Al-Rafidain Journal of Engineering Sciences

Journal homepage https://rjes.iq/index.php/rjes

ISSN 3005-3153 (Online)

A Systematic Review of Natural Fiber-Reinforced Polymer Composites in Prosthetic Socket Fabrication

Mohammed Mohammed[1*], Tijjani Adam[2], Aeshah M. Mohammed[3], Jawad K. Oleiwi[4], and Bashir O. Betar[5]

[1] Faculty of Chemical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Arau 02600, Perlis, Malaysia
[2] Faculty of Electronics Engineering Technology, Universiti Malaysia Perlis, Kampus Uniciti Alam Sg. Chuchuh, 02100 Padang Besar (U), Perlis, Malaysia
[3] University of Bagdad College of Education for Pure Science Ibn-Alhaitham
[4] Department of Materials Engineering, University of Technology, Baghdad, Iraq
[5] Research Center (NANOCAT), University of Malaya, Kuala Lumpur 50603, Malaysia

ARTICLE INFO

Article history:
Received 11 December 2023
Revised 15 December 2023
Accepted 26 December 2023
Available online 03 January 2024

Keywords:
Prosthetics socket design
Natural fibers
Clinical performance
3D printing
Lower limb

ABSTRACT

This scholarly review meticulously scrutinizes the rapidly evolving domain of natural fibers-reinforced polymer (NFRP) composites in the fabrication of prosthetic sockets. It commences with an exploration of the historical evolution and the contemporary transition towards biocompatible materials in prosthetic development, placing particular emphasis on NFRP. It delves into the composition and properties of NFRP, detailing fiber types and composite characteristics. The review highlights the advantages of NFRP in prosthetics, notably their biocompatibility, sustainability, and mechanical properties that are pertinent to prosthetic applications. The technical aspects of fabricating prosthetic sockets with NFRP are examined, discussing both traditional and advanced manufacturing techniques and design considerations that take into account anatomical and biomechanical factors, as well as the need for customization. The clinical outcomes and user experiences with NFRP prosthetic sockets are evaluated, focusing on their durability, functionality, and comparison with traditional materials. User-centric perspectives, including comfort, satisfaction, and adaptation challenges, are also considered. Crucial challenges and limitations in the field are identified, such as technical and fabrication complexities, consistency, and quality control issues, as well as clinical and practical barriers like accessibility, cost, and the necessity for specialized training. The review highlights future research paths and needs in NFRP, focusing on innovations, technology integration The review emphasizes NFRP's key role in developing advanced, sustainable, user-friendly prosthetics.

[*] Corresponding author E-mail address: hmn7575@yahoo.com
https://doi.org/10.61268/dnr76d24

1. Introduction

Prosthetic socket fabrication has been a cornerstone in the field of prosthetics, serving as the critical link between the residual limb and the artificial prosthesis. Historically, the focus has been on creating sockets that offer a balance between durability and comfort, using materials like plastic and silicone [1,2]. The design and material selection are crucial, as they directly affect the fit, comfort, and overall functionality of the prosthetic limb. Socket fabrication has evolved through continual improvements in material technology and manufacturing techniques, aiming to provide better outcomes for prosthetic users [3].

In recent years, there has been a paradigm shift towards the use of sustainable and biocompatible materials in prosthetic design [4]. The need for environmentally friendly solutions and materials that are compatible with human tissue, minimizing the risk of skin irritation and allergic reactions, drives This transition [5]. Such materials also offer the potential for enhanced comfort and user acceptance, which are critical factors in the successful adaptation of a prosthetic limb.

The emergence of natural fiber-reinforced polymers (NFRP) in prosthetic socket fabrication represents a significant innovation in this domain [6]. NFRP, made from natural fibers embedded in polymer matrices, is gaining attention for its potential to combine the strength and flexibility of traditional materials with the added benefits of biocompatibility and sustainability.

The incorporation of NFRP into prosthetic sockets promises several potential benefits. These include improved material properties such as lightness and flexibility, reduced environmental impact, and enhanced user comfort [7]. Understanding the full scope of these benefits, as well as any limitations, is essential for advancing prosthetic socket technology. Furthermore, natural fibers (plant, animal, and agro fibers) have the potential to substitute synthetic fibers for prosthetic socket applications [8]. Additionally, the influence of pineapple leaf fiber orientation and volume fraction on a methyl methacrylate-based polymer matrix for prosthetic socket application has been studied, indicating the potential for natural fibers as an alternative reinforcing material to commonly used materials [9]. The use of natural fiber-reinforced polymers in prosthetic socket fabrication addresses certain drawbacks of synthetic composites, such as high moisture uptake and low thermal stability [10]. Furthermore, altering the types and numbers of reinforcing materials, with a focus on natural fibers, significantly influences the properties of composite prosthetic sockets. Flax fibers, for example, have been identified as potentially beneficial for prosthetic sockets, providing lightweight sockets that reduce vibrations transmitted to the body during movement [11].

This review systematically evaluates literature on NFRP in prosthetic socket fabrication, analyzing its composition, application, fabrication techniques, and clinical outcomes for users. Special attention will be given to how these materials contribute to the overall functionality and user experience of prosthetic sockets. We selected studies for this review based on specific criteria, including their relevance to NFRP in prosthetic socket fabrication, scientific rigor, and contribution to the field. Both experimental and observational studies, as well as reviews and case reports, will be considered. We will subject the selected studies to a comprehensive synthesis and analysis process. This entails categorizing studies by focus, assessing methodologies, and summarizing findings to clearly overview NFRP's current state in prosthetic socket fabrication.

2. Natural Fiber-Reinforced Polymers: An Overview

Natural fiber-reinforced polymers (NFRP) are an innovative class of composite materials that incorporate natural fibers as reinforcing agent within a polymer matrix. Commonly used natural fibers in these composites include flax, hemp, jute, sisal, and bamboo. These fibers are selected for their unique properties, such as their high strength-to-weight ratio, flexibility, and environmental sustainability [12]. Each type of fiber offers distinct characteristics for the composite, influencing its overall performance and suitability for specific applications in prosthetic socket fabrication. A simplified model of a fiber cell wall is depicted in Figure 1.

The polymer matrices in NFRP are typically thermosetting or thermoplastic polymers, which serve as the binding agents for the natural fibers. The interaction between the natural fibers and the polymer matrix is crucial, as it determines the composite's mechanical properties [13]. NFRP offers enhanced impact resistance, lighter weight, and greater tensile strength than traditional polymers materials, with adaptable properties for diverse prosthetic socket designs [14].

The mechanical properties of NFRP make them highly suitable for prosthetic applications [16]. Their strength-to-weight ratio is particularly beneficial in creating lightweight prosthetic sockets that do not compromise on durability or functionality [17]. Additionally, the natural fibers' inherent flexibility can be harnessed to produce sockets that allow for a more natural range of motion, enhancing the overall comfort and usability for the end user. The ability to customize the mechanical properties of NFRP based on the type and proportion of natural fibers used allows for a high degree of adaptability to diverse prosthetic needs [18].

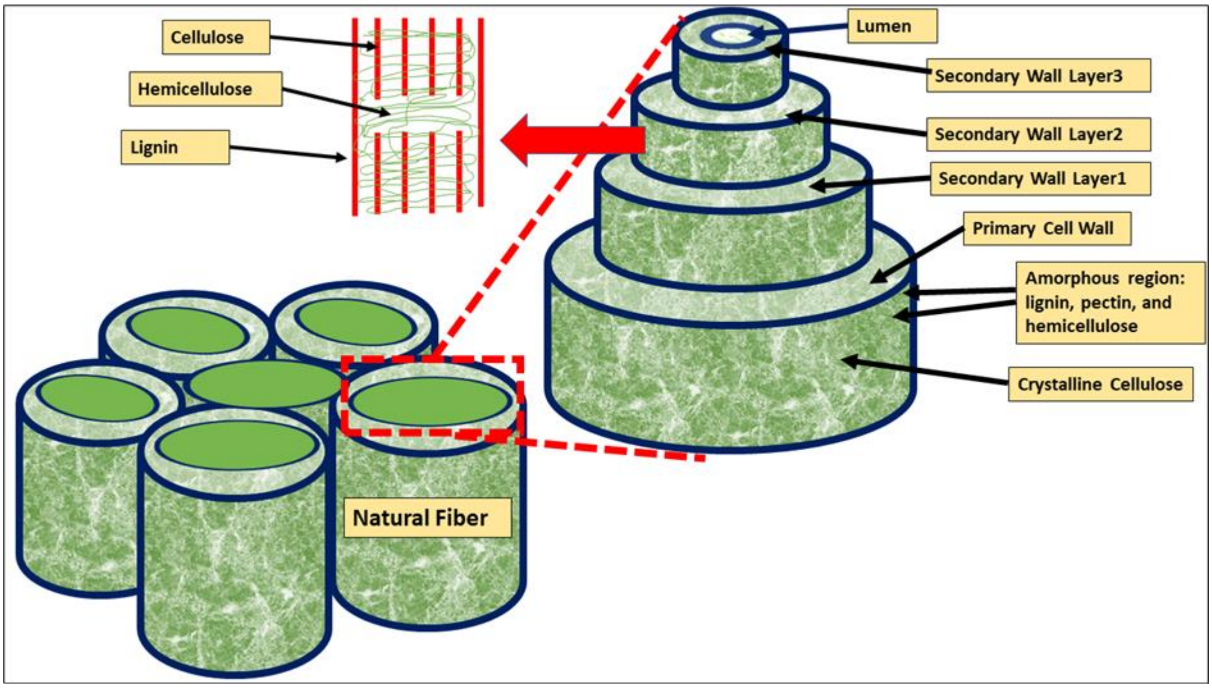

Figure 1. Schematic Representation of Structure of natural fiber

One of the most significant advantages of NFRP in prosthetics is their biocompatibility and sustainability. Natural fibers are renewable resources, offering an eco-friendly alternative to synthetic fibers [15]. Their biocompatibility is particularly important in prosthetics, as it reduces the risk of skin irritation and allergic reactions in users. This aspect is crucial for the long-term wear and comfort of prosthetic sockets, making NFRP an attractive choice for both users and manufacturers looking to embrace sustainable practices.

3. Prosthetic Socket Design with NFRP

The integration of natural fiber-reinforced polymers (NFRP) into prosthetic socket design involves innovative fabrication techniques. The most common method is the lay-up technique, where layers of natural fibers and polymer resin are manually arranged and then cured to form the composite. This method allows for the strategic placement of fibers to align with stress patterns in the prosthetic socket [19]. Another technique is resin transfer molding, where fibers are placed in a mold and resin is infused under pressure, creating a more uniform distribution of the matrix. These methods ensure that the natural fibers are adequately embedded within the polymer, enhancing the mechanical strength and durability of the prosthetic socket. The procedure for fabricating sockets using bamboo fiber epoxy composite is illustrated in Figure 2.

Recent advances in manufacturing technologies have significantly improved the fabrication of NFRP prosthetic sockets. 3D printing, also known as additive manufacturing, has emerged as a promising technique. It allows for the precise layering of NFRP materials, creating complex geometries that are difficult to achieve with traditional methods [20]. Computer-aided design (CAD) is often used in conjunction with 3D printing to model the socket before fabrication, ensuring a customized and accurate fit [21]. These technological advancements have not only streamlined the production process but have also opened new possibilities for innovative socket designs.

When designing prosthetic sockets with NFRP, it is crucial to consider both anatomical and biomechanical factors. The shape and size of the socket must conform closely to the residual limb to ensure a comfortable and secure fit. Biomechanically, the socket needs to distribute the load evenly across the limb, minimizing pressure points and reducing the risk of skin irritation [22]. NFRP can optimize its flexibility and strength to accommodate these biomechanical needs, providing adequate

Figure 2. Socket Fabrication Procedure Using Bamboo Fiber Epoxy Composite [24].

support while allowing for natural movement [23].

variability in fiber types and arrangements allows for a high degree of customization to meet individual user needs. Factors such as the user's activity level, limb shape, and personal preferences can be taken into account, tailoring the socket for optimal comfort and functionality. User feedback is integral to this process, informing adjustments and refinements in the design. This user-centric approach ensures that the prosthetic socket not only meets functional requirements but also aligns with the user's lifestyle and preferences.

4. Clinical Outcomes and User Experience

The efficacy of prosthetic sockets constructed from natural fiber-reinforced polymers (NFRP) is paramount in clinical settings, especially concerning their durability and functional performance [8]. The everyday demands imposed on prosthetic limbs need sockets to preserve structural integrity and durability under repetitive stress, and NFRP sockets have shown encouraging results in this regard. Another important result is functionality, which includes the capacity to carry out a range of tasks without pain or limitation. Research has shown that NFRP can provide the appropriate stiffness and flexibility needed for dynamic activities, implying a favourable effect on the overall functionality of the prosthesis [5].

In contrast to conventional materials such as thermoplastics and carbon fibre composites, NFRP presents a distinctive amalgamation of characteristics. Although conventional materials frequently demonstrate superior strength and light weight, NFRP distinguishes itself through its biocompatibility and potentially reduced expense [14]. However, a comparative analysis of NFRP with these conventional materials in clinical settings is necessary to fully understand their performance trade-offs. Such comparisons are crucial for determining the suitability of NFRP for various types of prosthetic applications.

User satisfaction and comfort are critical factors in determining the effectiveness of a prosthetic socket. The potential for improved comfort in NFRP receptacles has been demonstrated by their natural fibre composition, which provides enhanced breathability and diminished skin irritation in comparison to certain synthetic materials [25]. Users who have tried NFRP sockets have provided encouraging preliminary feedback, but more extensive studies are needed to ascertain broader user satisfaction levels.

The adoption of new materials like NFRP in prosthetic sockets can come with feedback and adaptation challenges. Users accustomed to traditional materials may experience a learning curve with NFRP sockets, both in terms of physical adaptation and expectations [25]. Gathering user feedback is crucial to identifying these challenges and addressing them in future design iterations. This feedback loop is essential for refining NFRP sockets to meet a wider range of user needs and preferences, ultimately enhancing the acceptance and success of these innovative prosthetics.

5. Challenges and Limitations

The fabrication of natural fiber-reinforced polymer (NFRP) composites for prosthetic sockets involves complex manufacturing processes that can present significant challenges [26]. The variability in natural fiber properties, such as fiber length, orientation, and moisture content, can affect the consistency of the composite material. Additionally, achieving a uniform distribution of fibers within the polymer matrix is crucial for material performance but can be difficult to control in practice. These complexities require precise manufacturing techniques and careful quality assurance to ensure the final product meets the required standards.

Consistency and quality control are paramount in the fabrication of NFRP prosthetic sockets. Variations in the material properties of NFRP can lead to inconsistencies in the performance and durability of the finished product. Ensuring a consistent quality of natural fibers and uniformity in the composite material is challenging but essential for the reliability of prosthetic sockets. Manufacturers must employ advanced manufacturing technologies and rigorous testing protocols to uphold high standards of quality and performance in NFRP prosthetic sockets [27].

While NFRP composites offer potential benefits in prosthetic socket fabrication, their accessibility and cost are significant considerations. The production of NFRP materials may involve specialized equipment and processes, potentially leading to higher costs compared to conventional materials. This can limit the availability and affordability of NFRP prosthetic sockets, especially in low-resource settings. Addressing these cost and accessibility issues is crucial for the wider adoption and impact of NFRP in prosthetics [28].

The successful integration of NFRP in prosthetic socket fabrication requires specialized training and expertise. Prosthetists and technicians need to be well-versed in the properties of NFRP, as well as the specific fabrication and fitting techniques required for these materials. This necessitates dedicated training programs and continuous professional development opportunities. Additionally, clinicians must be knowledgeable about the advantages and limitations of NFRP sockets to provide appropriate guidance and care to users [29].

6. Conclusion

This review concisely evaluates natural fiber-reinforced polymers (NFRP) in prosthetic socket fabrication, noting their rising prominence due to biocompatibility, sustainability, and mechanical superiority. Currently, NFRP shows potential in prosthetics, with ongoing research to optimize its use.

NFRP's advantages in prosthetics, such as eco-friendliness, improved user comfort, and customization potential, are tempered by challenges like manufacturing intricacies, quality consistency, and the need for specialized fabrication and fitting expertise, underscoring the need for ongoing research and development.

The future of prosthetics, shaped by NFRP development, focuses on sustainable, functional, and satisfying solutions. NFRP's integration into prosthetics aligns with eco-friendly healthcare and personalized medicine trends, heralding a new era where material innovation improves user quality of life and benefits the environment.

7. Future Directions and Research Needs

Future advancements in natural fiber-reinforced polymer (NFRP) composites are expected to focus on developing advanced formulations that enhance material properties. Innovations may include the optimization of fiber types, orientations, and treatments to improve the strength, durability, and flexibility of NFRP. Research into hybrid composites, which combine natural fibers with synthetic ones, could offer a balance of biocompatibility and mechanical performance. Additionally, the development of bio-based polymers as matrices in NFRP can further enhance environmental sustainability while maintaining or improving material performance.

The integration of NFRP with other emerging technologies presents a promising avenue for innovation. This includes the incorporation of smart materials and sensors within the NFRP matrix to create prosthetic sockets that can monitor and respond to changes in user activity, limb volume, and environmental conditions. Advanced manufacturing techniques like 3D bioprinting could revolutionize the fabrication of NFRP prosthetic sockets, enabling more precise customization and adaptation to individual user anatomy.

Bridging the gap between research and clinical practice is crucial for the successful implementation of NFRP in prosthetic socket fabrication. Translational research opportunities include conducting clinical trials to evaluate the efficacy and safety of NFRP sockets in real-world settings. Such research should focus not only on the immediate performance of these sockets but also on long-term outcomes, user satisfaction, and quality of life. This approach will help in validating the benefits of NFRP and identifying areas for further improvement.

Collaborative efforts between material scientists, engineers, and clinicians are essential to drive the development and clinical adoption of NFRP in prosthetics. Such collaborations can foster a multidisciplinary approach to addressing the challenges and leveraging the strengths of NFRP. Material scientists and engineers can provide insights into the properties and fabrication of NFRP, while clinicians can offer valuable perspectives on practical application and user needs. This collaborative approach is key to ensuring that innovations in NFRP are both technologically advanced and clinically relevant.

ACKNOWLEDGMENTS

The authors like to express their appreciation to the Faculty of Chemical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Special thanks to those who contributed to this project directly or indirectly.

References

[1] Andrysek, J. “Lower-limb prosthetic technologies in the developing world: A review of literature from 1994–2010”, *Prosthetics and orthotics international*, 34 (4), 378-398, 2010.

[2] Baars, E. and Geertzen, J. “Literature review of the possible advantages of silicon liner socket use in trans-tibial prostheses”, *Prosthetics and Orthotics International*, 29 (1), 27-37, 2005.

[3] Baer, G., & Fatone, S., “Scoping Review of Mechanical Testing of the Structural and Material Properties of Lower-Limb Prosthetic Sockets”, *JPO: Journal of Prosthetics and Orthotics*, 35 (2), e37-e47, 2023.

[4] Miller, L. A., Pickerill, T., & Kuiken, T. A. “A novel, low-cost transradial socket fabrication method using mass-producible components and expanding rigid foam” *Prosthetics and orthotics international*, 45 (1), 89-93, 2021.

[5] Kitila, L. G., & Wolla, D. W. “Fabrication, characterization, and simulation of hybrid flax-sisal fiber reinforced epoxy composite for prosthetic limb socket application” *Journal of Composite Materials*, 56 (10), 1605-1614, 2022.

[6] Pandey, J. K., Ahn, S. H., Lee, C. S., Mohanty, A. K., & Misra, M. “Recent advances in the application of natural fiber based composites” *Macromolecular materials and engineering*, 295 (11), 975-989, 2010

[7] Jagadish, Rajakumaran, M., & Ray, A. “Investigation on mechanical properties of pineapple leaf–based short fiber–reinforced polymer composite from selected Indian (northeastern part) cultivars” *Journal of Thermoplastic Composite Materials*, 33 (3), 324-342, 2020.

[8] Kumar, S., Bhowmik, S., & Mahakur, V. K.”Thermo-mechanical and degradation properties of naturally derived biocomposites for prosthesis applications: analysis of the interface pressure and stress distribution on the developed socket” *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, 237 (5), 2023.

[9] Gaba, E. W., Asimeng, B. O., Kaufmann, E. E., Foster, E. J., & Tiburu, E. K.”The influence of pineapple leaf fiber orientation and volume fraction on methyl methacrylate-based polymer matrix for prosthetic socket application” *Polymers*, 13 (19), 3381, 2021.

[10] Khan, M. Z., Srivastava, S. K., & Gupta, M. K.”Tensile and flexural properties of natural fiber reinforced polymer composites: A review” *Journal of Reinforced Plastics and Composites*, 37 (24), 1435-1455, 2018.

[11] Monette, D., Dumond, P., Chikhaoui, I., Nichols, P., & Lemaire, E. D. “Preliminary material evaluation of flax fibers for prosthetic socket fabrication” *Journal of Biomechanical Engineering*, 143 (2), 021006, 2021.

[12] Mohammed, M., Jawad, A. J. A. M., Mohammed, A. M., Oleiwi, J. K., Adam, T., Osman, A. F., & Jaafar, M. “Challenges and advancement in water absorption of natural fiber-reinforced polymer composites” *Polymer Testing*, 108083, 2023.

[13] Mohammed, M., Rahman, R., Mohammed, A. M., Betar, B. O., Osman, A. F., Adam, T., & Gopinath, S. C. “Improving hydrophobicity and compatibility between kenaf fiber and polymer composite by surface treatment with inorganic nanoparticles” *Arabian Journal of Chemistry*, 15 (11), 104233,2022.

[14] Mohammed, M., Oleiwi, J. K., Mohammed, A. M., Jawad, A. J. A. M., Osman, A. F., Adam, T., & Jaafar, M. “Comprehensive Insights on Mechanical Attributes of Natural-Synthetic Fibres in Polymer Composites” *Journal of Materials Research and Technology*. 2023.

[15] Mohammed, M., Rahman, R., Mohammed, A. M., Adam, T., Betar, B. O., Osman, A. F., & Dahham, O. S. “Surface treatment to improve water repellence and compatibility of natural fiber with polymer matrix: Recent advancement”, *Polymer Testing*, 107707, 2022.

[16] Bash, A. M., Othman, T. T., & Oleiwi, J. K. “Improving mechanical properties of laminated biocomposites for artificial lower limb socket”, *Tikrit Journal of Engineering Sciences*, 30 (3), 9-16, 2023.

[17] Faheed, N. K., Hamad, Q. A., & Oleiwi, J. K. “Enhancement of the flexural and impact properties laminated biocomposite by new natural fibres for artificial lower limb socket.”, *Advances in Materials and Processing Technologies*, 8 (4), 4347-4364, 2022.

[18] Oleiwi, J. K., Hamad, Q. A., & Abdulrahman, S. A. “Flexural, impact and max. shear stress properties of fibers composite for prosthetic socket”,

Materials Today: Proceedings, 56, 3121-3128, 2022.

[19] Odusote, J. K., & Oyewo, A. T. " Mechanical properties of pineapple leaf fiber reinforced polymer composites for application as a prosthetic socket.", *J. Eng. Technol*, 7 (1), 125-139, 2016.

[20] Nickel, E., Cataldo, A., Walker, N., Santa Ana, C., Barrons, K., Gravely, A., & Hansen, A. "Pilot Test of a Definitive Prosthetic Socket Made with 3D Printing Technology", *JPO: Journal of Prosthetics and Orthotics*, 2022.

[21] Nickel, E., Barrons, K., Hand, B., Cataldo, A., & Hansen, A. "Three-dimensional printing in prosthetics: Method for managing rapid limb volume change" *Prosthetics and Orthotics International*, 44 (5), 355-358, 2020.

[22] Sang, Y., Li, X., & Luo, Y. "Biomechanical design considerations for transradial prosthetic interface: A review "Proceedings of the Institution of Mechanical Engineers, Part H: *Journal of Engineering in Medicine*, 230 (3), 239-250, 2016.

[23] Paternò, L., Ibrahimi, M., Gruppioni, E., Menciassi, A., & Ricotti, L. "Sockets for limb prostheses: a review of existing technologies and open challenges" *IEEE Transactions on Biomedical Engineering*, 65 (9), 2018.

[24] Irawan, A. P., Sukania, I. W., Anggarina, P. T., Danendra, A. R., & Baskara, G. D. "Socket prosthesis manufacturing process made from bamboo fiber composite materials " *In IOP Conference Series: Materials Science and Engineering*, 852, 1, 012042, 2020.

[25] Mechi, S. A., Al-Waily, M., & Al-Khatat, A. "The mechanical properties of the lower limb socket material using natural fibers: a review" *In Materials Science Forum* (Vol. 1039, pp. 473-492, 2021.

[26] Kumar, S., & Bhowmik, S. "Potential use of natural fiber-reinforced polymer biocomposites in knee prostheses: a review on fair inclusion in amputees" *Iranian Polymer Journal*, 31 (10), 1297-1319, 2022.

[27] Faheed, N. K., Oleiwi, J. K., & Hamad, Q. A. "Effect of different fiber reinforcements on some properties of prosthetic socket" *Engineering and Technology Journal*, 39 (11), 1715-1726, 2021.

[28] Me, R. C., Ibrahim, R., & Tahir, P. M. "Natural based biocomposite material for prosthetic socket fabrication." *ALAM CIPTA, International Journal of Sustainable Tropical Design Research and Practice*, 5 (1), 2012.

[29] Bash, A. M., Oleiwi, J. K., & Othman, T. T. "A Review of some Characteristics of a Composite Hybrid Socket for Prosthetics Derived from Plant Fibers" *Key Engineering Materials*, 937, 99-106, 2022.