

Review Article

Properties of the Modified Polymethyl Methacrylate as Denture Base Materials: A Comprehensive Review

Issam Mohamed Aldwimi^{1, 2, 3} , **Hazizan Md Akil^{1, 2, *}** ,
Zuratul Ain Abdul Hamid^{1, 2} , **Ahmed Omran Alhareb^{1, 2}**

¹School of Materials and Mineral Resources Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, Malaysia

²Cluster of Polymer Composites, Universiti Sains Malaysia, Nibong Tebal, Malaysia

³The Faculty of Medical Technology of Msellata, Almorgab University, Treforest, Libya

Abstract

This paper presents a review that summarises research conducted over the past few decades on enhancing acrylic denture base resin, specifically focusing on the effects of fibre, filler, and nanofiller additions on the properties of poly (methyl methacrylate) (PMMA). The review incorporates scientific papers, abstracts, and studies published between 2015 and 2023, which explore the impact of additives, fibres, fillers, and reinforcement materials on PMMA. According to the reviewed studies, the addition of fillers, fibres, nanofillers, and hybrid reinforcement materials has been shown to enhance the properties of PMMA denture base material. However, it is important to note that most of these investigations were limited to in vitro experiments and did not thoroughly explore the bioactivity and clinical implications of the modified materials. Based on the findings of the review, it is concluded that there is no single ideal denture base material. However, the properties of PMMA can be improved through certain modifications, particularly the addition of silanised nanoparticles and the use of a hybrid reinforcement system. These modifications have shown promising results in enhancing the performance of PMMA as a denture base material.

Keywords

PMMA, Denture Base, Dental Materials, Fibres Reinforcement, Polymer Composites, Reinforcement Fillers, Nanoparticles, Hybrid Reinforcement

1. Introduction

The science of dental materials focuses on the study of various materials used in dentistry, including those for fillings, crowns, bridges, dentures, and orthodontic appliances. It involves understanding the composition, properties, and behaviour of these materials, as well as their interaction with the oral environment. The field encompasses multiple aspects,

including the study of physical properties (e.g. hardness, strength, elasticity), chemical properties (e.g. reactivity, corrosion resistance), biological properties (e.g. interaction with oral tissues, bacterial adhesion), and aesthetic properties (e.g. colour, translucency) [1].

Dental materials play a vital role in dentistry by remedying,

*Corresponding author: hazizan@usm.my (Hazizan Md Akil)

Received: 18 March 2025; **Accepted:** 31 March 2025; **Published:** 13 September 2025



Copyright: © The Author(s), 2025. Published by Science Publishing Group. This is an **Open Access** article, distributed under the terms of the Creative Commons Attribution 4.0 License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited.

restoring, and preserving oral health. When portions of teeth or oral tissues are lost due to oral diseases, accidents, or other factors, dental materials are commonly used for replacement or repair [2]. In cases where a substantial portion of a tooth is lost or weakened, dental crowns or bridges may be required. These restorations are typically made from materials such as ceramics, metal alloys, or a combination of both [3]. The chosen materials should possess excellent strength, durability, and aesthetics to ensure long-term functional and cosmetic results.

Dental materials are also used in other applications, including dentures, dental implants, orthodontic appliances, and periodontal treatments. Each of these applications requires specific material properties to achieve successful outcomes [4]. In dental restorations, various biomaterials can be used individually or in combination, including metals, ceramics, polymers, and composites. The selection of the appropriate material or combination of materials depends on several factors, including patient-specific considerations, dentist preferences, and the characteristics of the materials themselves. These characteristics include elastic modulus, fatigue strength, chemical resistance, fracture toughness, hardness, aesthetic appearance, and overall strength. Based on these factors, dentists evaluate the advantages and disadvantages of different materials to determine the best option for the patient's needs and preferences. In some cases, a combination of materials may be used, such as a metal substructure covered with a ceramic layer for dental crowns or composite resin bonded to a metal framework for dental bridges [5, 6].

Denture base fabrication involves considerations of material types, material enhancements, and surface treatments to create functional and comfortable denture bases [7]. These bases are typically made from polymers, specifically acrylic resins, which offer advantages such as ease of manipulation, biocompatibility, and the ability to be custom-fitted to the patient's oral tissues. There are different types of acrylic resins available, including heat-cured, self-cured, and microwave-cured variants. Poly (methyl methacrylate) (PMMA) is a widely used resin-based restorative material, particularly for removable dentures. PMMA has been the dominant polymer for denture bases in dentistry for many years [8]. It offers several advantages that make it ideal for denture base fabrication, including biocompatibility, ease of manipulation, aesthetic versatility, good mechanical properties, and repairability [9]. The denture base is the portion of the denture that rests on the oral mucous membranes, supporting the artificial teeth while providing stability and retention. It serves as the foundation of the denture and is custom-made to fit the contours of the oral tissues, including the gums and underlying bone [10].

When selecting a material for denture base fabrication, several key physical properties are required to ensure optimal performance. The denture base material should have sufficient stiffness to securely hold the artificial teeth during chewing and reduce uneven loading on the underlying oral

mucous membranes. This helps distribute forces evenly, preventing discomfort or tissue irritation [11]. Additionally, the denture base material should exhibit good aesthetics, resembling the natural appearance of the gums and oral tissues. This contributes to the overall aesthetic outcome of the denture, providing a more natural-looking smile [12].

Biocompatibility is crucial to ensure that the material is well-tolerated by the oral tissues, causing minimal or no adverse reactions. It should not irritate the mucous membranes or trigger allergic responses [13]. The material should also have high bond strength to ensure effective adhesion between the denture base and artificial teeth or other denture components, such as metal frameworks or clasps. This enhances the stability and longevity of the denture [14]. Radiopacity, or the ability of the material to be visible on dental X-rays, is important for identifying the denture base material and assessing any underlying issues or changes in the oral tissues during routine examinations [15].

The denture base material should also be easily repairable in case of damage or fractures, allowing for convenient and cost-effective maintenance over time [16]. Favourable physico-mechanical properties are essential, including appropriate hardness, durability, and resistance to wear and fracture. The material should withstand normal masticatory forces as well as any parafunctional habits (e.g. teeth grinding or clenching) the patient may have [17]. Moreover, the denture base material should be biologically inert, meaning it should not cause adverse reactions or inflammation when in contact with oral tissues [18]. Water absorption can lead to the development of unpleasant odours over time. Therefore, it is desirable for the denture base material to have low water absorption and emit minimal odour when exposed to moisture. This helps maintain oral hygiene and reduces potential embarrassment or discomfort for the denture wearer [19].

Denture manufacturers and dentists are continually researching and exploring new materials and techniques to improve denture designs. While there have been significant advancements in denture materials, ongoing efforts continue to address certain physical and mechanical concerns associated with these materials [20]. Researchers and manufacturers are actively developing new materials and techniques to overcome these challenges. For example, advancements in polymer chemistry have led to the creation of more resilient and flexible denture base materials with improved fracture resistance and wear properties. Reinforcing agents, fillers, and nanoparticles are also being incorporated to enhance the mechanical properties of denture base materials [21].

Poly (methyl methacrylate) (PMMA) is a type of plastic resin formed through the polymerisation of methyl methacrylate (MMA) monomer [22]. PMMA is commercially available under various brand names, including Plexiglas, Perspex, Plazcyl, Limacryl, R-Cast, Acrylex, Altuglas, Polycast, Acrylite, Acrylplast, Oroglass, and Lucite. It is also commonly referred to as acrylic glass or simply acrylic [23]. While these commercial brands of PMMA may have slight

variations in formulation and processing techniques, they all share the fundamental chemical structure and properties of PMMA [24].

PMMA is particularly valued for its excellent optical clarity, allowing it to mimic the appearance of natural teeth and gums. This transparency is especially important in dentistry, as it contributes to the aesthetic outcome of dentures and other dental restorations [25]. Another key advantage of PMMA is its high weather resistance. It is resistant to discolouration and degradation when exposed to environmental factors such as sunlight or UV radiation. Additionally, PMMA is known for its durability and impact resistance, making it well-suited for use as a denture base [23, 26].

2. Materials and Methods

A systematic and comprehensive search was conducted across multiple scientific databases, including PubMed, Scopus, and Google Scholar, to identify and retrieve relevant studies for this literature review. The search focused on publications from 2015 to 2023, using a predefined set of keywords to ensure a thorough exploration of the existing body of knowledge. These keywords included denture base materials, dental materials, mechanical properties of polymers, polymethyl methacrylate (PMMA) denture base, acrylic denture base materials, PMMA properties in dentistry, challenges of PMMA denture bases, mechanical properties of PMMA dentures, thermal properties of PMMA for dentures, PMMA copolymers for denture bases, hybrid polymer denture materials, reinforcement of PMMA denture bases, nanoparticle-reinforced PMMA, PMMA reinforced with fibers, nanotube-reinforced PMMA dentures, water absorption and solubility of PMMA, wear resistance of PMMA denture materials, and color stability in PMMA dentures.

To refine the search process and improve the precision of retrieved literature, Boolean operators (AND, OR, and NOT) were employed. These operators facilitated the inclusion of the most pertinent studies while filtering out irrelevant publications, thereby ensuring the relevance and specificity of the final selection.

The selection of literature for this review was guided by clearly defined inclusion and exclusion criteria to ensure the relevance, quality, and reliability of the studies considered. The inclusion criteria encompassed peer-reviewed original research articles, systematic and narrative reviews, book chapters, and other scholarly works published in English. Only studies explicitly focusing on denture base materials and their properties, particularly those investigating polymeric materials such as PMMA, were included.

Conversely, studies were excluded if they fell under any of the following categories: editorials, conference abstracts, opinion pieces, or non-peer-reviewed publications. Additionally, non-English language studies and research that did not specifically address denture base materials or polymer-based dental applications were omitted. Studies lacking

experimental data or empirical findings relevant to the research objectives were also excluded to maintain the scientific rigour of the review.

The initial search yielded 500 articles. After removing 110 duplicate entries, 390 articles remained for further evaluation. Screening commenced with a preliminary review of article titles and abstracts, leading to the exclusion of 90 articles deemed irrelevant to the scope of this review. A full-text assessment was subsequently conducted on the remaining 300 articles, applying the predefined inclusion and exclusion criteria. This rigorous evaluation led to the exclusion of a further 108 studies that did not meet the eligibility criteria. Ultimately, 192 articles were deemed suitable for inclusion in this review.

The systematic and methodical approach employed in this selection process ensured that only the most relevant, high-quality, and scientifically robust studies were incorporated into the final analysis. This methodological rigor strengthens the validity and reliability of the literature review, providing a solid foundation for the subsequent discussion and analysis of denture base materials.

3. Historical Review of the Development of the Denture Base Materials

Denture-based material fabrication has seen significant developments and advancements over the years. Polymers, particularly acrylic resins, have been widely used in this field for several decades due to their favourable properties and ease of fabrication. However, ongoing efforts continue to improve these materials and explore alternative options [27]. Acrylic resins, such as PMMA, have been the most commonly used denture base materials [28]. To enhance their mechanical properties, cross-linking agents are used during polymerisation, resulting in cross-linked acrylic resins with improved strength and durability [29].

High-impact resins are a variation of acrylic resins that incorporate rubber particles (usually butadiene-based) to enhance impact strength and toughness [30]. Polyamide (nylon) resins have gained popularity as an alternative denture base material due to their flexibility and durability. CAD/CAM denture fabrication has revolutionised the industry by using computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies to create precise and customised dentures [31].

Flexible denture base materials are made from thermoplastic materials, such as polyolefins or elastomers, offering patients greater comfort and adaptability. In certain cases where high strength and rigidity are required, metal denture base materials, such as cast cobalt-chromium alloys or titanium, may be used [32].

The Japanese have a rich history of woodcarving and were among the earliest to produce wooden dentures during the 8th century. These dentures were carved from a single piece of

fragrant wood, with natural teeth fixed onto the denture base using screws or other techniques. However, one of the challenges of using wood as a denture base material is its susceptibility to moisture. Wood tends to absorb moisture, which can cause denture bases to warp, crack, or deteriorate over time, posing both hygienic and aesthetic challenges for denture wearers [33, 34].

There was a significant gap in denture development between the 8th and 17th centuries. It was during the 17th century that Pierre Fauchard, often regarded as the father of modern dentistry, made notable advancements in prosthetic methods, including dentures [35, 36]. Fauchard used a variety of materials for denture fabrication, including human teeth as well as teeth made from hippopotamus or elephant ivory. These materials provided better stability compared to wooden dentures. However, despite the improvement in stability, aesthetic and hygienic challenges persisted [37].

The use of natural human or animal teeth posed difficulties in achieving a natural appearance, as the colour and shape of these teeth often did not perfectly match the patient's remaining natural teeth. Additionally, maintaining hygiene and preventing oral infections was a concern due to the porous nature of these materials and the limitations in sterilisation techniques at the time [38, 39].

Ivory dentures offered improved stability and aesthetics, but their major drawback was the scarcity and high cost of ivory. Sourced from animals such as hippopotamuses and elephants, ivory was not easily available. Obtaining it required specialised resources and labour, making it a limited and expensive material for denture fabrication. As a result, ivory dentures became a luxury option, affordable only to a select few, while their high cost restricted widespread use among the general population [40].

The use of polymers as denture base materials can be traced back to the latter part of the 19th century [41]. Charles Goodyear played a significant role in introducing the concept of rubber production in 1839 when he discovered the process of vulcanisation, which involves heating rubber with sulphur to create a harder and more durable material [42]. Nelson Goodyear, Charles Goodyear's brother, further developed the vulcanisation process in 1851, making it more efficient and practical. This advancement opened up new possibilities for the use of rubber in various applications [43].

In 1854, Thomas Evans, a dentist, utilised vulcanised rubber as a denture base material [43, 44]. He fabricated dentures for both Charles Goodyear Senior and Charles Goodyear Junior using this material. The resulting denture base, known as vulcanite, exhibited a reddish-brown colour and possessed several notable properties [45, 46].

Vulcanite proved advantageous for denture fabrication due to its hardness, stability, and resistance to deformation. Additionally, it was relatively easy to shape and adapt to the oral tissues of patients. These characteristics made vulcanite a popular choice for dentures in the late 19th and early 20th centuries [47].

After its introduction in the mid-19th century, vulcanite remained the primary denture base material for approximately 75 years. Its durability, stability, and ease of shaping contributed to its widespread use during that time [48]. However, in the 1930s, a new material called PMMA was introduced for denture fabrication. PMMA offered several advantages over vulcanite, including improved aesthetics, better colour stability, and a stronger bond with artificial teeth [49].

Dr Bean cast the first complete aluminium base in 1867 and is also credited with developing a casting machine around that time. In the 1880s, an innovative aluminium casting process called pressure die casting was developed by Charles Martin Hall in the United States and Paul Héroult in France. This process involved injecting molten aluminium into a metal mould under high pressure to create complex shapes and precise castings. It revolutionised aluminium casting by enabling mass production and improved accuracy [50, 51].

Although aluminium was once considered for denture bases, its use was later discouraged due to difficulties in relining, high fabrication costs, and concerns over its potential link to Alzheimer's disease. However, it is important to clarify the scientific basis of these concerns [52].

PMMA was first clinically evaluated by Wright in 1937, who determined that it met all the requirements of an ideal denture material [53]. By 1946, approximately 95% of all dentures were made from PMMA, marking a significant advancement in the application of acrylic resin. Initially, acrylic resins were produced through heat polymerisation. However, in 1947, German researchers developed a new method using chemical accelerators for polymerisation, leading to the introduction of self-polymerising resins [54, 55]. PMMA and its co-polymers continued to be widely preferred due to their numerous advantages. Over time, these materials became the most popular choice for non-metallic denture base materials [56].

4. Polymeric Denture Base Material

In 1973, new acrylic polymers were introduced in dentistry, replacing previously favoured denture materials such as celluloid, PVC, porcelain, phenol-formaldehyde, wood, vulcanite, bone, and ivory. These earlier materials had undesirable properties, including poor strength and aesthetics, which made them unsuitable for use as denture base materials [57, 58].

A polymer is a large molecule composed of repeating subunits called monomers. These monomers are small molecules that can react with each other to form a polymer chain. The monomer is the smallest repeating unit in the polymer structure. When two different but compatible monomers react together, they form a copolymer. Copolymers are polymers that contain two or more different types of monomers within their chain structure. The properties and characteristics of copolymers can vary depending on the composition and arrangement of the monomers within the chain [59, 60].

Polymers have been extensively used in both restorative and prosthetic dentistry. In the 1940s, resin-based materials began to be used for dental restorations, marking a significant advancement in dental materials [61]. While polymers have proven highly beneficial in dentistry, not all polymeric materials are ideal for clinical applications due to certain limitations, such as fracture resistance and radiopacity [62].

Fracture resistance is a critical property for dental materials, especially those used in restorations and prosthetics that are subjected to significant forces during mastication. Some polymeric materials may have lower fracture resistance compared to other dental materials, such as metals or ceramics. This can make them more prone to cracking or breaking under stress, leading to the failure of the dental restoration or prosthetic [63].

PMMA resin, specifically polymethyl methacrylate, gained recognition in the 1930s as one of the best materials for fabricating removable denture bases. It was highly regarded for its superior physical, biological, and aesthetic properties, making it highly suitable for dental applications [64].

PMMA resin's colourless and transparent nature, along with its high degree of translucency, allowed it to achieve excellent aesthetics in dentistry. When used as a denture base material, PMMA resin mimicked the appearance of natural gums, enhancing the overall aesthetic outcome of the denture. Its translucency enabled a natural blending with the underlying oral tissues, resulting in a lifelike appearance [65].

In terms of biological properties, PMMA resin demonstrated biocompatibility, meaning it was well-tolerated by oral tissues. This biocompatibility ensured that the material did not cause adverse reactions or allergies when in contact with the mouth. It was crucial for removable denture bases to be made from materials that did not irritate or harm oral tissues, and PMMA resin met this requirement effectively [66].

The discovery of rubber vulcanisation by Charles Goodyear played a significant role in the development of polymer materials for dentistry. Today, dental resins, including polymethyl methacrylate (PMMA) and acrylic resin, are commonly used in denture fabrication [67]. PMMA-based materials are widely used in the fabrication of denture bases, artificial teeth, and other dental prostheses. However, some patients may find PMMA-based denture bases too hard or uncomfortable. In such cases, softer liners can be used to improve the fit and comfort of the denture. These liners are typically made from rubber-like polymers that are compatible with PMMA [68].

While many rubber-like polymers are compatible with PMMA, not all of them are suitable for long-lasting dentures. The flexibility of the material needs to be balanced with durability to ensure the denture can withstand the forces of chewing and maintain its shape over time [69]. Apart from denture liners and bases, various types of polymers are used in different applications within dentistry. Tissue conditioners are temporary soft materials used to provide relief for irritated oral tissues and aid in the healing process. Impression materials, restoratives, temporary restoratives, and custom trays for impressions can also be made from different types of

dental resins and polymers [70, 71].

PMMA was developed as a hard plastic by Dr Walter Wright and the Vernon brothers in 1930 at the Rohm and Haas Company in Philadelphia. PMMA quickly gained popularity in dentistry and became a major material in dental restoratives and prosthodontics. In addition to restoratives and prosthodontics, PMMA was also commonly used as an impression material until 1999 [72, 73]. PMMA gained widespread use in dentistry due to its favourable properties, such as being lightweight, chemically stable, and having good aesthetics. It became widely used as a denture base material in the 1930s and 1940s and remains in use today [74].

In the case of Al-Shalawi et al., they combined the mechanical attributes of polymethyl methacrylate (PMMA), a synthetic polymer commonly used in bone cement, with the properties of another material, possibly a natural polymer [74]. This combination resulted in a composite material that exhibited long-term durability, similar to freshly prepared PMMA, even after being in use for 15–24 years [74].

Natural polymers have been utilised for various purposes for centuries. They are sourced from plant- and animal-derived materials such as wood, rubber, silk, cotton, wool, and leather [75]. These polymers, including cellulose, proteins, starches, and enzymes, are obtained through physiological and biological processes in plants and animals [76].

With advancements in scientific research and technology, it has become easier to characterise and understand the properties of these natural polymers. Moreover, researchers have been able to develop different types of polymers by assembling small organic molecules through chemical reactions. This has led to the creation of novel materials with tailored properties and functionalities [77].

Synthetic or man-made polymers have become widely used across various industries due to their cost-effectiveness and the ability to tailor their properties during the fabrication process. Unlike natural polymers, which are derived from natural sources such as plants or animals, synthetic polymers are produced through chemical reactions and processes [78].

The structural composition of synthetic polymers can be precisely controlled, allowing for the manipulation of properties such as strength, flexibility, thermal stability, and chemical resistance. By adjusting the monomers used, the polymerisation process, and other factors, manufacturers can create polymers with specific characteristics to suit a wide range of applications [79].

One significant advantage of synthetic polymers is their low cost compared to natural materials like metal and wood. Plastics, for example, can be produced in large quantities at relatively low costs, making them an attractive alternative for many applications. Additionally, synthetic polymers often possess superior properties compared to their natural counterparts, such as higher strength-to-weight ratios, corrosion resistance, and electrical insulation properties [80, 81]. Figure 1 presents the ideal properties required for materials used in denture-based applications.

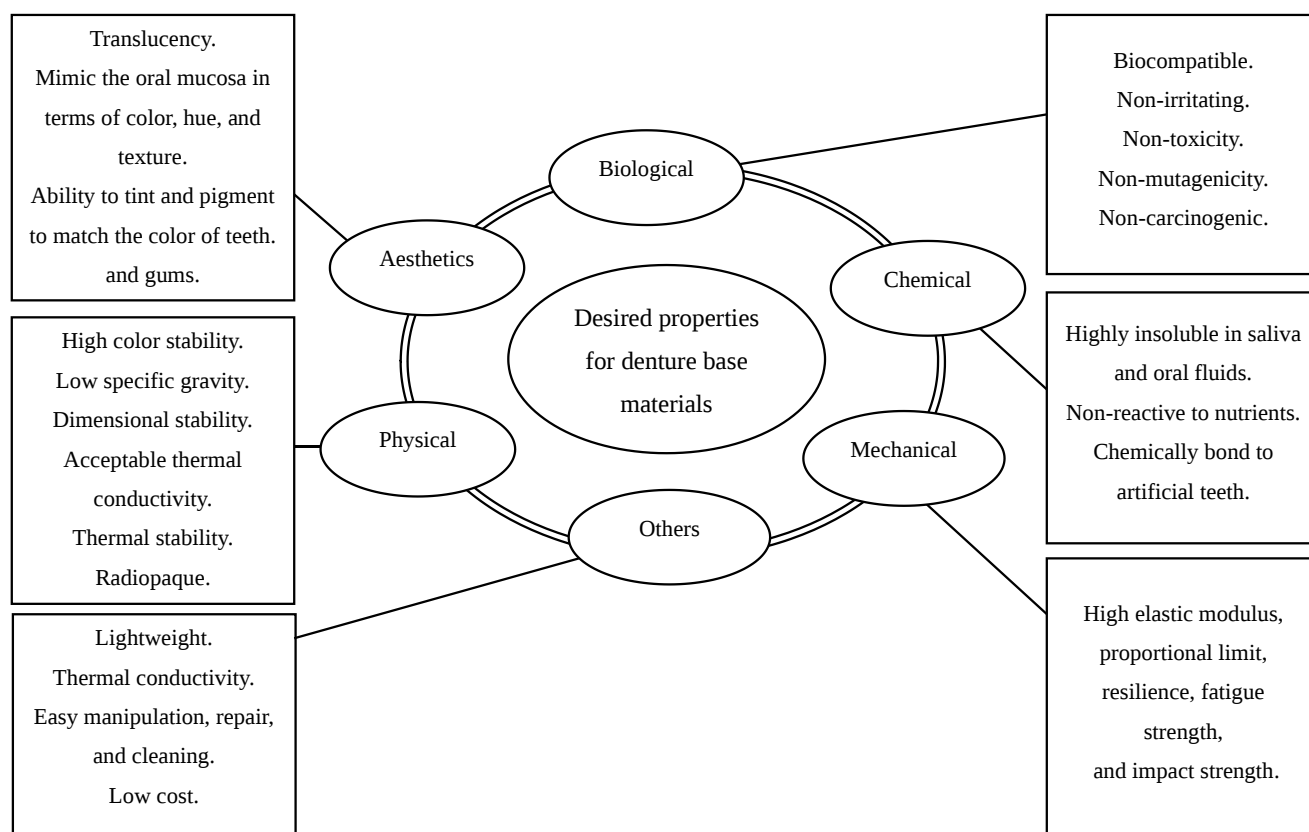


Figure 1. Ideal properties required for materials for denture base applications.

4.1. Classification of Polymeric Denture Base Materials

Acrylic resin has been widely used in the fabrication of dentures due to its favourable properties. It is a thermosetting, transparent plastic made from a synthetic polymer called polymethyl methacrylate (PMMA). The production of acrylic resin involves several processes, including emulsion polymerisation, bulk polymerisation, and solution polymerisation. Although the development of acrylic resin began in various laboratories in 1928, it was not until 1933 that it became commercially available through the efforts of the Rohm & Haas Company [82, 83].

The International Organization for Standardization (ISO) has established standards for polymeric denture base materials, categorising them into five types according to ISO 20795-1: 2013 (Table 1). Among these, Types 1 and 2 are commonly used in dental practice. This paper focuses on reviewing Type 1, which refers to PMMA as a heat-processed polymer in powder and liquid form [84].

Type 1 PMMA, as a heat-processed polymer, is widely

used in the fabrication of denture bases. It involves mixing a polymer powder with a liquid monomer to form a dough-like consistency. This dough is then heat-cured in a controlled environment, allowing it to polymerise and solidify, ultimately forming the denture base.

The advantages of using Type 1 PMMA include:

1. Transparency, which provides a natural appearance for the denture base.
2. Ease of adjustment and repair if necessary.
3. Good biocompatibility and satisfactory physical properties for denture applications [85, 86].

However, Type 1 PMMA also has some limitations:

1. It can be prone to discolouration over time due to factors such as staining from food and beverages.
2. It may exhibit relatively low impact strength and susceptibility to fracture under certain conditions [87].

In conclusion, Type 1 PMMA is a widely used material for denture fabrication. Its heat-processing properties and desirable characteristics make it a suitable choice for denture bases. However, it is important to recognise its limitations and ensure proper maintenance and care to maximise the longevity and functionality of dentures made from Type 1 PMMA.

Table 1. Classification of denture base polymers according to ISO 20795-1: 2013.

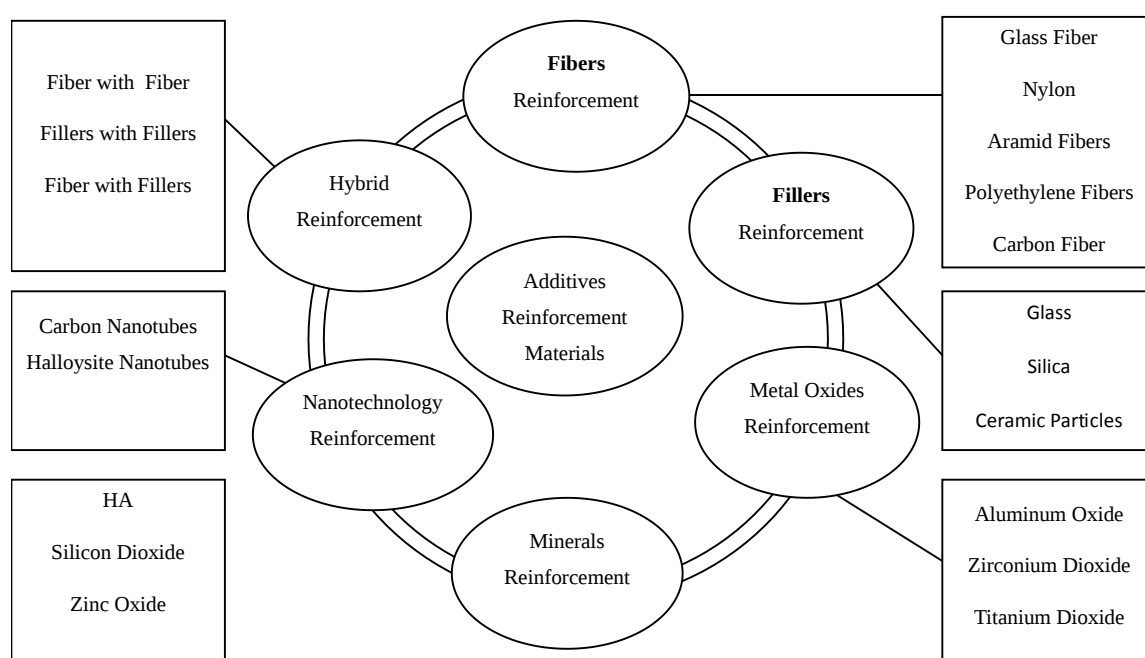
Type	Class	Description
1	1	Heat-processing polymers, liquid and powder
1	2	Heat-processed (plastic cake)
2	1	Auto polymerization polymers, powder, and liquid
2	2	Auto polymerization powder, powder, and liquid
3	-	Thermoplastic powder or blank
4	-	Light-activated materials
5	-	Microwave-cured materials

4.2. Types of Additives Used to Reinforce PMMA Denture Base

Several types of additives can be used to reinforce PMMA denture base materials. These additives are incorporated to enhance various properties of the denture base resin.

Some commonly used additives include:

1. Fibres (e.g., glass fibres, carbon fibres, polyethylene fibres)
2. Fillers (e.g., silica, alumina, zirconia particles)
3. Metal oxides (e.g., titanium dioxide and aluminium oxide nanoparticles)
4. Mineral reinforcements (e.g., glass or ceramic particles)
5. Nanotube technology (e.g., carbon nanotubes or other nanoscale reinforcements)
6. Hybrid reinforcements, which involve combining different types of additives to achieve synergistic effects. For example, a combination of fibres, fillers, and nanoparticles may be added to PMMA denture base material to improve its physical, mechanical, environmental, and thermal properties (see Figure 2).

**Figure 2.** Different types of additives are used to reinforce PMMA denture base.

4.2.1. Fibres

PMMA denture base reinforcement with fibres has indeed

been found to enhance various mechanical properties and characteristics of resins used in denture fabrication. The addition of fibres can improve the flexural strength, modulus of

elasticity, and impact strength of the PMMA denture base. It also enhances other important properties, such as hardness, water absorption resistance, fatigue resistance, and fracture toughness [88]. Various types of fibres have been investigated for their potential use as reinforcements in PMMA denture bases.

Nylon, polyamide fibre, and polyethylene are among the fibres that have been studied. These fibres are chosen for their desirable mechanical properties, biocompatibility, and ability to enhance the aesthetics of the denture. By incorporating these fibres into PMMA denture bases, dentists and dental technicians can create dentures with improved durability and longevity. This can lead to better patient satisfaction and a reduced need for denture repairs or replacements [89].

Glass fibre (GFs) reinforcement has been shown to have significant positive effects on the mechanical properties of acrylic resin, including impact strength, toughness, flexural strength, and Vickers hardness. When GFs are incorporated into acrylic resin, they act as reinforcing agents, enhancing the overall strength and toughness of the material [90]. The GFs distribute stress more effectively, which helps to resist crack propagation and improve impact resistance; flexural strength is also improved with the addition of GFs [91].

Alhotan et al. [92], investigated the effect of adding E-glass fibre with an average size of 14 to 18 μm into PMMA denture base material at different concentrations of 1.5, 3, 5, and 7 wt.% found that the flexural strength (FS) and surface hardness (VH) of PMMA dentures were significantly improved with the addition of 5 and 7 wt.% E-glass fibre compared to the PMMA matrix. The GFs reinforce the resin, making it more resistant to flexural forces and reducing the likelihood of fractures or failures. Furthermore, the incorporation of GFs in this study enhanced the hardness of PMMA resin. This improvement in hardness can contribute to better wear resistance and overall durability of the denture [92].

Indeed, the effect of GFs reinforcement on the impact strength of heat-polymerised acrylic denture base material (PMMA) has been studied by researchers such as [93]. Alhotan et al. [93], investigated the effect of adding E-glass fibre with an average size of 14 to 18 μm into PMMA denture base material at different concentrations of 1.5, 3, 5, and 7 wt.% examined its impact strength (IS) and fracture toughness (K_{IC}). The results of this study showed that the K_{IC} of PMMA dentures was significantly higher with all concentrations of added E-glass fibre compared to the PMMA matrix. In addition, the IS of reinforced PMMA dentures was significantly increased with the addition of 3, 5, and 7 wt.% of E-glass fibre compared to PMMA without fibres. The glass fibres act as reinforcement, distributing the impact forces more evenly and effectively throughout the material, which helps to prevent crack propagation and increases the material's ability to withstand sudden impacts [94].

A study conducted by Alhotan et al. [48] investigated the effects of adding treated E-glass fibres with a silane coupling agent into PMMA denture base material at different concen-

trations (1.5, 3, 5, and 7 wt.%) on water sorption, hygroscopic expansion, and solubility. The study involved immersing the control and reinforced PMMA samples in water for 180 days at room temperature and measuring various parameters. The study observed that the values of water sorption and mass sorption reached equilibrium within 180 days for all tested groups. While there was a noticeable difference in water sorption and mass sorption between the added E-glass fibre groups and the PMMA matrix, this difference was not statistically significant.

In other words, the inclusion of E-glass fibres did not significantly increase water sorption compared to the PMMA matrix. Researchers found that there were no significant differences in hygroscopic expansion percentage values between each respective PMMA-reinforced group and the control group [48]. This suggests that the addition of E-glass fibres did not lead to a significant increase in the hygroscopic expansion of the PMMA denture base material. Over a 28-day desorption period, there were no significant differences in the values of solubility and mass desorption between the PMMA matrix and the reinforced PMMA groups. This indicates that the presence of E-glass fibres did not lead to significant changes in solubility or mass desorption of the PMMA material.

Based on the study's findings, it can be concluded that the inclusion of E-glass fibres treated with a silane coupling agent into PMMA denture base material at the specified concentrations did not result in significant increases in water sorption, hygroscopic expansion, or solubility compared to the PMMA matrix [48].

Nylon is a synthetic polymer belonging to the polyamide family. Nylon and aramid are notable examples of polyamide fibres (Kevlar, DuPont, Wilmington, DE, USA). In denture base reinforcement, nylon fibres have been investigated for their potential to enhance the mechanical properties of denture base resins [95]. Denture base reinforcement with nylon offers several advantages and beneficial properties, leading to improved aesthetics and functional performance [96].

The advantages associated with using nylon as a reinforcement material in denture bases include excellent aesthetics, low density, abrasion resistance, insolubility in solvents, higher melting point, resistance to chemical attack, comfort and adaptability, flexibility in partially edentulous patients, resistance to shock and repeated stress, and higher fatigue resistance [97]. A study by Abbas et al. [98] examined the effect of nylon fibres on the impact strength (IS) of heat-cure acrylic resin (PMMA). The results indicated that the IS of heat acrylic was increased and improved with the incorporation of nylon fibres compared to the IS of the control group.

Aramid fibres, such as Kevlar, manufactured by DuPont, are also a type of polyamide fibre [99]. Aramid fibres are known for their exceptional strength and resistance to impact and abrasion. They have been extensively used in applications requiring high-strength materials, such as ballistic protection,

aerospace components, and structural reinforcements [100]. In dentistry, aramid fibres have been studied for their potential to reinforce denture base resins and improve their mechanical properties [101].

A study by He et al. [102] examined the effect of aramid fibre at several concentrations (1.5, 2.5, 3.5, and 4.5 wt.%) on the mechanical properties (flexural and compressive strength) of the PMMA/aramid composite. This study suggested that the flexural strength of the PMMA composite significantly increased to 114.37 MPa, a 27% improvement compared to the PMMA matrix. In addition, the compressive strength of the PMMA/aramid composite also increased to approximately 136.3 MPa compared to PMMA without aramid.

Polyethylene fibres (PE) have been reported to enhance the impact strength of PMMA. When polyethylene fibres are incorporated into PMMA, they can improve the toughness and elastic modulus of the material, contributing to its overall mechanical properties [94]. Raszewski [103] investigated the effect of adding polyethylene fibres at 5 wt.% on the flexural strength and impact resistance of heat-cured PMMA. This study found that the flexural strength and impact resistance of heat-cured PMMA were increased and improved after polyethylene fibres were added. The reinforcement with PE fibres can enhance the mechanical properties of the acrylic denture resin. The improved flexural strength indicates that the denture becomes more resistant to deformation and fracture when subjected to bending forces [104].

Abdulazeed et al. [104] found that the use of PE fibre (pre-silanised) as a reinforced filler in the composite (PMMA) led to an increase in the flexural strength (FS) of the composite up to 154.69 MPa compared to the control group. The FS of composites was also improved with other fibre materials in this study.

The same results were obtained by Apimanchindakul et al. [105] when they used ultra-high-molecular-weight polyethylene (UHMW-PE) at 1 and 2 wt.% to improve the flexural strength (FS) of self-cured acrylic resin. The results of this study showed that the addition of 2 wt.% of PE led to an increase in the FS of self-cured acrylic (PMMA), whereas the addition of only 1 wt.% of PE to self-cured PMMA resulted in the lowest FS.

According to another study, the reinforcement of heat-cured PMMA resin with silanised polypropylene fibres (PP) has been found to enhance the mechanical properties of the PMMA material. Mahmood [106] studied the improved mechanical properties (hardness, impact, and flexural strength) of heat-cured acrylic (PMMA) with the incorporation of 2 wt.% silanised PP fibres. The results showed that the hardness, impact resistance, and flexural strength of heat-cured PMMA were significantly increased with the addition of polypropylene fibres. This indicates that the incorporation of silanised PP fibres can improve the material's resistance to forces applied perpendicular to its surface, its tensile strength, and its ability to withstand impact [106].

Previous studies have explored the use of carbon fibre (CF)

as a means of strengthening denture bases [107]. Carbon fibre reinforcement is primarily aimed at improving the fatigue resistance and overall strength of denture base materials. Carbon fibre has been found to possess high strength and an ideal combination with matrix material, leading to enhanced mechanical properties of denture base materials [107]. The incorporation of carbon fibre into denture base matrices has been investigated in various research studies.

Sosiati et al. [108] explored the effect of carbon fibre (CF) on the flexural strength (FS), compression strength, and water absorption properties of PMMA-based composites. The study found that the FS properties (flexural strength and modulus) of the CF/PMMA composites presented significantly higher values compared to the control group and PMMA composites with other reinforcement materials used in this study, due to the good mechanical properties of CF. In addition, the compression strength of the PMMA base composite was significantly increased with the addition of CF into the PMMA composite. At the same time, the CF/PMMA composite showed the lowest water absorption [108].

The high strength of carbon fibre contributes to improved tensile strength, flexural strength, and impact resistance of the denture base material [107]. According to a study by H. Sosiati et al., they investigated the effect of treated carbon fibre (CF) on the tensile and flexural strength, as well as the thermal properties of Sisal/PMMA composites. The CF was treated by immersing it in a 68% HNO₃ solution for various durations, ranging from 24 to 96 hours. The outcome of the study showed that the mechanical properties (tensile and flexural strength) of the composites improved by incorporating the treated CF into the Sisal/PMMA composites. Additionally, the thermogravimetric (TGA) analysis indicated that the stability of the PMMA composites was increased with the addition of CF in the composites [107].

4.2.2. Fillers

Studies have demonstrated that the incorporation of different fillers significantly enhances the physico-mechanical properties of PMMA denture bases [48, 109]. Fillers such as glass fibres, silica, or ceramic particles can enhance the strength of the denture base resin. These fillers act as reinforcing agents, increasing the material's resistance to fracture or deformation under applied forces [110, 111]. Fillers such as nanoscale particles, like silica nanoparticles, can improve the physicochemical properties of the PMMA resin [112].

A study by Hata et al. focused on improving the mechanical and physico-chemical properties of PMMA-based resin by incorporating a silanised nano-silica filler, adding 6 wt.% of silanised nano-silica filler. The results of the study showed that the addition of the nano-silica filler led to a significant improvement in various mechanical properties of the PMMA-based resin. Specifically, the flexural strength (resistance to bending), flexural modulus, and Vickers hardness (resistance to indentation) values of the filler-loaded resin were significantly higher than those of the pure resin. This

suggests that the incorporation of the filler contributed to the overall mechanical strength and rigidity of the resin. Moreover, the physicochemical properties of the PMMA-based resin were improved. In terms of water sorption, there was no significant difference between the water sorption values of the pure resin and the filler-loaded resin [113].

However, a notable finding was that no water solubility was observed for the filler-loaded PMMA-based resin, whereas the pure resin exhibited some level of solubility. The absence of water solubility in the filler-loaded resin suggests improved resistance to degradation when exposed to water. The study concluded that the addition of the silanised nano-silica filler to the PMMA-based resin resulted in enhanced mechanical properties (higher strength, stiffness, and hardness) as well as improved physicochemical properties (reduced solubility) [113].

The addition of fillers enhances the material's ability to resist bending or breaking, providing better mechanical stability and reducing the risk of fracture [114]. Incorporating impact modifiers or toughening agents as fillers can enhance the impact resistance of the denture base resin. These fillers help absorb and dissipate energy upon impact, reducing the likelihood of damage [115]. Some fillers, such as inorganic particles or fibres, can enhance the dimensional stability of PMMA resin. This means that the denture base material is less prone to changes in shape or size due to temperature variations or moisture absorption [116]. The specific type, size, and concentration of fillers used can influence the extent of improvement in the physicochemical properties of PMMA resin. Additionally, it is crucial to ensure good dispersion and interfacial bonding between the fillers and the resin matrix to maximise their reinforcing effects [117].

The properties of nano-fillers-reinforced resin, such as PMMA, are influenced by several factors, including the shape, size, type, and quantity of the added particles. Nanofillers, which are typically nanoparticles or nanofibres, are used to enhance the mechanical, thermal, electrical, and other properties of polymer matrices [118]. In terms of thermal properties, the presence of nanofillers in PMMA can improve its thermal properties. The high surface area of nanofillers facilitates heat transfer within the composite material, leading to improved thermal conductivity. Additionally, nanofillers can act as barriers to heat flow, reducing the coefficient of thermal expansion and enhancing dimensional stability. By incorporating nanofillers into PMMA, these materials can exhibit enhanced thermal stability, reduced flammability, increased tensile strength, improved impact resistance, and other desirable properties compared to pure PMMA [119, 120].

4.2.3. Metal Oxides

Metal oxides are commonly used as fillers in PMMA denture base materials to improve their properties. There are many metal oxide fillers used in dentistry, specifically to enhance the properties of PMMA denture base materials. Aluminium oxide (Al_2O_3), zirconium dioxide (ZrO_2), and

titanium dioxide (TiO_2) are commonly used metal oxides in PMMA denture base materials to improve various properties [121], such as mechanical properties (including flexural and impact strength, and fracture toughness, making the dentures more resistant to deformation and fracture) [122], physical properties (such as reducing surface roughness and minimising the wear of denture teeth and opposing natural teeth during mastication) [123], environmental properties (such as water and saliva absorption and solubility) [124], and thermal properties (such as TGA and DSC) [125].

The addition of Al_2O_3 to PMMA denture base materials can indeed improve various properties, such as mechanical, physical, thermal, and environmental properties [27, 126]. The inclusion of Al_2O_3 powder in PMMA can enhance its thermal conductivity. Al_2O_3 is a ceramic material known for its excellent thermal conductivity. When added to PMMA as a filler, it can improve the overall heat transfer characteristics of the composite material [127]. Additionally, treating Al_2O_3 particles with a coupling agent before incorporating them into the denture base resin leads to improvements in the compressive, tensile, and flexural strength, as well as water resistance of the reinforced denture base material [128]. Silanised Al_2O_3 nanoparticles have been found to enhance the thermal properties and flexural strength of acrylic resin, while also reducing solubility and water absorption [27].

Kundie et al. conducted research aimed at studying how the addition of alumina micro- and nanoparticles to PMMA denture base materials affects their mechanical and thermal properties. The Al_2O_3 particles were treated with 3-methacryloxypropyl (γ -MPS) to improve their compatibility with the PMMA matrix [129]. Different concentrations of Al_2O_3 particles were added to the PMMA matrix. For micro-composites, the filler volume fractions were 0.5, 1, 2, 5, and 7 wt.%, while for nano-composites, they were 0.13, 0.25, 0.5, 1, 2, and 5 wt.%.

Fracture toughness and flexural tests were performed to evaluate the effects of filler size and loading on the mechanical properties. Both micro- and nano-particles led to increased fracture toughness. The addition of 0.5 wt.% Al_2O_3 nanoparticles resulted in a 39% increase, reaching a maximum value of $2.02 \text{ MPa m}^{1/2}$. Flexural strength did not show the same improvement as fracture toughness [129]. However, the flexural modulus increased with higher filler content. Thermogravimetric analysis (TGA) was conducted to assess the thermal stability of the PMMA/ Al_2O_3 composites. Micro-composites exhibited higher thermal stability compared to nano-composites. The study also investigated the water absorption and solubility characteristics of the prepared composites. The absorption and solubility of the composites were slightly higher than those of the control PMMA. The researchers suggested that using low concentrations of Al_2O_3 nanoparticles could be promising for improving the mechanical properties of PMMA denture base materials in future studies [129].

A research study conducted by Rohim et al. investigated the

effects of adding Al_2O_3 nanowires (Al_2O_3 NWs) at different weight fractions (wt.%) on the mechanical and tribological properties of heat-cured PMMA denture base material. The researchers created nanocomposite samples by incorporating Al_2O_3 nanowires into heat-cured acrylic resin. The nanofiller concentrations tested were 0, 0.1, 0.3, 0.5, 0.7, and 0.9 wt.% of Al_2O_3 NWs [130]. The fabrication process involved a water bath method. To assess the mechanical properties, a microhardness test was performed on all specimens. Microhardness values were recorded to understand how the incorporation of nanowires influenced the hardness of the material. The study also investigated the tribological properties (properties related to wear and friction) of both pure PMMA and its nanocomposites. This was done using a pin-on-disk tester under dry sliding conditions. The wear rate and coefficient of friction (COF) were measured and analysed.

Results indicated that as the nanofiller content (Al_2O_3 NWs) increased, there were improvements in the Vickers hardness number (VHN), wear rate, and COF. Specifically, there was an enhancement in these properties up to a certain concentration of nanofiller. VHN improved with increasing nanofiller content up to 0.5 wt.% of Al_2O_3 NWs, while the wear rate and COF improved up to 0.7 wt.% of Al_2O_3 NWs. The study also explored the impact of applied loads on wear behaviour. It was observed that the wear rate increased significantly with increasing applied loads up to 50N. On the other hand, the coefficient of friction decreased with increasing applied loads up to 40N [130].

Additionally, the study conducted by Gallab et al. focused on investigating the effects of incorporating Al_2O_3 NPs into PMMA denture base materials. The researchers fabricated PMMA nanocomposites with varying weight fractions (0.2, 0.4, 0.6, 0.8, and 1 wt.%) of Al_2O_3 NPs and compared their properties to pure PMMA samples (used as a control). The findings of the study indicated that the addition of Al_2O_3 NPs led to significant enhancements in the mechanical and tribological properties of PMMA denture base materials. The elastic modulus of PMMA dentures increased by 20.27% when 0.6 wt.% of Al_2O_3 NPs were added. The highest mean value of elastic modulus achieved was 3.56 GPa [126]. The compressive yield strength of PMMA dentures improved by 14.7% (138.21 MPa) with the addition of 0.6 wt.% of Al_2O_3 NPs compared to unfilled PMMA.

The hardness of the PMMA dentures was enhanced, with the highest improvements achieved with the addition of 0.8 and 1 wt.% of Al_2O_3 NPs (86.5 and 88.1 kgf/mm²). The fracture toughness of PMMA dentures increased with the incorporation of 0.8 and 1 wt.% of Al_2O_3 NPs, with improvements of 1.3 and 1.32 MPa m^{1/2}, respectively. The tribological (wear and friction) characteristics of PMMA dentures were positively impacted by the addition of Al_2O_3 NPs. The lowest coefficient of friction (COF) and wear rate were observed at a filler content of 0.6 wt.% of Al_2O_3 NPs [126].

The study by Omar et al. aimed to explore the utilisation of

PMMA composite materials suitable for dentures, while also investigating the properties of these materials. The researchers sought to enhance the properties of PMMA resin by incorporating nano- Al_2O_3 at various percentages (ranging from 1, 1.5, 2, 2.5, and 3 wt.%). The study's findings indicated that the inclusion of nano- Al_2O_3 had a positive impact on the properties of the composite materials. The density of the composite materials increased as the percentage of nano- Al_2O_3 increased. The composite materials exhibited higher compressive strength as the concentration of nano- Al_2O_3 increased. [131]

The tensile strength of the composite materials improved with the addition of nano- Al_2O_3 . The impact strength of the materials also increased as the percentage of nano- Al_2O_3 in the composite increased. The hardness of the composite materials showed an increase with the addition of nano- Al_2O_3 [131]. On the other hand, the porosity of the composite materials decreased as the concentration of nano- Al_2O_3 increased. The flexural strength of the materials decreased as the percentage of nano- Al_2O_3 increased [126].

However, Karci et al. [132] evaluated the effect of adding Al_2O_3 NPs at ratios of 1, 3, and 5 wt.% to heat-cured PMMA resins on flexural strength. The results of the study showed a significant increase in the flexural strength (FS) of PMMA with the addition of 1 wt.% of Al_2O_3 NPs, reaching up to 118.94 MPa. In contrast, the FS of heat-cured PMMA was reduced to 108.1 MPa when the concentration of Al_2O_3 NPs was increased to 5 wt.%, compared to the 1 wt.% and unreinforced heat-PMMA. Furthermore, the study found that the optimum ratio of Al_2O_3 NPs was up to 1 wt.%. The decrease in FS of heat-cured PMMA, as shown in the electron microscopy images, was attributed to the less homogeneous dispersion of Al_2O_3 NPs at higher ratios of nanofiller [132].

Additionally, a study by Aboshama et al. examined the flexural strength of strengthened denture base resin (heat-cured PMMA) after adding different concentrations of Al_2O_3 NPs at 1, 2, and 3 wt.%. The results showed that the highest mean value of FS for PMMA was obtained with the control group, while the mean FS value decreased from 77.96 to 54.22 MPa with the addition of 2 wt.% of Al_2O_3 NPs. The study also found that the addition of the metal oxide Al_2O_3 NPs into heat-cured PMMA led to a reduction in FS with all concentrations [121]. This phenomenon of reduced FS in PMMA is explained by the presence of agglomerates and voids in the material, which results from factors such as increased filler content. These agglomerates (clusters of filler particles) and voids (empty spaces) can significantly affect the material's performance and durability. The presence of agglomerates and voids can create stress concentrations within the material, which may become points of weakness and potential failure [121].

Several studies have shown that the addition of ZrO_2 fillers in PMMA can indeed improve certain properties of the PMMA denture base. ZrO_2 is a ceramic material with excellent mechanical and thermal properties, and when incorpo-

rated as fillers in PMMA, it can enhance several characteristics [133-135]. Some of the improvements observed with the addition of ZrO₂ fillers in PMMA include a significant increase in tensile strength, flexural strength, and impact resistance. The strong bonding between the ZrO₂ particles and the PMMA matrix enhances the overall mechanical performance of the material [114].

Alhotan et al. investigated the effect of adding ZrO₂ to PMMA denture base material at different concentrations (1.5, 3, 5, and 7 wt.%) on its flexural strength (FS) and surface hardness (VH). The results showed that the FS of the PMMA denture was significantly improved with the addition of 3 wt.% ZrO₂ compared to the PMMA matrix. The highest surface hardness of the PMMA denture base was obtained with the addition of 1.5 wt.% ZrO₂ [92].

In another study, Alhotan et al. examined the effect of adding ZrO₂ with an average size of 25 to 50 nm into PMMA denture base material at different concentrations (1.5, 3, 5, and 7 wt.%) on its impact strength (IS) and fracture toughness (K_{IC}). The results showed that the K_{IC} of the PMMA denture was significantly improved with the addition of 1.5 and 3 wt.% ZrO₂ compared to the PMMA matrix. The highest K_{IC} of the PMMA denture was achieved with the addition of 3 wt.% ZrO₂ compared to the PMMA matrix and other reinforced concentrations. However, the IS of the PMMA denture base only slightly increased [93].

The study by Azmy et al. investigated the influence of incorporating ZrO₂ NPs into PMMA denture base materials on the flexural strength (FS), impact strength (IS), hardness (VH), and wear resistance (WR) of PMMA. The study used two concentrations of ZrO₂ NPs at 3 and 7 wt.%. The results of the study showed that both FS and IS were significantly increased with the addition of ZrO₂ NPs in PMMA compared to the control group without filler [124]. The FS increased up to 87.3 MPa with the addition of 7 wt.% compared to unreinforced PMMA, which had 59.4 MPa. Additionally, the addition of 7 wt.% of metal oxide into the PMMA denture increased the IS of the composite from 1.87 to 3.3 KJ/m². At the same concentration of ZrO₂ NPs in the PMMA composite, the VH also increased to 44.4 kgf/mm², compared to pure PMMA, which had only 37.9 kgf/mm². The WR of reinforced PMMA with 3 wt.% of ZrO₂ NPs had the lowest WR at 0.0016 µm, compared to PMMA without filler, which had a WR of 0.0025 µm. The improvement in the properties of the PMMA denture base in this study was attributed to the uniform distribution of small ZrO₂ NPs [124].

The nanoparticles were uniformly distributed within the polymer matrix. This distribution helps fill the spaces between the linear chains of the polymer, which restricts the movement of the polymer chains. This suggests that the material becomes more resistant to breaking and bending under applied loads. When sufficient stresses are applied, and microcracks begin to propagate within the material, the ZrO₂ NPs undergo a crystalline transformation from tetragonal to monoclinic. This transformation absorbs the energy of the

microcrack and halts its propagation. The transformation of ZrO₂ NPs causes the material surrounding the crack to go into a compressed state. This compression places the microcrack under stress, effectively stopping its further propagation [124].

In the study conducted by Alfahdawi et al. [136], the focus was on investigating the effect of different concentrations of ZrO₂ on the transverse and impact strengths of acrylic resin, specifically polymethyl methacrylate (PMMA). According to the findings of the study, the addition of ZrO₂ nanofillers to PMMA resulted in a significant improvement in both transverse and impact strengths. The researchers tested various concentrations of ZrO₂, including 2, 4, 6, and 8 wt.%. The study revealed that as the concentration of ZrO₂ increased, the transverse and impact strengths of the PMMA composite also increased. Specifically, incorporating an 8 wt.% concentration of ZrO₂ led to the greatest enhancement in material characteristics [136].

Furthermore, the addition of silanised ZrO₂ NPs to acrylic resin has been shown to offer additional benefits, according to Beketova et al. [137]. Specifically, at certain percentages of addition (1 and 2 wt.%), the composite material exhibited improvements in fatigue strength, surface roughness, and hardness. Additionally, the apparent porosity, water sorption, and solubility of the acrylic resin decreased with the incorporation of silanised ZrO₂ NPs [137]. These findings suggest that the use of ZrO₂ NPs in acrylic resin can enhance its mechanical properties, surface characteristics, and durability. The specific percentages of addition and the silanisation process may vary depending on the study and the desired outcomes [137].

However, the study by Asopa et al. found that the addition of ZrO₂ NPs in concentrations of 10 and 20 wt.% led to a decrease in the surface hardness and impact strength of the acrylic resin. This may be because the particles were not well dispersed in the matrix, leading to aggregation and a reduced reinforcement effect [138]. The results of a study by Gad et al. [139] investigated the effects of adding ZrO₂ NPs to denture composites. According to the study, the maximum enhancement was achieved with a composite that contained 5 wt.% of ZrO₂ NPs. However, the study also found that increasing the amount of NPs to more than 2.5 wt.% resulted in agglomerations and clustering, which negatively impacted the flexural and impact strength of the composite. This highlights the importance of carefully controlling the amount of ZrO₂ NPs added to denture composites to ensure optimal performance [139].

Gad et al. reported that agglomeration of ZrO₂ NPs occurs when the addition percentage exceeds 5 wt.%, leading to cluster formation and material deterioration rather than strengthening. Therefore, to achieve maximum properties, the loading percentage of ZrO₂ NPs should be kept below a certain threshold, typically around 5 wt.% [139, 140].

Additionally, the study by Aboshama et al. investigated the improvement of flexural strength (FS) of strengthened denture

base resin (heat-cured PMMA) after the addition of several concentrations of ZrO₂ NPs at 1, 2, and 3 wt.%. The outcome of the study showed that the mean value of FS of PMMA decreased from 77.96 to 56.06 MPa with the addition of 2 wt.% of ZrO₂ NPs [121]. Furthermore, the incorporation of ZrO₂ NPs at different concentrations led to a decrease in the FS of heat-cured PMMA compared to PMMA without the added metal oxide. The effects of increasing filler content in heat-cured PMMA, poor dispersion, and the resulting impact on the resin matrix continuity could lead to material defects and weakening, which in turn results in a decrease in the mean values of FS of PMMA [121].

The addition of TiO₂ (titanium dioxide) particles into PMMA can have several beneficial effects on the properties of PMMA [141]. The incorporation of TiO₂ into PMMA has been found to improve impact strength, surface roughness, and hardness, resulting in increased surface durability and flexural strength of the material. This means that the PMMA composite with TiO₂ particles is more resistant to bending or deformation under applied loads [142, 143]. Ahmed et al. reported that the addition of TiO₂ particles to PMMA led to an increase in hardness and fracture toughness. The study found that the fracture toughness of PMMA increased by up to approximately 20% when reinforced with TiO₂ particles [144].

Similarly, the study by Alhotan et al. reported that the addition of TiO₂ particles to PMMA led to an improvement in thermal conductivity. The study found that the thermal conductivity of PMMA increased by up to approximately 35% when reinforced with TiO₂ particles. These findings highlight the potential of using TiO₂ particles to reinforce PMMA and improve its properties. This has led to increased interest in developing PMMA composites reinforced with TiO₂ particles for a wide range of applications [48, 93].

Hashem et al. found that the addition of TiO₂ nanoparticles into PMMA improved the wear resistance of the material. The wear resistance was found to increase by up to 27% upon the addition of 3 wt.% TiO₂ nanoparticles [145]. This improvement in wear resistance can be attributed to the formation of a hard and abrasion-resistant surface layer on the PMMA due to the addition of TiO₂ nanoparticles. Additionally, the research revealed that the introduction of TiO₂ nanoparticles into PMMA resulted in notable enhancements in material properties. Specifically, the hardness of the tested material increased by 20%, 30%, and 34% when 1, 2, and 3 wt.% TiO₂ were added to pure PMMA, respectively [145].

Furthermore, the flexural modulus exhibited an increase ranging from 11% to 31%, culminating in a linear increase in flexural strength to 106.7 MPa, representing a remarkable 95% increase compared to pure PMMA. Through Dynamic Mechanical Analysis (DMA), it was observed that the storage modulus increased from 1500 to 2120 MPa as the test frequency escalated from 0.01 to 100 Hz. Simultaneously, the loss modulus also experienced growth, rising from 120 to 222 MPa concerning the test frequency. Likewise, as the temperature rose from 25 °C to 120 °C, the storage modulus displayed

a significant decrease, diminishing from 1820 to 300 MPa, with the glass transition temperature of PMMA measured at 118.6 °C [145].

Furthermore, Alrahlah et al. also found that the addition of TiO₂ nanoparticles (TiO₂NP) into PMMA improved the thermal stability of the material. They found that the addition of 3 wt.% TiO₂NP into PMMA resulted in a significant increase in the onset of thermal degradation temperature and a decrease in the rate of thermal degradation [146]. This indicates that the addition of TiO₂ NP can improve the thermal stability of PMMA, making it more suitable for use in high-temperature applications.

In addition to the mechanical and electrical properties, the addition of TiO₂NP also improves the optical properties of PMMA [146]. The study by Aziz [147] found that the addition of 3 wt.% TiO₂NP into PMMA increased light absorption capacity, making the specimens darker than pure PMMA. This is due to the high atomic number of TiO₂NP, which allows it to absorb more light than the polymer matrix [147].

Another study by Naji et al. aimed to investigate the effect of TiO₂ nanotubes (NTs) on the mechanical properties and antimicrobial effect of PMMA nanocomposites [148]. The TiO₂ NTs were prepared by the alkaline hydrothermal process and were added to PMMA at different concentrations of 2.5 and 5 wt.%. The results showed that the hardness and flexural strength of the samples filled with TiO₂ NTs were significantly higher compared to the control samples. Furthermore, the fracture toughness was also improved in the filled samples, except for the sample filled with 2.5 wt.% TiO₂ NTs.

In terms of antimicrobial effect, the study found that the presence of TiO₂ NTs resulted in a significant reduction in the planktonic cell count and biofilm formation on UV-activated acrylic samples compared to the control group. These findings suggest that the addition of TiO₂ NTs to PMMA can improve both the mechanical properties and antimicrobial activity of the resulting nanocomposite [148].

Alhotan et al., who investigated the effect of TiO₂ on PMMA denture base material with different concentrations at 1.5, 3, 5, and 7 wt.% on its flexural strength (FS) and surface hardness (VH), found that the FS of the PMMA denture was significantly improved with the addition of 7 wt.% TiO₂ compared to the PMMA matrix. The higher surface hardness of the PMMA denture base was obtained when 1.5 wt.% TiO₂ was added to the PMMA denture [92].

In another study, Alhotan et al. examined the effect of adding TiO₂ with an average size of 20 to 30 nm into PMMA denture base material at different concentrations (1.5, 3, 5, and 7 wt.%) on its impact strength (IS) and fracture toughness (KIC). The results showed that the KIC of the PMMA denture was significantly improved with the addition of 1.5 wt.% TiO₂ compared to the PMMA matrix. However, the IS of the PMMA denture base was slightly increased [93].

The research by Azmy et al. focused on the influence of adding TiO₂ nanoparticles (TiO₂ NPs) at 3 and 7 wt.% concentrations to PMMA denture base material, assessing their

impact on mechanical properties such as flexural strength, impact strength, hardness, and wear resistance. The study found that both FS and IS were increased with the addition of TiO₂ NPs in PMMA compared to pure PMMA [124]. The FS increased to 83.4 MPa with the addition of 3 wt.% TiO₂ compared to 59.4 MPa for unreinforced PMMA. Furthermore, adding 3 wt.% TiO₂ to PMMA denture led to an improvement in IS, rising from 1.87 to 2.26 KJ/m². At 7 wt.% TiO₂ concentration in the PMMA composite, the VH also increased to 41.3 kgf/mm², compared to pure PMMA which had only 37.9 kgf/mm². The wear resistance (WR) of the reinforced PMMA with 3 wt.% TiO₂ NPs was the lowest, at 0.0017 µm, compared to PMMA without filler (0.0025 µm).

The improvement in the properties of the PMMA denture base in this study was attributed to the uniform distribution of small TiO₂ NPs. The enhancement in the mechanical properties of the material can be explained by the effective bonding between the PMMA resin matrix and the nano-TiO₂ NPs [124]. This strong bond limits segmental motion within the material, while the high surface area of the TiO₂ NPs contributes to energy dissipation within the material. The observed increase in mechanical properties can also be attributed to the interfacial shear strength between the resin matrix (PMMA) and the nanoparticles (nano-TiO₂) [124].

However, the investigation conducted by Aboshama et al. studied the effect of adding different amounts of TiO₂ NPs (1, 2, and 3 wt.%) on the flexural strength of strengthened denture base resin (heat-cured PMMA). The results of the investigation showed that the mean value of the flexural strength (FS) of PMMA in the control group was higher compared to the other samples reinforced with metal oxide TiO₂ NPs at all concentrations. However, the mean value of FS decreased from 77.96 MPa to 50.57 MPa with the addition of 2 wt.% TiO₂ NPs. The effects of increasing filler content in heat-cured PMMA, poor dispersion, and the resulting impact on the continuity of the resin matrix could lead to material defects and weakening, which contributed to the decrease in the mean FS of PMMA [121].

Additionally, a study by Hashem et al. found that the addition of TiO₂ NPs had no impact on the melting temperature of PMMA. Both pure PMMA and PMMA with 3% TiO₂ began disintegrating and losing weight at 200 °C and lost 90% of their weight at 400 °C [145].

4.2.4. Minerals Reinforcement

Many researchers have used silicon dioxide nanoparticles (SiO₂ NPs) in PMMA denture base materials to improve their properties. The incorporation of silicon (SiO₂) nanoparticles into PMMA has been shown to enhance its thermal and mechanical properties in various studies. SiO₂ nanoparticles improve the rigidity, strength, and toughness of PMMA by reinforcing the polymer matrix at the nanoscale level. Studies have demonstrated that the incorporation of SiO₂ nanoparticles (NPs) into polymethyl methacrylate (PMMA) can enhance its thermal and mechanical properties.

Several studies, including those by Karci et al. [132] and Gad et al. [139], have reported this finding. Additionally, the thermal stability of PMMA can be improved by adding silicon nanoparticles. This is because the high thermal conductivity of silicon nanoparticles can dissipate the heat generated during processing, thus reducing the thermal degradation of PMMA [27].

The study conducted by Cevik & Yildirim - Bicer [149] investigated the effects of incorporating SiO₂ nanoparticles and prepolymer at different percentages (1 and 5 wt.%) on various properties of PMMA acrylic samples. The properties examined in the study included surface hardness, flexural strength, surface roughness, and flexibility. The results of the study showed that the flexural strength of the composite acrylic resin did not show a significant improvement with the addition of fillers. However, the flexibility and hardness of the PMMA silica composites increased significantly as the percentage of filler increased. In contrast, the surface roughness decreased as the percentage of filler increased [149].

Kamil et al.'s findings suggest that the addition of silanised SiO₂ NPs can improve some physical characteristics of PMMA acrylic resin but may also have negative effects on other properties [150]. Specifically, Kamil et al. found that the addition of 0.125 wt.% of SiO₂ NPs improved the surface roughness, thermal conductivity, and surface hardness of the PMMA resin, but reduced the transverse and impact strength. However, when the amount of SiO₂ NPs increased to 0.25 wt.%, the thermal conductivity and surface hardness continued to improve without significant reduction in transverse and impact strength [150].

The work done by Azmy et al. studied the influence of the combination of SiO₂ NPs at 3 and 7 wt.% concentrations in PMMA denture based on some of its properties, such as flexural strength (FS), impact strength (IS), Vickers hardness (VH), and wear resistance (WR). The outcome of the research showed that the FS and IS increased with the incorporation of SiO₂ NPs into the PMMA denture base compared to unfilled PMMA. The FS increased by 70.3 MPa with the addition of 3 wt.% compared to the 7 wt.% and unfilled PMMA, which had a lower FS [124]. In addition, the IS of the PMMA composite had the highest mean value of 2.45 kJ/m² with the addition of 3 wt.% SiO₂ NPs compared to pure PMMA denture. At the addition of 7 wt.% of SiO₂ NPs in the PMMA composite, the VH was highest with a mean value of 41.1 kgf/mm², compared to pure PMMA, which had only 37.9 kgf/mm². Meanwhile, the WR of the filled PMMA with 3 wt.% SiO₂ NPs had the lowest WR of 0.0017 µm compared to PMMA without filler (0.0025 µm) [124].

This improvement in the properties of the PMMA denture base can be attributed to the incorporation of SiO₂ nanofillers and their interaction with the polymer matrix. The enhancement of properties could be due to the even distribution of nanofillers within the polymer matrix. This uniform dispersion likely leads to more efficient load transfer and stress distribution throughout the material, improving its overall

mechanical properties. Additionally, the nanofillers may have the ability to penetrate spaces within the interpolymeric chain structure of the polymer [124]. This penetration could influence the movement of the polymer chains, contributing to the control of their mobility, which may result in increased strength and reduced deformation under stress.

The interaction between the silane-treated nanofillers and the polymer matrix could involve cross-linking or supramolecular bonding [124]. These interactions contribute to the creation of a three-dimensional network that reinforces the material and prevents the spread of cracks. Ultimately, this results in better mechanical interlocking and resistance to deformation [124]. The increased concentration of nano-SiO₂ could be due to its uniform distribution and ability to occupy the interpolymeric chain spaces, thereby restricting movement, as reported by other studies such as Karci et al. [132] and Cevik et al. [149].

Other studies have used zinc oxide nanoparticles (ZnO NPs) to improve the properties of PMMA denture bases. Salahuddin et al. [151] reported that the addition of ZnO nanoparticles (NPs) or nanotubes to PMMA (polymethyl methacrylate) increased the flexural strength of the composites, with an increase in the amount of ZnO NPs from 0.2 to 0.4 wt.%. This demonstrates the potential of using ZnO NPs or nanotubes as filler materials for PMMA-based composites to enhance their properties. The properties of a composite material depend on several factors, such as the type and amount of filler, the processing method, and the interaction between the filler and the matrix. Therefore, it is crucial to conduct comprehensive research to understand the behaviour of composites under different conditions.

Additionally, the results showed that the addition of ZnO nanotubes to PMMA improved its thermal stability, as evidenced by the increased maximum temperature and decreased temperature degradation rate [151]. The study also reported improved optical properties of PMMA composites reinforced with ZnO NPs and nanotubes, such as increased transmittance and reduced haze. This was attributed to the high refractive index of ZnO and its ability to scatter light effectively.

The results reported by Salahuddin et al. indicated that the flexural strength of the PMMA-ZnO NP composites decreased at higher filler concentrations of 0.8 to 1 wt.%. This demonstrates the non-linear behaviour of the composites and highlights the need for careful optimisation of the filler concentration to achieve the desired properties. Furthermore, the thermal stability of the PMMA-ZnO NP composites was improved compared to pure PMMA. This is a significant advantage of incorporating ZnO NPs into PMMA, as enhanced thermal stability can provide improved resistance to thermal degradation, making the composites more suitable for high-temperature applications [151]. The studies by Cierech et al. and Kamonkhantikul et al. also support this finding [152, 153].

The study by Vikram and Chander [154] reported that the addition of ZnO nanoparticles to the polymer matrix led to an

improvement in the flexural strength of the composite. This is consistent with the findings of Salahuddin et al., whose study showed that the addition of ZnO NPs to polymer matrices can enhance their mechanical properties [151]. The improvement in the flexural strength of the composite depends on several factors, such as the concentration of the filler, the type of polymer matrix, and the processing conditions. Therefore, it is crucial to carefully optimise these factors to achieve the desired properties.

The findings of the study by Vikram and Chander [154] suggest that the addition of ZnO nanoparticles to acrylic resin may not result in a significant improvement in its flexural strength. When compared with conventional heat-cured acrylic that was not reinforced, no significant improvement was observed. These findings are important for dentistry as they provide information on the potential use of ZnO nanoparticles as reinforcement materials in denture resins [154].

The study by Cierech et al. focused on the effect of ZnO nanoparticles on PMMA and investigated their impact on the colour and roughness of the material [152]. The results showed that the incorporation of ZnO nanoparticles into PMMA was successful and did not result in any difference in the roughness of the nanocomposite compared to pure PMMA control specimens. The study also found that the colour of the PMMA changed to some extent, but the bleaching was both aesthetically and clinically acceptable. These findings are important in the field of dentistry as they provide information on the potential use of ZnO nanoparticles as reinforcing materials in dental materials. However, more research is needed to fully understand the effect of ZnO nanoparticles on the properties of PMMA and to determine the optimal concentration of ZnO for the best results [152].

On the other hand, the study by Kamonkhantikul et al. [153] investigated the effect of silanised ZnO nanoparticles on the antifungal, mechanical, and optical properties of acrylic resin. This research is important in dentistry as it explores the potential use of ZnO nanoparticles as reinforcing materials in dental materials and their ability to provide antifungal properties. The results of this study can provide valuable information for the development of new dental materials with improved mechanical and antifungal properties. Further research is needed to fully understand the effect of silanised ZnO nanoparticles on acrylic resins and to determine the optimal concentration of ZnO particles for the best results [153].

Kamonkhantikul et al. suggested that the silanisation of ZnO nanoparticles can improve their antifungal properties and increase their flexural strength values in acrylic resin composites. The results showed that the formation of *Candida albicans* was lower in the silanised group compared to the non-silanised group. The least growth of *Candida albicans* was observed in the group with 5 wt.% silanised filler [153]. Additionally, increased contact between silanised particles and *Candida albicans* may further enhance the antifungal effect. The study also found that the non-silanised group

showed antifungal effects only in the composites with 5 wt.% of ZnO particles, while the silanised groups had greater flexural strength values [153].

However, the addition of ZnO nanoparticles caused discolouration of the composites. These findings are important in the field of dentistry as they provide information on the potential use of ZnO nanoparticles as reinforcing materials in dental materials and their potential to provide antifungal properties. Further research is needed to fully understand the effect of silanised ZnO nanoparticles on acrylic resins and to determine the optimal concentration of ZnO particles for the best results [153]. In their study, Khan, A. et al. added zinc oxide (ZnO) to PMMA to prepare composite materials using the process of melt mixing. They found that the tensile strength of the composites slightly decreased with an increase in ZnO content [155].

4.2.5. Nanotube Technology

Nanotube fillers can indeed be used as reinforcements in the fabrication of denture bases made from PMMA. By incorporating nanotube fillers, such as carbon nanotubes (CNTs) or other types of nanotubes, into the PMMA matrix, the mechanical properties of the denture base can be significantly improved. The nanotubes act as reinforcing agents, enhancing the strength, toughness, and overall performance of the denture base material [62, 156]. Additionally, CNTs can also improve the biocompatibility and antioxidant properties of PMMA [157].

The addition of carbon nanotubes to PMMA has been found to significantly improve its mechanical properties, making it stronger and more resilient than the pure PMMA matrix with the addition of 1 and 1.5 wt.% of single-walled carbon nanotubes (SWCNTs) [158]. Studies have suggested that carbon nanotubes are 10–100 times stronger than the strongest steel at a fraction of the weight when incorporated into PMMA, resulting in improved matrix properties [159]. Other researchers have also found that incorporating CNTs into PMMA composites can enhance the thermo-mechanical properties of PMMA. Studies incorporating varying concentrations of CNTs, such as 0.25, 0.5, 1, and 2 wt.%, have noted increases in properties such as strength and thermal stability [160]. Additionally, the use of dynamic mechanical analysis has shown that the storage modulus of PMMA improves with the addition of CNTs [160].

Mahmood WS found that the addition of CNTs at 1 wt.% into PMMA led to higher impact strength (IS) and flexural strength (FS) of the PMMA denture base [161]. Ibrahim RA reported that the addition of 1.5 wt.% of single-walled carbon nanotubes (SWCNTs) to the PMMA denture base improved both the impact strength and transverse strength [162].

In the study by Kim et al., the aim was to enhance the antimicrobial and anti-adhesive properties of PMMA by incorporating multi-walled carbon nanotubes (MWCNTs) and evaluating their effects on oral microbial species [163]. Multiwalled CNTs were created and added to PMMA to create

composite materials, with different concentrations of CNTs (1 and 2 wt.%) used. The study found that the total fracture work of the composite material was improved with the addition of 1 and 2 wt.% CNTs [163]. However, other mechanical properties were gradually compromised as the concentration of CNTs increased. Incorporating MWCNTs led to an increase in surface roughness and water contact angle, suggesting changes in the surface characteristics of the composite.

The study demonstrated significant anti-adhesive effects (ranging from 35 to 95%) against three different oral microbial species (*Staphylococcus aureus*, *Streptococcus mutans*, and *Candida albicans*) for the composite material containing 1 wt.% CNTs [163]. This anti-adhesive effect was observed through metabolic activity assays and staining for adherent cells. The composite material with 1 wt.% MWCNTs showed no cytotoxic effects on oral keratinocytes, indicating its potential biocompatibility. The anti-adhesive mechanism of the composite involved disrupting the chains of adherent microbes, preventing their attachment to the surface. The drug-free antimicrobial adhesion properties observed in the CNT-PMMA composite suggest the potential utility of these materials in preventing microbial-induced complications in clinical settings, such as Candidiasis [163].

Functionalising multi-walled carbon nanotubes (MWCNTs) can indeed improve the bonding with polymethyl methacrylate (PMMA) and lead to enhanced mechanical and electrical properties of PMMA composites [164]. MWCNTs have a high aspect ratio and a large specific surface area, which makes them suitable for reinforcing polymer matrices such as PMMA. However, the pristine surface of MWCNTs is typically inert, which hinders strong interfacial bonding with the polymer matrix. To overcome this limitation, MWCNTs are often functionalised by introducing chemical groups or modifying their surface properties [165].

Functionalisation of MWCNTs can be achieved through various methods such as covalent functionalisation, non-covalent functionalisation, or a combination of both. Covalent functionalisation involves attaching functional groups to the surface of MWCNTs through chemical reactions, while non-covalent functionalisation relies on physical interactions between the MWCNTs and functional molecules [166]. By functionalising MWCNTs, the specific surface area of the nanotubes increases, providing more sites for interaction with the PMMA matrix. This increased interfacial area promotes better adhesion between the MWCNTs and PMMA, resulting in improved stress transfer from the polymer to the nanotubes. As a result, the overall mechanical properties of the PMMA-MWCNT composite, such as stiffness, strength, and toughness, are enhanced [167].

Furthermore, the presence of functional groups on the MWCNT surface can also facilitate the dispersion of nanotubes within the PMMA matrix, preventing their agglomeration and ensuring a more homogeneous distribution. This uniform dispersion further contributes to improved mechanical properties [168]. In addition to the mechanical en-

hancements, functionalised MWCNTs can also improve the electrical conductivity of PMMA composites. The functional groups on the nanotube surface can act as charge carriers and facilitate electron transfer through the composite material, leading to enhanced electrical conductivity [159].

Mohammed et al. evaluated and compared the flexural strength and surface roughness of conventional heat-cured denture base resins and high-impact resins reinforced with MWCNTs at a concentration of 1 wt.%. The introduction of MWCNTs into the denture base resins led to a statistically significant improvement in flexural strength, with an increase in flexural strength measured at 73.5 MPa when MWCNTs were added. However, the study found no statistically significant difference in surface roughness between the groups with MWCNTs and those without. This suggests that the incorporation of nanotubes did not increase surface roughness of the denture [169].

Another study by Ghosh and Shetty aimed to compare the flexural strength (FS) of heat-polymerised PMMA denture base resins modified with additions of multi-walled carbon nanotubes (MWCNT) at a ratio of 0.5 wt.%. The results of the study showed that the mean flexural strength recorded was 36.5 MPa when MWCNTs were added to the PMMA denture base, indicating an improvement in flexural strength compared to the pure PMMA denture base material. In essence, the study suggests that incorporating MWCNTs at a specific ratio into the PMMA denture base resin led to an improvement in flexural strength compared to using the base PMMA material alone [170].

The study by Kashan et al. investigated the effects of incorporating MWCNTs into PMMA/ZrO₂-CaO biocomposites to create a novel hybrid biocomposite system for bone recovery and replacement applications [171]. The research involved the fabrication of four groups of composite samples, varying the weight percentages of ZrO₂-CaO (ranging from 0%, 5%, 10%, 15%, and 20%) and incorporating different concentrations of MWCNTs (ranging from 0%, 0.1%, 0.25%, 0.5%, and 1 wt.%) into each group. The results of X-ray Diffraction (XRD) analysis indicated a high level of uniform mixing of the composite materials. The smooth peaks observed in the XRD patterns suggested a homogeneous distribution, leading to enhanced phase stability in the composites [171].

In addition, Field Emission Scanning Electron Microscopy (FE-SEM) analysis revealed the presence of fibrous structures following the addition of MWCNTs. This finding suggested that the incorporation of MWCNTs facilitated the formation of fibrous arrangements within the composite materials, which could potentially promote tissue adhesion and healing. This arrangement was designed to mimic the natural bone structure, enhancing the biomimetic properties of the composites [171].

The study demonstrated improvements in mechanical properties, specifically fracture strength, in composite materials. The addition of MWCNTs resulted in a noticeable in-

crease in fracture strength compared to samples without MWCNTs. The specific percentage improvements in fracture strength were approximately 57%, 38%, 45%, and 6.5% for different MWCNT concentrations (0.1%, 0.25%, 0.5%, and 1 wt.%) [171].

While the addition of SWCNTs to PMMA may lead to a decrease in hardness, PMMA's relatively high hardness means that the introduction of SWCNTs can influence the material's hardness properties. The exact mechanism behind this decrease in hardness can vary and is dependent on factors such as the dispersion and interaction between the SWCNTs and the PMMA matrix. The presence of SWCNTs may disrupt the polymer chains' organisation, resulting in a reduction in overall hardness [157, 172].

However, a study conducted by Swaroop et al. investigated the effects of adding graphene (at 0.25% and 0.5 wt.%) and MWCNTs (at 0.25% and 0.5 wt.%) to PMMA [173]. The study aimed to evaluate the flexural strength (FS) and impact strength (IS) of composite materials. The results of the study showed that the addition of nanofillers, whether graphene or MWCNTs, led to a decrease in both flexural strength and impact strength in all groups when compared to the control group without nanofillers. This suggests that the incorporation of graphene and MWCNTs into the PMMA matrix negatively impacted the mechanical properties of the composite material [173].

The use of Halloysite nanotubes (HNTs) as a nanocarrier and as a filler for drug loading and composite preparation has been previously investigated [174, 175]. Abdallah investigated the mechanical properties of HNT-modified PMMA and found that the hardness value of PMMA was significantly increased with the addition of low percentages of HNTs [176]. The study reported that at a lower concentration of 0.3 wt.% of HNTs, there was a notable rise in hardness measurements, yet there was no considerable elevation in both flexural strength and Young's modulus values for the PMMA resin. Conversely, at higher concentrations (0.6 and 0.9 wt.%), there was a substantial reduction in hardness readings, but there was no significant reduction in flexural strength and Young's modulus values when compared to the control group [176].

Another study evaluated the antimicrobial potential of dental resin composites based on Farnesol-loaded HNTs as fillers. Farnesol (Fa) is a novel antibacterial agent that has been found to have higher antibacterial activity than traditional agents. The use of Farnesol-Halloysite nanotubes (Fa-HNTs) in dental composites can improve mechanical properties and increase surface coarseness without causing agglomeration. A study found that 7 wt.% Fa-HNT-reinforced composites had uniformly distributed Fa-HNTs and glass microparticles in the matrix [177].

Gaaz et al. reported that the combination of polymer and HNTs yielded significant improvements in terms of strength, elastic modulus, non-flammability, impact strength, and thermal stability by doping a low percentage of HNTs (>7%) [178]. The addition of HNTs also produced soft liner material with better shear bond strength and thermal conductivity;

however, there was no improvement in thermal diffusivity and surface roughness at increased HNT concentrations [178, 179].

The TGA results showed that the onset temperature of thermal degradation shifted to a higher temperature, indicating that the HNTs provided a protective barrier against thermal degradation. Similarly, the DSC results showed that the glass transition temperature (T_g) increased, indicating that the HNTs improved the thermal stability of the PMMA matrix. This increased thermal stability means that the PMMA nanocomposite will be able to withstand higher temperatures without degrading, making it more suitable for applications that require high thermal resistance. The mechanical properties of the PMMA nanocomposite were also improved by the addition of HNTs [179, 180].

A study by Chen et al. reported that the nanocomposite had a higher tensile strength and modulus compared to pure PMMA. This means that the PMMA nanocomposite is stronger and more resistant to deformation than pure PMMA, making it more suitable for applications that require high mechanical strength. The incorporation of Farnesol-loaded HNTs (Fa-HNTs) into dental composites is a promising strategy to improve their mechanical properties and antimicrobial activity [180].

Barot et al. have reported that the incorporation of Fa-HNTs into dental composites can significantly improve their mechanical properties, including flexural strength and modulus [181]. According to Barot et al., the incorporation of 7-13 wt.% Fa-HNTs into dental composites resulted in an improvement in the mechanical strength of the composite. The study found that the dental composite containing 7 wt.% Fa-HNTs exhibited the best mechanical properties, with higher flexural strength and modulus compared to the control group. This indicates that a low concentration of Fa-HNTs can already provide a significant improvement in the mechanical properties of dental composites [181].

Moreover, Barot et al. found that the incorporation of Fa-HNTs into dental composites also resulted in an improvement in the curing depth and antimicrobial activity of the composite. The study found that dental composites containing 7 wt.% Fa-HNTs had the best antimicrobial activity against *Streptococcus mutans*, one of the most common oral bacteria that can cause dental caries. This suggests that Fa-HNTs can not only improve the mechanical properties of dental composites but also enhance their antimicrobial activity, making them more suitable for dental applications [181].

In conclusion, the incorporation of HNTs into a PMMA matrix can greatly enhance the thermal and mechanical properties of the material. The HNTs provide a protective barrier against thermal degradation and improve the thermal stability and mechanical strength of the PMMA.

4.2.6. Hybrid Reinforcement

Hybrid reinforcement schemes are commonly used in the field of materials science and engineering to enhance the

physical, mechanical, and environmental characteristics of a PMMA denture material. By mixing different types of reinforcements, such as metal oxides and fibres, the resulting material can exhibit improved mechanical properties, such as increased strength, stiffness, and toughness. One advantage of using hybrid reinforcement schemes is that they can be tailored to meet specific application requirements. For example, if a material needs to be lightweight but also strong, a combination of fibres and metal oxides may be used to achieve this goal. Similarly, if a material needs to be resistant to wear and abrasion, a hybrid reinforcement scheme that includes both metal oxides and fibres with high wear resistance can be used. Another advantage of using hybrid reinforcement schemes is that they can lead to cost savings. By using a combination of different materials, it may be possible to achieve the desired physical properties while minimising the amount of expensive materials required [27, 139, 182-184].

These materials include a variety of fibres such as glass fibres, polyethylene fibres, polyester fibres, and Kevlar fibres, as well as fillers such as Al_2O_3 , ZrO_2 , TiO_2 , clay, glass powder, SiO_2 , and plasma-treated polypropylene fibres [27]. These materials are often combined in various ways to create different types of hybrid reinforcement for PMMA denture base materials, such as glass fibres with polyethylene fibres [163], Al_2O_3 with ZrO_2 [123], ABWs with Al_2O_3 [27], ZrO_2 with TiO_2 [135], polyester fibre-reinforced PMMA with clay, glass powder, SiO_2 , or ZrO_2 [27], Al_2O_3 with plasma [27], PMMA with nHA and glass fibre [185], PMMA with ZrO_2 and glass fibre [140], PMMA with nHA and Kevlar fibre [186], and PMMA with ZrO_2 and Kevlar [95], as shown in Table 2. These combinations help to improve the mechanical properties, such as strength, stiffness, and toughness, of the PMMA denture base materials, making them more durable and resistant to fracture [95, 140, 183, 184, 186].

Table 2. Different types of hybrid reinforcement material.

Hybrid type	Hybrid Materials
Fibers	Glass fibers with polyethylene fibers [163]
Fillers	Al_2O_3 with ZrO_2 [123],
	ABWs with Al_2O_3 [27],
	ZrO_2 with TiO_2 [135]
Fibers with Fillers	Al_2O_3 with plasma [27]
	nHA and glass fiber [185]
	PMMA with ZrO_2 and glass fiber [140]
	PMMA with nHA and Kevlar fiber [186]
	PMMA with ZrO_2 and Kevlar [95]

To strengthen the mechanical properties of the denture base made of PMMA acrylic, Alhareb et al. investigated the effects of mixing nitrile butadiene rubber (NBR) particles (5, 7.5, and

10 wt.%) with silanised ceramics (aluminium oxide, yttria stabilised zirconia, and silicon dioxide) at 5 wt.% [187]. The produced PMMA composite, strengthened by NBR particles with ceramic fillers, exhibited improved mechanical properties in fracture toughness (K_{IC}) and impact strength (IS). The best results for IS and K_{IC} were obtained with 10 wt.% of NBR particles and 5 wt.% Al_2O_3 , yielding the highest impact strength of 8.26 kJ.m^{-2} and the best fracture toughness of $2.77 \text{ MPa.m}^{1/2}$ [187].

Basima & Aljafery evaluated the effects of a 2 wt.% filler of nanoparticles blended at a weight ratio of (2:1, ZrO_2 : Al_2O_3) on the transverse strength, impact strength, hardness, roughness, and adaptability of the denture base of PMMA [188]. According to the findings, adding nanofillers to PMMA significantly increased the impact strength when compared to the control group [187, 188]. Hybrid reinforcement can improve the impact strength of materials, such as epoxy composites reinforced with both glass fibres and nanoparticles, and aluminium-based composites reinforced with both silicon carbide particles and carbon fibres [189].

Basima & Aljafery also evaluated the effects of characterising and synthesising inorganic zirconium oxide (ZrO_2) and organic components (triethylene glycol dimethacrylate (TEGDMA) + bisphenol A diglyceryl ether dimethacrylate (Bis-GMA)). The results showed that hybrid nanofibres made of ZrO_2 , Bis-GMA/TEGDMA/PTEGDMA, and ZrO_2 /Bis-GMA/TEGDMA significantly improved the flexural strength and flexural modulus, fracture toughness, and impact strength of PMMA acrylic resin [188].

Ali Sabri et al., Gad et al., and Zafar reported that a hybrid of glass fibres and titanium dioxide fillers improved the flexural modulus and tensile strength of acrylic resin. In addition, hybrid reinforcement has also been used to improve the radiopacity and reduce the shrinkage of dental materials [27, 139, 182].

Rongrong et al. investigated the biomedical properties, cytotoxicity, and mechanical properties of PMMA composites produced by combining antibacterial materials with silanised zirconia nanoparticles (ZrO_2 ; 2 wt.%) and silanised aluminium borate whiskers (ABW; 4 wt.%). The inorganic antibacterial compounds used were silver-supported titanium dioxide, titanium dioxide, silver-supported zirconium phosphate, and whisker-like zinc oxide. To create the test samples, the aforementioned ingredients were each combined separately at a percentage of 3 wt.% with a mixture of ZrO_2 -ABWs/PMMA. The findings showed that the composites of ZrO_2 -ABWs/PMMA mixed with silver-supported zirconium phosphate and tetrapod-like zinc oxide whiskers exhibited the greatest antibacterial action, surface hardness, flexural strength, and non-cytotoxic properties [190].

Gad et al. found that adding a mixture of 2.5 wt.% nano- ZrO_2 and 2.5 wt.% glass fibres to PMMA acrylic resin significantly improved its flexural strength (94.05 MPa) and impact strength (3.89 kJ.m^{-2}) [140]. In the study by Gad et al., the researchers investigated the effect of adding different amounts of glass

fibres and zirconium oxide nanoparticles to PMMA and compared the results to a control sample with no additives. The test samples had varying mixtures of nano- ZrO_2 and glass fibres at a total concentration of 5 wt.%, while the control sample had no additives. In comparison to unreinforced PMMA samples, the impact and flexural strengths of the most recent hybrid composites were significantly improved. The greatest flexural strength (94.05 MPa) and impact strength (3.89 kJ.m^{-2}) were obtained with a 2.5 wt.% mixing ratio of both ZrO_2 nanoparticles and glass fibres, with the ideal values of impact and flexural strengths achieved at this level [140].

By combining electrospun polystyrene (PS) fibres with nano-zirconia (ZrO_2) as a hybrid material, a study by Elmadani et al. investigated the characterisation and processing of hybrid PMMA composites. The strengthening materials were chosen to enhance the mechanical and physical properties of the resulting hybrid composite [191]. To improve the filler's adhesion to the PMMA matrix, 3-methacryloxypropyltrimethoxy silane (MEMO) was used to modify the surface of the inorganic particles. As ceramic nanoparticle fillers tend to aggregate in the polymer matrix, the PS fibre material is a promising solution to reduce the brittleness caused by this aggregation. The best outcomes were achieved by mixing PS fibres and ZrO_2 /MEMO in an acrylate matrix, according to microhardness and impact tests [191].

Rebecca Lilda et al. calculated the flexural and impact strengths of high-impact acrylic resin reinforced with silanised titanium dioxide (1 weight per cent) and zirconium dioxide nanoparticles (5 wt.%), as well as their hybrid combination with a percentage of the additive mixture (2% weight per cent) (1 wt.% ZrO_2 and TiO_2). The highest maximum value of flexural strength in the acrylic composite was detected in reinforcement with a hybrid mixture of ZrO_2 / TiO_2 , in contrast to reinforcement with zirconium dioxide or titanium dioxide nanoparticles individually. The highest impact strength of the acrylic resin was observed with TiO_2 nanoparticle reinforcement [192].

5. Conclusion

The current article provides a comprehensive overview of PMMA-based materials, encompassing their characteristics, dental uses, and recent modifications. In dental practice, PMMA appliances often encounter issues such as discolouration, hydrolytic degradation, and fractures, highlighting the need for enhancements in PMMA properties. In recent decades, extensive research has focused on improving the physical and mechanical attributes of PMMA. Modifications have involved reinforcing PMMA chemically or mechanically with additional materials like fibres, nanofillers, nanotubes, and hybrid substances. These efforts have led to significant improvements in mechanical aspects such as impact strength, flexural strength, and wear resistance, as well as physical characteristics like thermal conductivity, water absorption, solubility, and dimensional stability.

Nevertheless, the challenge remains in improving one aspect of PMMA without adversely affecting others. For instance, while the addition of nanoparticles or fibres can boost PMMA's strength, it may compromise aesthetics in terms of colour and translucency or raise concerns about biocompatibility due to the potential leaching of degradation products in the oral cavity. Despite promising outcomes from current PMMA modifications, there is still a considerable journey ahead before modified PMMA materials can be widely adopted in dental practice. The biocompatibility and real-world performance of these modified materials remain uncertain and warrant further investigation. Future research should concentrate on understanding the molecular-level interactions of modified materials, assessing various properties, and evaluating clinical performance in simulated oral environments or in vivo clinical trials.

Acknowledgments

The authors would like to express their sincere gratitude to Prof Hazizan Bin Md Akil for her invaluable guidance and advice in the preparation of this review proposal. Her expertise and insights have greatly contributed to the quality of this work. Furthermore, the authors gratefully acknowledge the Ministry of Higher Education, Malaysia, and the Polymer Composite Research from Universiti Sains Malaysia for their financial support through the Fundamental Research programme. This support was instrumental in facilitating the completion of this study. Lastly, the authors are thankful for the support provided by the grant project (1001/PBAHAN/8014047) from Universiti Sains Malaysia. This grant has played a vital role in enabling the research and experimentation necessary for this study.

Author Contributions

Issam Mohamed Aldwimi: Conceptualization, Data curation, Funding acquisition, Methodology, Resources, Writing – original draft, Writing – review & editing

Hazizan Md Akil: Supervision

Zuratul Ain Abdul Hamid: Supervision

Ahmed Omran Alhareb: Field supervision.

Funding

We would like to express our gratitude to the Ministry of Higher Education in Malaysia and the Polymer Composite Research Centre at Universiti Sains Malaysia for their valuable financial support of this research project, provided through the Fundamental Research Grant Number (1001/PBAHAN/8014047).

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Shen, C., Rawls, H. R., & Esquivel-Upshaw, J. F. (Eds.). (2021). *Phillips' Science of Dental Materials E-Book*. Elsevier Health Sciences.
- [2] Sreenivasalu, P. K. P., Dora, C. P., Swami, R., Jasthi, V. C., Shiroorkar, P. N., Nagaraja, S.,... & Anwer, M. K. (2022). Nanomaterials in Dentistry: Current Applications and Future Scope. *Nanomaterials*, 12(10), 1676.
- [3] Wang, D., Wang, Y., Tian, W., & Pan, J. (2019). Advances of tooth - derived stem cells in neural diseases treatments and nerve tissue regeneration. *Cell Proliferation*, 52(3), e12572.
- [4] Han, B., Chen, C., Wei, J., Ding, J., & Yu, T. (2023). Advanced materials for the restoration and reconstruction of dental functions, volume II. *Frontiers in Bioengineering and Biotechnology*, 11, 1144275.
- [5] Bhargav, A., Sanjairaj, V., Rosa, V., Feng, L. W., & Fuh YH, J. (2018). Applications of additive manufacturing in dentistry: A review. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, 106(5), 2058-2064.
- [6] Coffman, C., Visser, C., Soukup, J., & Peak, M. (2019). Crowns and prosthodontics. *Wiggs's Veterinary Dentistry: Principles and Practice*, 387-410.
- [7] Saeed, F., Muhammad, N., Khan, A. S., Sharif, F., Rahim, A., Ahmad, P., & Irfan, M. (2020). Prosthodontics dental materials: From conventional to unconventional. *Materials Science and Engineering: C*, 106, 110167.
- [8] Kumar, S., & Bhowmik, S. (2022). Potential use of natural fiber-reinforced polymer biocomposites in knee prostheses: a review on fair inclusion in amputees. *Iranian Polymer Journal*, 31(10), 1297-1319.
- [9] Alharbi, N. A. B. (2020). Physico mechanical Characterisation of a Novel and Commercial CAD/CAM Composite Blocks. *The University of Manchester (United Kingdom)*.
- [10] Merheb, J. (2018). Jaw bone characteristics and their influence on dental implant therapy outcome. *Doctor in the Biomedical Sciences, Lebanese university in Beirut*.
- [11] Milutinović, M., Lendjel, R., Baloš, S., Zlatanović, D. L., Sevršek, L., & Pepelnjak, T. (2021). Characterisation of geometrical and physical properties of a stainless steel denture framework manufactured by single-point incremental forming. *Journal of Materials Research and Technology*, 10, 605-623.
- [12] Kaur, G., Kaushal, R., & Prabhakar, D. (2021). Esthetic Restorations and Smile Designing: A Review. *International Journal of Health Sciences*, 10-22.

- [13] Bacali, C., Baldea, I., Moldovan, M., Carpa, R., Olteanu, D. E., Filip, G. A.,... & Badea, F. (2020). Flexural strength, biocompatibility, and antimicrobial activity of a polymethyl methacrylate denture resin enhanced with graphene and silver nanoparticles. *Clinical Oral Investigations*, 24, 2713-2725.
- [14] Takaichi, A., Fueki, K., Murakami, N., Ueno, T., Inamochi, Y., Wada, J.,... & Wakabayashi, N. (2022). A systematic review of digital removable partial dentures. Part II: CAD/CAM framework, artificial teeth, and denture base. *Journal of Prosthodontic Research*, 66(1), 53-67.
- [15] Dean, J. A. (Ed.). (2021). *McDonald and Avery's dentistry for the child and adolescent-E-book*. Elsevier Health Sciences.
- [16] Thayer, M. L., & Ali, R. (2022). The dental demolition derby: bruxism and its impact-part 3: repair and reconstruction. *British Dental Journal*, 232(11), 775-782.
- [17] Jo, Y. H., Lee, W. J., Lee, J. H., & Yoon, H. I. (2022). Antifungal activity, mechanical properties, and accuracy of three-dimensionally printed denture base with microencapsulated phytochemicals on varying post-polymerization time. *BMC Oral Health*, 22(1), 611.
- [18] Ahmed, S., Sameen, D. E., Lu, R., Li, R., Dai, J., Qin, W., & Liu, Y. (2022). Research progress on antimicrobial materials for food packaging. *Critical Reviews in Food Science and Nutrition*, 62(11), 3088-3102.
- [19] Alhamdan, E. M. (2023). Influence of Contemporary Photo-activated Disinfection on the Mechanical Properties and Antimicrobial Activity of PMMA Denture Base: A Systematic Review and Meta Analysis. *Photodiagnosis and Photodynamic Therapy*, 103523.
- [20] Selvaraj, S. K., Prasad, S. K., Yasin, S. Y., Subhash, U. S., Verma, P. S., Manikandan, M., & Dev, S. J. (2022). Additive manufacturing of dental material parts via laser melting deposition: A review, technical issues, and future research directions. *Journal of Manufacturing Processes*, 76, 67-78.
- [21] Samir, A., Ashour, F. H., Hakim, A. A., & Bassyouni, M. (2022). Recent advances in biodegradable polymers for sustainable applications. *npj Materials Degradation*, 6(1), 68.
- [22] Kurniasari, N. M. W., Trisanti, P. N., Hernugrahanto, K. D., Ferdiansyah, F., & Sumarno, S. (2023, June). Synthesis and purification process of PMMA by suspension polymerization for bone cement material. In *AIP Conference Proceedings* (Vol. 2703, No. 1). AIP Publishing.
- [23] Lacina, D., Neel, C., & Dattelbaum, D. (2018). Shock response of poly [methyl methacrylate](PMMA) measured with embedded electromagnetic gauges. *Journal of Applied Physics*, 123(18), 185901.
- [24] Saxena, P., & Shukla, P. (2022). A comparative analysis of the basic properties and applications of poly (vinylidene fluoride) (PVDF) and poly (methyl methacrylate) (PMMA). *Polymer Bulletin*, 79(8), 5635-5665.
- [25] Tsui, J. K., Bell, S., da Cruz, L., Dick, A. D., & Sagoo, M. S. (2022). Applications of three-dimensional printing in ophthalmology. *Survey of Ophthalmology*.
- [26] Qin, J., Jiang, J., Tao, Y., Zhao, S., Zeng, W., Shi, Y.,... & Xiao, M. (2021). Sunlight tracking and concentrating accelerated weathering test applied in weatherability evaluation and service life prediction of polymeric materials: A review. *Polymer Testing*, 93, 106940.
- [27] Ali Sabri, B., Satgunam, M., Abreeza, N. M., & N. Abed, A. (2021). A review on enhancements of PMMA denture base material with different nano-fillers. *Cogent Engineering*, 8(1), 1875968.
- [28] Gad, M. M., Abualsaud, R., Rahoma, A., Al-Thobity, A. M., Al-Abidi, K. S., & Akhtar, S. (2018). Effect of zirconium oxide nanoparticles addition on the optical and tensile properties of polymethyl methacrylate denture base material. *International journal of nanomedicine*, 13, 283.
- [29] Ceylan, G., Emik, S., Yalcinyuva, T., Sunbuloglu, E., Bozdog, E., & Unalan, F. (2023). The Effects of Cross-Linking Agents on the Mechanical Properties of Poly (Methyl Methacrylate) Resin. *Polymers*, 15(10), 2387.
- [30] Pałka, K., & Sowa, M. (2022). Miscibility and Optimization of the Liquid Rubber Content in the Resins of Light-Cured Dental Composites. *Materials*, 16(1), 87.
- [31] Tan, Y. Y., Ho, T. K., & Goo, C. L. (2022). Effect of training on time efficiency and marginal adaptation of computer - aided design/computer - aided manufacturing crowns among dental students. *European Journal of Dental Education*, 26(3), 468-474.
- [32] Das, A., Bryant, J. S., Williams, C. B., & Bortner, M. J. (2023). Melt-Based Additive Manufacturing of Polyolefins Using Material Extrusion and Powder Bed Fusion. *Polymer Reviews*, 1-66.
- [33] Spennemann, D. H., & Singh, C. L. (2023). Computed Tomography Analysis of the Manufacture of Cast Head-Bust Figurines by PATRICIA 'Pat' Elvins (1922–2011). *Heritage*, 6(2), 2268-2291.
- [34] Das, S. K., Ahmed, B., Mia, R., Bakar, A., Huq, I. U., & Xie, D. (2020). Crystallinity of FRCM/GPM with High PB through Microbial Growth. *Advances in Nanoparticles*, 9(4), 81-116.
- [35] Lin, C. S. (2021). *Dental Neuroimaging: The Role of the Brain in Oral Functions*. John Wiley & Sons.
- [36] Yang, T. (2023). *Nothing But the Tooth: An Insider's Guide to Dental Health*. Rowman & Littlefield.
- [37] BACALI, C., BUDURU, S., POPA, D., ISPAS, A., CRACIUN, A., NEGUCIOIU, M.,... & CONSTANTINIUC, M. (2021). NATURAL DENTAL MATERIALS. A HISTORICAL PERSPECTIVE. *International Journal of Medical Dentistry*, 25(4).
- [38] Ghazali, N., & Ariff, T. F. T. M. (2023). The Fundamental Properties and Biocompatibility Classification of Extraoral Prosthesis: A Review. *Journal of Medical Device Technology*, 2(1), 19-30.
- [39] Yu, H. (2023). *Digital Removable Partial Denture Technology: From Design Analysis to Practical Skills*. Springer Nature.

- [40] Gama, L. T., Bezerra, A. P., Schimmel, M., Garcia, R. C. M. R., de Luca Canto, G., & Gonçalves, T. M. S. V. (2022). Clinical performance of polymer frameworks in dental prostheses: A systematic review. *The journal of prosthetic dentistry*.
- [41] Fan, L., Ren, Y., Emmert, S., Vučković, I., Stojanovic, S., Najman, S.,... & Xiong, X. (2023). The Use of Collagen-Based Materials in Bone Tissue Engineering. *International Journal of Molecular Sciences*, 24(4), 3744.
- [42] Silva Alves Muniz, T. (2023). Materiality of Rubber: An Emerging Past from the Brazilian Amazon that Entangled the World. *International Journal of Historical Archaeology*, 1-27.
- [43] O'Connor, S. M. (2019). The Damaging Myth of Patent Exhaustion. *Tex. Intell. Prop. LJ*, 28, 443.
- [44] Stephens, C. (2023). A brief history of the development and use of vulcanised rubber in dentistry. *British Dental Journal*, 234(8), 607-610.
- [45] Young, J. S. (2021). Bond Strength of Resilient Denture Liners to Printed Denture Base Resin (Doctoral dissertation, The University of Texas School of Dentistry at Houston).
- [46] Rothman, R., & Ryan, A. J. (2023). The History and Future of Plastics. In *Plastic Pollution In The Global Ocean* (pp. 21-46).
- [47] David, T. J., & Lewis, J. M. (2023). Forensic odontology: Historical perspectives and current applications for identification of human remains. *Forensic Genetic Approaches for Identification of Human Skeletal Remains*, 529-547.
- [48] Alhotan, A. Z. R. (2022). Physiomechanical Properties of Denture Base Resin Reinforced with Nanoparticles and Fibres. *The University of Manchester (United Kingdom)*.
- [49] Sati, S., Bamola, V. D., Chaudhry, R., Jit, B. P., & Gupta, M. (2023). Nanoparticles and Inert Coating Materials: A Potential Enhancer of Antimicrobial Property of Polymethyl-Methacrylate (PMMA) Based Denture. *J Dent Oral Epidemiol*, 3(1).
- [50] Kateman, B. (2022). *Meat Me Halfway: How Changing the Way We Eat Can Improve Our Lives and Save Our Planet*. Rowman & Littlefield.
- [51] Vargel, C. (2020). *Corrosion of Aluminium* (2nd ed.). Elsevier Science. Retrieved from <https://www.perlego.com/book/1814595/corrosion-of-aluminium-pdf> (Original work published 2020).
- [52] Cagna, D. R., Donovan, T. E., McKee, J. R., Eichmiller, F., Metz, J. E., Albouy, J. P.,... & Troeltzsch, M. (2020). Annual review of selected scientific literature: A report of the Committee on Scientific Investigation of the American Academy of Restorative Dentistry. *The Journal of Prosthetic Dentistry*, 124(3), 274-349.
- [53] Salgado, H., Fonseca, P., Vaz, M., Figueiral, M. H., & Mesquita, P. (2022). The use of graphene for dental polymethyl-methacrylate reinforcement—A systematic review. *Rev Port Estomatol Med Dent Cir Maxilofac*, 63(4), 179-188.
- [54] Krishnamoorthi, D., Suma, K., Ali, S. A., Rajkumar, G., Santhakumari, S., & Ashna, S. (2022). Effect of Recycled Denture Base Polymeric Powder Incorporation on the Surface Properties of Heat-cured PMMA Denture Base Acrylic Resin: An In Vitro Study. *World*, 13(5), 528.
- [55] Dhawale, P. V., Vineeth, S. K., Gadhave, R. V., MJ, J. F., Supekar, M. V., Thakur, V. K., & Raghavan, P. (2022). Tannin as a renewable raw material for adhesive applications: a review. *Materials Advances*.
- [56] Nikolova, M. P., & Apostolova, M. D. (2022). Advances in Multifunctional Bioactive Coatings for Metallic Bone Implants. *Materials*, 16(1), 183.
- [57] Cadenaro, M., Josic, U., Maravić, T., Mazzitelli, C., Marchesi, G., Mancuso, E.,... & Mazzoni, A. (2023). Progress in dental adhesive materials. *Journal of Dental Research*, 102(3), 254-262.
- [58] Alkaltham, N. S., Aldhafiri, R. A., Al-Thobity, A. M., Al-ramadan, H., Aljubran, H., Ateeq, I. S.,... & Gad, M. M. (2023). Effect of denture disinfectants on the mechanical performance of 3D-printed denture base materials. *Polymers*, 15(5), 1175.
- [59] Wang, C., Akbulatov, S., Chen, Q., Tian, Y., Sun, C. L., Couty, M., & Boulatov, R. (2022). The molecular mechanism of constructive remodeling of a mechanically-loaded polymer. *Nature communications*, 13(1), 3154.
- [60] Kocak, E. D., & Yildiz, Z. (2023). 18 Polymers for the Textile. *Specialty Polymers: Fundamentals, Properties, Applications and Advances*, 265.
- [61] Hashemikamangar, S. S., Farahani, S., Khoshgoo, S., & Doroudgar, P. (2023). Comparative Efficacy of Four Stain Removal Methods for Bleach-Shade Composite Resins after Immersion in Staining Solutions: An In Vitro Study. *International Journal of Dentistry*, 2023.
- [62] Atallah, W., AlFuraiji, N., & Hussein, O. H. (2023). Nanocomposites for Prosthetic Dental Technology: A Systemic Review. *Journal of Techniques*, 5(1), 129-136.
- [63] Ziębowicz, A., Ośwald, B., Kern, F., & Schwan, W. (2023). Effect of Simulated Mastication on Structural Stability of Prosthetic Zirconia Material after Thermocycling Aging. *Materials*, 16(3), 1171.
- [64] Montoya, C., Roldan, L., Yu, M., Valliani, S., Ta, C., Yang, M., & Orrego, S. (2023). Smart dental materials for antimicrobial applications. *Bioactive Materials*, 24, 1-19.
- [65] Vasiliu, S., Racovita, S., Gugoasa, I. A., Lungan, M. A., Popa, M., & Desbrieres, J. (2021). The benefits of smart nanoparticles in dental applications. *International Journal of Molecular Sciences*, 22(5), 2585.
- [66] Wancket, L. M., Schuh, J. C., & Drevon-Gaillot, E. (2023). Biomedical materials and devices. In *Haschek and Rousseaux's Handbook of Toxicologic Pathology, Volume 2: Safety Assessment Environmental Toxicologic Pathology* (pp. 427-466). Academic Press.
- [67] Pretel, D. (2023). Hidden Connections: The Global History of Jungle Commodities. *Technology and Culture*, 64(1), 202-219.

- [68] Ioannidou, A., Yannikakis, S., Caroni, C., Kourkoulis, S. K., & Papavasileiou, A. (2023). Shear bond strength between denture teeth and denture base using different bonding resins and tooth surface treatments. *Materials Today: Proceedings*.
- [69] Nath, S. D., & Nilufar, S. (2020). An overview of additive manufacturing of polymers and associated composites. *Polymers*, 12(11), 2719.
- [70] Verma, R., Azam, M. S., & Kumar, S. R. (2023). Comparative investigation of fabrication, roughness, mechanical and wear properties of glass ionomer and nanofillers reinforced dental composite: A review. *Materialwissenschaft und Werkstofftechnik*, 54(6), 700-708.
- [71] Gronwald, B., Kozłowska, L., Kijak, K., Lietz-Kijak, D., Skomro, P., Gronwald, K., & Gronwald, H. (2023). Nanoparticles in Dentistry—Current Literature Review. *Coatings*, 13(1), 102.
- [72] Laganà A., David, M., Dautre, M., de Groot, S., van Keulen, H., Madden, O.,... & van Bommel, M. (2021). Reproducing reality. Recreating bonding defects observed in transparent poly (methyl methacrylate) museum objects and assessing defect formation. *Journal of Cultural Heritage*, 48, 254-268.
- [73] De Angelis, F., Vadini, M., Buonvivere, M., Valerio, A., Di Cosola, M., Piattelli, A.,... & D'Arcangelo, C. (2023). In Vitro Mechanical Properties of a Novel Graphene-Reinforced PMMA-Based Dental Restorative Material. *Polymers*, 15(3), 622.
- [74] Al-Shalawi, F. D., Mohamed Ariff, A. H., Jung, D. W., Mohd Ariffin, M. K. A., Seng Kim, C. L., Brabazon, D., & Al-Osaimi, M. O. (2023). Biomaterials as Implants in the Orthopedic Field for Regenerative Medicine: Metal versus Synthetic Polymers. *Polymers*, 15(12), 2601.
- [75] Cai, H., Xu, X., Lu, X., Zhao, M., Jia, Q., Jiang, H. B., & Kwon, J. S. (2023). Dental Materials Applied to 3D and 4D Printing Technologies: A Review. *Polymers*, 15(10), 2405.
- [76] Pires, P. C., Mascarenhas-Melo, F., Pedrosa, K., Lopes, D., Lopes, J., Macário-Soares, A.,... & Paiva-Santos, A. C. (2023). Polymer-based biomaterials for pharmaceutical and biomedical applications: A focus on topical drug administration. *European Polymer Journal*, 111868.
- [77] Selvaraj, M., PT, R., & Mysamy, B. (2023). Extraction and Characterization of a New Natural Cellulosic Fiber from Bark of Ficus Carica Plant as Potential Reinforcement for Polymer Composites. *Journal of Natural Fibers*, 20(2), 2194699.
- [78] Hasan, K. F., Al Hasan, K. N., Ahmed, T., György, S. T., Pervez, M. N., Bejál, L.,... & Alpár, T. (2023). Sustainable bamboo fiber reinforced polymeric composites for structural applications: A mini review of recent advances and future prospects. *Case Studies in Chemical and Environmental Engineering*, 100362.
- [79] Png, Z. M., Wang, C. G., Yeo, J., Lee, J. J. C., Suratman, N. E. B., Tan, Y. L.,... & Zhu, Q. (2023). Stimuli-responsive Structure-Property Switchable Polymer Materials. *Molecular Systems Design & Engineering*.
- [80] Akhlaq, M., Mushtaq, U., Naz, S., & Uroos, M. (2023). Carboxymethyl cellulose-based materials as an alternative source for sustainable electrochemical devices: a review. *RSC advances*, 13(9), 5723-5743.
- [81] De Fazio, D., Boccarusso, L., Formisano, A., Viscusi, A., & Durante, M. (2023). A Review on the Recycling Technologies of Fibre-Reinforced Plastic (FRP) Materials Used in Industrial Fields. *Journal of Marine Science and Engineering*, 11(4), 851.
- [82] López-Saucedo, F. (Ed.). (2023). *Synthesis of Nanomaterials*. Bentham Science Publishers.
- [83] Clothier, G. K., Guimarães, T. R., Thompson, S. W., Rho, J. Y., Perrier, S., Moad, G., & Zetterlund, P. B. (2023). Multiblock copolymer synthesis via RAFT emulsion polymerization. *Chemical Society Reviews*, 2023, 52, 3438-3469.
- [84] Wijekoon, M. J. O., Mahmood, K., Ariffin, F., Nafchi, A. M., & Zulkurnain, M. (2023). Recent advances in encapsulation of fat-soluble vitamins using polysaccharides, proteins, and lipids: a review on delivery systems, formulation, and industrial applications. *International Journal of Biological Macromolecules*, 124539.
- [85] Lakshmi, D., Mukherjee, S., Pal, A. K., Manish, A. T., Moharana, G., & Bedia, S. (2023). Using a Three-Dimensional Superimposition Technique, Studying the Effects of Different Cooling Procedures on the Adaptability of Rapidly Heat-Cured Acrylic Denture Bases. *Journal of Coastal Life Medicine*, 11, 1257-1263.
- [86] Idrissi, H. A., Annamma, L. M., Sharaf, D., Jaghsi, A. A., & Abutayyem, H. (2023). Comparative Evaluation of Flexural Strength of Four Different Types of Provisional Restoration Materials: An In Vitro Pilot Study. *Children*, 10(2), 380.
- [87] Khan, A. A., Zafar, M. S., Fareed, M. A., AlMufareh, N. A., Alshehri, F., AlSunbul, H.,... & Vallittu, P. K. (2023). Fiber-reinforced composites in dentistry—An insight into adhesion aspects of the material and the restored tooth construct. *Dental Materials*, 39, (2), 141-151.
- [88] Khan, A. A., Fareed, M. A., Alshehri, A. H., Aldegeishem, A., Alharthi, R., Saadaldin, S. A., & Zafar, M. S. (2022). Mechanical properties of the modified denture base materials and polymerization methods: a systematic review. *International Journal of Molecular Sciences*, 23(10), 5737.
- [89] Mann, G. S., Azum, N., Khan, A., Rub, M. A., Hassan, M. I., Fatima, K., & Asiri, A. M. (2023). Green composites based on animal fiber and their applications for a sustainable future. *Polymers*, 15(3), 601.
- [90] Alimi, L., Chaoui, K., Boukhezar, S., Sassane, N., Mohamed, H., & Temam, T. G. (2020). Structure and mechanical properties of PMMA/GF/Perlon composite for orthopedic prostheses. *Materials Today: Proceedings*, 31, S162-S167.
- [91] Raza, S. S., Qureshi, L. A., Ali, B., Raza, A., & Khan, M. M. (2021). Effect of different fibers (steel fibers, glass fibers, and carbon fibers) on mechanical properties of reactive powder concrete. *Structural Concrete*, 22(1), 334-346.

- [92] Alhotan, A., Yates, J., Zidan, S., Haider, J., & Silikas, N. (2021). Flexural strength and hardness of filler-reinforced PMMA targeted for denture base application. *Materials*, 14(10), 2659.
- [93] Alhotan, A., Yates, J., Zidan, S., Haider, J., & Silikas, N. (2021). Assessing fracture toughness and impact strength of PMMA reinforced with nano-particles and fibre as advanced denture base materials. *Materials*, 14(15), 4127.
- [94] Somani, M. V., Khandelwal, M., Punia, V., & Sharma, V. (2019). The effect of incorporating various reinforcement materials on flexural strength and impact strength of polymethylmethacrylate: A meta-analysis. *The Journal of the Indian Prosthodontic Society*, 19(2), 101.
- [95] Aldegheishem, A., AlDeeb, M., Al-Ahdal, K., Helmi, M., & Alsagob, E. I. (2021). Influence of reinforcing agents on the mechanical properties of denture base resin: A systematic review. *Polymers*, 13(18), 3083.
- [96] Nejatian, T., Pezeshki, S., & Syed, A. U. Y. (2019). Acrylic denture base materials. In *Advanced Dental Biomaterials* (pp. 79-104). Woodhead Publishing.
- [97] Pradhan, S., Mathuriya, S., Sonkesriya, S., Maheshwari, A., Gaur, G., & Choubey, A. (2022). Evaluation of Surface Topography of Heat Cure Acrylic Denture-base Resin before and after Reinforcement with Different Fibers Using Stylus-based Profilometer. *The Journal of Contemporary Dental Practice*, 23(4), 415-418.
- [98] Abbas, S. O., Mahfouz, O. A., Aboushelib, M. N., & Rady, N. A. (2021). Evaluation of impact strength of heat cure acrylic resin reinforced with nylon fiber mesh with and without prestressing (in vitro study). *Alexandria Dental Journal*, 46(1), 85-90.
- [99] Sikkema, D. J. (2022). Rigid-chain polymers: Aromatic polyamides, heterocyclic rigid rod polymers, and polyesters. *Advanced Industrial and Engineering Polymer Research*, 5(2), 80-89.
- [100] Dharmavarapu, P., & MBS, S. R. (2022). Aramid fibre as potential reinforcement for polymer matrix composites: a review. *Emergent Materials*, 5(5), 1561-1578.
- [101] Abdulrazzaq Naji, S., Jafarzadeh Kashi, T. S., Behroozibakhsh, M., Hajizamani, H., & Habibzadeh, S. (2018). Recent advances and future perspectives for reinforcement of poly (methyl methacrylate) denture base materials: A literature review. *Journal of Dental Biomaterials*, 5(1), 490-502.
- [102] He, X., Qu, Y., Peng, J., Peng, T., & Qian, Z. (2017). A novel botryoidal aramid fiber reinforcement of a PMMA resin for a restorative biomaterial. *Biomaterials science*, 5(4), 808-816.
- [103] Raszewski, Z. (2020). Reinforce Acrylic Resin with Different Kinds of Fibers After Breaking. *Journal of Research in Medical and Dental Science*, 8(6), 125-130.
- [104] Abdulazeez, A. M. A., Jaber, A. A., Siswomihardjo, W., Sunarintyas, S., & Warreth, A. (2023). The Effect of Combination of E-glass and Polyethylene Fiber-Reinforced Composites on Flexural Strength. *Journal of Medical Sciences*, 18(1), 35-41.
- [105] Apimanchindakul, C., Na Nan, P., & Aimjirakul, N. (2022). Effect of Reinforced Self-Cured Acrylic Resin on Flexural Strength. *International Journal of Dentistry*, 2022.
- [106] Mahmood, W. S., Abdullah, Z. S., & Fatalla, A. A. (2021). The Effect of Addition of Salinized Polypropylene Fibers and Hydroxy Apatite Macro Fillers on Some Mechanical Properties of Clear Heat Cured Acrylic before and after Artificial Aging. *Indian Journal of Forensic Medicine & Toxicology*, 15(3), 1665-1672.
- [107] Sosiati, H., Yuniar, N. D. M., Saputra, D., & Hamdan, S. (2022). The influence of carbon fiber content on the tensile, flexural, and thermal properties of the sisal/pmma composites, composites 9 (1), pp. 32-40, 2022-03.
- [108] Sosiati, H., Al-Giffary, F., Adil, F. A., Kamiel, B. P., Adi, R. K., & Yusuf, Y. (2022). The properties of kenaf/carbon/PMMA hybrid composites by adding chitosan nano and microparticles. *Materials Today: Proceedings*, 66, 2908-2913.
- [109] Gad, M. M., Abualsaud, R., Al - Thobity, A. M., Baba, N. Z., & Al - Harbi, F. A. (2020). Influence of addition of different nanoparticles on the surface properties of poly (methyl-methacrylate) denture base material. *Journal of Prosthodontics*, 29(5), 422-428.
- [110] Jaafar, M. (2018). Review on poly-methyl methacrylate as denture base materials. *Malaysian Journal of Microscopy*, 14(1).
- [111] Smitha Sharan, M. D. S., Ulla, M. S., & Divya, K. S. (2023). Comparison of Impact Strength of Non-Reinforced Polymethyl Methacrylate Resin, Polymethyl Methacrylate Resin Reinforced with Glass Nanoparticles and Polymethyl Methacrylate Resin Reinforced with Carbon Nanotubes as a Denture Base Material. *Eur. Chem. Bull.* 2023, 12(1), 506-515.
- [112] Roshanali, M., Nodehi, A., & Atai, M. (2020). Synthesis and characterization of core-shell nanoparticles and their application in dental resins. *Journal of the Mechanical Behavior of Biomedical Materials*, 110, 103926.
- [113] Hata, K., Ikeda, H., Nagamatsu, Y., Masaki, C., Hosokawa, R., & Shimizu, H. (2022). Dental poly (methyl methacrylate)-based resin containing a nanoporous silica filler. *Journal of Functional Biomaterials*, 13(1), 32.
- [114] Alshamrani, A., Alhotan, A., Kelly, E., & Ellakwa, A. (2023). Mechanical and Biocompatibility Properties of 3D-Printed Dental Resin Reinforced with Glass Silica and Zirconia Nanoparticles: In Vitro Study. *Polymers*, 15(11), 2523.
- [115] Alhareb, A. O., Akil, H. M., & Ahmad, Z. A. (2018). Effect of nitrile butadiene rubber/Al₂O₃/YSZ fillers for PMMA denture base on the thermal and mechanical properties. *Journal of Thermal Analysis and Calorimetry*, 134, 941-951.
- [116] Raju, R., Rajan, G., Farrar, P., & Prusty, B. G. (2021). Dimensional stability of short fibre reinforced flowable dental composites. *Scientific Reports*, 11(1), 4697.

- [117] Elshereksi, N. W., Muchtar, A., & Azhari, C. H. (2021). Effects of nanobarium titanate on physical and mechanical properties of poly (methyl methacrylate) denture base nanocomposites. *Polymers and Polymer Composites*, 29(5), 484-496.
- [118] Michael, F. M., Krishnan, M. R., Li, W., & Alsharaeh, E. H. (2020). A review on polymer-nanofiller composites in developing coated sand proppants for hydraulic fracturing. *Journal of Natural Gas Science and Engineering*, 83, 103553.
- [119] Danial, W. H., & Abdul Majid, Z. (2022). Recent advances on the enhanced thermal conductivity of graphene nanoplatelets composites: a short review. *Carbon Letters*, 32(6), 1411-1424.
- [120] Barik, S. B., Patidar, P., Bagade, S. S., Kumar, A., Nayak, R. K., & Patel, P. K. (2023). Recent progress in reinforcement of nanofillers in epoxy-based nanocomposites. *Materials Today: Proceedings*.
- [121] Aboshama, M., Helmy, N., & Ammar, M. (2021). Effect Of Flexural Strength Of Denture Base Resin Reinforced By Three Different Nanoparticle Materials (In Vitro Study). *Al-Azhar Assiut Dental Journal*, 4(1), 31-36.
- [122] Akay, C., & Avukat, E. (2019). Effect of nanoparticle addition on polymethylmethacrylate resins. *Acta Scientific Dental Sciences*, 3(7), 91-97.
- [123] Nabhan, A., Taha, M., & Ghazaly, N. M. (2023). Filler loading effect of $\text{Al}_2\text{O}_3/\text{TiO}_2$ nanoparticles on physical and mechanical characteristics of dental base composite (PMMA). *Polymer Testing*, 117, 107848.
- [124] Azmy, E., Al-Kholy, M. R. Z., Al-Thobity, A. M., Gad, M. M., & Helal, M. A. (2022). Comparative Effect of Incorporation of ZrO_2 , TiO_2 , and SiO_2 Nanoparticles on the Strength and Surface Properties of PMMA Denture Base Material: An In Vitro Study. *International Journal of Biomaterials*, 2022.
- [125] Pensa, E. (2018). Enhanced properties of polymethyl methacrylate coated with atomic layer deposited ceramic nanofilm (Doctoral dissertation, University of Illinois at Chicago).
- [126] Gallab, M., Taha, M., Rashed, A., & Nabhan, A. (2022). Effect of low content of Al_2O_3 nanoparticles on the mechanical and tribological properties of polymethyl methacrylate as a denture base material. *Egyptian Journal of Chemistry*, 65(8), 1-9.
- [127] Agrawal, A., & Satapathy, A. (2019). Thermal, mechanical, and dielectric properties of aluminium oxide and solid glass microsphere - reinforced epoxy composite for electronic packaging application. *Polymer Composites*, 40(7), 2573-2581.
- [128] Tuttle, C. M. D. (2021). Surface modification of intracanal post by using hydrogen peroxide for endodontically treated teeth: an integrative review.
- [129] Kundie, F., Azhari, C. H., & Ahmad, Z. A. (2018). Effect of nano-and micro-alumina fillers on some properties of poly (methyl methacrylate) denture base composites. *Journal of the Serbian Chemical Society*, 83(1), 75-91.
- [130] Rohim, M. N., El-Sheikh, M. N., Ali, W. Y., & Hassan, A. E. S. M. (2021). Effect of Al_2O_3 nanowires and ZrO_2 nanoparticles addition on the mechanical and tribological properties of heat-cured PMMA acrylic denture base material. *high Temp*, 24, 28.
- [131] Omar, M. H., Amin, M. H., & Younis, H. A. (2022). Comparison of using nano-ZnO and nano- Al_2O_3 to improve the properties of prepared polymethyl methacrylate denture base. *Applied Physics A*, 128(4), 313.
- [132] Karci, M., Demir, N., & Yazman, S. (2019). Evaluation of flexural strength of different denture base materials reinforced with different nanoparticles. *Journal of Prosthodontics*, 28(5), 572-579.
- [133] de Souza Leão, R., de Moraes, S. L. D., de Luna Gomes, J. M., Lemos, C. A. A., da Silva Casado, B. G., do Egito Vasconcelos, B. C., & Pellizzer, E. P. (2020). Influence of addition of zirconia on PMMA: A systematic review. *Materials Science and Engineering: C*, 106, 110292.
- [134] Janardanan Kavitha, V. S. (2021). Effect of zirconium oxide and cellulose nanoparticles addition on the flexural strength, impact strength and translucency of heat polymerized acrylic resin: an in vitro study. *Int J Dent Mater* 2021; 3(4): 112-119.
- [135] Asim, F. A., Al-Mosaweb, E. H., & Hussain, W. A. (2022). Studying The Physical and Biological Characteristics of Denture Base Resin PMMA Reinforced with ZrO_2 and TiO_2 Nanoparticles. *Journal of Modern Science*, 8(3), 21.
- [136] Alfahdawi, I. H., & Abdulateef, M. A. (2023). Study the Influence of Zirconium Oxide Nanofillers on the Transverse and Impact Stresses of Heat-Cure Acrylic Resin Polymerization. <https://doi.org/10.21203/rs.3.rs-2795542/v1>
- [137] Beketova, A., Tzanakakis, E. G. C., Vouvoudi, E., Anastasiadis, K., Rigos, A. E., Pandoleon, P.,... & Kontonasaki, E. (2023). Zirconia Nanoparticles as Reinforcing Agents for Contemporary Dental Luting Cements: Physicochemical Properties and Shear Bond Strength to Monolithic Zirconia. *International Journal of Molecular Sciences*, 24(3), 2067.
- [138] Asopa, V., Suresh, S., Khandelwal, M., Sharma, V., Asopa, S. S., & Kaira, L. S. (2015). A comparative evaluation of properties of zirconia reinforced high impact acrylic resin with that of high impact acrylic resin. *The Saudi Journal for Dental Research*, 6(2), 146-151.
- [139] Gad, M. M., Fouda, S. M., Al-Harbi, F. A., Nănkangas, R., & Raustia, A. (2017). PMMA denture base material enhancement: a review of fiber, filler, and nanofiller addition. *International journal of nanomedicine*, 3801-3812.
- [140] Gad, M. M., Al-Thobity, A. M., Rahoma, A., Abualsaud, R., Al-Harbi, F. A., & Akhtar, S. (2019). Reinforcement of PMMA denture base material with a mixture of ZrO_2 nanoparticles and glass fibers. *International journal of dentistry*, 2019.
- [141] Gad, M. M., & Abualsaud, R. (2019). Behavior of PMMA denture base materials containing titanium dioxide nanoparticles: A literature review. *International journal of biomaterials*, 2019.

- [142] Giti, R., Firouzmandi, M., Zare Khafri, N., & Ansarifard, E. (2022). Influence of different concentrations of titanium dioxide and copper oxide nanoparticles on water sorption and solubility of heat - cured PMMA denture base resin. *Clinical and Experimental Dental Research*, 8(1), 287-293.
- [143] Fahad, N. K., & Sabry, R. S. (2022). Study of some mechanical and physical properties of PMMA reinforced with (TiO₂ and TiO₂-GO) nanocomposite for denture bases. *Journal of Polymer Research*, 29(10), 439.
- [144] Ahmed, M. A., El-Shennawy, M., Althomali, Y. M., & Omar, A. A. (2016). Effect of titanium dioxide nano particles incorporation on mechanical and physical properties on two different types of acrylic resin denture base. *World Journal of Nano Science and Engineering*, 6(3), 111-119.
- [145] Hashem, M., Rez, M. F. A., Fouad, H., Elsarnagawy, T., El-sharawy, M. A., Umar, A.,... & Ansari, S. G. (2017). Influence of titanium oxide nanoparticles on the physical and thermo-mechanical behavior of poly methyl methacrylate (PMMA): a denture base resin. *Science of Advanced Materials*, 9(6), 938-944.
- [146] Alrahlah, A., Fouad, H., Hashem, M., Niazy, A. A., & AlBadah, A. (2018). Titanium oxide (TiO₂)/polymethylmethacrylate (PMMA) denture base nanocomposites: mechanical, viscoelastic and antibacterial behavior. *Materials*, 11(7), 1096.
- [147] Aziz, H. K. (2018). TiO₂-nanofillers effects on some properties of highly-impact resin using different processing techniques. *The open dentistry journal*, 12, 202.
- [148] Naji, S. A., Kashi, T. S. J., Pourhajibagher, M., Behroozibakhsh, M., Masaeli, R., & Bahador, A. (2018). Evaluation of antimicrobial properties of conventional poly (methyl methacrylate) denture base resin materials containing hydrothermally synthesised anatase TiO₂ nanotubes against cariogenic bacteria and candida albicans. *Iranian journal of pharmaceutical research: IJPR*, 17(Suppl2), 161.
- [149] Cevik, P., & Yildirim - Bicer, A. Z. (2018). The effect of silica and prepolymer nanoparticles on the mechanical properties of denture base acrylic resin. *Journal of prosthodontics*, 27(8), 763-770.
- [150] Kamil, A. S. (2019). The effect of silicon carbide nanoparticles addition on some physical and mechanical properties of heat cured acrylic resin denture base material. Master of Science in prosthetic dentistry. College of Dentistry at the University of Baghdad.
- [151] Salahuddin, N., El - Kemary, M., & Ibrahim, E. (2018). Reinforcement of polymethyl methacrylate denture base resin with ZnO nanostructures. *International Journal of Applied Ceramic Technology*, 15(2), 448-459.
- [152] Cierech, M., Osica, I., Kolenda, A., Wojnarowicz, J., Szmigiel, D., Łojkowski, W.,... & Mierzwińska-Nastalska, E. (2018). Mechanical and physicochemical properties of newly formed ZnO-PMMA nanocomposites for denture bases. *Nanomaterials*, 8(5), 305.
- [153] Kamonkhantikul, K., Arksornnukit, M., & Takahashi, H. (2017). Antifungal, optical, and mechanical properties of polymethylmethacrylate material incorporated with silanized zinc oxide nanoparticles. *International Journal of Nanomedicine*, 2353-2360.
- [154] Vikram, S., & Chander, N. G. (2020). Effect of zinc oxide nanoparticles on the flexural strength of polymethylmethacrylate denture base resin. *European oral research*, 54(1), 31-35.
- [155] Khan, M. A., Madhu, G. M., & Sailaja, R. R. N. (2017). Reinforcement of polymethyl methacrylate with silane-treated zinc oxide nanoparticles: fire retardancy, electrical and mechanical properties. *Iranian Polymer Journal*, 26, 765-773.
- [156] Castro-Rojas, M. A., Vega-Cantu, Y. I., Cordell, G. A., & Rodriguez-Garcia, A. (2021). Dental applications of carbon nanotubes. *Molecules*, 26(15), 4423.
- [157] Aldwimi, I. M., Alhareb, A. O., & Akil, H. M. (2021, February). Effect of HNTs and MWCNTs nanotubes on the impact strength and hardness of PMMA denture base. In *AIP Conference Proceedings* (Vol. 2332, No. 1). AIP Publishing.
- [158] D éz-Pascual, A. M. (2022). PMMA-based nanocomposites for odontology applications: a state-of-the-art. *International Journal of Molecular Sciences*, 23(18), 10288.
- [159] Mohd Nurazzi, N., Asyraf, M. M., Khalina, A., Abdullah, N., Sabaruddin, F. A., Kamarudin, S. H.,... & Sapuan, S. M. (2021). Fabrication, functionalization, and application of carbon nanotube-reinforced polymer composite: An overview. *Polymers*, 13(7), 1047.
- [160] Nurazzi, N. M., Sabaruddin, F. A., Harussani, M. M., Kamarudin, S. H., Rayung, M., Asyraf, M. R. M.,... & Khalina, A. (2021). Mechanical performance and applications of cnts reinforced polymer composites—A review. *Nanomaterials*, 11(9), 2186.
- [161] Mahmood WS (2019). The effect of incorporating carbon nanotubes on impact, transverse strength, hardness, and roughness to high impact denture base material. *J Bagh Coll Dent*. 2015; 27: 96–99.
- [162] Ibrahim RA (2019). The effect of adding single walled carbon nanotube with different concentrations on mechanical properties of heat-cure acrylic denture base material. *J Bagh Coll Dent*. 2015; 27: 28–32.
- [163] Kim, KI., Kim, DA., Patel, K. D. (2019). Carbon nanotube incorporation in PMMA to prevent microbial adhesion. *Sci Rep* 9, 4921 (2019). <https://doi.org/10.1038/s41598-019-41381-0>
- [164] Sadati, V., Khakbiz, M., Chagami, M., Bagheri, R., Chashmi, F. S., Akbari, B., & Lee, K. B. (2022). Experimental investigation and finite element modelling of PMMA/carbon nanotube nanobiocomposites for bone cement applications. *Soft Matter*, 18(36), 6800-6811.
- [165] Su, X., Wang, R., Li, X., Araby, S., Kuan, H. C., Naeem, M., & Ma, J. (2022). A comparative study of polymer nanocomposites containing multi-walled carbon nanotubes and graphene nanoplatelets. *Nano Materials Science*, 4(3), 185-204.

- [166] Pal, N., & Agarwal, M. (2021). Advances in materials process and separation mechanism of the membrane towards hydrogen separation. *International Journal of Hydrogen Energy*, 46(53), 27062-27087.
- [167] Kumar, T. V., Shanmugapriya, N., Arun, S., & Ramasubramanian, G. (2023). Analysis of the Multiwalled Carbon Nanotubes Reinforced Polymethyl Methacrylate Bone Cement's Characteristics and In Vitro Bioactivity to Prolong Its Functionality in Orthopedic Application. *Advances in Polymer Technology*, 2023.
- [168] Feng, P., Wang, K., Shuai, Y., Peng, S., Hu, Y., & Shuai, C. (2022). Hydroxyapatite nanoparticles in situ grow on carbon nanotube as a reinforcement for poly (ϵ -caprolactone) bone scaffold. *Materials Today Advances*, 15, 100272.
- [169] Mohammed, H. S., Dutta, A., Prasad, A. H., Anand, M., Kundapur, V., & Roopwani, K. (2019). Comparison of the Flexural Strength and Surface Roughness of Conventional Heat Cure and High Impact Denture Base Resins on Micro-additions of Carbon Nanotubes-An In Vitro Study. *Int J Biomed Sci*, 15(1), 6-10.
- [170] Ghosh, M., & Shetty, S. (2020). Effect of Addition of Graphene and Carbon Nanotubes on Flexural Strength of Polymethylmethacrylate—A Comparative In-Vitro Study. *J Evol Med Dent Sci*, 9, 1494-99.
- [171] Kashan, J. S., Al-Allaq, A. A., Fouad, H., & Yahia, M. E. (2023). Effect of Multi-Walled Carbon Nanotube on the Microstructure, Physical and Mechanical Properties of ZrO_2 -CaO/Poly (methyl methacrylate) Biocomposite for Bone Reconstruction Application. *Science of Advanced Materials*, 15(3), 405-411.
- [172] Yang, K., Zhang, F., Chen, Y., Zhang, H., Xiong, B., & Chen, H. (2022). Recent progress on carbon-based composites in multidimensional applications. *Composites Part A: Applied Science and Manufacturing*, 106906.
- [173] Swaroop, N., Katiyar, P., Pandey, K. K., Tarannum, F., Umar, M., Paul, S.,... & Singh Jr, R. (2023). A Comparative Evaluation of Flexural and Impact Strength of Polymethyl Methacrylate (PMMA) Reinforced with Graphene and Multi-Walled Carbon Nanotubes: An In Vitro Study. *Cureus*, 15(6).
- [174] Kushwaha, S. K. S., Kushwaha, N., Pandey, P., & Fatma, B. (2021). Halloysite nanotubes for nanomedicine: Prospects, challenges and applications. *BioNanoScience*, 11, 200-208.
- [175] Saadat, S., Pandey, G., Tharmavaram, M., Braganza, V., & Rawtani, D. (2020). Nano-interfacial decoration of Halloysite Nanotubes for the development of antimicrobial nanocomposites. *Advances in Colloid and Interface Science*, 275, 102063.
- [176] Abdallah, R. M. (2016). Evaluation of polymethyl methacrylate resin mechanical properties with incorporated halloysite nanotubes. *The journal of advanced prosthodontics*, 8(3), 167-171.
- [177] Lisuzzo, L., Cavallaro, G., Milioto, S., & Lazzara, G. (2020). Effects of halloysite content on the thermo-mechanical performances of composite bioplastics. *Applied Clay Science*, 185, 105416.
- [178] Gaaz, T. S., Sulong, A. B., Kadhum, A. A. H., Al-Amiery, A. A., Nassir, M. H., & Jaaz, A. H. (2017). The impact of halloysite on the thermo-mechanical properties of polymer composites. *Molecules*, 22(5), 838.
- [179] Hasan, W. Y., & Ali, M. M. (2018). Evaluation of thermal conductivity and some other properties of heat cured denture soft liner reinforced by halloysite nanotubes. *Biomedical and Pharmacology Journal*, 11(3), 1491-1500.
- [180] Chen, S., Yang, Z., & Wang, F. (2018). Investigation on the properties of PMMA/reactive halloysite nanocomposites based on halloysite with double bonds. *Polymers*, 10(8), 919.
- [181] Barot, T., Rawtani, D., Kulkarni, P., Hussain, C. M., & Akkireddy, S. (2020). Physicochemical and biological assessment of flowable resin composites incorporated with farnesol loaded halloysite nanotubes for dental applications. *Journal of the mechanical behavior of biomedical materials*, 104, 103675.
- [182] Zafar, M. S. (2020). Prosthodontic applications of polymethyl methacrylate (PMMA): An update. *Polymers*, 12(10), 2299.
- [183] Mohammed, M. R., & Hadi, A. N. (2022). Enhancing the mechanical behaviour and antibacterial activity of bioepoxy using hybrid nanoparticles for dental applications. *International Journal of Biomaterials*, 2022.
- [184] Alqutaibi, A. Y., Baik, A., Almuzaini, S. A., Farghal, A. E., Alnazzawi, A. A., Borzangy, S.,... & Zafar, M. S. (2023). Polymeric Denture Base Materials: A Review. *Polymers*, 15(15), 3258.
- [185] Safwat, E. M., Khater, A. G., Abd-Elsatar, A. G., & Khater, G. A. (2021). Glass fiber-reinforced composites in dentistry. *Bulletin of the National Research Centre*, 45, 1-9.
- [186] Mohameed, T. A., Salih, S. I., & Salih, W. M. (2020). Preparation and study of flexural strength and impact strength for hybrid composite materials used in structural applications. *Engineering and Technology Journal*, 38(8), 1117-1125.
- [187] Alhareb, A. O., Akil, H. M., & Ahmad, Z. A. (2015). Mechanical properties of PMMA denture base reinforced by nitrile rubber particles with Al_2O_3 /YSZ fillers. *Procedia Manufacturing*, 2, 301-306.
- [188] Basima, M. A., & Aljafery, A. M. (2015). Effect of addition ZrO_2 - Al_2O_3 nanoparticles mixture on some properties and denture base adaptation of heat cured acrylic resin denture base material. *Journal of Baghdad College of Dentistry*, 27(3), 15-21.
- [189] Chavhan, G. R., & Wankhade, L. N. (2020). Improvement of the mechanical properties of hybrid composites prepared by fibers, fiber-metals, and nano-filler particles—A review. *Materials Today: Proceedings*, 27, 72-82.
- [190] Rongrong, C., Zhihui, H., Zhuoli, H., Junu, K. A. R. K. I., Chenxin, W., Bangshang, Z., & Xiuyin, Z. (2017). Antibacterial activity, cytotoxicity and mechanical behavior of nano-enhanced denture base resin with different kinds of inorganic antibacterial agents. *Dental Materials Journal*, 36(6), 693-699. <https://doi.org/10.4012/dmj.2016-301>

[191] Elmadani, A. A., Tomić, N., Radović, I., Vuksanović, M. M., Stojanović, D., Heinemann, R. J., & Radojević, V. (2019). Salt template zirconia reinforcing particles as possible reinforcement for PMMA matrix composite. *Advanced Composites Letters*, 28, 0963693519879696.

[192] Rebecca Lilda G., Rupesh P. L., Unni Pymallil, Basavaraj S.

Salagundi, Pallavi N. T and Vachan Poonacha (2020); A comparative evaluation of the impact and flexural strengths of high impact acrylic resin reinforced with silanated zirconium dioxide and titanium dioxide nanoparticles and its hybrid combination - an invitro study *Int. J. of Adv. Res.* 8 (Feb). 781-791 (ISSN 2320-5407).

Biography



Issam Mohamed Aldwimi received a bachelor's in dental technician from Elmergib University, Al Khums, Libya, in 2009. The M.Sc. in material engineering from Universiti Sains Malaysia (USM), Nebong Tebal, Penang, Malaysia, in March 2021. In April 2022, he started his PhD degree at the Department of Material Engineering, Faculty of Material and Mineral Engineering, Universiti Sains Malaysia (USM), Malaysia. Currently, he is a PhD condition at the School of Materials and Mineral Resources Engineering, Universiti Sains Malaysia (USM), Penang, Malaysia since April 2022. He has authored many well-recognized journals and conference papers.



Hazizan Md Akil is currently a full professor of polymer composites in the School of Materials and Mineral Resources Engineering, Universiti Sains Malaysia. Professor Hazizan received his PhD degree in composite materials from the University of Liverpool, UK, in 2002. He has ORCID number 0000-0002-7422-4627. His research interests include polymer composites with special emphasis on natural fibre reinforced composites, mechanics of composites, impact response of composites and sandwich structures, chitosan and dynamic response of composites using Split Hopkinson Pressure Bar Technique. He is one of the team leaders for Cluster of Polymer Composites Research in USM focusing on producing Pultruded Composites from kenaf fibres.



Zuratul Ain Abdul Hamid, is an associate professor of polymer composites in the School of Materials and Mineral Resources Engineering, Universiti Sains Malaysia. She has experience in Polymeric biomaterials. She has an ORCID number of 000-0002-5267-6091.



Ahmed Omran Alhareb is Dr in the Post of Tutor at the Faculty of Medical Technology at Elmergib University in Libya. He received his PhD degree in Materials Engineering from the Universiti Sains Malaysia, in 2017. He got the Gold Medal In 2011 Malaysia from the Ministry of Higher Education Malaysia (Incorporation Business Partnering Sessions) Under Project (High Performance of $\text{Al}_2\text{O}_3/\text{Y-Tzp}$ Filled PMMA Denture Base) (Kuala Lumpur Convention Centre- September 2011).