IOP Conference Series: Earth and Environmental Science

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To cite this article: I.P. Okokpujie *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1322** 012006

Study of the Characteristics of Polyurethane as a Sustainable Material used for Buildings, Polymer Composite, Biomedical, and Electronics Application

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Abstract. This research is focused on studying the characteristics of Polyurethane in engineering applications as a sustainable material employed for buildings and as reinforcement for polymer composite, electronics, and biomedical applications. This study discussed and reviewed papers cut across the Polyurethane Formation, Engineering Attributes of Polyurethane, and Polyurethane Applications in various fields such as Buildings, Polymer Composite Materials, Biomedical, and Electronic, which has proven that Polyurethane is a multi-functional material that has been employed in biomedical engineering used for tissue, wound treatment, breast implant, drug delivery systems. Also, it has been applied for sensors, actuators, Flexible electronics, Energy harvesters and storage, and Shape memory applications. Furthermore, its application in buildings, Polyurethane (PU) foam as an insulation material embedded in the aluminium roofing system for sustainable human comfort. This study also identifies the challenges of Polyurethane and provides sustainable solutions. In conclusion, site materials and structural application have shown excellent performance from studying the Polyurethane characteristics as embedded materials for roofing sheets.
Keywords: Polyurethane Foam, Buildings, Polymer Composite Materials, Biomedical, Electronics application.

1. Introduction

The application of Polyurethane in various engineering applications must be considered when looking for multi-facet materials for smart implementation [1]. Polyurethane can be applied in several engineering applications such as buildings, polymer composite materials, biomedical and electronics [2]. Building energy use is increasing yearly and is a variable needed for either heating or cooling a building [3]. Without the threatening presence of energy, these structures could not have formed and would never have been fit for human habitation. The existing insulation procedures are constantly being improved with the help of new systems. Onysko and Bomberg [4] According to their 2008 study, the building industry is progressively facing tough times, along with the commitment to achieve a carbon-neutral 2030 future. The European Union (EU) has played a vital role in identifying long-term remedies for the effects of climate change. Regarding their participation, they provided the UN with their planned contributions to the UN Framework Convention on Climate Change in March 2015. By 2030, greenhouse gas emissions are to be 40% lower than they were in 1990, according to the planned target. The primary use of this energy is attributed to heating systems used in buildings and hot water production [5]. Naturally, the Middle East's endowed countries have seen the natural gas available in this region exploited to the total capacity. As a result, this has resulted in the emission of CO2, which occurs in large percentages. These countries have reportedly contributed to almost 50% of carbon emissions in this region, with Iraq, UAE, Saudi Arabia, Kuwait, and Egypt recorded as the top five contributors [6]. A key challenge in developing most future buildings is the minimal energy required. The United Nations Environment Program for Development revealed in a survey that buildings specifically contribute up to 40% consumption of global power, which invariably constitute 25% of the worldwide water and one-third of the greenhouse gas emission of the whole planet. Further studies by the Department of Energy in the United States supported these values [7].

Buildings with sustainable engineering attempt to reduce air pollution and control water flow while also making the best use of the resources and materials that are already available. Sustainable engineering, however, requires innovative measures and techniques while creating more awareness with regards to the synergy between materials and assemblies with a critical and mindful examination of the environmental factors associated with where the building is to be erected while also considering climate change, energy efficiency, renewable resources, and comfort as well as durability [8].

Polyurethane (PU) has received much attention for its excellent biocompatibility, flexibility, and shape memory properties to create various objects for specific applications in the biomedical and electronic areas. Shape memory effect (SME)-equipped products with complicated geometries are challenging to start using traditional manufacturing techniques like extrusion and injection moulding. Thus, 3D or 4D printing can be used to address this issue. Pristine PU has several material drawbacks, particularly mechanical strength [9]. Reinforcements, such as fibres, nanoparticles, and other polymers, can be incorporated to increase the mechanical strength, shape memory ability, thermal conductivity, and electrical conductivity of PU [10]. However, due to a lack of awareness of the positive impacts of thermal insulation materials installed in buildings, many houses in Nigeria still need to be adequately insulated. Therefore, this research analysis will provide clear awareness and will also opt for the PU form for better thermal comfort.

2. Polyurethane

This section examines the utilisation of polyurethane as a thermal insulation material for building applications and as reinforcement materials for polymer composite manufacturing, biomedical and electronics processes. Polyurethane formation is further examined along with engineering attributes, applications, and comparative analysis with other thermal insulation materials based on thermal conductivity. Polymer materials have grown consistently for construction and are regarded as the most widely used. Polymers, however, are a combination of thousands of repeating chains that, in turn, result in a very long chain of molecules. Applications of polymers are not only limited to the construction industry as they have invariably been employed in the automotive sector and for furniture making. It is also being utilised in the electrical department for appliances and biomedical materials for wounding treatment, tissues, and breast implants [11]. Polyurethane is widely recognised and used in various fields because of its mechanical properties. These properties make it suitable for multiple applications, like its ability to extend to a large capacity, absorption rate, resistance against the aggressive environment, flexibility, and ease of use with its cost-effectiveness. It is the best pick against other insulation materials [12]. Officially the large-scale production of polyurethane began in 1940 while a study carried out by Carther showed the unique properties of polyurethane, which was from observation of polyamides and nylon further when taking into cognisance the launch into the exploitation of polyurethane, the credit will be given to Otto Bayer and co-workers who were carried out in 1937 (U.S EIA 2017)

The demand for polyurethane is on a significant rise at an approximation of 7.4% and had an average annual growth rate of 66.4 million USD in 2018. (Albany, New York, May 16, 2013/PRNewswire). Polyurethane has served the infrastructural industry in a wide range of applications. Polyurethane products are used in various applications and are usually rigid and flexible foams. There are generally employed as coating materials for fibre and fabrics and thermoplastics. It can also be used in structural and non-structural applications [13]—plane retardants, retraction, and grouting technologies. Polyurethane is a predictable polymer with high-strength properties, which will make it be added to other substrates to bring about more durable compounds. PU is employed in the building department because of its insulating properties used for roof and wall insulation and to fill gaps between windows and doors. The PU foam is presented in Figure 1. Its properties making it suitable as a good insulator, are increased mechanical and thermal properties. Energy efficiency and its various environmental benefits make it ideal for insulation and multi-functional materials [14-15].

Figure 1: Polyurethane Foam [16]

Polyurethane serves as a strengthening and retrofitting material. Because of its significant contribution to applications about construction, it has gathered massive attention as to where it can be applied per time. In structural applications, these techniques have proven too great significance in future. Polyurethane also has good mechanical and physical properties. There is relatively cheap and remarkable resistance against chemicals and adverse environmental conditions [17]. One chance at a better efficiency of a building's energy is reducing the heat loss through the building envelope, which is achieved through internal or external wall insulation [18-19]. The thermal conductivity values for polyurethane foams are between 0.02 and 0.03 $W.m^{-1}.K^{-1}$. The efficiency of polyurethane foams results from the blowing agent gas present within the closed porous structures and its low thermal conductivity.

2.1. Polyurethane Formation

A study by Bjorn [20] highlighted that polyurethane is usually obtained from a combination of isocyanates and polyols (i.e., alcohols that contain many hydroxyl classes). In the development stage, closed outlets are replete with an expansion gas (CO_2, HFC, or C_6H1_2). Polyurethane is usually manufactured as boards over time across the production line. Polyurethane is formed when there is a polymerisation reaction of diisocyanates with polyols. Usually, the chemical functional group possessed by the materials used to start should be at least two for polymerisation [21]. The addition polymerisation reaction to form polyurethane occurs through the chemical reaction shown in Figure 2. And the General Mechanism for the formation of polyurethane is also shown in Figure 3

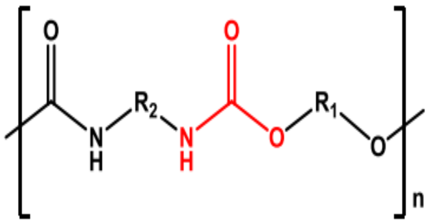


Figure 2: Chemical Structure of Polyurethane

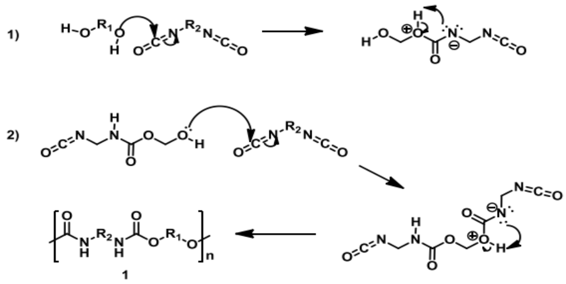


Figure 3: General Formation for the Formation of Polyurethane [21]

Recently, polyurethane has been employed as expanding foam in building construction; this is usually incorporated into the building envelope and around the cavities and seals put around doors and windows. The most comprehensive occurrence of polyurethane foam thermal conductivity falls in the range of 20 to 30 mW/(mK), which, compared to other materials like mineral wool, cellulose, and polystyrene products, is least in value as against these different materials. The thermal conductivity of polyurethane differs with temperature, the density of material mass and moisture content; for example, the thermal conductivity (TC) of polyurethane can rise from 25mW/(mK) to 46mW/(mK) with increasing moisture volumes of 0 vol% to 10 vol% respectively. Polyurethane products can be punctured, cut, and fine-tuned at the construction site without any form of loss in heat resistance [22-23].

According to Somarathna et al. [24], examining polyurethane production from a chemical point of view was considered. According to analysis, di- or polyisocyanate and micro-diol (with functional group -OH) are polyurethane's basic building blocks (active group –NCO). Both of these functional groups create extended chains and networks via the exothermic reaction-generated urethane link (-O(CO)(NH)-). In order to meet the requirements for diverse applications, polyurethane can be synthesised to attain various mechanical properties [25]. Polyol, chain extender, and di-isocyanate were highlighted as essential constituents in polyurethane synthesis. Polyurethane's physical and mechanical attributes heavily depend on the types of di-isocyanates and polyols used for synthesis [26]. The design of most polyurethane products contrasts with other polymer products as they are typically manufactured straight into final products [27]. Various polymers like polypropene and polyethene are manufactured in distinct locations and sold as powder, films, and granules. Eventually, these thermal insulation materials create products using heating, shaping under pressure, and cooling. This makes them almost wholly reliant on end-product characteristics compared to the model polymer [28]. Construction companies usually use three major polyurethane products: elastomers, adhesives, and foams. The elastomers are formed by combining di-isocyanate with two diols (high and low molecular weight diols) [29].

Polyurethane foams undergo synthesising in a reaction between di-isocyanate, a high molecular triol, and water (H_2O). At the same time, the adhesives are obtained by combining di-isocyanate, in stoichiometric surplus, with a mix of two macro diols (one amorphous and the other crystalline) [30]. Long-chained polyols having high functionality yield inflexible cross-linked polyurethane produce. Furthermore, aromatic di-isocyanate presents a means for more rigid attributes of polyurethanes when compared to aliphatic ones [31]. Generally, catalysts are included to realise a controlled reaction rate at a reduced temperature. This is because of the exothermic attributes of the reaction. Production of polyurethanes can be obtained through several processes, such as quasi-pre-polymer, single-step polymerisation, and pre-polymerization [32].

2.2 Engineering Attributes of Polyurethane

Polyurethane is considered an elastic material due to its excellent properties, architecture, and ability to be used as a reinforcement polymer composite. This is seen in its capability to modify its microstructure while obtaining distinct product models with a broad range of mechanical attributes [33]. That is, flexibility, rigidity, elasticity, and considerably excellent damping characteristics with a reasonable degree of resistance to impact, weather, and abrasion [34]. This ability to alter its structural architecture allows polyurethane to be the most rigid plastic and be regarded as a highly flexible thermal insulation material. This trait will also enable it to have the softest rubbers with softness likened to jelly [35]. According to Somarathna [24], polyurethane, generally, is a "linear-segmented blocked copolymer" that is composed of "soft" and "hard" sections. The soft cells have a low glass transition temperature, which gives PU a rubber-like attribute. In contrast, the tricky areas with high glass transition temperatures, in comparison, allow PU to portray glassy and crystalline details [36]. These two segments are micro-separated due to the difference in properties. This micro separation accounts for the extensive attribute range PU possesses. Adding other elements like fillers, stabilisers, plasticisers, and chain transfers can also alter the attributes of polyurethane to satisfy material specifications for several applications. Another advantage of PU when it undergoes synthesis and in its application is its rough and low gel time (i.e., the time requisite by the resin to transition from liquid to a non-flowing gel), making it ideal for several applications and repairs. For practical and application purposes, polyurethane is split into two main classes: elastic and rigid.

Elastic polymers constitute flexible foams, elastomers, PU coatings, fibres, adhesives, etc., while structural foams, solid polymers, wood substitutes, and rigid foams make up rigid polymers [37]. Polyurethane foams are composite solid-gas materials in which the solid state is designed using polymer parts, and the gas state is manufactured using gas. These foams are made up mostly of non-linear materials, and their characteristics are decided by thickness, internal air cavities, and the kind of cross-linking present in the structure of their molecules. Polyurethane foams are often classified as flexible, partially flexible/partially rigid or rigid concerning the chemical system, the stubbornness of the resin employed as a matrix, the mechanical responsiveness of the foams, and their cross-link identities [38]. Polyurethane has an open-cell and closed-cell foam cell structure, and this depends on the process adopted in its production [39]. The open-cell design of polyurethane foams enables the interconnection of pores. This results in similarly high flexibility, reduced density, decreased compressive attributes, increased resilience (sponge-like look), and considerably good sound-absorbing characteristics. The architecture of the closed-cell structure polyurethane foam does not allow the polyurethane pores to be interconnected, allowing comparatively dimensional stability, increased compressive features, and reduced moisture absorbance levels compared to the open-cell structure foams. In some instances, polyurethane foam can be made by combining open and closed-cell structures giving it flexible and rigid properties [40].

The polyurethane matrix comprises other base resins and elements that likely consist of surfactants, plasticiser fillers, stabiliser pigments, and fire retardants [41]. The constituents of this matrix play a crucial function because it substantially influences foam attributes like thermal stability, toughness, flammability, chemical resistance transition temperature, and specific heat. According to Tu et al. [42], the compression stress-strain characteristics of polyurethane foams initially show a linearly increasing uniform elastic compression, accompanied by yielding and stress softening due to the weakening of the foam cell structure.

3. Polyurethane Applications

Polyurethane (PU) comes from an exciting group of polymers with a wide application area: thermal insulation, automotive parts, construction, seating materials, coatings, elastomers, flexible and inflexible foams, and recent applications in the medical field [43]. Polymer materials have recorded the highest growth rate in construction materials. Polymers are labelled as "excessively lengthy molecules that are usually made up of thousands of several repeat parts". Polyurethane is seen as the leading polymer amongst polymer materials due to its exceptional mechanical attributes. These attributes are high energy absorption capacity, high elongation capacity, good levels of thermal stability, high resistance in harsh regions, excellent chemical resistance levels, versatility and flexibility in the products and application areas, cost-effectiveness, easily applicable and sustenance of final products [44]. Polyurethane, generally, is a considerably high-strength polymer with easily scalable and predictable materials attributes and can be combined with and applied to numerous substrates. This allows for large-scale applications in biomedical, composite materials, electronics device manufacturing, construction, and building infrastructure.

3.1 Buildings
A major application of polyurethane in building construction is the utilisation of polyurethane foams in the manufacture of insulation panels, as well as insulation of roof and wall insulation and as gap fillers for areas around windows and doors [45-46]. Using polyurethane foams as insulation benefits thermal and mechanical effectiveness, environmental benefits, and energy efficiency [14]. It is also adopted and regularly used as a protective covering in building structures and construction in general. This provides quick-curing characteristics, a polished appearance, long-lasting products, and increased tolerance in harsh and adverse environmental conditions. The usePolyurethanerotective covering can also be seen in the production of wood floors, basements, and several other consumer and commercial products [48].

The production of decreased-cost polyurethane polyols and polyurethane coverings fostered the adoption of polyurethane for automotive applications due to its ability to improve the lifespan, scratch, corrosion resistance, and colour retention of products and provide product exteriors with the needed high lustre. Polyurethane in adhesives is another application that gives an excellent market for polyurethane materials. These adhesives are primarily used in Roofing, flooring, door, window, and wall and board installations due to their self-supportive exceptional bond strength, weather resistance, and swift cure time [49]. Polyurethane sealants form another crucial part of structural and infrastructural sectors, including expansion joint sealants, energy-efficient window sealants, and basement and driveway sealants. Elastomers manufactured with polyurethane can be applied in producing running tracks and thermal breaks for metal frames in building structures and industrial machine parts designed to function at high performance, such as pulleys, gaskets, rollers, and belts. Another application of polyurethane is in polyurethane binders, which are used in binding re-modelled wood and products made with fibre into adjustable board products that are adopted in making structural panels for construction and mobile phone manufacturing [50].

Furthermore, the work of Essien et al. [51] says that when considering the environmental changes brought on by thermal radiation, the prediction and usage of polyurethane foam in developing roofing sheets must be regarded. An application of artificial neural networks (ANN) is presented in this paper to simulate and forecast polyurethane (PU) roofing in residential structures' ability to withstand high inside temperatures. The study used a data logger to measure the indoor and outside temperatures for two hours each in the three simulated scenarios (morning, afternoon, and night-time). In addition, the authors used the Levenberg-Marquardt algorithm to transform and forecast the internal temperature recorded in the polyurethane roofing house of the residential building. The outcome demonstrates that the PU roofing system could retain heat and lower the temperature of the home model by 6.9% in the morning, 15.8% in the afternoon, and 6.8% in the evening.

Okokpujie et al. [52] In Nigeria's southern and northern regions, high thermal solar radiation impacts occur during the dry season because of the ozone layer's depletion. This problem highlights the need for an insulated roofing system to create a cosy atmosphere. This study aims to evaluate the effectiveness of polyurethane (P.U.) foam as a thermal insulation material incorporated into the aluminium roofing system for adequate human satisfaction. Using a data logger, temperature data with temporal fluctuation were gathered for the indoor and outdoor settings of the two-house models for the thermal study. In the morning, afternoon, and evening, two hours of study were conducted on polyurethane roofing and urethane aluminium roofing. The authors looked at the effects of time variation on the roofing house models using a contour plot for a one-factor analysis, as seen in Figure 4. The results show that an aluminium roofing sheet with polyurethane added minimises the risk of temperature compared to a roofing sheet without the material. The P.U. foam coating on the aluminium roofing also provides a sustainable, eco-friendly atmosphere, displaying uniform heat dispersion. This study suggests using PU-form as insulation for roofing sheets to offer cleaner and more environmentally friendly thermal comfort.

According to Okokpujie et al. [53], thermal insulation materials reduce energy loss in residential and commercial structures. By utilising the maximum capacity of the available heating and cooling systems, these insulation solutions can be used all year long. Additionally, it considerably lowers the high ongoing costs of these systems and the cost of electrically powered air conditioners. When there is a considerable decrease in CO_2, electricity consumption can be reduced in the environment, resulting in higher living standards and a calmer environment for people.

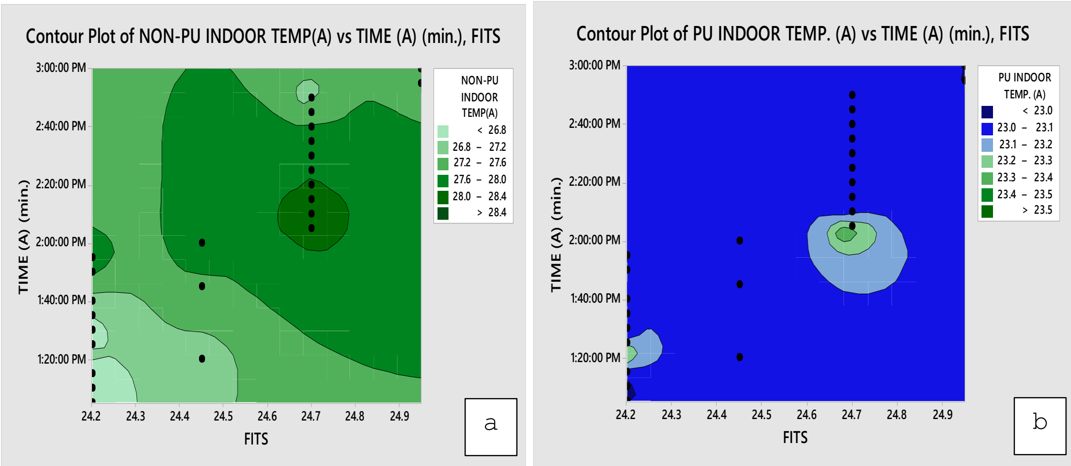
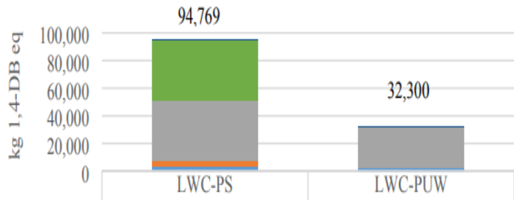


Figure 4: Fits vs Time Variation Thermal Resistance indoor temperature for the afternoon (a) Non-PU- Roofing (b) PU- Roofing [53].

3.2 Polymer Composite Materials

Sandwich panels made using the core of polyurethane foams have been on the market for over 60 years. They provide effective, efficient, and flexible structural frameworks applicable in several areas, such as panels of roofs and floors, wall claddings and decks on pedestrian bridges [54]. This is due to their exceptional and excellent characteristics, which include low density, amazing insulation attributes, increased strength, and increased stiffness-to-weight ratio [55]. The idea of sandwich panels was further introduced in aeroplanes, shipbuilding industries, and automobiles, according to Zhang et al. [56]. In recent years, polyurethane has been used with other materials to attain composites with increased toughness, high ductility, decreased density, efficient sound insulation, excellent mechanical attributes, and increased resistance to impact. The products' mechanical properties may be improved by strengthening polyurethane foams using fibre materials and adding the polyurethane matrix to other composite designs. Thermoset and Thermoplastic composites, currently manufactured from synthetic polymer (e.g., polyurethane filled with natural and synthetic fibres), have attained immense advancements on a global scale [57]. Another area in polyurethane applications that has gained increasing interest and ground in the construction industry is its use in retrofitting and reinforcement materials. These usages show increased possibilities for structural applications as alternatives for more cutting-edge designs. Due to their exceptional physical and mechanical attributes, they have excellent resistivity against an extensive scope of chemical and extreme natural colt also ions. It also decreases costs, elementary synthesis and processes involved in its application [58].



	LWC-PS	LWC-PUW
PU foam waste	0.0	0.0
PS foam slab	42,905.2	0.0
Sand	0.0	190.1
Tap water	13.6	50.1
Portland cement	44,297.9	29,890.7
Clay	4,106.1	0.0
Electricity and heat	3,249.4	2,169.1

Figure 5. Shows the impact of the waste produced on the human toxicity on the developed LWC-RPUW [59]

In the work of Tantisattayakul et al. [59], the effects of PU on human toxicity were taken into account when producing lightweight concrete (LWC) combined with RPUW (LWC-RPUW). Compared to LWC-PS, the LWC-RPUW had upsides of 32,300 and 94,769 kg 1,4DBeq, respectively. Because of its existence pattern, Portland concrete and PS froth chunk discharges selenium and manganese to water sources at the removal contact of sulfidic tailings ruins from lignite and coal mining, making them the main boosters of human poisonousness influence. Figure 5 demonstrates that the PU foam is entirely non-toxic to humans, making it more suitable for engineering applications.

Gradinaru et al. [60] used Polyether urethane (PU)-based magnetic composite materials created and examined as a novel hybrid platform that might be employed in various applications, particularly for improving MRI image quality. The nanoparticles of iron oxide (Fe_2O_3 and Fe_3O_4) of multiple types and concentrations were added. In order to magnetic nanomaterials, hematite (Fe_2O_3) and magnetite (Fe_3O_4) nanoparticles were first added to the PU framework using a polyaddition process. The kind and concentration of iron oxide nanoparticles affected the material's structural, morphological, mechanical, dielectric, and magnetic properties. As a result, the number of iron oxide nanoparticles included in the matrices affected the PU composite materials surfaces' shape and wettability. The composites' mechanical, dielectric, and electromagnetic properties were enhanced compared to specimens of the single PU matrix. The evaluation of the produced PU nanocomposites' in vitro cytocompatibility revealed that these samples are excellent prospects for biomedical applications, with cell survival levels in the 80–90% range. Considering all the research, the authors say that including magnetic particles gave the composite new features that might greatly increase the functionality of the materials used in this work. The research carried out by Tiuc et al. [61] developed new synthetic fibres with sound-absorbing qualities using sawdust as a reinforcing material and polyurethane foam as a binding agent. Due to the sound-absorbing attributes these kinds of materials provide, 11 new composite systems with different sawdust particle types and sizes, amounts of binder, and material thicknesses have been developed. The materials' composition, thickness, air gap samples and the rigid wall directly affect the new materials' ability to absorb sound. The mechanical, thermal conductivity and morphological properties of the newly produced materials were also tested. The results proved that applying polyurethane foam reinforcement with wood is viable, which is supported by several studies on composite materials [62-66].

According to Luo et al. [67], Density minimisation has emerged as a pressing concern in wood composite materials used in construction and furniture. This work added 30-weight per cent of wood particles to lightweight wood-polyurethane (W-PU) composite foams. To create robust W-PU foams, industrial kraft lignin was employed as a biopolyol to replace the petroleum-based diethylene glycol (DEG) partially. Variable lignin levels (5, 10, 15 and 20 wt% based on DEG mass) were studied for their effects on the foams' reactivity, shape, density, compressive characteristics, water absorption, and thermal stability. All the foam samples had the creation of distinctive urethane linkages, according to Fourier transform infrared (FTIR) research, as shown in Figure 6(a) and Figure 6 (b). The foam's cellular structure changed when lignin was added, and huge cells developed. Poor cellular architecture and a higher percentage of open cells were seen in W-PU foams. As the lignin percentage rose from 0 to 20%, the density of W-PU foams increased from 47 to 96 kg/m^3 presented in Figure 6(c), the morphology cross-section of the Pu and W-PU. Even though lignin's insertion reduced the foam's reactivity, it boosted the material's compressive strength and modulus. Additionally, the lignin concentration of W-PU foams rose from 0 to 20%, increasing their specific compressive strength and modulus by 55% and 48%, respectively, and decreasing their 20-day water absorption by 38%. A thermal gravimetric study revealed that adding lignin had no appreciable impact on foam degradation's thermal behaviour but instead increased char residue's mass. This work offers a promising technique for using technical lignin in W-PU lightweight composites to provide value.

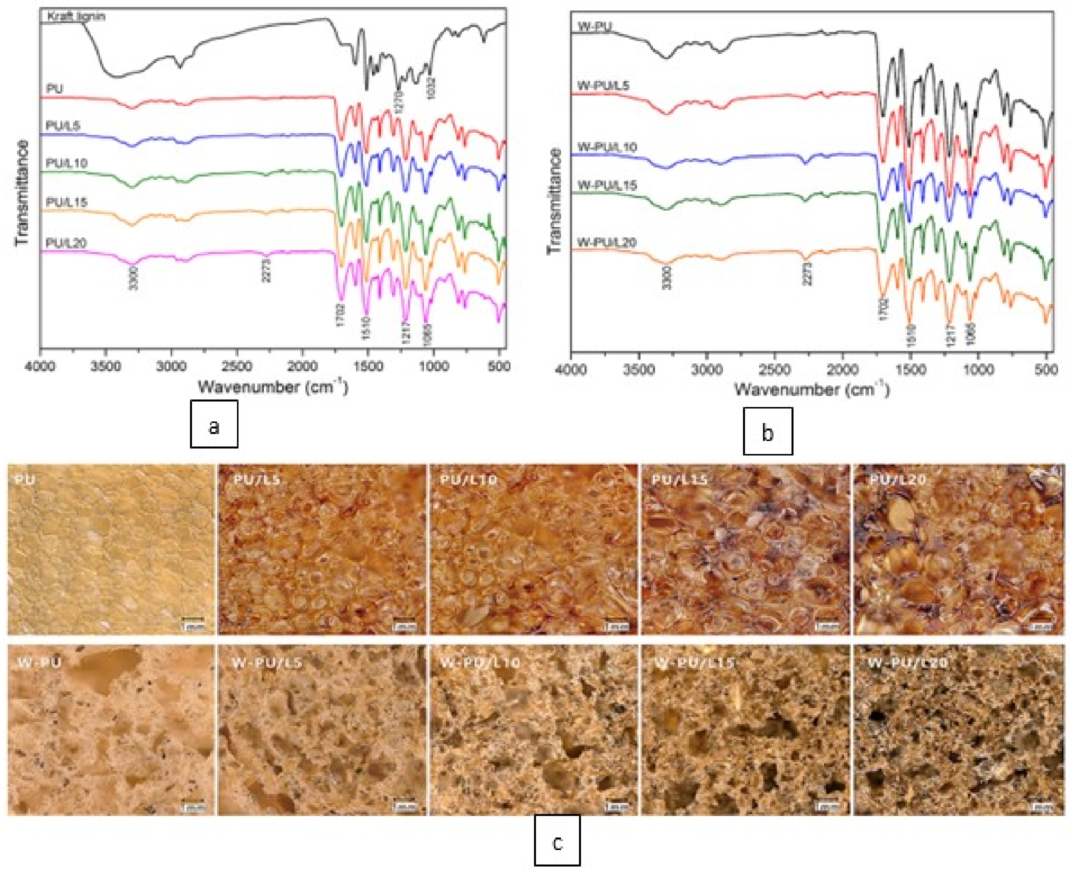


Figure 6: (a) FTIR spectra for PU-foam, (b) FTIR spectra for W-PU foam and (c) Morphology of the PU and W-PU foam cross sections with different percentages of lignin of the composite [67]

3.3 Biomedical

There are many different industrial applications for polyurethanes (PUs), which are created when diisocyanates react with polyols (or an equivalent) in the presence of a catalyst, as shown in Figure 7 [68]. Its biological applications have recently attracted much interest due to their biocompatibility, biodegradability, and flexible chemical and physical structures [69]. Examples of such application sectors include the development of antimicrobial surfaces and catheters, stents, pressure-sensitive adhesives and surgical dressings, tissue engineering scaffolds and electrospinning, nerve regeneration, cardiac patchwork, and PU coatings for breast implants. Intelligent biomaterials with specialised characteristics are essential for effective tissue regeneration [70-74]. The creation and characterisation of graphene (G)-based electroconductive materials for biomedical applications, as well as a comparison of the production techniques of the materials to the 3D scaffold, were the two objectives of this study carried out by Bahrami et al. [75]. G is conductive and has excellent mechanical and biological qualities. At 0.1, 2, 5, and 10 wt% concentrations, multilayer G flakes were homogeneously incorporated into the polyurethane (PU). Membranes made of PU/G were created utilising electrospinning and solvent casting. The membranes' electrical, mechanical, physiochemical, and biological characteristics were studied. The electrospun mats had much better electroconductivity than comparable casting films, and G served as electrical bridges, improving the electroconductivity of the composites. The mats' mechanical properties were better than those of the movie, thanks to an increase in G concentration of up to 5 weight percent, which was later decreased. The ability of composite materials to facilitate cell adhesion, growth, and spreading was demonstrated in biological investigations employing fibroblast and endothelial cells. Due to surface topography, mats' substantially higher cell-supporting behaviour appears to be explained. The provided nanofibrous electroconductive PU/G composites are anticipated to have potential use in tissue engineering. Diselenide-crosslinked PEGylated PU nano gels with pH- and oxidation-responsive characteristics were reported to be easily prepared by Cheng et al. [76]. MDEA served as the pH-responsive functional group. The diselenide crosslinking was said to give the nano gels enhanced colloidal stability.

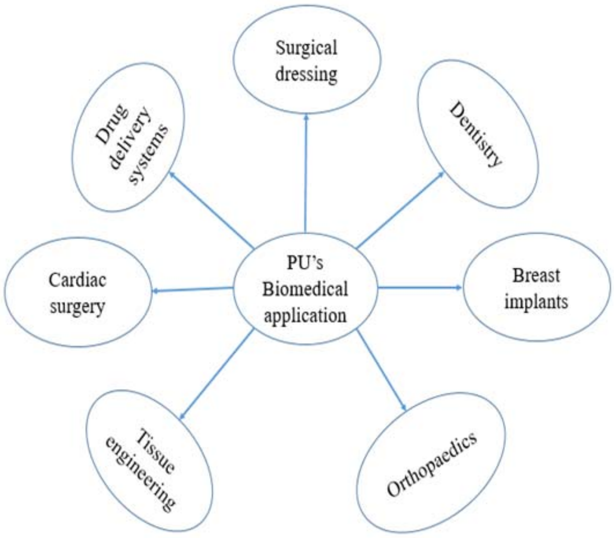


Figure 7: applications of Pus in Biomedical [76]

According to the study, drug loading efficiency using nano gels was 76.3%, higher than non-crosslinked micelles. The nano-gels' dense inner core also worked to stop any potential medication leakage throughout the dialysis procedure. Due to the drug's swelling tendency in acidic environments and the protonation of tertiary amines, which promotes rapid diffusion into the manage, accelerated drug release was seen in high H_2O_2 concentration and pH 5.0. Indomethacin (IND), the model drug, and diselenide linkages were integrated into the nano-gels, producing a network see Figure 8. The PEGylated PU is self-assembled into nano-gels. Networks swell and expand in situations with lower pH levels due to MDEA protonation, and networks contract due to diselenide bonds breaking in conditions with high H_2O_2 concentrations.

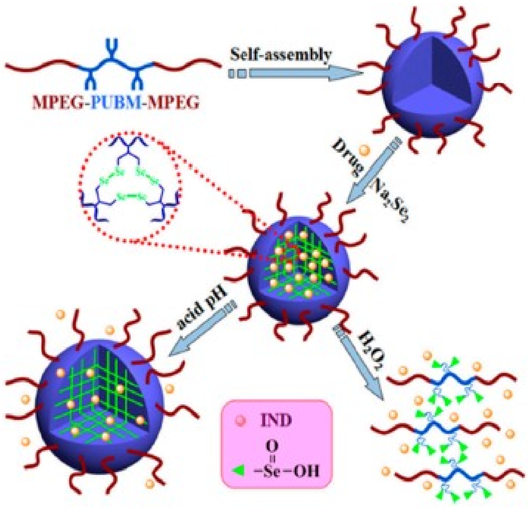


Figure 8: Indomethacin (IND), the model drug, and diselenide linkages were integrated into the self-assembling nanogels made of the EGylated PU, creating a network [76].

According to Tan et al. [77], Recent studies have made considerable advancements in using pH-responsive polyurethanes as a regulated drug delivery method for oral administration, endoscopic administration, and targeted drug delivery systems for treatment with radiation and chemotherapy. This review also covers other applications, such as optoelectronic probes, sensors, and surface biomaterials. As mentioned, after being exposed to blood-vessel pH, SMPUs can also regain their structure [78]. Sulfamethazine-based hydrogel SMPUs with radio-opacity capabilities have been created as injectable embolic agents [79-80]. A gel that occludes the aneurysm is produced following a brief sol-gel procedure at body pH, as shown in Figure 9. Even after 12 weeks, the hydrogel was still practical and durable for renal artery in vivo in rat models. MTT assay on cells produced from kidney cells and in vivo results revealed high biocompatibility, showing a prospective candidate for a street embolic agent. Therefore, the summary of the method and its application of PU in Biomedical is presented in Table 1.

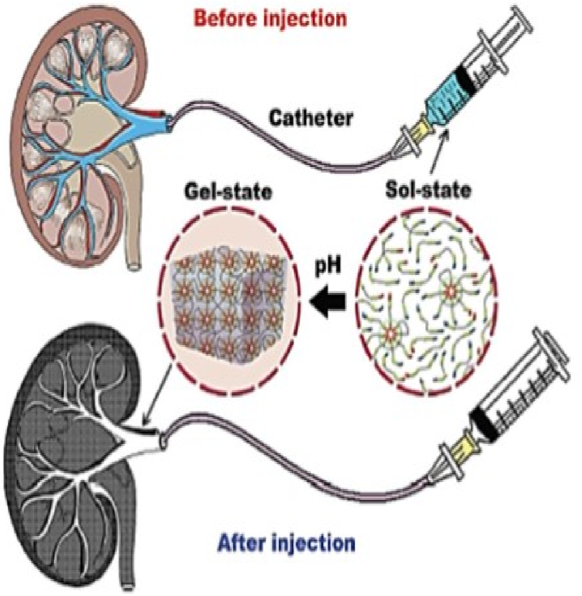


Figure 9: A pH-responsive SMPU schematically acting as an embolic agent [78].

To minimise early marginal bone loss, contemporary implant designs should allow for sufficient primary stability while minimising mechanical stress on buccal bone Schulz et al. [88]. The thread geometry and shift in core diameter of a dental implant were examined. When placing implants, polyurethane foam was employed as a substitute for bone. Insertion torque and buccal bone strain development were measured using strain gauges, and primary stability was evaluated using damping capacity tests. The test group utilised the innovative experimental implant (n = 10), while the control group utilised an existing tapered bone-level implant. T-tests (= 0.05) were the foundation of the statistical study. Compared to the innovative implant design, control implants had higher maximum insertion torque ($p = 0.0016$) and led strain development in buccal bone ($p = 0.1069$).

Table 1. Summary of the method of developing PU and its applications and findings in Biomedical.

Authors Details	Method	Reaction Agent	Applications	Findings
Gholami and Yeganeh [81]	The non isocyanate method is used to create a soybean oil-based polyol with built-in urethane and quaternary ammonium groups to form polyurethane wound dressings	isophorone diisocyanate	Surgical wound dressings (PUWD1-4)	By reacting with isophorone diisocyanate, various formulations from this polyol and castor oil are transformed into polyurethane wound dressings. It also has good cytocompatibility and effective antimicrobial activity against different microbial strains. Evaluation of the optimised dressing for a full-thickness non-sterilized wound has demonstrated excellent success in wound healing.
Zhao et al. [82]	based on a biological hybrid covering comprised of polyethene glycol and gold nanorods (Au NRs) that responds to near-infrared light	Gold nanorods (Au NRs)	multifunctional antibacterial applications	The PU-Au-PEG showed substantial electrocatalytic bactericidal properties under 808 nm light irradiation, especially against multidrug-resistant bacteria, and revealed a better precision to resist bacterial adherence. Additionally, the PU-

				Au-PEG may prevent the growth of biofilms in the long run.
Tondnevis et al. [83]	Electrospinning, a versatile and effective technique, was applied to develop the gelatin and SWNTs with polyurethane chains	gelatin and single-walled carbon nanotube (gelatin-SWNTs)	tissue engineering applications	The hydrophilicity of nanofibrous scaffolds was discovered to have significantly increased. Gelatin was used to modify the scaffold degradation profile. SWNTs enhanced scaffolds' young modulus and ultimate strength up to 16.47 0.5 and 23.73 0.5 MPa, respectively. Biomimetic mechanical properties of composite platforms, such as those of a standard blood vessel, were created.
Neamonitou et al. [84]	Acellular dermal matrix (ADM) complete wrap with polyurethane implants is used in prefectorial breast reconstruction.	Matrices for Braxton. operational information, patient demographics, and surgical complications	breast implant	The study's findings demonstrate instant implant-based breast restoration using protectoral polyurethane. Our preliminary observational series indicate a positive outcome and sizable multicentred research is necessary to predict long-term outcomes.
Alisani et al. [85]	two-nozzle electrospinning to the method was employed to develop the composite nanofibers.	Multi-walled carbon nanotubes (MWCNTs/ cellulose acetate (CA), poly (tetramethylene ether) glycol-polyurethane (PCL-Diol/PTMG-PU),	Drug delivery systems	The authors evaluated the drug release from nanofibers with nanofibers loaded with MWCNTs/ glycol-polyurethane and discovered a better performance during the experimentation.
Grzęda et al. [86]	The production of viscoelastic polyurethane foams with varying isocyanate indexes (0.6-0.9) and water content (1, 2 and 3 PHP)	isocyanate indexes and water content	Prosthetic applications under Orthopaedics	The discussion of the outcomes involved changing the foam formulation. The performance characteristics of the foams, such as recovery time, hardness, resilience, and sweat absorption, show that foams with a water content of 2 php generated with an isocyanate index of 0.8 and 0.9 will be suitable for prosthetic applications.
Jiang et al. [87]	polyurethane concrete (PUC) samples are created by combining dolerite aggregates with liquid reactants such as polycarbonate diol, aliphatic isocyanate, and glycerine.	polycarbonate diol, aliphatic isocyanate, and glycerine	paving bridge decks under the Dentistry application	According to the alkaline hydrolysis tests, PUC has outstanding durability, low-temperature solid toughness, and excellent dynamic stability (remained strong after 24 days of hot alkaline water treatment). These findings confirm that PUC is a suitable paving material for bridge decks.

The innovative implant design prevented mechanical overstretching of the buccal bone while allowing for a greater undersizing of osteotomies [89]. Trabecular bone provided comparable primary stability instead of compressing cortical bone, as with traditional tapered implant designs.

3.4 Electronics

Developing appropriate multifunctional materials that can concurrently address various characteristics, such as flexibility, lightweight, conductivity, environmental effect, and production cost, is one of the current and future issues in electronics [90]. A new technical area called polymer electronics could lead to various innovative uses and goods. Applications for these include electrolytes for supercapacitors and batteries, electrostatic dissipation, sensors, actuators, EMI shielding, shape memory, and electrolytes for actuators. The global market for printed electronics has enormous potential. Flexible and printed electronics have used PU and adhesives based on their composites [91-96]. The application of PUs in

Electronics cut across the development of an actuator, EMI shielding, Shape memory, Sensors, Flexible electronics, Energy harvester and storage [97], as presented in Figure 10. Shang et al. [98] This study defines a novel multiwall carbon nanotube (MWNT) and polyurethane-based elastic conductive nanocomposite (PU). The MWNTs can create highly developed conducting networks in the PU matrix with the help of an ionic liquid and under uniaxial stress. In particular, the high conductivity of the MWNTs and the high elastomeric mechanical capabilities of the PU were favourable qualities that the produced nanocomposite acquired from its constituents. The stretchy conductive nanocomposite's electrical conductivity can be uniaxially stretched up to 100% without noticeably changing. A 3D hopping mechanism predominates in the conductivity of MWNTs, according to the measurement of temperature-dependent conductivity.

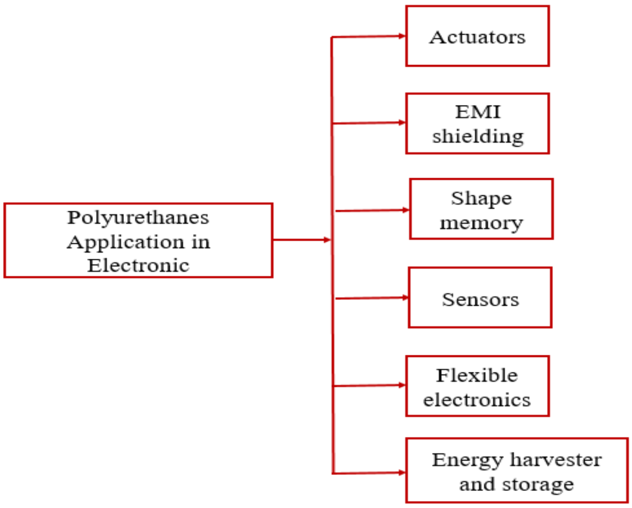


Figure 10: Electronics used for polyurethane and its composites [97].

The study of Jia et al. [99] provided a method to create outstanding dynamics of urethane bonds at low temperatures by introducing a fluorinated group with high electron-withdrawing action. It engineered a new fluorinated phenolic polyurethane elastomer with CANs. We also thoroughly examined how fluorine atoms affected the advanced materials' mechanics, thermal stability, processability, self-healing, surface-free energy, hydrophobicity, and dielectric constant. Additionally, the dynamics of the phenol-carbamate bonds were quantified by analysing the results of temperature-dependent stress relaxation studies and variable-temperature FTIR results. The potentials of this self-cleaning, self-healing, stretchy, and processable FPPU were assessed by creating a TENG and composite conductor. This invention served as inspiration for several fluorinated dynamic polyurethanes with various uses. Zhou et al. [100] The self-healing, flexible, multifunctional film with octadecane-loaded titanium dioxide nano-capsules (OTNs), graphene, and multi-branched polyurethane (PU) is effectively created in the current study. The completed film exhibits a new self-repair potential with disulfide connections in the leading chains for efficient self-healing of PU damage and multiple amino groups in the branches for damage between OTNs-graphene and PU. The developed flexible film displays an outstanding showing in piezoresistive sensing and an appealing consequence of ultraviolet protection qualities, which can substantially prolong its service life, mainly when utilised outdoors. The built-in self-healing system influences these properties and well-dispersed OTNs-graphene. Additionally, the film demonstrates thermal insulating qualities that can provide a viable path for the thermal protection of a system of bio-integrated wearable electronic devices. Consequently, wearable electronics, human-machine interaction, and artificial intelligence devices show promise for this self-healing multifunctional film [101].

According to Tabbai et al. [102], The pyroelectric effect, which converts thermal energy into electrical energy, is demonstrated by the authors using charged polyurethane (PU) with various concentrations (20%, 30%, and 40%) of lead zirconate titanate (PZT). These PZT/PU composites are subsequently used as pyroelectric energy harvesting devices. The second is the development of energy harvesting and storage. The PZT/PU composite created is regarded as one of the most promising composites for energy harvesting systems due to its many advantages, including mechanical flexibility, high-temperature sensitivity, low cost, and excellent electro-active functional properties. 140 s of temperature change-related current generated by the specimens have been corrected and saved in a 1 F charge capacitor. The largest quantity of stored energy for a composite loaded with 40% PZT can hold a maximum of the range of 14 W. Hence, these composites demonstrate an intriguing potential for utilisation in a variety of applications. Our findings provide insight into the thermoelectric energy conversion capability of a novel PZT/PU composite material. According to Fan et al. [103], By turning solar energy into thermal energy stored in phase transition materials, the energy dilemma can be addressed, and energy consumption efficiency boosted (PCMs). Nonetheless, the straightforward synthesis of form-stable PCMs (FSPCMs) continues to be challenging for the simultaneous integration of energetic solar-thermal conversion, storage, and manufacturing. The authors present a practical solar-thermal energy transformation and storage system that concurrently achieves a high solar-thermal energy conversion efficiency (93.7%) and restricts the fluidity of melting paraffin. The system uses paraffin (PW) as energy storage units and polyurethane (PU) foam that has been functionalised with silver and polypyrrole as a cage and energy conversion platform. The created FSPCMs have a high thermal energy storage density of 187.4 J/g and a good leak-proof characteristic. Two hundred accelerated solar-thermal energy conversion-cycling experiments were also performed.

Georgopoulou et al. [104] investigated the Sh18A shore hardness pneumatic actuators were printed using a pellet-based fused deposition modelling (FDM) printer. The technique also permitted the in-situ integration of soft piezoresistive sensor components throughout manufacturing. The incorporated piezoresistive elements were constructed from the three distinct styrene-ethylene-butylene styrenes (SEBS) thermoplastic elastomers, each filled in a 1:1 ratio with carbon black (CB). SEBS produced the best sensor behaviour with a shore hardness of Sh50A. The dynamic and quasi-static sensor behaviour on SEBS strips with integrated piezoresistive sensor composite material was investigated, and the findings were contrasted with TPU strips from a previous study.

4. Limitations, Challenges and Way Forward of the Polyurethane Applications

Isocyanate toxicity, especially in the case of aromatic isocyanates, has been considered a serious problem despite the apparent biocompatibility of PU-based materials and their early application as biomaterials. The following are the limitations or disadvantages of PUs.

i. Poor thermal performance
ii. Poor weather ability.
iii. most of the solvents attack.
iv. Use hazardous isocyanates.
v. Flammable.

The way forward is to carry out studies to identify materials that can be employed to reinforce the PUs to reduce the poor thermal capability, weather-ability, and the attraction of solvent and flammability of the materials [105].

5. Conclusion

The application of polyurethane as a sustainable multi-functional material has been studied via a critical review of various literature showing the quality attribute of polyurethane (PU). This research focuses on the formulation of PU, its characteristics, engineering application, and its details. The study also carried out a literature survey of the applications of PUs in buildings (roofing, window) as a reinforcement to form polymer composite materials in biomedical applications (such as tissues, wounding treatment, breast implant, Cardiac surgery, and drug delivery systems). Also, its application in electronics such as materials to develop sustainable Actuators, EMI shielding, Shape memory, Sensors, Energy harvester and storage, and Flexible electronics. From the comprehensive review, the following conclusion is drawn as follows:

i. The review proves that the PU-aluminium roofing sheet is durable and can withstand thermal radiation longer without causing health challenges.
ii. The bioavailability, biodegradability, and adaptability of PU's chemical and physical forms are why it can be used to make stents, pressure-sensitive surgical dressings, antibacterial surfaces and catheters, drug delivery devices, pressure-sensitive acrylics, tissue engineering scaffolds, cardiac patches, and nerve regeneration.
iii. PU coatings for breast implants Create intelligent biomaterials with specialised characteristics for effective tissue regeneration.
iv. In producing energy storage systems, implementing polyurethane as a combined material paraffin (PW) has good functionality with silver and polypyrene as a cage and energy conversion platform for a sustainable energy storage system.

Furthermore, this study will recommend the application of polyurethane forms in developing bio-composite materials and polymer composites for electronics applications to obtain multi-functional materials to create flexible wires for engineering applications. Also, from studies, it was seen that most PU foams are developed 21 inches in size. This study will recommend that material characterization be done to improve the development and make manufacturing industries produce innovative PU foams.

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