



COBEM2021-1479 - IMPROVEMENT IN FIBER / MATRIX ADHESION THROUGH CHEMICAL TREATMENTS: A REVIEW

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Abstract. *The growing concern with sustainability foments the development of researches regarding to polymer composites reinforced with natural fibers, which represent an ecological alternative to the commonly used synthetic ones. However, natural fiber reinforced polymer composites present obstacles due to the weak interfacial interaction between the fiber and the polymeric matrix. To minimize this problem, chemical treatments can be performed to improve the adhesion and consequently the mechanical properties of the composite. The objective of this research is to produce a bibliographic review about chemical treatments made on natural fibers for application in polymer composites. The search for papers was carried out through a systematic review of the literature on Scopus and Science Direct databases. The parameters defined for the selection of the papers for the bibliographic data are related to the influence of chemical treatments on the fiber/matrix interface on polymer composites. The results show that the most applied treatment in natural fibers is the alkaline treatment with NaOH (mercerization), due to its widely spread methodology. Nonetheless, mercerization does not have great effectiveness in removing the wax, so it is often applied as a pre-treatment. Seeking a better efficiency in the fiber/matrix adhesion, and besides improving the stability of the composite, treatments with silane and permanganate were also analyzed in this review.*

Keywords: *Polymer Composites, Natural Fibers, Chemical Treatments, Alkaline treatment, Coupling Agents.*

1. INTRODUCTION

In general, a composite is a mixture of materials created by either synthetic or natural combination of two or more physically and chemically distinct components. The first component is called filler or reinforcement (discontinuous phase), while the other component is a compatible matrix binder (continuous phase). This multiphase material exhibits a significant proportion of the properties of both constituent phases, such that the best combination of properties is obtained (KABIR *et al.*, 2012; CALLISTER and RETHWISCH, 2021).

Taking this into account, allied to the growing ecological concern and rigorous environmental regulations, several researches have been carried out regarding the development of alternative natural fiber reinforced polymer composites. They have received a lot of attention in the last few years due to their attractive properties, such as high tensile strength and elastic modulus. The natural fibers represent an ecological friendly substitute to conventional synthetic fiber reinforcements. In addition, natural fibers are emerging as low-cost, lightweight, energy saving and biodegradable alternatives (DHAKAL *et al.*, 2013; DHAKAL *et al.*, 2014).

Despite their excellent properties, due to their biochemical composition, these fibers are hydrophilic and need some type of treatment to increase their compatibility with hydrophobic matrices. This deficiency of natural fiber composites restricts the use of these materials in many structural and non-structural applications. Moisture absorption can lead to fiber swelling, creating voids and microcracks in the region of the fiber-matrix interface, resulting in a significant reduction in the load transfer capacity from the matrix to the reinforcing fibers, promoting the reduction of the mechanical properties. Many research projects ascertained that these deficiencies on natural fiber reinforced composites were minimized by modifying the fiber surfaces using various treatments. Hence, improvements in physical, mechanical, and thermal properties are achieved, making them compatible with different polymeric matrices (MOHANTY *et al.*, 2000).

Some disadvantages of the natural fiber composites, such as low wettability, high moisture absorption, in addition to the weak interfacial adhesion between the fiber and the polymeric matrix are caused by the intrinsic structural composition of plant fibers composed of cellulose, hemicellulose, lignin, pectin and waxes, thus favoring the hydrophilic nature of the fibers (DOAN *et al.*, 2006; SANJAY *et al.*, 2018).

To solve these problems, fiber surface modifications can be made by mechanical, physical or chemical methods. These treatments are generally based on the use of reagent functional groups that are capable of reacting with the fiber structures and altering their composition. As a result, the hydrophilicity of the fibers is reduced and this facilitates greater compatibility with the polymeric matrix (SAIFUL ISLAM and MOYNUL ISLAM, 2021).

Some of the methods currently studied for fiber surface modification are as follows:

1.1 Silane Treatment

Silane is one of the most important coupling agents used to allow natural fiber to adhere to a polymeric matrix, thus stabilizing the composite material. The organo-functional group in the coupling agent causes the reaction with the polymer, either by copolymerization or the formation of an interpenetrating network (IPN) (PLUEDDEMANN, 1991). This curing reaction of the silane-treated natural fiber increases wetting of the resin. They are represented by a general formula, $R-(CH_2)_n-Si(OR')_3$ where $n=0, 1, 2, 3$, OR' is the alkoxy group that can be hydrolyzed and R is the functional organic group (CHAND and FAHIM, 2021).

1.2 Potassium permanganate (KMnO₄) Treatment

Permanganate is a compound that contains the permanganate group MnO_4^- . The treatment with permanganate leads to the formation of the cellulose radical through the formation of the MnO_3^- ion. Therefore, highly reactive Mn^{+3} ions are responsible for initiating a graft copolymerization (FREDERICK and NORMAN, 2004). This process roughens the surface of the natural fiber and produces mechanical interlocks with the matrix, similar to an alkaline treatment. Therefore, the interfacial adhesion between the natural fiber treated with permanganate and the matrix is improved (CHAND and FAHIM, 2021).

1.3 Alkaline Treatment

Alkaline treatment or Mercerization is one of the most used chemical treatments on natural fiber. It consists of immersing the fibers in a NaOH solution for a certain period (BOGOEVA-GACEVA *et al.*, 2007). This treatment has two typical effects on fiber, (1) it increases surface roughness, resulting in better mechanical interlocking and (2) it increases the amount of cellulose exposed on the fiber surface, thus increasing the number of possible reaction sites (SAIFUL ISLAM and MOYNUL ISLAM, 2021).

In this sense, this research work aims to review the recent progress in the use of the main physicochemical treatments performed in natural fibers for application in polymer composites, focusing on their use with the unsaturated polyester matrix. The effects of the chemical treatments on the properties of fibers and their composites were discussed and the interaction mechanisms between the phases clarified.

2. METHODOLOGY

The methodology used in this review work was a systematic examination of the literature for research papers that described the performance of chemical treatments on natural fiber reinforced polymer composites. For this, several search parameters were determined, and a methodological search procedure was followed as showed in the flowchart in Figure

1. First, it was defined that the search for papers would be carried out in the Scopus and Science Direct databases. Next, the keywords used as search filters were defined, as well as the period of time for each publication, ranging from 2016 to 2021. After defining the filters, a duplicity check was performed, since the same paper can be found in different databases, thus avoiding an erroneous statistical survey. Finally, the titles and abstracts were read to verify the direct relationship with the proposed theme, followed by a complete analysis of the most relevant papers.

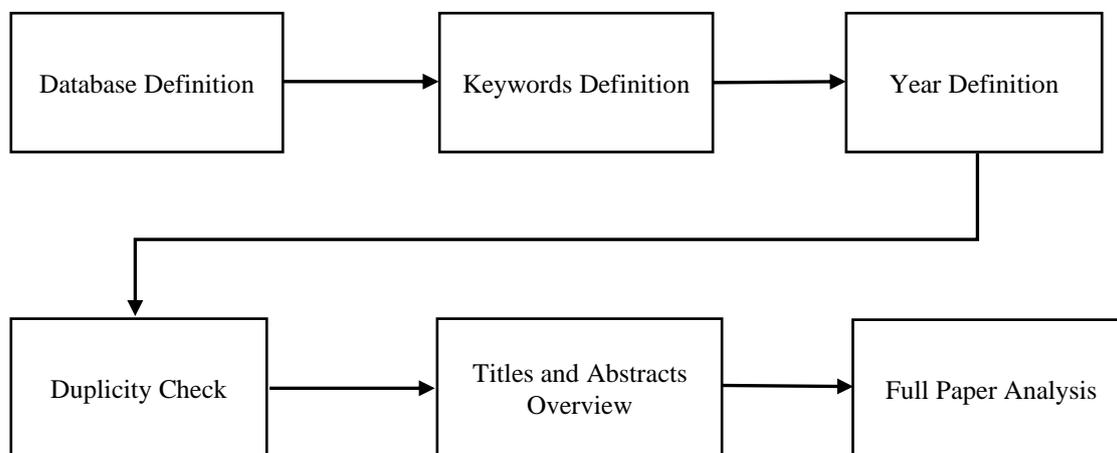


Figure 1. Methodological procedure applied to the study object.

The bibliographical research was based on the application of alkaline, permanganate and silane chemical treatments in polymer composites reinforced by natural fibers. The different types of fibers and their respective mechanical properties were analyzed regarding their use in unsaturated polyester matrices.

From the bibliographic portfolio, a survey was made of the main journals that publish on the subject and how these researches have been evolving in the last few years. Afterwards, the final selection of papers was evaluated, exemplifying some details such as manufacturing processes, fibers used, and mechanical efficiency of the treatments studied.

Finally, the analysis of the relative mechanical properties of tensile and flexural strengths of the composites were performed. The relative strength values are obtained from the ratio between the strengths obtained by the authors of the treated composite by the untreated composite. From these values, it is possible to determine if the treatment applied to the natural fiber was able to improve the tensile or flexural strength of the composite. When the value obtained is greater than 1, it indicates improvement of the property. When the value is smaller than 1, it indicates that the treatment did not present any improvement.

3. RESULTS AND DISCUSSION

3.1 Survey of results found in the databases (Scopus, Science direct)

For data collection, three independent selections were performed for each type of treatment studied, as shown in table 1.

Table 1. Summary for paper selection

Chemical Treatment	Keywords	Most relevant papers	Most relevant papers using unsaturated polyester resin	Analyzed papers
Silane Treatment	Silane Treatment. Polymer Composites. Natural Fibers.	129	10	9
Permanganate Treatment	Permanganate Treatment. Polymer Composites. Natural Fibers.	105	12	
Alkaline Treatment	Alkaline Treatment. Polymer Composites. Natural Fibers.	116	12	

The first selection step consisted of the search for papers regarding silane treatments. In the last 6 years, 129 papers were found with this theme, but only 10 using unsaturated polyester matrix.

The second selection step consisted of the search for papers focusing on permanganate treatments (KMnO_4). In the last 6 years, 105 papers were found, but only 12 using unsaturated polyester matrix.

The third selection step consisted of the search for papers involving alkaline treatments in polyester-based composites. Since it is one of the most performed treatments on natural fibers, a more specific filter was used. In the last 6 years, 116 papers with this theme were found, but only 12 analyzed the mechanical properties of these composites when reinforced by plant-based natural fibers.

These results indicate that despite chemical treatments are a very studied subject by researchers around the world, little interest was shown regarding the interfacial improvement of natural fibers and the polyester matrix, thus fomenting the creation of an area of study with great potential to be explored yet.

3.2 Analysis of the bibliographic portfolio

The number of publications by year for each type of treatment studied was evaluated. Figure 2 shows the volume of publications from 2016 to 2021.

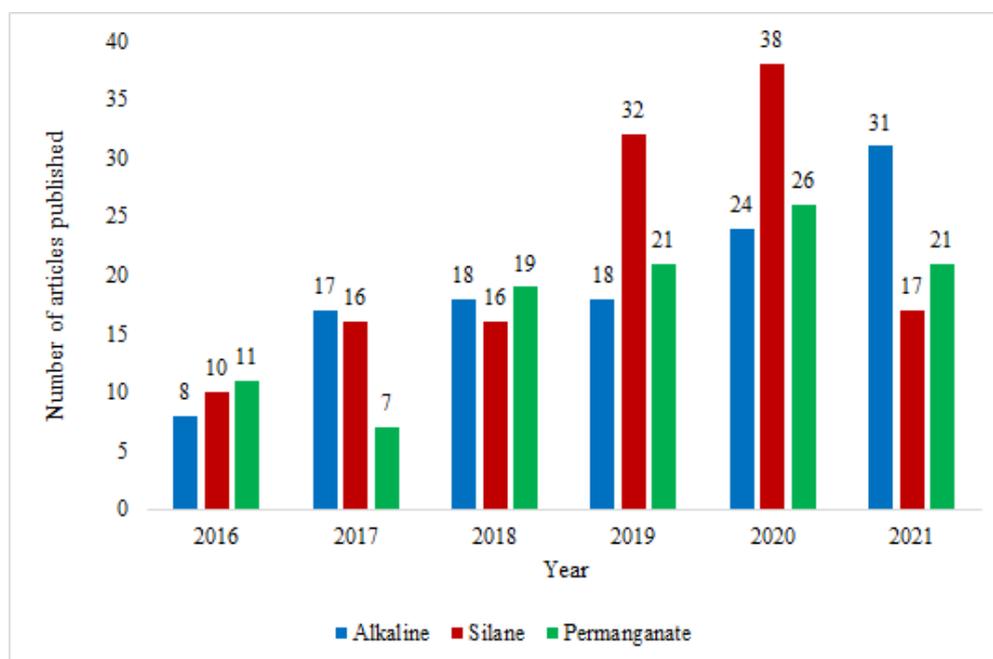


Figure 2. Number of papers published by year for each chemical treatment.

There was a growing tendency regarding the development of studies on the subject from 2016 to 2020, as it can be seen in Figure 2. It demonstrates the high relevance that this area has gained in the last few years. A partial drop was also observed in 2021, which can be explained either by the fact that this review work was carried out in the first half of the year concerned or the effect caused by the COVID-19 pandemic in the world scientific production, slowing it down. As a result, many researchers were forced to stop their researches or migrate to remote work and combined with several budget cuts and lack of investments arising from the health crisis, academic research has been heavily impacted.

It was determined that 2020 was the year with the highest number of publications, with a total of 88 published papers related to the 3 chemical treatments. The silane treatment was the most studied, with 38 published papers, followed by permanganate with 26 and mercerization with 24 published papers. It is noteworthy that some authors have studied the combination of two treatments, such as the alkaline/silane and alkaline/permanganate treatments. According to the papers studied, alkaline treatment is often used as a pre-treatment in order to make the initial cleaning of the fiber and consequently obtain a better interfacial adhesion between the fiber and the matrix.

Regarding the journals that published the most on the subject, 5 journals were selected based on either their largest number of publications or greater academic relevance. Figure 3 shows the number of papers published in these main journals, namely: Composites Part A: Applied Science and Manufacturing, Composites Part B: Engineering, Composites Science and Technology, Construction and Building Materials, Industrial Crops and Products and Materials Science and Engineering: C.

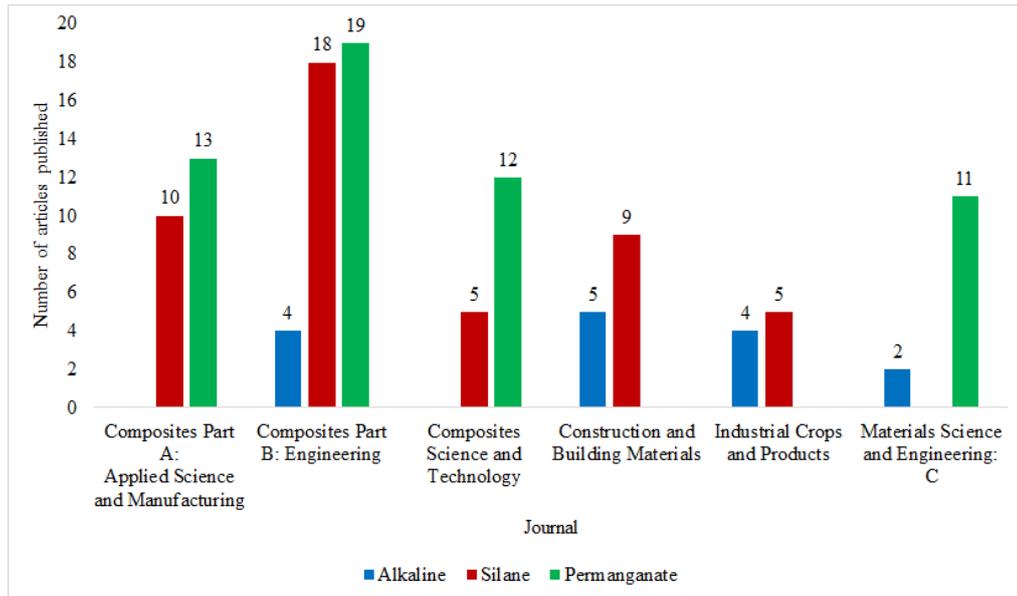


Figure 3. Number of papers published by journal.

The journal with the highest number of publications was Composites Part B: Engineering, totaling 41 published papers. Of these publications, 4 used alkaline treatment, 18 used silane and 19 used permanganate (KMnO_4). It was also possible to verify this journal was the only one, among all the selected journals, which the 3 chemical treatments were analyzed.

In addition, it was observed that among the 6 journals, only 4 published papers referring to chemical treatment using NaOH in natural fiber polymer composites, totaling 15 papers. This can be explained by the fact that mercerization is one of the most used treatments and it was massively studied in years prior to those surveyed. Besides, there is a tendency in current researches to use mercerization as a pre-treatment associated with others, and not individually.

3.3 Comparative study (Chemical Treatments / Manufacturing Processes / Mechanical Tests)

Nine papers were selected from 2016 to 2021, in order to evaluate: the matrix used, the fiber, the type of manufacturing process, the chemical treatment used, and the mechanical properties studied, as shown in Table 2.

Table 2. Comparative table of chemical treatments in polyester matrix

Reference	Fiber	Manufacturing process	Treatment	Mechanical tests
Arumugam <i>et al.</i> (2020)	Woven kenaf fiber/AgNPs@PVA (nanosilver)	Compression molding technique	Alkali Treatment Formic acid (FA) Treatment Acetic anhydride Treatment Hydrogen peroxide Treatment Permanganate Treatment	Tensile Test (ASTM 3039) Flexural Test (ASTM D790) Compression Test (ASTM D3410) Izod impact Test (ASTM D256)
Chu <i>et al.</i> (2018)	Ramie fabric	Hand lay-up /oven vacuum bag manufacturing method	Phosphorus (and nitrogen) containing silane (TMSAP)	Tensile Test (GB/T 1447-2005)

Table 2. Comparative table of chemical treatments in polyester matrix

(To be continued)

Reference	Fiber	Manufacturing process	Treatment	Mechanical tests
Haameem <i>et al.</i> (2016)	Napier grass fibre	Compression molding method	Alkali Treatment	Tensile Test - Fiber (ASTM D3822-07) Tensile Test - Composites (ASTM D638-02) Flexural Test (ASTM D790-02)
Kusmono <i>et al.</i> (2020)	Woven fan palm	Hand lay-up / Vacuum-bag technique (VBT)	Alkali - Silane Treatment	Tensile Test (ASTM D638-02) Flexural Test (ASTM D790-02) Impact Test (ASTM D5942-96)
Mahesha <i>et al.</i> (2018)	Grewia Serrulata tree	Hand lay-up	Alkali Pre-treatment Acetylation Silane Treatment Potassium permanganate treatment	Tensile Test (ASTM 3039) Flexural Test (ASTM D790-03)
Mayandi <i>et al.</i> (2018)	Veldt grape fibers	Compression molding machine	Alkali Treatment Calcium hydroxide powder Silane Treatment	Tensile Test (ASTM 3039) Flexural Test (ASTM D790)
Rajesh <i>et al.</i> (2018)	Pineapple Leaf Fiber	Hand lay-up	Alkali Treatment/ Bleaching (H ₂ O ₂)	Tensile Test (ASTM D638-02)
Sivakumar <i>et al.</i> (2021)	Palmyra	Hand lay-up moulding techniques	Permanganate - Acetone Treatment	Tensile Test (ASTM D3379-75) Three-point Flexural Test (ASTM D790-10)
Wirawan <i>et al.</i> (2020)	Woven fiber <i>hibiscus tiliaceus</i>	Vacuum method/VAPRI (vacuum pressure resin infusion)	Alkali Treatment Alkyl Silane Treatment	Tensile Test (ASTM D638-03)

Considering that all the papers analyzed in Table 2 were manufactured using unsaturated polyester as matrix and plant-based natural fibers as reinforcement, it is clear that mercerization, even associated with other treatments, is the most used treatment in natural fibers, promoting good fiber/matrix adhesion by removing the waxy layer present on their surface (NUNNA, 2012).

In addition, it is observed that the most used manufacturing process among the papers evaluated was the Hand Lay-up. Although it naturally requires more time to make the specimens, this technique uses less machinery and technology (and consequently lower costs with electricity and maintenance) compared to other techniques. It is economically viable for researchers during the manufacturing stage of the composites because it makes the study independent from the structure provided by the research centers. It is also worth noting that, in almost all the works presented in Table 2, the tensile test was the most used, followed by the flexural test to assess the effect of chemical treatment on the mechanical characteristics of the composite.

3.4 Analysis of relative tensile and flexural strengths

The interface is the common limit between the reinforcement and the polymeric matrix, whose mechanisms of interfacial bonding in composite materials include molecular entanglement; inter-diffusion of elements; electrostatic attraction; chemical reaction between groups on reinforcement and matrix surfaces; chemical reaction; and mechanical interlocking (HUANG *et al.*, 2021). In addition, there are also some low energy forces such as hydrogen bonds and van der Waal forces.

These mechanisms ensure an improvement in the fiber/matrix adhesion, favoring the increase in the efficiency of load transfer from the matrix to the reinforcement and, consequently, increasing the response of composites in relation to mechanical tests, as in tensile and flexural strengths tests.

In terms of the studied treatments, two mechanisms are predominant. The first is the formation of a chemical bond at the interface, formed by the connection of compatible chemical groups between the reinforcement and the matrix. The most common way to improve chemical bonding is to use coupling agents, such as silane. In silane molecules, one end can react with hydroxyl groups (hydrophilic groups) in the plant-based fiber; the other end reacts with the hydrophobic groups in the matrix (PICKERING *et al.*, 2016).

Furthermore, another interface mechanism that predominates in the papers studied is the mechanical interlocking that occurs between the matrix and the rough surface of the fiber. The fiber surface roughness can be regular or irregular valleys, protuberance, and crevices of the fiber surface (LIU *et al.*, 2012). When the surface is rougher, the bond area between matrix and fiber increases and therefore the bond strength tends to be greater. This type of mechanism is seen in alkaline and permanganate treatments.

Figure 4 shows works that evaluated the gains in mechanical resistance obtained from the chemical treatments on the fibers, based on the relative results of tensile and flexural strengths. It was identified that two studies analyzed the influence of alkaline treatment on tensile strength (in blue), four evaluated the treatment using silane with or without alkaline pretreatment (in red), two that verified the treatment using permanganate with or without alkaline pretreatment (in green) and one that evaluated the treatment using permanganate and silane with alkaline pretreatment. From these works, six of them also evaluated the influence of treatments on flexural strength.

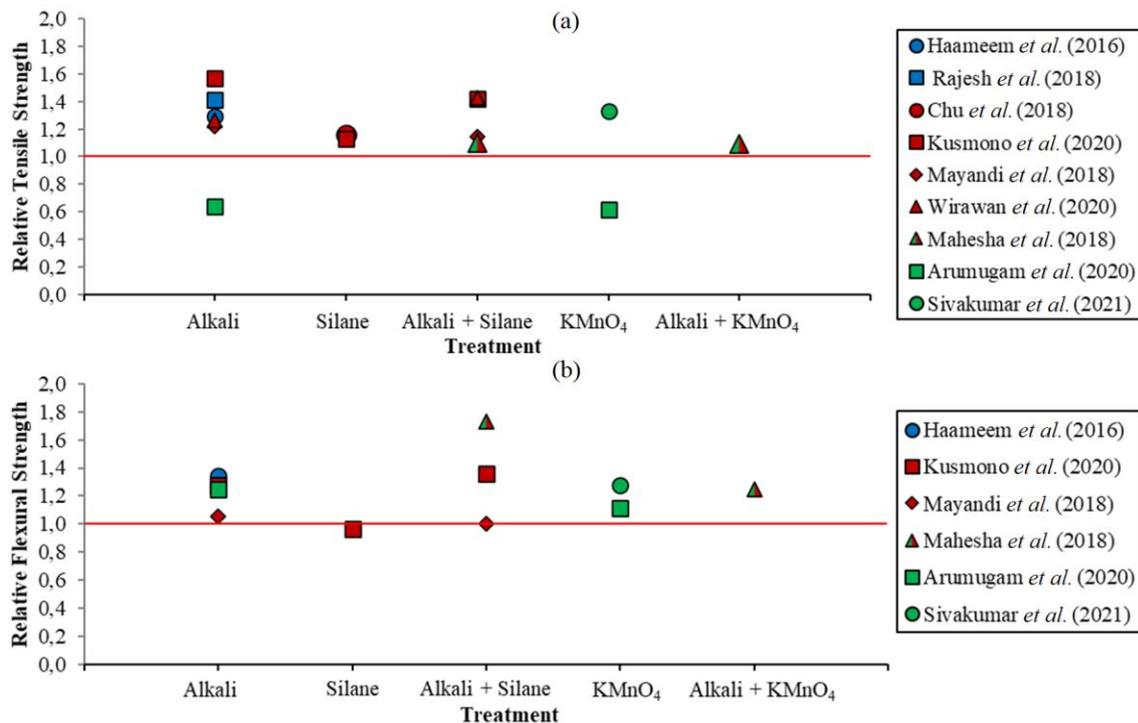


Figure 4. Graphs of (a) Relative Tensile Strength and (b) Relative Flexural Strength.

In relation to the treatments, it was verified that in only one work there was no improvement in the properties of tensile and flexural strengths. In Arunugam *et al.* (2020), the authors found that treatments with NaOH and KMnO₄ caused the degradation of kenaf fiber, due to the removal of part of the cellulose, hemicellulose, and lignin. This degradation was responsible for the reduction of the mechanical properties of the fiber, which lost its reinforcing capacity, and it was reflected in the tensile strength of the polyester/kenaf composite. This demonstrates the importance of correctly evaluating the time and concentration parameters of the reagents used to treat each type of natural fiber, as well as the effects on each property. When these parameters are correct, alkaline and potassium permanganate treatments can strengthen the

fibers, as it is seen in Kusmono *et al.* (2020), Haameem *et al.* (2016), Rajesh *et al.* (2018), Mayandi *et al.* (2018) and Wirawan *et al.* (2020).

The highest level of improvement was recorded by Kusmono *et al.* (2020) in their work that evaluated the effects of treatment with silane, NaOH and the use of alkaline pretreatment with silane in woven fan palm fibers in an unsaturated polyester matrix. The authors found that the alkaline treatment with sodium hydroxide provided a 57% gain in tensile strength, compared to the composite with untreated fiber. When only the treatment with silane was carried out, there was a gain of only 17%. However, the association of the two treatments contributed to an improvement of 47% in mechanical strength compared to the treatment with silane alone. Therefore, the association brought an improvement in the binding of the silane coupling agents with the fiber, due to the higher level of cleaning that the alkaline treatment brings to natural fibers, when carried out in the correct concentration and time. However, the increase in the concentration of coupling agents did not bring better results when compared to the alkaline treatment, which indicates the effectiveness of this treatment for the woven fan palm fiber. For fibers in which the alkaline treatment is not as effective, the use of silane can improve their mechanical properties.

This effect is verified in Wirawan *et al.* (2020) when studying the effect of the silane treatment on woven fibers (*Hibiscus tiliaceus*) in an unsaturated polyester matrix. When evaluating the composite reinforced by the fiber treated with NaOH, the authors found a gain in tensile strength of 26%. By associating the alkaline treatment with silane, it was verified a gain of 43% compared to the composite with the untreated fiber. Due to differences in fiber configuration and percentages of cellulose, hemicellulose, and lignin of the different types of plant-based fibers, the treatments will not necessarily have the same effects on all fibers.

4. CONCLUSIONS

In the context of polymer composites reinforced by natural fibers, the study of chemical treatments has been showing importance and consistency in the last 6 years. This is verified by the increasing number of publications performed during this period in journals of great academic relevance. This relevance comes from the viability of using natural fibers as reinforcement in composites for applications with greater mechanical demands, since they have better adhesion between fiber and matrix and, consequently, better mechanical properties. The results of the papers in which the mechanical properties were evaluated show that alkaline treatments, associated with both potassium permanganate and silane, are effective in improving the adhesion between natural fibers and the polyester matrix. It happens either by cleaning the fiber and increasing its surface roughness, resulting in better mechanical interlocking, or by adding coupling agents, forming chemical bonds at the interface. Nonetheless, the effect of these treatments and their association on the mechanical properties of the reinforced composite has particular effect, and it is necessary to study the influence of each treatment, besides optimizing the parameters used during manufacturing processes. It is important in order to prevent degradation of the fiber and to contribute to the correct cleaning of its surface. In this way, it is possible to obtain the best levels of mechanical resistance of the materials concerned, which expands its range of applications.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

- ARUMUGAM C., ARUMUGAM S., MUTHUSAMY S. **Mechanical, thermal and morphological properties of unsaturated polyester/chemically treated woven kenaf fiber/AgNPs@PVA hybrid nanobiocomposites for automotive applications.** Journal of Materials Research and Technology, Volume 9, Issue 6, 15298-15312, 2020. <https://doi.org/10.1016/j.jmrt.2020.10.084>.
- BOGOEVA-GACEVA G., AVALLA M., MALINCONICO M., BUZAROVSKA A., GROZDANOV A., GENTILE G., *et al.*, 2007. **Natural fiber eco-composites.** Polym. Compos. 28 (1), 98_107. Available from: <https://doi.org/10.1002/pc.20270>
- CALLISTER W. D., RETHWISCH D. G. **Ciência e engenharia de materiais: uma introdução.** 10ª Ed., Rio de Janeiro: LTC, 2021.
- CHAND N., FAHIM M., **1 - Natural fibers and their composites**, Editor(s): Navin Chand, Mohammed Fahim, In Woodhead Publishing Series in Composites Science and Engineering, Tribology of Natural Fiber Polymer Composites (Second Edition), Woodhead Publishing, 2021, Pages 1-59, ISBN 9780128189832, <https://doi.org/10.1016/B978-0-12-818983-2.00001-3>.
- CHU F., YU X., HOU Y., MU X., SONG L., HU W. **A facile strategy to simultaneously improve the mechanical and fire safety properties of ramie fabric-reinforced unsaturated polyester resin composites.** Composites Part A: Applied Science and Manufacturing, Volume 115, 264-273, 2018. <https://doi.org/10.1016/j.compositesa.2018.10.006>.

- DHAKAL H.N., SKRIFVARS M., ADEKUNLE A., ZHANG Z.Y., 2014. **Falling weight impact response of jute/methacrylated soybean oil bio-composites under low velocity impact loading.** *Compos. Sci. Technol.* 92, 134-141.
- DHAKAL H.N., ZHANG Z.Y., GUTHRIE R., MACMULLEN J., BENNETT N., 2013. **Development of flax/ carbon fibre hybrid composites for enhanced properties.** *Carbohydr. Polym.* 96 (1), 1-8.
- DOAN T.T.L., GAO S.L., MADER E. **Jute/polypropylene composites I. Effect of matrix modification.** *Compos Sci Technol*, 66(7-8), 952-63, 2006
- FREDERICK T.W., NORMAN W., **Natural Fibers Plastics and Composites**, Kluwer Academic Publishers, New York, 2004.
- HAAMEEM J.A.M., MAJID M.S.A., AFENDI M., MARZUKI H.F.A., HILMI E. A., FAHMI I., GIBSON A.G., **Effects of water absorption on Napier grass fibre/polyester composites.** *Composite Structures*, Volume 144, Pages 138-146, 2016. <https://doi.org/10.1016/j.compstruct.2016.02.067>.
- HUANG S., FU Q., YAN L., KASAL B., **Characterization of interfacial properties between fibre and polymer matrix in composite materials – A critical review,** *Journal of Materials Research and Technology*, Volume 13, Pages 1441-1484, ISSN 2238-7854, 2021. <https://doi.org/10.1016/j.jmrt.2021.05.076>.
- KABIR M.M., WANG H., LAU K.T., CARDONA F. **Chemical treatments on plant-based natural fibre reinforced polymer composites: An overview.** *Composites: Part B*, 43, 2883 – 2892, 2012.
- KUSMONO, HESTIAWAN H., JAMASRI. **The water absorption, mechanical and thermal properties of chemically treated woven fan palm reinforced polyester composites.** *Journal of Materials Research and Technology*, Volume 9, Issue 3, Pages 4410-4420, 2020. <https://doi.org/10.1016/j.jmrt.2020.02.065>.
- LIU D., SONG J., ANDERSON D.P. *et al.*, **Bamboo fiber and its reinforced composites: structure and properties.** *Cellulose* 19, 1449-1480, 2012. <https://doi.org/10.1007/s10570-012-9741-1>.
- MAHESHA G.T., SHENOY S. B., KINI V. M., PADMARAJA N.H., **Effect of fiber treatments on mechanical properties of Grewia serrulata bast fiber reinforced polyester composites.** *Materials Today: Proceedings*, Volume 5, Issue 1, Part 1, Pages 138-144, 2018. <https://doi.org/10.1016/j.matpr.2017.11.064>.
- MAYANDI K., RAJINI N., PITCHIPOO P., WINOWLIN JAPPES J.T., VARADA RAJULU A. **Properties of Untreated and Chemically Treated Cissus Quadrangularis Natural Fibers and Their Composites With Polyester as the Matrix.** *Polymer Composites*, Volume 39, Issue 3, Pages 876 – 886, 2018
- NUNNA P.S., CHANDRA R., SHRIVASTAVA S., JALAN A.K. **A review on mechanical behavior of natural fiber-based hybrid composites,** *J. Reinf. Plast. Compos.*, 31, 759-769, 2012
- MD. SAIFUL ISLAM, MD. MOYNUL ISLAM, **3 - Sustainable reinforcers for polymer composites**, Editor(s): Md. Rezaur Rahman, In *Woodhead Publishing Series in Composites Science and Engineering, Advances in Sustainable Polymer Composites*, Woodhead Publishing, 2021, Pages 59-88, ISBN 9780128203385, <https://doi.org/10.1016/B978-0-12-820338-5.00003-5>.
- MOHANTY A.K., MISRA M., HINRICHSSEN G. **Biofibres, biodegradable polymers and biocomposites: an overview.** *Macromol. Mater. Eng.* 266-277 (1), 1-24, 2000.
- PICKERING K. L., EFENDY M. A., LE T. M., **A review of recent developments in natural fibre composites and their mechanical performance.** *Composites Part A Applied Science Manufacturing*, 83, 98-112, 2016. <https://doi.org/10.1016/j.compositesa.2015.08.038>.
- PLUEDDEMANN E.P., **Silane Coupling Agents**, second ed., New York, Plenum Press, 1991.
- RAJESH G., SIRIPURAPU G., LELLA A. **Evaluating Tensile Properties of Successive Alkali Treated Continuous Pineapple Leaf Fiber Reinforced Polyester Composites.** *Materials Today: Proceedings*, Volume 5, Issue 5, Part 2, Pages 13146-13151, 2018. <https://doi.org/10.1016/j.matpr.2018.02.304>.
- SANJAY M.R., MADHU P., JAWAID M., SENTHAMARAIKANNAN P., SENTHIL S., PRADEEP S., 2018. **Characterization and properties of natural fiber polymer composites: a comprehensive review.** *J. Clean. Prod.* 172 (1), 566_581. Available from: <https://doi.org/10.1016/j.jclepro.2017.10.101>.
- SIVAKUMAR S., VIGNESH V., ARASU I. V., VENKATESAN G., RABI B. R. M., KHAN M. A., **Experimental investigation on tensile and flexural properties of randomly oriented treated palmyra fibre reinforced polyester composites.** *Materials Today: Proceedings*, 2021. <https://doi.org/10.1016/j.matpr.2021.01.511>.
- WIRAWAN W.A., CHOIRON M.A., SISWANTO E., WIDODO T.D. **Analysis of the fracture area of tensile test for natural woven fiber composites (hibiscus tiliaceus-polyester).** *Journal of Physics: Conference Series*, 1700 (1), 2020.

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