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An Overview of The Below Knee Prosthesis Socket Fabrication Made from Natural Fiber Composite

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Abstract

The prevalence of disability in Indonesia is considerable, necessitating a significant demand for prosthetic limbs. In addition, the global demand for prosthetics continues to increase due to several factors such as wars, disasters, and the prevalence of chronic diseases. This article provides a comprehensive overview of the techniques used for fabricating socket prostheses utilizing natural fiber composites based on various studies conducted. The findings from this study indicate that the manufacturing of prosthetic sockets requires consideration of characteristics such as comfort, functionality, biocompatibility, and flexibility. The utilization of natural fiber composites in the production of prosthetic sockets has several benefits, including cost-effectiveness, weight reduction, and biodegradation, making it a sustainable alternative for prosthetic socket fabrication. The utilization of natural fiber composites in the fabrication of socket prostheses has been the subject of much discussion, with particular emphasis on the influence of various matrices, reinforcing materials, and manufacturing methods on the characteristics and attributes of socket prostheses made from natural fiber composites. Natural fibers are utilized due to their notable attributes, including exceptional impact resistance, improved biocompatibility, superior strength-to-weight ratio, environmental sustainability, and economic advantages. Natural fiber composites are becoming a promising material for future prosthetic socket production.

1. Introduction

The high demand for prostheses worldwide can be attributed to wars, natural disasters, and chronic diseases [1]. The expected size of the worldwide Orthopedic Prosthetics Market is projected to increase from approximately USD 1.73 billion in 2021 to $1.96 billion in 2022. The market is expected to achieve a value of USD 3.97 billion by 2030, with a compound annual growth rate (CAGR) of 9.5% [2]. The prosthetic socket is a medical device that is specifically tailored for usage in individuals with certain morphological characteristics and medical disorders related to the amputated limb. This device was developed to accommodate the unique needs of these individuals, taking into consideration the various accessible options on the market [3–5]. The prosthetic socket constitutes an integral component of a prosthetic apparatus that is tailored to accommodate the specific state and anatomical structure of the amputated limb. Amputated limbs frequently arise as a consequence of many factors, such as diseases, injuries, or accidents. The prosthetic socket serves as a crucial structural element, functioning as the interface between the residual limb and the prosthetic device [6]. The socket facilitates the transmission of weight from the wearer to the other prosthetic member while ensuring the preservation of the health of the remaining limb tissue and enabling control of the prosthetic device [7]. The primary objective of utilizing this technology is to facilitate recovery and preserve the inherent functionality of the severed limb. Subsequently, the amputated limb will be substituted with a meticulously engineered prosthetic limb.

Indonesia exhibits a notable prevalence of individuals with disabilities throughout its population. Based on data from the National Socio-Economic Survey (Susenas) conducted in March 2019, it is estimated that around 9 percent of the Indonesian population, equivalent to roughly 23.3 million people, possesses a disability. Among this group, approximately 2.2 percent, or approximately 5.7 million individuals, are classified as having severe disabilities. In the specified year, the total number of individuals with disabilities amounted to 23,301,517. Moreover, it is noteworthy that approximately 85% to 90% of all instances of amputation pertain to the lower extremities [8]. Furthermore, it is worth mentioning that below-the-knee amputation stands out as the most commonly executed surgical treatment in this domain. The demand for prosthetic devices in Indonesia is currently substantial, although it remains disproportionate to the low manufacturing level.

Commercial below-knee prosthetic sockets are specifically engineered to establish a comfortable and secure connection between the residual limb and the prosthesis while effectively transmitting force. A significant number of individuals who wear prosthetics have significant difficulties as a result of discomfort experienced in the prosthetic socket. The high quality and comfort of the prosthetic socket are crucial in determining the user's daily wear time and preventing soft tissue injuries such as blisters and ulcers. There are various demands on prosthetic devices, including user comfort, excellent performance, biocompatibility, and versatility, to enable users to enjoy a standard quality of life that is as feasible. Recent advancements in socket technology, prioritizing cushioning as a factor in enhancing comfort in prosthetic sockets, have effectively alleviated pain in the user's remaining limb. A lightweight socket can enhance the user's comfort and improve energy efficiency [6]. Commercial below-knee prosthesis sockets display varying mechanical characteristics depending on the composite materials utilized in their production. Numerous research shows that prosthetic sockets constructed from composite materials, such as carbon fiber, perlon, glass fiber, and kenaf-glass fiber composites, have distinct features. As an illustration, the maximum stress and the stress at which deformation begins for carbon fiber sockets can vary from 135 MPa to 39 MPa [9,10]. In contrast, the kenaf-glass fiber composite exhibits a flexural strength of 7.11 MPa [11]. Although various prosthetic sockets are available for transfemoral amputees, they are generally created based on molds of the remaining limb. However, these sockets fail to consider the deformations of the soft tissues and the areas of high pressure that occur during activities like walking. Consequently, they can result in issues such as pressure ulcers, chronic skin problems, excessive stress on the joints, and a reduced overall quality of life for the amputee [12].

Nagarajan et al.'s (2024) research concluded that prosthetic sockets must adhere to the strength criteria outlined in ISO 10328 to withstand amputee patients' body weight adequately. The strength requirements are categorized into two levels: A100, which can withstand a maximum load of 100 kg, and A125, which can withstand a maximum load of 175 kg. Their findings also demonstrated that sockets constructed from materials such as SPLA meet, at minimum, the strength requirements of the A100 standard. Materials such as SPET, DGF, and DCF can surpass this requirement and satisfy the more rigorous A125 standard. The prosthetic socket must have the capacity to withstand loading within the range of 3020 N to 4426 N [13].

Developing a prosthetic device design is important to be able to provide support, enhance, or add functionality to the amputee limb for the user. A prosthesis refers to a device that serves as a substitute for a lower limb that has been amputated below the knee. On the other hand, a transfemoral prosthetic is designed to replace a leg that has been amputated above the knee. The core components of the transtibial prosthesis encompass a socket, tube, and foot, whereas transfemoral prostheses incorporate an additional knee joint [14]. The manufacture of prosthetic sockets must consider several factors such as comfort, optimal functionality, biocompatibility and flexibility.

Moreover, the importance of quality and comfort of the prosthetic socket is required to reduce soft tissue damage for the user [15]. A comprehensive understanding of the load conditions exerted on the user as well as the lifecycle of the socket is necessary to develop a prosthetic socket [16].

To achieve optimal fit and functionality with consistent success, it is imperative that the socket possess precise volume and shape, be lightweight, and be structurally aligned with the user's level of physical activity [17]. The objective is to mitigate the user's pain and facilitate the restoration of a standard level of well-being. Prosthetic sockets are often composed of thermoplastic or thermoset polymers, which are blended with different types of fibers to serve as reinforcement agents, transforming these materials into composite structures. Prosthetic sockets are predominantly fabricated using synthetic fiber-based polymer composites, with carbon fiber and glass being the prevailing materials of choice. The composite material has exceptional strength and stiffness characteristics while also possessing a lightweight nature. Furthermore, it demonstrates a superior strength-to-weight ratio [18].

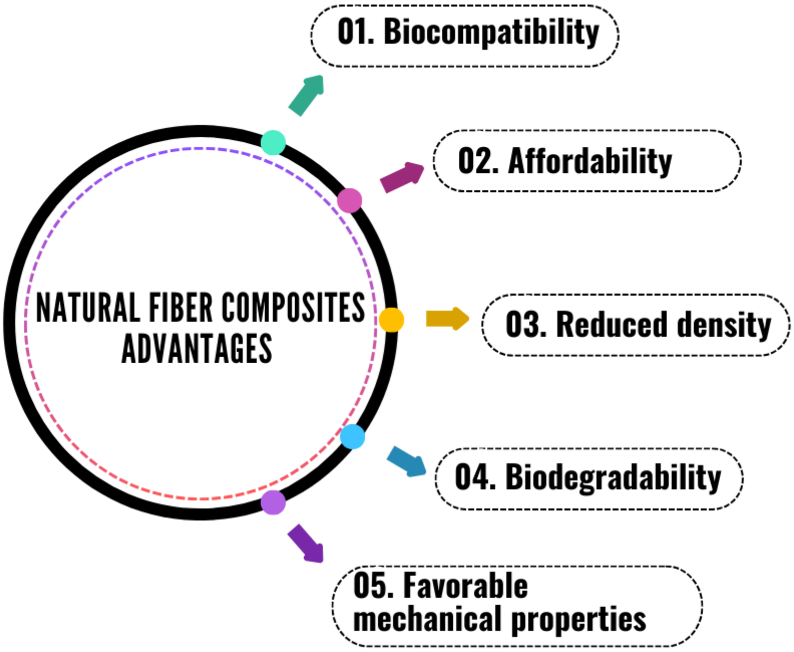

Fig. 1 *The advantages of natural fiber composites*

The composite material is often fabricated using a cotton blend to attain the desired levels of elasticity and quality for prosthetic devices. Currently, there is extensive utilization of natural fiber-based polymer composites as multiphase materials in the production of prosthetic sockets. The utilization of natural fibers is motivated by their notable attributes, including their exceptional impact resistance, favorable strength-to-weight ratio, enhanced biocompatibility, and economic advantages [19]. In additions, natural fiber composites provide numerous advantages in comparison to conventional synthetic materials when utilized in prosthetic sockets. These advantages include biocompatibility, affordability, reduced density, biodegradability, and favorable mechanical properties (Fig. 1) [20,21]. In addition to environmental factors, the utilization of natural fibers can be used to reduce production costs in the future because they are cheap, plentiful, and easily available [22–26].

The utilization of natural fibers, such as flax and jute, in the construction of prosthetic sockets has demonstrated encouraging outcomes in relation to the attenuation of vibrations and enhancement of mechanical robustness. Table 1 displays the physical and mechanical properties of the most widely used natural fibers. Despite the significance of these medical devices, there is a lack of standardized or widely acknowledged rules specifically dedicated to the manufacturing of sockets or their mechanical testing [1]. The preferred approach for evaluating and examining mechanisms within prosthetic sockets mostly relies on the ISO 10328:2016 standard [27]. According to ISO 10328:2016, the estimated time frame for the setup and execution of a single static test is 15 minutes. During this test, the machine operates using force control, and a load is continuously applied at a consistent speed ranging from 100 to 250 N/s until the socket fails. The ultimate load at failure is compared to loading levels P5 and P6, which correspond to 4025 and 4425 N, respectively. Sockets that do not meet the requirement of condition P5 (4025 N) are determined to have failed the test. Sockets that achieved the

P5 loading criteria but did not reach P6 (failure occurring between 4025 and 4425 N) were classified as borderline.

Sockets that achieve a loading level of P6 (4425 N) or greater have been considered to have passed the test. According to a licensed prosthetist from the INAIL Prosthetic Center, attachments that weigh more than 600 g have been considered redundant. Sockets with mechanical strength above P6 and weighing more than 600 g are classified as over-dimensioned. If multiple alternatives yield identical outcomes in load and weight, the selected option has the most straightforward structure, involving less material and a simpler layout [17].

Table 1 *The physical and mechanical properties of the natural fibers* [26,28]

No	Natural Fibers	Young's modulus (GPa)	Tensile strength (MPa)	Density (g/cm^3)
1	Sugarcane	15-18	257.3-290.5	0.31-1.25
2	Softwood	40	1000	1.5
3	Sisal	9.0–38.0	400–700	1.33–1.5
4	Rice straw	24.67-26.33	435-450	0.86-0.87
5	Rice husk	-	-	0.50–0.70
6	Ramie	44–128	220–938	1.5
7	Pineapple	5.51-6.76	166-175	1.25-1.60
8	Palm kernel shell (PKS)	2.7-3.2	227.5-278.4	0.93-2.3
9	Kenaf	-	295	1.2
10	Jute	10–30	393–800	1.3–1.46
11	Hemp	70	550–900	1.48
12	Flax	27.6–80	345–1500	1.4–1.5
13	Cotton	5.50–12.60	287–597	1.50–1.51
14	Coconut (coir)	4–6	173.5-175.0	0.67-1.15
15	Bamboo	22.2–54.2	360.5–590.3	0.6–1.1
16	Abaca	31.10–33.60	430–813	1.5

The objective of this review is to assess the suitability of natural fiber composites as alternative materials for the socket below knee prosthesis. This study establishes the basis for future studies and developments by comprehensively analyzing the attributes, production techniques, benefits, and drawbacks of natural fiber composites. Furthermore, this review also presents the minimum criteria that natural fiber composites have to meet as materials for the socket below knee prosthesis. This study supports creating and manufacturing cost-effective, eco-friendly, and high-performing prosthetic devices, ultimately enhancing the quality of life for individuals who have experienced limb loss.

2. Natural Fiber Composite Prosthetic Socket

Kahtan Al-Khazraji et al. (2012) conducted a comprehensive study on the utilization of different forms of reinforcement in laminated composite materials to produce prosthetic sockets for lower limbs. They created five laminated composite materials to produce lower-limb prosthetic sockets through vacuum molding. The composites were made of Epoxy matrix material. They were reinforced with five woven fibers and particles: perlon, glass, carbon, hybrid (carbon and glass), and hybrid (carbon and drink) with micro & nano silica particles. Additionally, their research highlights using the finite element technique (ANSYS-11) to scrutinize and assess fatigue features. Their study showed that the alteration in the reinforcement form significantly impacted the evaluated attributes of the laminated composite materials used for manufacturing lower-limb prosthetic sockets. Moreover, according to their research, composites made of epoxy and carbon reinforcement yielded the most favorable experimental, numerical, and theoretical outcomes, making them the ideal choice for enhancing the fatigue features of trans-tibial prosthetic sockets [29].

Irawan et al. (2015) analyzed lower limb prostheses that employed sockets reinforced with rattan fiber-reinforced epoxy composites. Their study revealed that the Rattan Fiber Reinforced Epoxy Composites (RFREC) materials possess ample potential for further development as socket prosthesis materials. Their study utilized the mat lamination method, incorporating a pressure and vacuum process (-50 bar) to eliminate any cavities in socket manufacturing. Various tests, including compressive load tests, gait analysis, and physical analysis, were conducted as a part of their research. The results demonstrated that multiple factors were within normal ranges, such as walking speed, cadence, step width, stride length, stride total, and walking length total. Furthermore, the measured pulse rate before and following testing showed no significant difference. In light of these findings, the study suggests that RFREC materials may be utilized as prosthesis socket materials [30].

Mankai et al. (2021) conducted the feasibility of using natural fibers derived from alpha plants as a substitute for expensive synthetic fibers in producing transtibial sockets for prosthetic limbs. Their study employs static and dynamic testing methods to scrutinize the performance of transtibial sockets made of alpha and carbon fibers. Static testing determines the socket's final strength, while dynamic testing, such as fatigue testing, assesses its durability and resistance to repeated loading. Their analysis reveals that the ultimate power attained during static tests on the carbon and alpha fiber sockets was 3,400 and 2,900 N, respectively. Fatigue testing on the alpha fiber socket resulted in fatigue life of approximately 2,325,000 cycles. Based on the static tests, alpha fiber can replace conventional reinforcement materials in orthopedic applications like transtibial sockets. The findings of this study can serve as the initial step toward establishing specific standards for socket testing, particularly fatigue testing.

Further evaluations, such as compression and economic feasibility tests, should be conducted to determine the cost of socket-reinforced prostheses made with alpha fiber nonwovens compared to other fibers [31].

Gashawtena et al. (2021) evaluate the various materials used to fabricate lower limb prosthetic sockets at a cheaper cost. Their research will look into the viability of using alternative materials to make low-cost prosthetic sockets that are robust, sturdy, and comfortable for patients. Their study found that prosthetic sockets built of biodegradable natural fiber-reinforced polymer and metal composites were less expensive, less stiff, and more comfortable for patients than typical synthetic fiber-polymer composites. Because of their excellent mechanical qualities, hemp, kenaf, pineapple, and banana fiber-reinforced polymer matrix composites were mentioned as future possibilities for prosthetic socket applications in their study. Furthermore, their study discussed using SiO_2 nanoparticles as a synthetic fiber-reinforced prosthetic socket reinforcement material. This minimizes stress distribution and deformation, creating a more solid and resistant prosthetic socket [32].

Faheed et al. (2022) discuss using natural fibers as a substitute for creating a below-knee prosthesis socket. Their research looks at the impact of different fiber stacking patterns on a laminated bio composite's physical and mechanical properties. The epoxy and PMMA matrix materials employed in their investigation were reinforced with woven flax, sisal, cotton, carbon, and glass fiber created in the laminates. The process involves placing the composite material in a vacuum bag and removing the air to create a vacuum. The vacuum compresses the composite material and forces the resin to flow into the fibers, resulting in a strong and uniform composite. Their findings revealed that different reinforcing materials considerably impacted the properties of manufactured composites, with the virtues of flexural strength, flexural modulus, and maximum forces. As the volume proportion of materials grew, so did shear stress, impact strength, and fracture toughness. Their research also discovered that the prosthesis socket archetype made of lamination materials could be regarded as a substitute artefact that clients can use with a safe and satisfying goal, as well as positively impacting the use of natural materials that are environmentally friendly and can be reused [33].

Mechi et al. (2021) investigated the use of natural fibers in the manufacture of prosthetic sockets. Their study highlights recommended techniques for building natural fiber-based socket industries to address hot and humid regions using materials like kenaf and other natural fibers. According to the findings, previous research has investigated using polymer composites reinforced with glass, carbon fiber, and Kevlar fibers to fabricate prosthetic sockets. On the other hand, natural fibers are gaining popularity as reinforcements in these composite materials. It is now feasible to change the mechanical properties of sockets while lowering production costs by adding natural fibers into resin matrices or inserting nanomaterials. Comprehensive research was done to acquire insights into the socket models used in developing nations, focusing on design, modelling, and finite element analysis (FEA). Their study aims to evaluate and assess existing socket designs, laying the groundwork for future developments in prosthetic socket technology for those in low-income situations [34].

Widayat et al. (2021) conducted a study to assess the bending and impact strength of Co/G/Co and C/G/C composites commonly used by Garuda Medica for making prosthetic sockets. Their study focused on two types of reinforcement fibers: glass fiber and carbon fiber, incorporated into the Co/G/Co and C/G/C composites. The composites were fabricated using the hand layup method, with different layer variations (2/1/2 and 4/2/4) for each composite. The results indicated that increasing the number of laminate layers and replacing the outer laminate contributed to enhanced composite strength. Substituting cotton with carbon as the outer laminate led to improved stability. Among the composites, the [Co2/G/Co2] variant demonstrated the lowest impact strength but still met the required standards for socket impact strength. However, considering the power and classification of the constituent laminates, the stacking sequence of Co/G/Co and C/G/C is not recommended.

Their study emphasizes the importance of material property data for ensuring optimal prosthetic practices and establishing product standards. Access to accurate information and specifications enables producers and consumers to make informed decisions [35]. Campbell et al. (2012) conducted a study to explore the viability of utilizing a renewable plant oil-based polycarbonate-polyurethane copolymer resin and plant fiber composite for prosthetic limb sockets. They conducted experiments to determine suitable combinations of resin and plant fibers by evaluating the tensile strengths of various test pieces. They then fabricated test sockets using stockinette woven from the most effective yarn and compared them to conventional ones. A reusable plaster mold of the individual's residual limb was utilized to create the socket, and a plastic mold was generated from it.

The plant-based resin and ramie fiber stockinette was then applied to the plaster mold to form the socket. The findings indicated that incorporating plant resin with either banana or ramie fibers led to composite materials exhibiting superior tensile strengths. Furthermore, the performance of the conventional composite material socket and the plant resin with ramie composite socket demonstrated similar failure loadings, surpassing the ISO 10328 standard. Their study also emphasized the significance of wall thickness and the adhesion between fibers and the matrix in determining the overall strength of the socket. These results underscore the importance of considering wall thickness and fiber-matrix adhesion to enhance composite sockets' strength [1].

Widhata et al. (2019) investigated the potential use of water hyacinth fiber composites as an alternative to the standard layup for fabricating trans-femoral sockets. Their primary objective was to evaluate the structural performance of water hyacinth fibers as reinforcing materials in socket production.

Tensile and compressive flexural tests were conducted on water hyacinth fiber composites laminated with methyl methacrylate resin. The results showed no significant difference in strength and flexibility between water hyacinth fibers and the commonly used nylon glass fiber in orthopedic technology. This suggests that water hyacinth fibers, with their renewable and readily available nature, have the potential to provide a safer manufacturing option for artificial limb sockets without compromising their strength, thereby benefiting users. Their study also identified that factors such as wall thickness, fiber direction, and fiber-matrix resin lamination played significant roles in determining the strength of the sockets [36].

Jawaid et al. (2017) examine the utilization of fiber-reinforced composite materials in prosthetic applications. Their research encompasses a comprehensive review of the current designs of prosthetic sockets, highlighting their structure and functionality, as well as the importance of considering the comfort of the residual limb within the socket. Their study aims to guide designers in enhancing contemporary prosthetic socket designs, considering factors such as the environment and the individual's condition to improve the quality of life and facilitate a more normal existence for amputees. The findings emphasize that fiber-reinforced composites are extensively employed in upper and lower-limb prostheses due to their outstanding strength and excellent biocompatibility. Additionally, ensuring patient satisfaction and incorporating comfort measurements for the residual limb within the prosthetic socket are pivotal aspects to consider. It is worth noting that ongoing technological advancements have significantly broadened the array of modern orthopedic and prosthetic devices available, granting individuals a more comprehensive range of options tailored to their specific requirements [37].

Odusote et al. (2016) examined the mechanical properties of thermoset composites reinforced with pineapple leaf fibers. The primary objective of their research was to develop a lower limb prosthetic socket using polymers supported with agricultural wastes, specifically pineapple leaf fibers. This aim aimed to provide an eco-friendly alternative to prosthetic sockets reinforced with non-recyclable synthetic fibers. In their study, continuous pineapple leaf fibers were treated with sodium hydroxide and acetic acid and incorporated into epoxy and polyester matrices using the hand lay-up method to create fiber-reinforced composites. Their principal findings indicated that pineapple leaf fiber-reinforced thermoset composites showed great potential as a substitute for fiberglass polyester prosthetic sockets, particularly for above-knee sockets that require higher strength. Their study revealed that pineapple leaf fiber-reinforced composites, especially at a 40% fiber loading, exhibited superior mechanical properties to those of fiberglass polyester composites [38].

Nurhanisah et al. (2018) studied kenaf woven fabric composites, aiming to replace traditional glass cloth-based polymer composites. They utilised the lamination method to assess how the layering order of kenaf fabrics affected the volumetric and mechanical properties containing woven kenaf, glass-silk knitted fabric, and nylon knitted fabric as reinforcement. Their findings revealed that a 2-layer laminate made of kenaf fiber exhibited higher flexural and impact strength than a composite with a single layer of kenaf fiber. They concluded that woven kenaf composites hold the potential to replace conventional glass-based polymer composites, offering a biodegradable, environmentally friendly, locally available, lightweight, comfortable, and socially acceptable option for prosthetic sockets [39].

Che Me et al. (2012) suggest using biocomposites from natural fibers to produce prosthetic sockets. Their investigation demonstrated that natural fiber-based biocomposites, particularly kenaf-derived ones, could be viable alternatives for fabricating prosthetic sockets. They proposed a lamination method using these biocomposite materials for the prosthetic foot socket. The materials presented were cost-effective, environmentally friendly, and comparable in quality to the conventional materials used in various applications. Their study concluded that utilizing alternative materials to manufacture prosthetic sockets could greatly benefit young individuals who face challenges in meeting their basic needs, allowing them to lead more independent lives [40].

Alwan et al. (2019) developed a comprehensive database of material properties for laminates commonly employed in below-the-knee prosthetic sockets. Experimenting with different fiber and resin combinations showed that the prosthetic socket constructed with 12 carbon and perlon fiber layers exhibited the highest tensile and flexural strength. Moreover, they observed that the 12-layer composite demonstrated superior tensile and fatigue characteristics compared to the 8-layer composite. To understand the fatigue behavior of the samples and their relative correlation factors, they provided equations derived from their study. They utilized a vacuum technique during specimen fabrication, which effectively prevented the occurrence of cavities or defects. Their research aims to enhance the physical, mechanical, and overall properties of composite materials employed in prosthetic sockets, contributing to technological advancements [41]. Abdulrahman et al. (2021) conducted a study exploring the fabrication of prosthetic sockets using various laminated composite materials, specifically fiber-reinforced polymers, to create designs that offer high strength and durability. They employed polyester resins reinforced with Jute, carbon, glass, and perlon fibers to create seven laminated composites through a vacuum molding technique. Their investigation's main objective was to enhance prosthetic sockets' performance by examining the influence of the number of layers of hemp reinforcing fiber and the impact of adding glass or carbon to the best lamination on the mechanical and physical properties.

Their study revealed that the most effective laminated composite specimens consisted of three layers of jute fiber with four layers of carbon, boasting a compressive strength of 67 MPa and a hardness of 86 Shore-D. Additionally, they demonstrated that utilizing natural fibers like jute as an alternative to synthetic fibers in composite prosthetic sockets can lead to increased compression strength and decreased density, making it a promising approach for enhancing the performance of prosthetic socket designs [42].

Oleiwi et al. (2022) performed a comparative study on fiber-reinforced laminated polymer composites, analyzing various prosthetic sockets using DSC (Differential Scanning Calorimetry) and FTIR (Fourier Transform Infrared) spectroscopy. They aimed to investigate the interaction between the fibers and the matrix material. FTIR spectroscopy examined the composite specimens' interaction between the fiber and the matrix material. On the other hand, the DSC tests were conducted to evaluate different laminated blended fabrics for prosthetic sockets. Regarding the FTIR results, no new peaks were observed in the polyester composite specimens containing natural and synthetic fibers, indicating a lack of additional chemical interactions. Conversely, the DSC results revealed that the glass transition temperature (Tg) increased with the number of jute fiber layers in the composite. The composite specimen reinforced with three layers of jute fiber and four layers of carbon fiber (3 jute + 4 carbon) exhibited the highest Tg at 107°C [43].

Abbas et al. (2020) investigated the impact strength and toughness of diverse fibers and resins utilized in laminated grooved composites to produce prosthetic sockets. Their research's primary objective was to assess these materials' efficacy in withstanding impact loads and preventing fractures. Their study shed light on standard fabrication methods for creating samples involving combinations of glass, Kevlar, and carbon fibers with three types of resins and various layering arrangements. Their results demonstrated that models incorporating laminated layers (4 perlon + 4 kevlar + 4 perlon) exhibited favorable ultimate stress and elastic modulus, along with acceptable impact energy, toughness, and fracture toughness when using acrylic resin. Their research concluded with recommendations for rehabilitation centres to consider using Kevlar fibers for manufacturing sockets, as they effectively absorb energy and act as impact absorbers [44].

Quintero-Quiroz et al. (2019) documented various polymers used in lower limb sockets, external prosthetic, and orthotic interfaces, and their functional requirements and potential skin problems. They conducted a comprehensive literature review covering material needs, device advances, and common skin issues associated with these devices. They highlighted the importance of mechanical properties in supporting the gait cycle and avoiding negative impacts on device use. These interfaces' safety, durability, and patient well-being were critical functional requirements. They stressed using durable composite materials to prevent skin damage and control temperature and humidity at contact points. They also emphasized the need for collaborative research and development of such materials [45]

Abbas et al. (2019) investigate how different composite material layers affect the mechanical properties of partial leg prosthetic sockets. They examined the tensile and fatigue properties of nine laminated composite materials in these sockets. The researchers utilized a vacuum pressure system to fabricate a portion of the prosthetic socket. The composite materials were reinforced with various laminates, including perlon, n-glass, fiberglass, and carbon, with varying thicknesses according to the laminates. Their findings revealed that increasing the number of layers of carbon fiber, glass fiber, and n-glass enhanced the mechanical properties of the socket. The optimal combination of mechanical properties was achieved with a lamination comprising three layers of perlon, two layers of carbon fiber, and three layers of perlon. These laminates also demonstrated higher wear resistance limits, increasing the lifespan of prosthetic socket patients. Their study provides valuable data for creating suitable laminations for partial leg prosthetic sockets for patients with below-ankle amputations [46].

Chiad et al. (2017) embarked on developing an enhanced prosthetic socket by incorporating bamboo fiber for a prosthetic sheath socket. Their research focused on creating prosthetic sockets for above-the-knee amputations, using a four-ply lamination process with bamboo and carbon fiber as reinforcement. Their analysis involved conducting tensile and fatigue tests and pressure interference tests between the patient's residual limb and the socket. The results demonstrated a significant improvement in yield stress, tensile stress, Young's modulus, and stress resistance, with increases of 20.1%, 162.7%, 0.80%, and 0.241%, respectively. To further assess the socket's performance, they conducted simulations using the ANSYS 14.5 program to analyze stress and deformation. The simulations revealed an enhanced safety factor, increasing from 0.998 to 3.85, and a reduction in the maximum deformation from 10 mm to 5.5 mm when using the proposed material. In conclusion, their novel material has the potential to enhance the mechanical and physical properties of the prosthetic socket, resulting in a lighter, more cost-effective, and easier-to-fabricate design [47].

Monette et al. (2021) conducted an assessment of hemp fibers for the fabrication of prosthetic sockets. Hemp fiber, a renewable natural resource and a cost-effective alternative to synthetic fibers, was claimed to possess remarkable vibration-dampening properties. Their study used epoxy and acrylic resins as matrices, with hemp fiber as the composite prosthetic socket's reinforcement. To evaluate hybrid lining options, they utilized traditional socket manufacturing methods and the Vacuum Assisted Resin Transfer Molding (VARTM) process to create flat and socket-shaped composite samples.

Their results indicated that composite sockets made solely from hemp fiber were lighter and exhibited superior vibration-damping capabilities, reducing vibration amplification by nearly four times compared to sockets made solely from carbon fiber. However, hemp sockets fabricated using traditional socket manufacturing methods demonstrated bending stiffness, elastic modulus, and flexural strength ten times lower than the theoretical values reported for hemp composites in the existing literature. They suggested that by increasing the fiber volume fraction in the traditional socket manufacturing process, the mechanical properties composite's mechanical properties, especially vibration dampening, further explore the advantages of using hemp fiber [21].

Abdulsadah et al. (2019) explored using carbon fiber composites as a material for Chopart prosthetic sockets. They conducted a comparative study between carbon fiber composites and the commonly used polyethene materials for prosthetic sockets. They developed and tested a 3Perlon-2Karbon-3Perlon carbon fiber laminate with 80:20 polyurethane reinforcement and c-orthocryl laminating resin and compared its mechanical properties to polyethene. They employed a vacuum molding method with gypsum molds to fabricate the laminated carbon fiber composites. Their study revealed that carbon fiber exhibited higher yield stress and final strength than polyethene. Additionally, they utilized finite element modelling to analyze stresses and deformations in the Chopart prosthetic socket. Their simulations demonstrated that carbon fiber reduced stress by 70.6% compared to polyethene. Based on their findings, the study concluded that carbon fiber is a mechanically superior material for Chopart prosthetic socket designs compared to polyethene [48].

Hamad et al. (2023) conducted an experimental investigation into the behavior of various fiber-reinforced laminated composite materials used as base materials for prosthetic sockets. Their research involved working with seven laminated composites created by vacuum bagging. These composites were composed of polyester resin as the binding matrix, reinforced with ramie, glass, carbon, and perlon fibers. The laminate specimens were subjected to mechanical tensile tests, including Tensile Strength, Young's Modulus, and Percent Elongation. Physical examinations, such as density measurements, were also conducted to assess specific strength and modulus. Their findings revealed that the best laminated composite specimen consisted of three layers of Jute with four layers of Carbon fiber, exhibiting a tensile strength of 162 MPa and a modulus of elasticity of 3.60 GPa. The specific power and modulus were measured to be 134 MPa.cm^3/gm and 2.544 GPa.cm^3/gm, respectively. Additionally, the SEM results indicated a transformation from a brittle to semi-ductile behavior in the composite [49].

Yogeshvaran et al. (2023) assessed the strength of PET composite prosthetic sockets. In their study, they utilized polyethene terephthalate (PET) as a matrix and reinforced it with PET fibers to create functional lower limb prosthetic sockets using PET fiber-reinforced composites. They employed a vacuum-assisted resin transfer molding (VARTM) process to fabricate these composites, producing two types of PET fiber-reinforced composites with woven and knitted fabrics. They compared these PET-based composites with traditional prosthetic socket materials, such as laminated composites (glass fiber-reinforced) and monolithic thermoplastics (polypropylene (PP) and high-density polyethene (HDPE)). Their study demonstrated that PET-based composites could replace monolithic socket materials in creating durable and cost-effective prostheses. Static structural tests showed that the PETW and PETK sockets met the 125 kg load-bearing capacity target. Moreover, PETW and PETK sockets exhibited higher resistance to deformation and greater rigidity compared to monolithic sockets made of PP and HDPE. Based on their findings, the researchers recommended conducting field trials with amputees to assess the effectiveness of PET fiber-reinforced composites in producing durable prosthetics, especially in resource-constrained countries [50].

Sankaran et al. (2022) have designed and manufactured biocompatible sockets for transfemoral amputees using cutting-edge composite materials. They have developed innovative materials by combining nature-based fibers with a polymer matrix for socket fabrication. Jute fiber was the reinforcing material due to its favorable mechanical and thermal properties. The polymer matrix used is epoxy, which belongs to the polymer family and is known for its moisture resistance and low shrinkage properties. The socket casting process involves a simple hand lay-up method. The resulting Jute fiber-reinforced epoxy composite (JFREC) exhibits higher Ultimate Tensile Strength (UTS) and stiffness than other fibers like perlon, glass, spectral one, nylon, cotton, and glass.

The composite samples demonstrated a remarkable 82% increase in strength when subjected to compressive and impact strength tests. Moreover, the prototype sockets resisted regular water and seawater [20].

Irawan et al. (2011) developed socket prostheses using natural fibers, particularly hemp fiber-reinforced epoxy composites (RE). Their research aimed to replace a fiberglass composite polyester (FGP) socket prosthesis with a new RE material. The filament winding method produced a prototype socket prosthesis, and tensile and flexure tests were performed on the specimens. Their results showed that the RE composite had the highest tensile and flexural strength compared to RP and FGP materials. The tensile strength and Young RE modulus were measured to be 86 ± 6.07 MPa and 9.56 GPa, respectively, while the flexural strength was 103 ± 15.62 MPa. They concluded that RE composites can be an alternative material for socket prostheses due to their locally available, biomechanically appropriate, lightweight, comfortable and psychosocially acceptable properties. The process involves dry rolling with a fiber-to-matrix ratio of 40:60 by weight at room temperature, with pressure and vacuum applied throughout the lamination to minimize voids.

The resulting socket prosthesis (RE) prototype has six layers, symmetrical fiber orientation, and a thickness of 4 mm. A 1:1 mix of epoxy and hardener was used for this prototype. The socket prosthesis (RP) prototype also has six layers, symmetrical fiber orientation, and is 4 mm thick, with 2% hardener mixed with polyester. On the other hand, FGP composite laminates are produced via a hand lay-up process with a thickness of 4 mm, using pressure and vacuum during lamination for cavity reduction [51].

Ahmed et al. (2022) addressed the necessity for alternative materials in prosthetic sockets to overcome the limitations of current rigid and inadequate options. They proposed using renewable, low-hazard, cost-effective natural fibers combined with shell nanoparticles as an alternative to conventional reinforcement materials. The mechanical properties of the biobased epoxy reinforced by hemp fibers and shell nanoparticles were assessed through tensile and flexural tests, with further analysis using the finite element technique. Their results demonstrated that the nanocomposite displayed higher tensile and flexural strength than additive-free biobased epoxy. The hybrid nanocomposite, consisting of three layers of hemp fiber and three wt% shell nanoparticles, exhibited the highest mechanical properties compared to unmodified resin and biobased epoxy filled with other reinforcement percentages. Additionally, the composite system demonstrated effective antibacterial activity against various pathogenic microorganisms. Based on their findings, the researchers concluded that this fabricated hybrid system shows promise as a candidate for a prosthetic socket due to its favorable and antibacterial properties, cost-effectiveness, and availability. However, further testing and evaluation in real-life situations, such as daily activities, are needed to confirm its effectiveness as a candidate for a transtibial prosthetic socket [52].

Jamiu et al. (2016) explore using natural plant fibers, particularly banana pseudostem fibers, as reinforcement in environmentally friendly polymer composites. Their research aims to assess banana pseudostem-reinforced epoxy composites' tensile, flexural, and hardness properties as a potential replacement for synthetic glass fibers in transtibial prosthetic sockets. Banana pseudostem fiber is known for its strength, lightweight nature, and cost-effectiveness, as it is often considered waste material. Their findings showed that the mechanical properties of the epoxy composite improved by up to 50% with the addition of banana pseudostem fibers, with the best performance observed at a 40% fiber loading compared to higher values. The banana pseudostem composites exhibited higher mechanical strength than glass fiber composites, particularly at 40% and 50% fiber loading, surpassing the power of 30% glass fiber loading. In conclusion, their study suggests that banana pseudostem epoxy composites (BPEC) have the potential to serve as a suitable substitute for polyester fiberglass prosthetic sockets due to their superior strength compared to glass fiber composites. The materials used in their research included banana pseudostem fiber, epoxy resin (TKL 121), glass fiber, polyester resin, cobalt naphthenate catalyst, Methyl ethyl ketone peroxide (MEKP) hardener, sodium hydroxide (NaOH), acetic acid, polyvinyl acetate, and ethanol. They utilized the hand-lay-up method with various fiber ratios (0, 20, 30, 40, and 50%) to manually prepare composite samples and compared the results with a 30% glass fiber polyester composite (GFPC) produced in their study [53].

Gaba et al. (2021) investigated the utilization of pineapple leaf fiber (PALF) as an affordable alternative for producing prosthetic sockets. Their research focused on identifying composites' optimal strength and stiffness suitable for potential prosthetic socket applications based on fiber volume fraction and orientation. For their study, they used a matrix composed of Methyl methacrylate-based Prosthetic lamination resin (Orthocryl lamination resin), consisting of 40-70% Methyl methacrylate (MMA) and 0.1-1% N, N-Bis(2-hydroxypropyl)-p-toluidine, which acted as a hardener. The reinforcement material employed in their investigation was pineapple leaf fiber (PALF). Their research findings indicated that the PALF/MMA composite with 0° fiber orientation and 40% fiber volume fraction exhibited the highest flexural strength and stiffness, making it suitable for transferring socket-limb loads during prosthetic socket fabrication. Furthermore, PALF, being a low-cost option, could be employed as an alternative reinforcement material to carbon fiber-reinforced composites (CFRC) for manufacturing prosthetic sockets. In regions where access to polymers might be challenging, composite systems with significantly less MMA, yet retaining most of the desired mechanical properties, can still be achieved [54].

Kumar et al. (2022) studied naturally derived bio composites with potential prosthetic applications. The research focused on knee prosthetic sockets and had two main components. Initially, the researchers created sockets using different laminated bio composites (FFF, KKK, and RRR) and analyzed their mechanical performance, thermal stability, and degradation behavior. They utilized an F-socket sensor to measure the interface pressure between the socket and the residual limb. In the second part, the team performed numerical analysis using data from experimental tests and measured interface pressures to investigate equivalent stress, deformation, and socket safety under various loading conditions (500 N, 700 N, and 900 N). The RRR bio composite exhibited higher hardness and fatigue resistance due to its increased brittleness. Interestingly, despite the gait cycle generating voltage in the socket, it had no discernible impact on its performance as it remained lower than the calculated force. The results indicated that laminated bio composites could be suitable alternative biomaterials for knee prosthetic applications. These materials offered advantages such as lighter weight, greater flexibility, and cost-effectiveness, improving user comfort. Consequently, they presented a viable option to replace plastic and conventional materials in prosthetic design [55].

Table 2 *Natural fiber composites for socket prosthesis fabrication*

No	Matrix	Reinforcement	Fabrication Method	References
1.	Epoxy Resin	Perlon, Carbon, Glass, Hybrid (carbon and glass), and Combination (carbon and glass)	Vacuum Molding	[29]
2.	Epoxy resin	Rattan Fiber	Lamination Process	[30]
3.	PMMA (Polymethyl Methacrylate)	Carbon and Alfa Fiber	Static and Dynamic Testing	[31]
4.	Epoxy and PMMA (Polymethyl Methacrylate)	Woven flax, Sisal, Cotton, Carbon, and Glass Fiber	Vacuum Bagging Process	[33]
5.	Polyester Resin	Glass Fiber and Carbon Fiber	Hand Lay-up Method	[35]
6.	Plant oil-based resin	Stockinette Fabric (Banana and Ramie Fiber) and Plant-Based Resin	Reusable Plester Mold	[1]
7.	Methyl Methacrylate Resin	Water Hyacinth Fiber	Hand Lay-up Method	[36]
8.	Polymer resin	Kenaf fiber	-	[37]
9.	Epoxy and Polyester	Pineapple Leaf Fibers	Hand lay-up method	[38]
10.	Acrylic resin and UN 3106 hardener	Woven kenaf, Glass silk knitted Fabric, and Nylon	Lamination Method	[39]
11.	Acrylic resin	Carbon fiber and perlon fiber	Vacuum technique	[41]
12.	Polyester Resin	Jute, Carbon, Glass, and Perlon Fibers	Vacuum molding technique	[42]
13.	Polyester Resin	Jute, Carbon, Glass, and Perlon Fibers	Vacuum technique	[43]
14.	Araldite, polyester, and orthocryl lamination resin	Fiberglass, Kevlar, and carbon fibers	Lamination Method	[44]
15.	Laminated composite	Lamination 80:20 (Perlon, n-glass, fiberglass, and carbon)	Vacuum Pressure System	[46]
16.	Laminations resin 80:20 polyurethane	Bamboo and Carbon Fiber	Lamination Method	[47]
17.	Epoxy and Acrylic Resins	Hemp Fiber	Vacuum Assisted Resin Transfer Molding (VARTM) process	[21]
18.	Polyurethane and Orthocryl lamination resin	Ottobock carbon fiber and Ottobock perlon stockinet	Vacuum molding	[48]
19.	Polyester Resin	Ramie, Glass, Carbon, and Perlon Fibers	Vacuum Bagging Technique	[49]
20.	IP2 polyester infusion resin	PET-fiber (woven and knitted fabric forms)	Vacuum-assisted resin transfer molding	[50]

No	Matrix	Reinforcement	Fabrication Method	References
			(VARTM) process	
21.	Epoxy	Jute fiber	Simple hand lay-up method	[20]
22.	Epoxy	Ramie Fiber	Filament winding method	[51]
23.	Biobased epoxy	Jute fibers and seashell nanoparticles	Mixing method	[52]
24.	Epoxy (TKL 121)	Banana pseudo stem fiber	Hand-lay-up method	[53]
25.	Orthocryl lamination resin	Pineapple leaf fiber (PALF)	Mixing method	[54]

Natural fiber composite materials have been developed with various types of resins, reinforcements and fabrication methods to produce prosthesis sockets (Table 2). The various types of natural fiber composites that have been developed can be a solution to replace the acrylic and glass fiber composite materials currently used in the manufacture of prosthetic sockets. In addition, natural fiber composites can be used as an alternative material option for socket production. In general, available prosthetic socket materials are made of knit perlon, woven carbon fiber, 80:20 polyurethane resin laminate, and hardener powder.

Natural fiber composites hold great promise to replace synthetic fiber composites in the future. This is because synthetic fibers generally have several disadvantages when used as materials in prosthetic socket fabrication. These include poor vibration-damping ability, potential allergic reactions, negative environmental impact, and high cost. Meanwhile, natural fibers such as hemp and flax offer a promising alternative, with several advantages over synthetic fibers, including biocompatibility, low cost, low density, and biodegradability [1,20,21,47].

3. Challenges of Utilizing Natural Fiber Composites for Below-knee Socket Prosthesis Applications

The potential of natural fiber composites in diverse applications is considerable, owing to their sustainable and renewable characteristics. Natural fibers have many advantages compared to synthetic fibers due to their low density, recyclable, biodegradable, renewable, and relatively high strength and stiffness characteristics [56]. The use of natural fibers such as jute, ramie, kenaf, banana, hemp, flax, sisal, bamboo, etc., has increased as reinforcing materials in polymeric composites [57]. Typically, composites' properties depend upon the type of fiber, manufacturing procedure, the matrix in use, and other factors. Synthetic fiber-based composites typically exhibit greater strength than natural fiber-based composites when considering the type of fiber utilized.

Nevertheless, composites utilizing natural fibers have reduced specific weight in comparison to composites employing synthetic fibers. This can benefit applications where weight is crucial, such as in the aircraft and automobile sectors [58–60]. Typically, composites made from natural fibers are less expensive than composites made from synthetic fibers. The cost of production and processing natural fibers is frequently lower, rendering them more cost-effective for specific applications. Composites fabricated from synthetic fibers provide superior resilience against chemical degradation, moisture, and mold. Composites fabricated from natural fibers may exhibit increased susceptibility to environmental conditions and may necessitate specific measures to enhance their longevity. Regarding environmental impact, natural fiber-based composites are generally regarded as more ecologically sound than synthetic fiber-based composites because they come from renewable sources and break down more quickly at the end of their lifespan [58].

Extensive research has been conducted on the development of below-knee socket prostheses utilizing natural fiber composites. The biocompatibility, strength, and low weight characteristics of these natural fiber composites render them a feasible substance for use in prosthetic applications. The integration of natural fiber composites into below-knee socket prostheses is designed to enhance the comfort, durability, and performance of amputees. The integration of natural fibers into composite materials enables the fabrication of prosthetic sockets that possess both reduced weight and sufficient resilience to endure the forces encountered during daily activities. The durability and strength of prosthetic sockets made from composites reinforced with synthetic fibers can be enhanced through the manipulation of fiber orientation and the incorporation of nanoparticles comprising varying volume fractions. Nevertheless, they are characterized by higher expenses, inflexibility, and a fixed structure. Prosthetic sockets fabricated from biodegradable natural fiber reinforced composite are more affordable, and less rigid compared to traditional synthetic fiber polymer composite, and provide enhanced comfort for patients. Research has demonstrated that ramie, kenaf, pineapple, and banana fiber reinforced polymer matrix composites have favorable mechanical properties, making them very suitable for prosthetic socket applications [32]. According to Irawan et al. (2020), socket prostheses comprising bamboo fiber-reinforced composites can generate compressive strengths that surpass the specified requirements for sockets

[61]. Nevertheless, employing natural fiber composites for below-knee socket prosthesis applications presents significant challenges. Natural fibers possess various drawbacks, including inadequate bonding between the matrix and fibers, elevated water absorption, and strongly polar characteristics resulting from the existence of hydroxyl (-OH) or hydrophilic groups. These characteristics will undeniably impact the stability of the dimensional structure and mechanical properties of the obtained composite [62–65]. The water absorption in natural fiber composite materials is influenced by specific elements such as fiber volume fraction, fiber arrangement, fiber treatment, matrix viscosity, presence of voids, temperature, and humidity [66–70]. Water absorption in natural fiber composites typically occurs through three distinct mechanisms: diffusion, capillary action, and water molecule transport (Fig. 2). Diffusion pertains to the transportation of water molecules throughout the polymer matrix, whereas capillary action arises when water is pulled into holes or small spaces within the composite as a result of surface tension. Water molecule transport occurs when water molecules migrate within a composite material through routes or micro-cracks that are formed by the fiber reinforcement or the polymer matrix [71]. Research conducted by Mechi et al., (2021) indicates that using natural fibers in prosthetic sockets reduces durability compared to prosthetic sockets utilizing synthetic fibers. This phenomenon arises due to the propensity of prosthetic sockets made from natural fibers to absorb water, resulting in alterations in dimensions and probable deterioration of the socket over time [34].

However, these drawbacks can be mitigated through surface treatments of the fibers. In prior studies, researchers performed a variety of surface treatments, which were classified into two groups: physical treatments and chemical treatments.

Both physical and chemical surface treatments possess their advantages and drawbacks. The physical treatment process is a dry technique that generates less air, water, and land pollution than the wet chemistry procedure [72,73]. Alternatively, researchers and industry commonly employed chemical treatments such as alkaline treatment, silane coupling agent, permanganate, and peroxide for natural fibers [74–76].

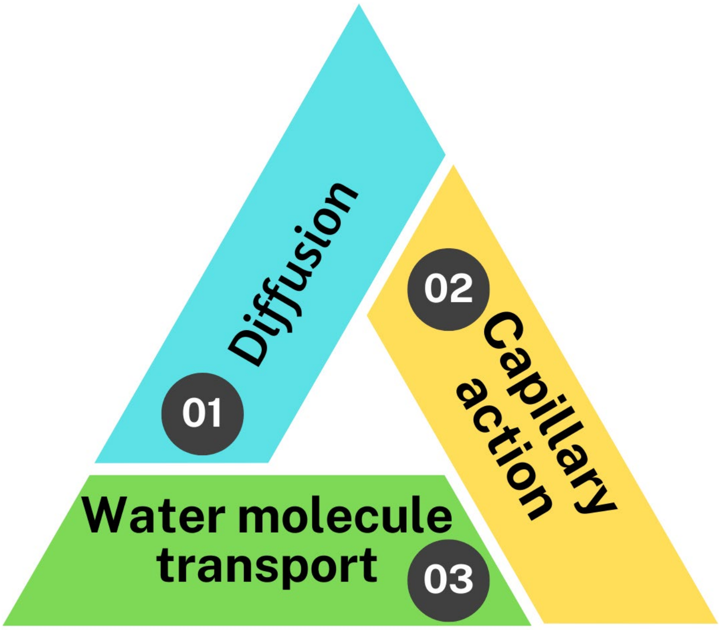

Fig. 2 *The water absorption in natural fiber composites mechanism*

An alternative approach for handling water absorption in natural fiber composite materials is the utilization of hybrid composites. Hybrid composites are formed by combining diverse fibers or integrating additional components to improve overall performance and minimize water absorption. Integrating synthetic fibers, such as glass or carbon fibers, into natural fiber composites can enhance their ability to resist water absorption. Synthetic fibers possess intrinsically low water absorption characteristics, and their incorporation into the composite can establish a barrier that diminishes the infiltration of water molecules into the substance. Hybridization can also entail the amalgamation of distinct natural fibers possessing complementary characteristics. Through the amalgamation of fibers possessing distinct attributes, such as superior strength and little water absorption, the resultant hybrid composite demonstrates enhanced resistance to water absorption in comparison to composites composed of a single type of fiber. The hybridization strategy has the benefit of customizing the composite material to fulfil specific criteria, such as minimizing water absorption. Hybrid composites can achieve superior mechanical qualities and increased resistance to environmental variables, such as water absorption, by blending several fibers or integrating additional components [77–79].

Extensive research has been conducted on the utilization of hybrid composites in the research and development of below-knee prosthetic sockets. The study conducted by Oleiwi et al (2022) determined that the quantity and composition of reinforcing layers had a substantial impact on the mechanical characteristics of prosthetic sockets. The most optimal configuration consisted of three layers of hemp combined with four layers of carbon, resulting in enhanced flexural strength, maximum shear stress, flexural modulus, impact strength, and fracture toughness [80]. The study conducted by Faheed et al (2022) concluded that it is possible to create below-knee prosthetic sockets utilizing sustainable natural fibers and polymethyl methacrylate (PMMA) lamination resin. The below-knee sockets incorporate natural fibers such as sisal, cotton, and jute. Carbon fiber, glass fiber, and perlon stockinet (623T5) were employed as synthetic fibers. The findings demonstrated that the composite hybrid fibers exhibited superior load-bearing capabilities compared to individual fibers in several orientations. Additionally, the matrix effectively preserved their optimal locations and orientations, acting as an intermediary for load transfer. The utilization of natural fibers, perlon, glass, and carbon fibers in laminated specimens has potential applications in the development of below-knee prostheses.

This approach aims to address the requirements of socket material design, enhanced mechanical properties, and cost reduction [33]. Similar findings were also seen in a study performed by Al-khafaji et al (2023). The findings indicated that composite transtibial prosthetic sockets, consisting of two layers of perlon and two layers each of bamboo fiber, carbon fiber, and perlon, exhibited higher yield stress, ultimate stress, elasticity modules, and fatigue resistance when compared to the other specimens [9].

The challenges for manufacturing purposes prosthetic sockets using natural fibers involve identifying appropriate natural fibers that can offer the required mechanical characteristics, optimizing the arrangement of the fibers to attain the desired properties, and ensuring effective bonding between the fibers and the matrix. Moreover, the utilization of natural fibers may necessitate alterations to the manufacturing procedure and could lead to elevated production expenses in comparison to conventional materials. Ensuring the accessibility and cost of socket prostheses is crucial to meet the needs of those requiring prosthetic devices. The cost of socket prostheses can fluctuate based on various factors, including the composition of materials, production techniques, and market dynamics. Exorbitant expenses can hinder access, hence restricting the availability of prosthetic devices for individuals in need. Prosthetic producers and providers can enhance the accessibility of these crucial devices to a broader population by aiming for fair pricing. Furthermore, the fabrication of socket prosthesis using natural fibers may encounter difficulties associated with lengthy manufacturing processes and scaling up. A challenge that may arise is the requirement for specialized manufacturing techniques to guarantee appropriate bonding between the fibers and matrix, as well as to maintain the overall excellence of the socket prosthesis. The implementation of these methods may necessitate supplementary procedures or methodologies in contrast to conventional prosthetic manufacture, hence resulting in extended production durations. The production challenging of socket prosthesis from natural fiber composites is shown in Fig. 3. In general, increasing the production of socket prosthesis made from natural fibers can pose challenges, including the availability and uniformity of natural fibers, the requirement for a qualified workforce, and the intricacy of the manufacturing procedure. To provide a reliable standard of excellence and fulfil the increasing need for prosthetic devices on a broader scope, it may be necessary to make investments in machinery, infrastructure, and personnel training.

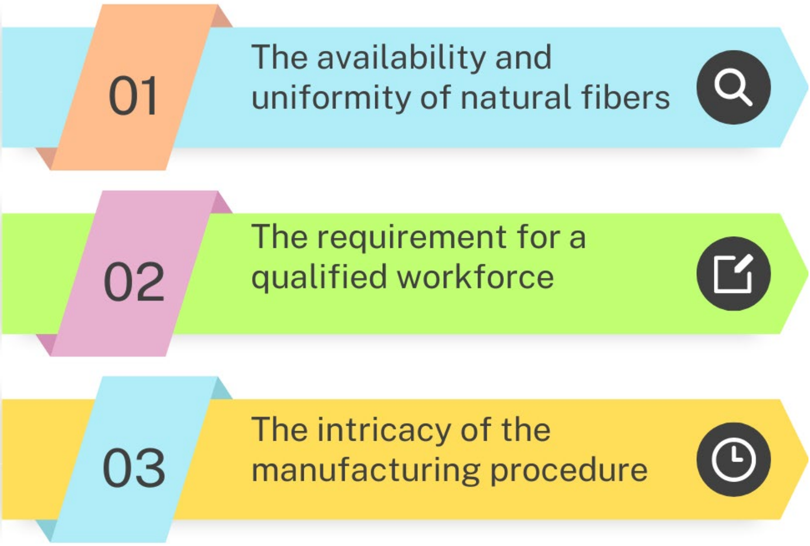

Fig. 3 *The production challenging of socket prosthesis from natural fiber composites*

4. Conclusions

Investigating using natural fiber composites to fabricate below-knee prosthetic sockets is a highly innovative and environmentally friendly method with numerous benefits compared to conventional synthetic materials. This study included thorough research on a variety of natural fibers such as sugarcane, softwood, sisal, rice straw, rice husk, jute, pineapple, palm shell, kenaf, hemp, cotton, coconut (coir), bamboo, and abaca for their potential use in below-knee prosthetic socket applications. The selection of each natural fiber was based on its exceptional biocompatibility, high impact resistance, and favorable strength-to-weight ratio. These organic fibers have several advantages, including ecological sustainability, decreased expenses, and enhanced availability for individuals using prosthetics. The natural compatibility of these fibers reduces negative responses, while their mechanical characteristics guarantee the strength and long-lasting nature needed for prosthetic sockets. Although there are potential advantages, including natural fibers in producing prosthetic sockets poses specific difficulties. Variations can influence the inconsistency and unreliability of prosthetic sockets in fiber characteristics. Additionally, the processing and fabrication methods for natural fiber composites might be more intricate and necessitate fine-tuning to get the necessary degree of performance. Furthermore, natural fibers may be sensitive to environmental deterioration over time, necessitating preventative treatments or a combination with synthetic materials. Successfully addressing these problems is crucial for the progress of utilizing natural fibers in prosthetic applications.

To address these challenges and optimize the utilization of natural fibers in below-knee prosthetic socket applications, future research needs to focus on advanced processing techniques, hybrid composites, surface treatments, and long-term performance investigations. Examining the combining of natural and synthetic fibers can enhance the overall characteristics of materials while advancing processing methods can improve the uniformity and effectiveness of composites made from organic fibers. The study incorporated surface treatment investigation on natural fibers to boost interfacial adhesion with the matrix and increase the mechanical properties of the generated composites. Furthermore, the feasibility of natural fiber prosthetic prostheses under various conditions will be evaluated through long-term performance and durability studies. Even though natural fiber composites are currently in development and applications are still restricted, they are highly promising as a sustainable alternative to socket below-knee prosthesis materials. The potential for natural fiber composites to substitute for synthetic fiber composites in the future is considerable. Through ongoing innovation and study, natural fibers can transform prosthetic technology by providing a feasible, environmentally friendly, and advantageous substitute for conventional materials like synthetic fibers.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design**: **Agustinus Purna Irawan, Didi Widya Utama**; **data collection:** Deni Fajar Fitriyana, Yazid Surya Wicaksana; **analysis and interpretation of results:** Samsudin Anis, Jamiluddin Jaafar, Tezara Cionita, Januar Parlaungan Siregar; **draft manuscript preparation:** Dwinita Laksmidewi, Putri Agustin Priyani. All authors reviewed the results and approved the final version of the manuscript.*

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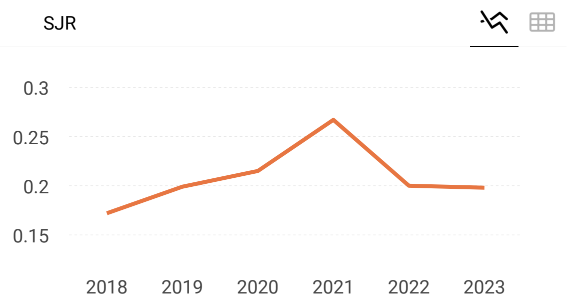
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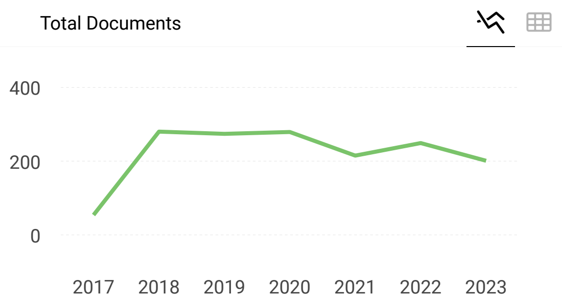
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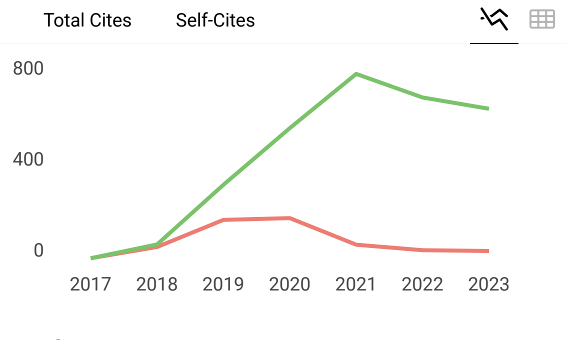
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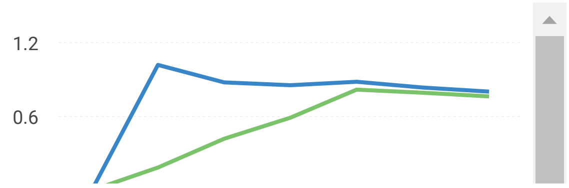

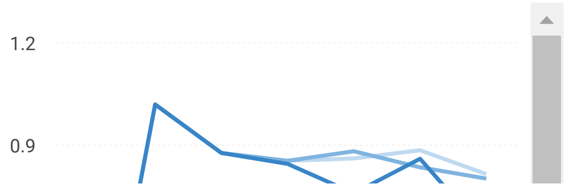

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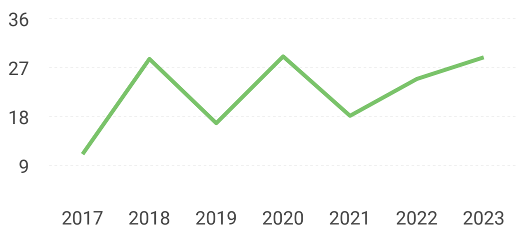

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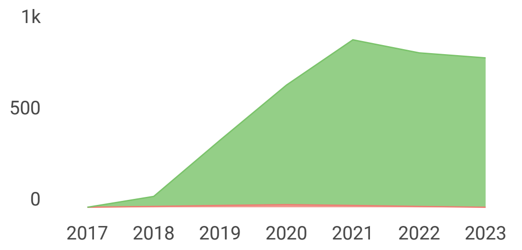

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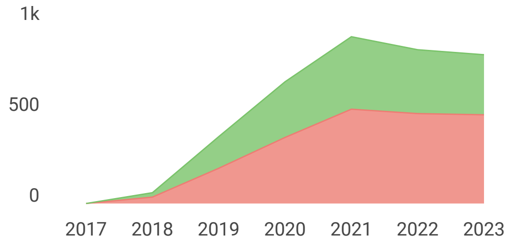

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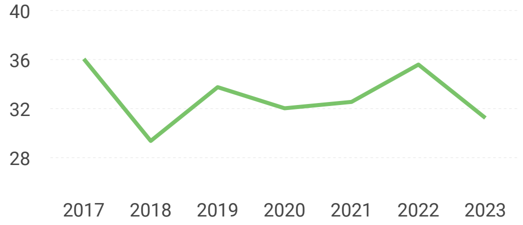

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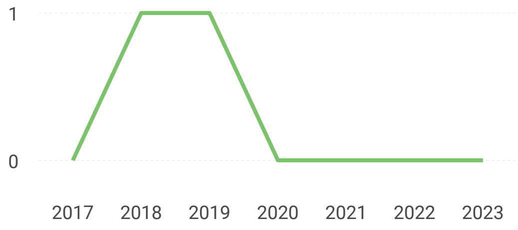

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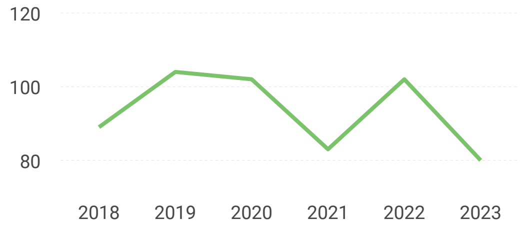

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