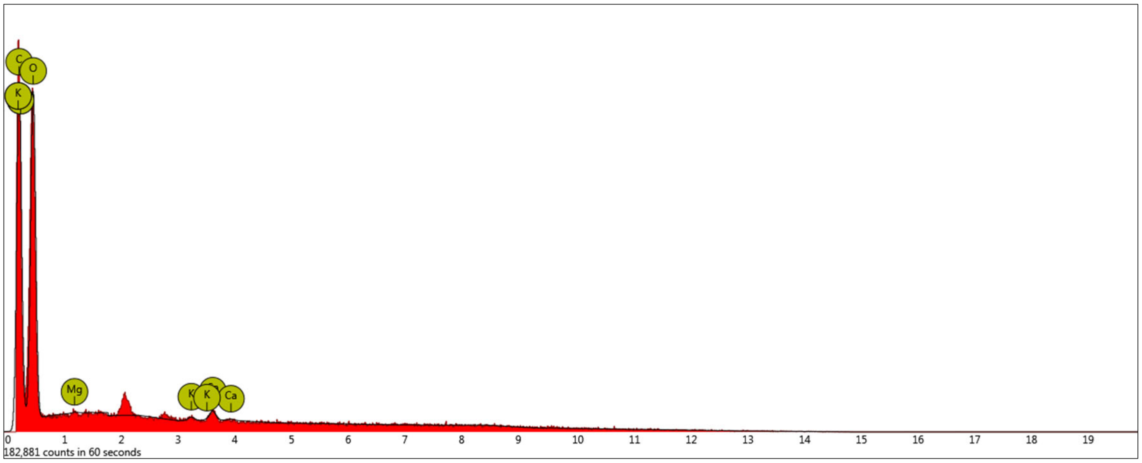

Fig. 7. EDX for Untreated Fibre

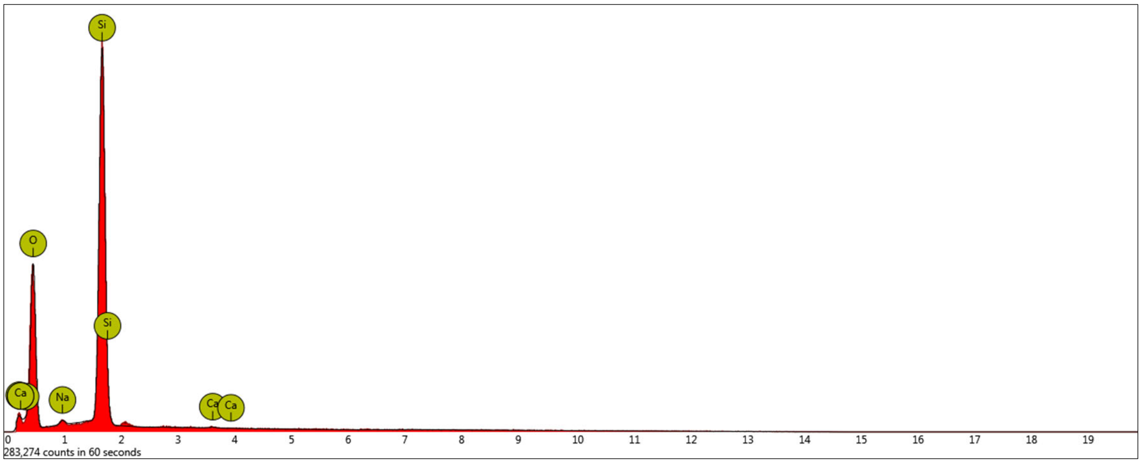

Fig. 8. EDX for 5% NaOH-Treated Fibre

Table 1. Elemental Composition for Untreated and Treated Fibre

Elemental Symbol	**Average of Weight Concentration**			
	Untreated	**2% of NaOH**	**3.5% of NaOH**	**5% of NaOH**
Oxygen (O)	48.25	48.43	45.46	45.68
Carbon (C)	50.92	31.88	36.89	38.99
Silicon (Si)	0.05	9.20	11.93	9.54
Calcium (Ca)	0.59	0.28	0.26	0.12
Magnesium (Mg)	0.06	0.004	-	-
Potassium (K)	0.11	-	0.09	-
Aluminium (Al)	0.02	-	-	-
Sodium (Na)	-	0.73	1.66	1.18
Chlorine (Cl)	-	0.03	-	-
Nitrogen (N)	-	9.45	3.70	4.49

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3.2 Surface Functional Group of Coconut Fibre

Fig. 9 demonstrates that FTIR identifies molecular vibrations by absorbing infrared radiation at specific wavenumbers, generating absorption bands characteristic of the material's chemical structure. The spectra are typically divided into two main regions which are the functional group region (4000 to 1500 cm^{-1}), which contains absorption bands corresponding to specific bond vibrations such as O-H, C-H, and C=O, and the fingerprint region (1500 to 400 cm^{-1}), which is highly complex and unique to each material, often associated with skeletal vibrations and bending modes of the molecular framework [39]. For lignocellulosic fibres such as coconut fibre, FTIR is particularly useful for assessing the main structural components of coconut fibre, namely cellulose, hemicellulose and lignin, which consist of various organic functional groups such as aromatic, ketone, and alcohol groups [23], as well as monitoring chemical modifications induced by treatments such as alkaline or chemical functionalization. Changes in peak position, intensity, or the appearance/disappearance of bands provide insights into the structural and chemical alterations of the fibres [4].

All fibre samples exhibited a broad O-H stretching band in 3400 cm^{-1}, characteristic of hydroxyl groups in lignocellulosic materials [2, 4-5, 15, 21, 24] . This absorption band is associated with the intermolecular hydrogen-bonding network present within the cellulose chains [27]. But the peak position varied with NaOH concentrations. Both the 2% and 5% NaOH-treated fibres showed shifts to higher wavenumbers, while 3.5% NaOH-treated fibre showed a lower band intensity, which may reflect progressive disruption of hydrogen bonding present in OH groups [5] and increased exposure of free hydroxyl groups with higher alkaline concentration. These results suggest that alkaline treatment alters the fibre surface chemistry. A C-H stretching peak at approximately 2925 cm^{-1} was observed in all fibres, corresponding to C-H stretching vibrations of methyl and methylene groups [21-22] present in polysaccharides and the phenylpropane structure of lignocellulosic components [4, 15, 27]. However, the 5% NaOH-treated fibre showed noticeably lower intensity than the untreated, 2%, and 3.5% fibres, suggesting a reduction in hemicellulose and lignin concentrations with more aggressive alkaline treatment.

Absorption bands in the region around 1600 cm^{-1} are associated with skeletal vibrations of the aromatic ring (C=C) in lignin, as well as COO- stretching vibrations originating from hemicellulose [4]. The band at near 1630 cm^{-1}, associated with aromatic ring skeletal vibrations, was present in all fibres, with the 5% NaOH-treated fibre exhibiting reduced intensity, implying partial modification of aromatic C=C components in lignin [15]. The band at 1424 cm^{-1} corresponds to C-H bending vibrations in CH_2 and CH_3 groups linked to the lignin and cellulose structure [4], [27]. The untreated fibre exhibited low to negligible absorption. In contrast, pronounced bands were observed for the 2% and 3.5% NaOH-treated fibres, followed by reduced intensity for the 5% treated fibre, indicating concentration-dependent structural reorganisation of cellulose-related groups. The band at 1262 cm^{-1} was observed in all fibres and corresponds to the C-O stretching vibrations associated with ester, ether, and phenolic functional groups in lignin, with possible contributions from acetylated hemicellulose and lignin-carbohydrate complexes [2, 4, 15, 21, 27]. However, the 5% NaOH-treated fibre showed lower intensity, suggesting further modification of lignin- or hemicellulose-related functional groups at higher alkaline concentrations. A strong absorption band at approximately 1059 cm^{-1} was observed in all fibre samples and is a well-known cellulose fingerprint band, associated with C1 group vibrations, ring asymmetric stretching, C-O-C asymmetric stretching, and CH_2 symmetric bending in native cellulose. [4]. Peak intensities decreased sequentially from untreated fibres to those treated with 2%, 3.5%, and 5% NaOH, suggesting that the cellulose structure becomes increasingly disrupted as the alkaline treatment concentration increases.

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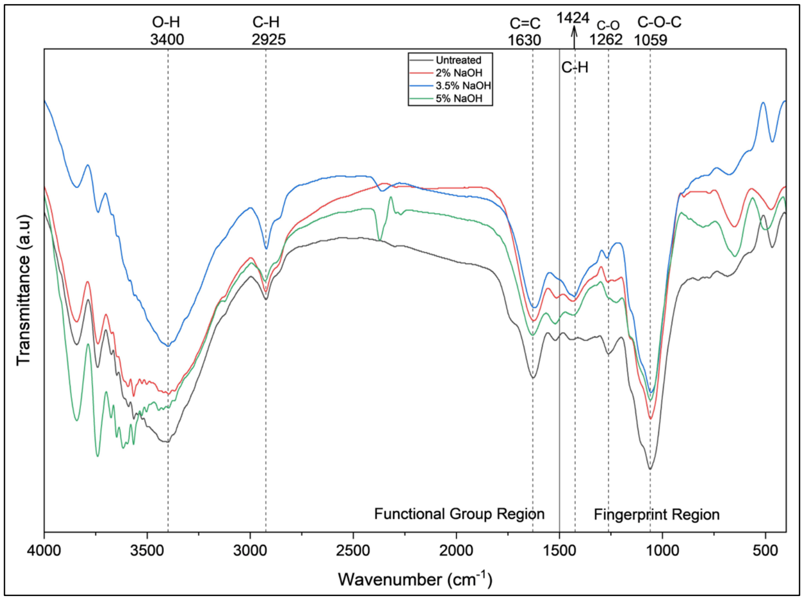

Fig. 9. Fourier Transform Infrared Spectroscopy of Untreated and Treated Coconut Fibre

4. CONCLUSION

In conclusion, this study demonstrated that alkaline treatment with NaOH progressively alters the surface morphology, chemical composition, and functional groups of the coconut fibres, respectively. SEM analysis confirmed that untreated fibres consist of compact bundles with rough surfaces, while these effects became more pronounced with increasing NaOH concentration. In comparison of the concentrations of NaOH treatments tested, 5% NaOH induced the most significant morphological changes, producing highly porous, sponge-like surfaces with exposed cellulose microfibrils. Furthermore, this finding is anticipated to improve both mechanical interlocking and chemical reactivity as a fibre. EDX analysis confirmed that the fibres' lignocellulosic composition remained largely intact after treatment, with changes in carbon and oxygen content reflecting the selective removal of hemicellulose, lignin, and surface impurities. FTIR results further indicated that alkaline treatment modifies hydroxyl, C–H, and cellulose-related functional groups, thereby increasing the exposure of reactive sites and promoting structural reorganisation at higher NaOH concentrations. The 5% NaOH treatment was identified as the optimal condition, achieving maximal surface roughness, porosity, and fibril exposure without compromising fibre integrity. These modifications enhance the suitability of treated coconut fibres for applications requiring improved interfacial bonding, chemical reactivity, and structural performance. Future research may focus on assessing the mechanical properties and water absorption behaviour of treated fibres, as well as optimising treatment parameters for specific composite systems.

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6. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted without any self-benefit, commercial, or financial conflicts, and declare no conflicts of interest with the funders.

7. AUTHORS' CONTRIBUTIONS

Siti Nursyazwani Shahizam: Conceptualisation, methodology, formal analysis, investigation and writing-original draft; **Mohd Samsudin Abdul Hamid**: Conceptualisation, methodology, supervision, writing-review, editing; **Noor Husna Mohammad Nor**: Conceptualisation, formal analysis, review and validation; **Endah Kanti Pangestuti**: Investigation and validation; **Arief Kusbiantoro**: Validation; **Anggy Rio Pratama**: Validation

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