



Protocols of improvements for PMMA denture base resin: An overview

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Abstract

Polymethyl methacrylate (PMMA) is a polymer that is expansively employed in denture base construction due to its low cost, aesthetics, lightweight, reparability, and processability. Nevertheless, this material is not ideal to fulfill the mechanical and physical characteristics of dental restorations. Despite the popularity of the thermal polymerization method, the main shortcoming is the prolonged curing period. Thus, correctly selecting a polymerization cycle and post-polymerization treatment is needed to achieve promising outcomes. In autoclave polymerization, pressure plays a crucial function in accelerating the initial polymerization as well as decreasing the pores and remaining monomer level, thereby improving the flexural strength. Besides, ultrasound can speed up conventional chemical reactions by generating intensive local heating, higher pressures, and very short periods. This article reviews the currently employed protocols for enhancing PMMA denture base polymers and discusses the properties of modified acrylic materials. Moreover, this work explores the effects of the post-polymerization treatment, autoclave process, ultrasonic treatment, and gamma irradiation on the PMMA performance, as well as the positive influence of these treatments on functional properties and clinical longevity.

1. Introduction

Polymethyl methacrylate (PMMA) resin has developed the preparation procedures employed ever since this material has been utilized as a denture base polymer [1]. PMMA became the favored polymer for fabricating denture bases because of its required features like easy handling and processing, low cost, ease of repair and polishing, good appearance, and biocompatibility [1-3]. Nevertheless, this material has shortcomings such as poor wear resistance, inadequate surface hardness, polymerization shrinkage, and low strength [3-5]. Although numerous polymers have been advanced to be used as denture bases, PMMA continues to be the preferred material for removable prostheses [1,2,6].

The development of PMMA properties is a vital aim in dental materials research. The capability of a material to resist the formation of indentations and crack growth is an essential aspect influencing denture behavior. The causes of fractures include unbalanced occlusion, lack of adaptation of the dentures to the oral tissues, improper occlusal plans, internal stress inherent to the time-of-use, difficulties through the production of the prosthodontics, or limitations due to the material itself [7]. According to a previous study, approximately 70% of removable dentures had fragmented during the initial three years of delivery. Also, the repairs of detached teeth and midline breakages were 30% and 29%, respectively [8]. One technique is to enhance the mechanical performance of PMMA via the incorporation of reinforcing additives [4,5,9]. Other approaches contain modification of the PMMA

chemical structure via copolymerization [10-12] or the addition of chemical solutions such as cross-linking agents [13-15]. The cross-linked polymers revealed essential features not only for dental applications but also for industrial purposes [16-18].

PMMA is categorized as thermally or chemically cured polymer depending on the factors that initiated the reaction. For fabricating removable dentures, heat-cured polymers are employed. The widespread methods used for PMMA polymerization are microwaves and water baths [19]. The water bath system has been the most broadly utilized because of cost-effectiveness and easy handling. Meanwhile, the microwave technique exhibits shorter processing periods, but its influences on mechanical characteristics, porosity, and longevity are extremely reliant on polymerization circumstances [7,13]. Several attempts have been made to examine the impact of these two systems on the physical and mechanical characteristics of PMMA; however, controversial outcomes have been found, and both processing systems produced PMMA polymer with varying behaviors [7,20-25]. The careful choice of material and curing technique is critical to confirm the best product in prosthodontic treatments [26]. Developing the polymerization protocols led to promising enhancements in the performance of dental composites [27]. Thus, improving the processing methods is required to develop the mechanical and physical characteristics of the polymer. Therefore, the present review aims to shed some light on the current status of research on denture base materials, processing technologies, and the need for developing polymerization methods. The work focuses on the various state-of-

the-art protocols for improving the performance of PMMA polymers, with particular emphasis on the properties of the structurally modified acrylic resins. Polymerization techniques including post-polymerization treatment, autoclave process, ultrasonic treatment, gamma irradiation and their effects on PMMA performance are also described.

2. Materials and methods

An electronic search for data published from 2001 to 2021 was performed using Science Direct PubMed, Web of Science, Scopus, and Google Scholar databases. The keywords used include denture base polymer, cross-linking agent, interpenetrating polymer network, polymerization techniques, residual monomer, dental composites, and oxygen-inhibited layer. Besides that, a reference list of previous works was reviewed to detect other studies. Each article that suggested a probable counterpart or did not fit the exclusion criteria according to the evidence offered in the title was assessed.

The first assessment was achieved according to the paper's title. After that, checking of the abstracts of the related titles to evaluate their relevance. After that, an estimation of the relation of full papers with the related abstracts to the work topic was performed. Irrelevant studies were excluded. Only studies published in English were reviewed. The final selection comprised a total of 70 studies. No additional manual search was performed.

3. Alternative polymers

Several polymers, such as polyamide (PA), polyurethane (PU), polycarbonate, high-density polyethylene (HDPE), poly(ethylene methacrylate) (PEMA), polystyrene, poly(vinyl acrylic), poly(L-lactide) (PLLA), Polyvinyl chloride (PVC) and Epoxy resins, have been investigated as alternative materials for making prosthodontic restorations [28-32]. However, none of these polymers provides the exceptional aesthetic and physical properties displayed by PMMA [2,3,19].

Recently, Polyetheretherketone (PEEK) has been introduced as an innovative dental polymer to replace PMMA. PEEK (Figure 1) is a semicrystalline thermoplastic biomaterial. This material is one of the Polyaryletherketones (PAEKs) polymer group family, which is characterized by ultra-high molecular weight polyethylene. The mechanical behavior of PEEK as a denture base material has been determined [33]. It has been indicated that the PEEK polymer that was milled or pressed at 200°C mold temperature demonstrates superior mechanical properties compared to PMMA. Furthermore, the flexibility and highly elastic nature of the PEEK polymer could potentially decrease the stress on abutment teeth, which in turn could be advantageous in designing clasps using deep undercuts on

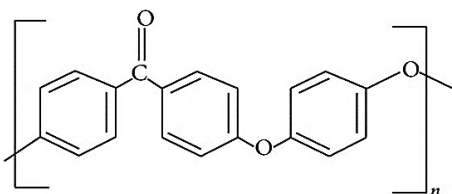


Figure 1. Chemical formula of PEEK.

the remaining teeth, thus eliminating denture pain due to excessive local pressure. However, due to its high tendency of discoloration and greyish-brown color, PEEK is not suitable for aesthetic prosthodontics [6,34]. Therefore, as yet no material fully satisfies the ideal criteria for a denture base.

4. Modified acrylic materials

The popular acrylic resins are employed in their unmodified forms. Denture base resin is typically constructed by polymerizing pre-polymerized PMMA (Figure 2) mixed with methyl methacrylate (MMA) monomer. Some products have been produced; nevertheless, attempts have been taken to enhance their physical and mechanical characteristics [9,35].

The denture base polymer encounters several stresses through its function, including tensile, compressive, and shear stresses [36]. In situ fractures of the denture base frequently happen due to fatigue; slight flexural stresses over time can ultimately result in the generation of cracks that propagate within the denture, eventually leading to breakage. Besides this, when a patient removes his/her dentures for overnight soaking or cleaning, there is a risk of fracture if the denture is fortuitously fallen onto a rigid surface. Impact fractures of dentures may occur in situ if the patient sustains severe trauma to the facial region [35]. Typically, a denture base polymer needs to show excellent strength to avoid fractures on accidental falls, but not at the loss of the other characteristics.

4.1 Copolymerization

Numerous efforts have been attempted to convert PMMA into a copolymer. Due to the different polymers mixed in varying volumetric proportions, an innovative material with better characteristics could be obtained [11]. The copolymerization mechanism affords the polymer structure arrangements, brings about several promising alterations such as an increase in polymerization rate, higher mechanical and physical properties, as well as a reduction in water solubility [15]. The strength of the polymers can be enhanced substantially by the impregnation of elastomers because of their ability to absorb energy and thus avoid acrylic breakage. A substitute for incorporating

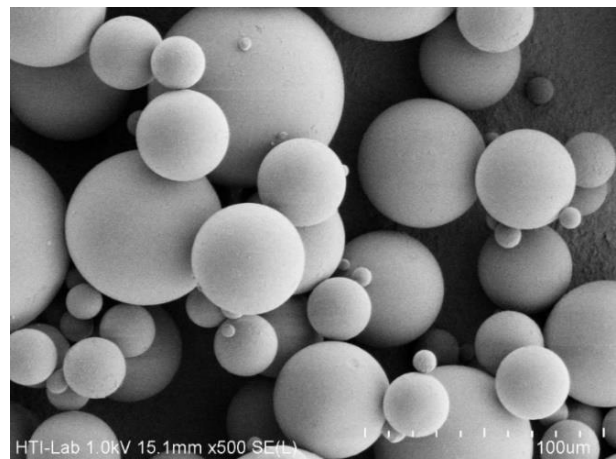


Figure 2. Scanning electron microscopy image of PMMA powder beads.

elastomers is the usage of acrylic elastomer copolymers, e.g., MMA-butadiene or MMA-butadiene-styrene [11]. Although impact strength can be improved nearly tenfold, these polymers are not commonly employed as they are expensive [35]. Moreover, stiffness, fatigue resistance, modulus of elasticity, and transverse strength are reduced [37,38].

Although several monomers have been employed to investigate their effects on PMMA behavior, controversial findings have been reported. Ranganathan *et al.* [39] investigated the mechanical performance of the acrylic resin after modifying the MMA by tricyclodecane-based monomers. The outcomes revealed that considerable improvements in the flexural and impact strength of PMMA denture base polymer were found. These monomers enable decelerating the polymerization rate and lowering the unreacted monomer level. However, a remarkable reduction in flexural strength was observed when the amount of acrylamide monomers (AAM) was raised from 15% to 20% [10]. This decline could be explicated by the extreme saturation of the neat PMMA, which was advanced by the inclusion of AAM, and the additional monomer disrupted the cross-linked polymer.

Spasojevic *et al.* [12] conducted a study to explore the mechanical performance of PMMA modified with itaconates. They inferred that dramatic reduction in glass transition temperature (T_g), storage modulus, tensile strength, and impact resistance as itaconates level increased. This behavior was attributed to the plasticizing effect of itaconates. Moreover, the influence of fluoroalkyl methacrylate on the flexural strength of PMMA denture base material was investigated [40]. The synthesized resin exhibited an inferior flexural modulus and strength because of the various intermolecular detachments due to the existence of fluorine in the methacrylic polymers. Meanwhile, others [41] examined styrene and fluoro-substituted monomers; nevertheless, the resultant material was also inferior to PMMA due to the existence of hydrophobic group monomers. Accordingly, when the polymer couples did not react with each other due to the incompatibility of the monomers, a polymer with lower mechanical behavior could be generated. The search for alternative materials to use as a denture base continues to be in progress [10,11].

4.2 Homogeneity of copolymers

The performance of innovative polymers relies on the affinity of the mixed monomers. The compatible monomers have been found to produce copolymers with better mechanical behavior. Consequently, to form homogeneous copolymers, monomers containing the identical functional group were favored [15]. In this way, copolymer formation could be obtained without detrimental the chemical resin of PMMA. Table 1 displays the common comonomers used for PMMA copolymerization. In addition, the physical properties could be affected by the polymerization degree, which is correlated to the molecular weight. Hence, through molecular weight, the polymerization degree has the potential to influence mechanical properties [42]. The copolymerization method, monomer nature, and concentration could also be considerable factorial parameters that significantly affect the performance of the resultant copolymer.

With regard to MMA's chemical structure, as shown in Figure 3, isobutyl methacrylate (IBMA) and 2-hydroxyethyl methacrylate (HEMA) possess greater groups that achieved a copolymerization effect through the polymerization MMA as seen in Table 1. By the rising ratio of HEMA and IBMA, the bigger molecules partook part in the chemical composition and decreased the flexural strength of the produced material. Increasing the ratio of IBMA led to a reduction of the flexural strength because of having significant molecules and the impediment of employing monomers [15].

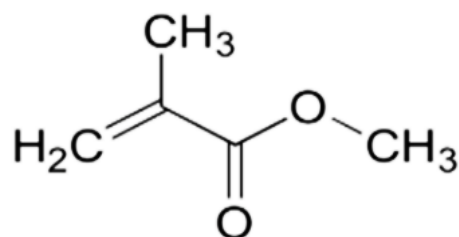


Figure 3. The chemical formula of methyl methacrylate.

Table 1. The described comonomers used for PMMA copolymerization.

Comonomer	Abbreviation	Chemical structure	Molecular weight (g·mol ⁻¹)
Isobutyl methacrylate	IBMA		142.2
2-hydroxyethyl methacrylate	HEMA		130.14
Butyl methacrylate	BMA		142.1956
Ethyl methacrylate	EMA		114.14

Hayran *et al.* [11] examined the flexural properties of PMMA copolymers using ethyl methacrylate (EMA), butyl methacrylate (BMA), and IBMA, respectively. They found that the PMMA copolymerization with these monomers enhanced the flexural modulus and strength of the PMMA. The greater the ratio, the more significant the alterations in the extreme flexural modulus and strength. The inclusion of 10% HEMA and 10% IBMA considerably improved the flexural strength of denture base polymer due to durable van der Waals attractiveness between MMA-HEMA and MMA-IBMA [42]. These findings are consistent with others who reported higher flexural strength values were achieved by the addition of 2%, 3%, and 5% IBMA and HEMA to the conventional PMMA denture base resin [15]. In the major chain of PMMA, by replacing the CH₃- group with an alkyl group with a bigger number of carbon, the flexibility of the resin could be improved [43].

4.3 Cross-linking processes

PMMA can be produced as a linear chain or cross-linked in a complicated three-dimensional network. Crosslinking is a process of interlinking the polymer chains through ionic or covalent bonds. Such processes have been extensively applied to defeat the substantial weak points in linear PMMA, e.g., strength, rigidity, modulus, and stiffness [18]. Characteristics such as glass transition, thermal degradation, particle size, pore-volume, pore size, surface area, craze resistance, and creep are modified after cross-linking occurred [14]. The cross-linked polymers exhibit higher thermal stability levels as the three-dimensional network could restrict the mobility of the polymer chain, thus improving the abrasion and heat resistance of the resulting materials [17,18]. This method is performed by applying physical or chemical cross-linking to improve the chemical and physical characteristics of the produced cross-linked polymer, which is entirely influenced by the nature and the ratio of cross-linking agents.

In general, polymers used for making denture bases are typically provided as a combination of PMMA powder and MMA liquid. Little ratios of cross-linkers are included in the monomer composition.

During the polymerization, a middle layer between the PMMA beads and cross-linked polymer matrix, known as a semi-IPN (interpenetrating polymer network), is produced [44]. The most often monomers employed as a cross-linker for MMA are ethylene glycol dimethacrylate (EGDMA) which offers a short cross-linkage between the chains of linear monomers (Figure 4). In contrast, dimethacrylates polymerize to a highly cross-linked network [45]. The monomer structures with improved mechanical characteristics could effectively modify the features of denture base polymer and develop their applicability. The extent of cross-linkage works as an essential key in the performance of the polymer [35]. The addition of a 10 wt% cross-linking agent (1,6-hexanediol dimethacrylate; HDDMA) improved the toughness and flexural strength, but further raises in the HDDMA level failed to offer a similar effect [13]. The composition is influenced by both the remaining double bonds as well as the cross-link density of the resultant polymer formations. The crucial cross-linkers could be categorized to be hydrophobic, hydrophilic, flexible, or rigid. Table 2 displays the popular cross-linking agents and their short forms mainly utilized as cross-linking agents in the cross-linkage processes for PMMA.

The mechanical characteristics of PMMA denture base polymer were further investigated after incorporating methacrylated dendrimer (DD1; Figure 5) as a cross-linking agent [44]. The results confirmed that the inclusion of DD1 to monomer displayed greater surface hardness and flexural modulus than EGDMA. This might describe how the production of cross-linking in the polymer with DD1 offers anchoring points that can resist extreme movement. Consequently, the flexural modulus is increased and provides improved stiffness to the PMMA denture base polymer. The impact of amount variations of the cross-linking agent was statistically substantial on flexural strength. The flexural modulus and strength were enhanced with a minor quantity of cross-linkers and reduced with a more significant level of cross-linkers. This could be attributed to the formation of the IPN layer varying with an increased level of cross-linkers, thus progressively influencing flexural characteristics.

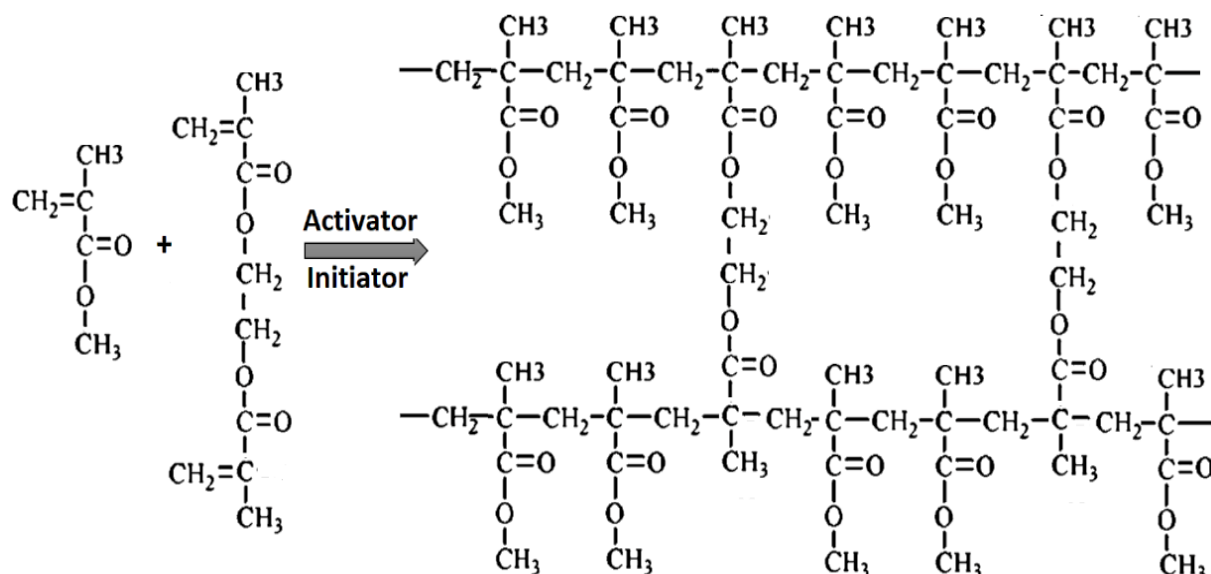
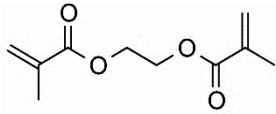
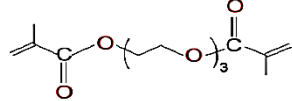
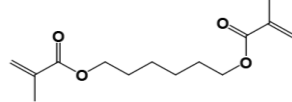
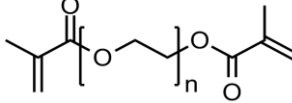
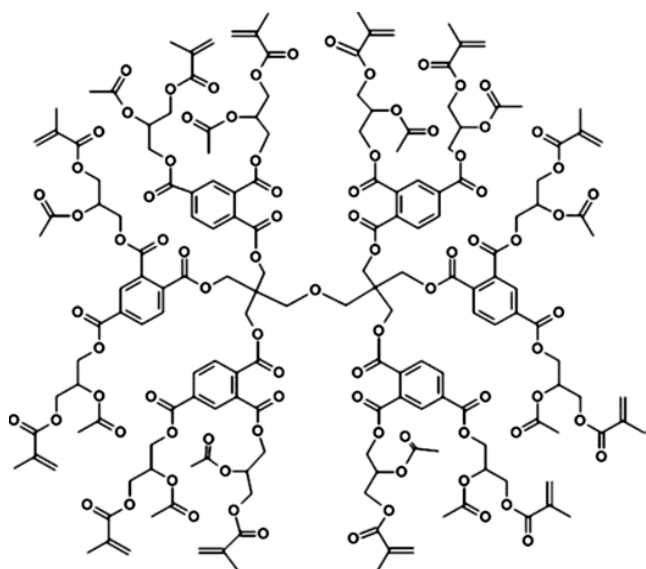


Figure 4. Chemical basis for the development of cross-linked PMMA.

Table 2. The frequent cross-linkers employed in the cross-linkage of PMMA.

Crosslinker [^]	Abbreviation	Chemical structure
Ethylene glycol dimethacrylate	EGDMA	
Triethyleneglycol dimethacrylate	TEGDMA	
Hexamethyleneglycol dimethacrylate	HMGDM	
Poly(ethylene glycol) dimethacrylate	PEGDMA	


Figure 5. The structural formula of dendrimer DD1.

The structure of the monomer affects the cross-link density of a polymer composition. Therefore, an elevated level of bifunctional monomers brings about a great degree of conversion, leading to increased cross-linking density. These two characteristics improve in dental composites with rising triethylene glycol dimethacrylate (TEGDMA). However, a reduction in flexural strength and an increment in volumetric shrinkage is recorded. In such a situation, the raised volumetric shrinkage is attributed to a greater reactive group level and a better degree of conversion [46]. Increasing TEGDMA contents lead to reducing free volume loss, thereby improving cross-linking density [45]. It has also been reported that the length of the dimethacrylate molecule establishes the theoretic cross-linking density of a consequent polymer system. The lesser the space between double bonds, the greater the cross-linking density. Higher cross-linking density gives rise to a reduction in the potential of chain reorganization, eventually leading to an increase in the modulus [47].

4.4 Heat treatment of PMMA powder

The improvements in the mechanical performance of PMMA can be achieved not only by modifying the MMA monomer but also by causing physical changes in the PMMA powder. Heat treatment is one of the processing systems utilized to enhance the mechanical performance of the dental polymer [48] and taking into account the favorable effects of heating PMMA beads to 100°C on the mechanical behavior of acrylic denture base, leading to improving the longevity of PMMA denture base material.

Heat treatment at 130°C demonstrated to be an efficient technique to advance the hardness and flexural strength of the PMMA denture base polymer [48]. Despite that, the thickness of the swollen PMMA layer was reduced by the heat treatment, increased mechanical properties of the PMMA were found. This could be attributed to the presence of sufficient adhesive substrate of semi-IPN between the PMMA beads and the matrix, even after heat treatment, to defend the strength of the PMMA. Moreover, such a process could lead to the elimination of oxygen and water absorbed on the bead's surface, affecting the mechanical attributes of PMMA denture base polymer [49]. PMMA powder was also heat-treated using an autoclave, and its effect on the polymer's performance was evaluated [50]. The findings confirmed that autoclave treated samples exhibited higher transverse strength than conventional samples due to increased conversion.

4.5 Oxygen inhibited layer

Oxygen disseminates a decremental impact on polymerization and restricts the initiation phase of a polymerization reaction. Therefore, it causes a stoppage of the reaction and imperfect curing because of the creation of an oxygen inhibited layer (OIL). This layer is a coating of obstructed monomer existent on the outer layer of methacrylates cured in the existence of oxygen. As a result of incomplete polymerization and the presence of imperfections, the mechanical behaviors would be significantly diminished [49]. The OIL forms due to the higher attraction of the free radicals toward oxygen, which is larger than

their affinity toward the C=C, thereby hindering polymer production [51]. When a polymer specimen is exposed to the air, the numeral of radicals in a slim layer is diminished because of oxygen inhibition. The double bonds conversion by radicals is slowed. Hence, numerous unreacted double bonds remain nearby the surface, even the material under the surface is appropriately treated [52].

Keh *et al.* [49] concluded that by eliminating oxygen, the induction stage of the polymerization was considerably reduced, and its exothermic reaction was improved. The depth and degree of oxygen inhibition at the surface of a methacrylate resin could be affected by numerous factors such as monomer functionality and structure, cross-linking agent content, the type and concentration of initiators, and polymerization conditions [51]. Accordingly, several approaches could be adopted to avoid such impact, such as altering irradiation wavelength, augmenting initiator ratio, applying various chemical modifications, and treating in an oxygen-free environment [52]. Oxygen inhibition can be entirely prevented by achieving polymerization in the overall lack of oxygen. However, this way is only helpful for restricted applications [53].

5. Polymerization techniques

In prosthetics, the curing of materials is very important. Further enhancements of their characteristics could be attained by the suitable choice of acrylics and additives along with appropriate processing. The energy needed to polymerize heat-cured PMMA is frequently supplied in a water bath or, less commonly, a microwave oven. Even though the physical attributes of PMMA denture base resins activated by microwave have been proven to be similar to heat-cured polymers by the conventional heat process, porosity has been reported when polymerized by microwave method the rapid increase in temperature during polymerization processing [20]. Lai *et al.* [23] declared that selecting a proper power and polymerization period is crucial to decrease porosity to the lowest ratio. Furthermore, depending on the polymerization temperature and time spent in the conventional process, varying quantities of monomer remain in the PMMA, and these can lead to various levels of cytotoxicity [54]. Therefore, it is rational to indicate that selecting the proper polymerization cycle and post-polymerization could achieve promising outcomes.

5.1 Post-polymerization treatment

Through the polymerization of PMMA, the monomers' conversion to polymers is imperfect, and some residual monomers remain in the cured polymers. The unreacted monomer level is the main factor affecting the performance of the polymer [19,46]. Polymerization temperature and time affect the remaining MMA content, which is more significant in self-curing than in heat-curing PMMA [55]. Therefore, when the temperature is elevated, more diffusion takes place. The release behavior of monomers and other components could be prompted by treatments implemented after polymerization

including soaking in hot water or microwave radiation, thereby considerably decreasing the level of remaining monomers in cured PMMA [56].

The post-polymerization water bath was an efficient method in lowering the cytotoxicity levels of denture base resins [54]. The lower unreacted MMA ratios after polymerization are because of continuing polymerization at the sites of active radicals; the MMA molecules can diffuse more quickly to these active sites at elevated temperatures, thus increasing the MMA content fall rate. Moreover, the applied post-polymerization techniques enhanced the mechanical properties of acrylic materials [55]. The impact of the post-polymerization on the conversion degree of the PMMA polymer is also evaluated [57]. The results showed that acrylic resin revealed a considerable improvement in conversion after the post-polymerization by a water bath. The heat-polymerized denture base resin also exhibited a remarkable reduction in the remaining MMA liquid after soaking in hot water. Post-polymerization in a water bath can be a substitute way to enhance the mechanical characteristics of acrylates, by diffusion of non-polymerized monomers into the water and possibly by additional polymerization in places with active radicals.

5.2 Ultrasonic treatment

PMMA is the most extensively employed heat-cured acrylic material utilized to produce denture bases and temporary dental prostheses. One drawback of this polymer is the unreacted monomer which remains even after its curing is terminated [55]. Various efforts have been made to reduce the level of unpolymerized monomers. The effects of the curing process, temperature, time, pressure, and mixing ratio have been evaluated [57,58]. Table 3 summarizes different polymerization methods used to enhance the performance of the denture base polymer.

The use of ultrasound to accelerate conventional chemical reactions was introduced by Richards and Loomis in 1927 [59]. The ultrasonic energy penetrates the liquid leading to the creation, development, and breakdown of vacuum bubbles [60]. During this process, the bubbles break down and generate intensive local heating, higher pressure, and brief periods. These transient and localized hot spots drive high energy toward completing chemical reactions faster [59].

In earlier research, the utilization of ultrasonication for decreasing the existence of unreacted monomers in acrylic resins was investigated [60,61]. It has been concluded that sonication could lower the level of remaining monomers in heat-cured PMMA. Besides, ultrasonication can improve the removal rate of the remaining monomer from the polymer and produce post-polymerization of the remaining monomers. The effect of the processing condition by ultrasonication on the mechanical performance of PMMA was also performed [59]. The results exhibited that the ultrasonicated polymer at 80 kHz and 100% power revealed superior elastic modulus and flexural strength. Consequently, the PMMA treated by ultrasonication performed better compared to PMMA from microwave processing.

Table 3. Several polymerization techniques utilized for enhancing the performance of the PMMA denture base resin.

Polymerization technique	Method	Comment	Ref.
Post-polymerization	<ul style="list-style-type: none"> • 55°C for 60 min. 	Lower residual monomer levels.	[54]
		Improved biocompatibility.	
		Decreased cytotoxicity.	[56]
Autoclave	<ul style="list-style-type: none"> • 100°C/30 min or 650 W/3 min in the microwave oven after aging in a water bath at 37°C/1,day,7 day, and 30 day. • 60°C for 30 min, then 130°C for 10 min • 60°C for 30 min, then 130°C for 20 min. • 121°C, 210 kPa/15 min or 30 min. • 60°C for 30 min, then 120°C for 10 min. • 60°C for 30 min, then 120°C for 20 min. • 60°C, 2.1 bar for 30 min, then 120°C/10 min 	The applied post-polymerization methods increased the modulus of elasticity and flexural strength.	[55]
		Significant reduction in remaining monomer level and better hardness.	[19]
		Reduction in porosity.	[62]
		Increased mechanical properties.	
		Improved elastic modulus and flexural strength.	[63]
		Increased surface hardness.	[64]
		Ultrasonic	<ul style="list-style-type: none"> • Ultrasonic frequency 80 kHz. • 50°C for 3 min, 5 min, 10 min, and 15 min. • Ultrasonic frequency 40 kHz. • 50°C/10 min with ultrasonic frequency 28 kHz, 40 kHz, and 60 kHz.
50°C water for 3 min for heat-cured PMMA with ultrasonic treatment decreased the remaining monomer content.	[60]		
Reduced the residual monomer at low frequencies.	[61]		
Gamma radiation	<ul style="list-style-type: none"> • 60°C to 70°C in a water bath followed by exposing γ rays with doses of 7.5 krad, 15 krad, 22.5 krad, 30 krad, 45 krad, 52.5 krad, 360 krad, and 2160 krad. • gamma irradiation (15 kGv, 25 kGv, and 35 kGy) 		
		Reduced residual monomer. Lower flexural strength	[66]

5.3 Autoclave process

The curing system employed to polymerize the denture base polymer is a crucial factor. It can prompt stress into the denture base through processing and take part in fatigue failure [67]. Processing systems have been adapted to advance the mechanical and physical characteristics of dental polymers and support the procedural effort of the professional. An adequate method for acrylic polymerization maximizes the attributes of the polymer, such as lower porosity, monomer release, and flexural strength [68]. Despite the benefits offered by the conventional method, such as simplicity, ease, and cost-effectiveness, the main drawback has been the prolonged curing period desired [26]. The pressure plays a crucial function in accelerating the initial polymerization as well as decreasing the pores and remaining monomer level, thereby improving the flexural strength. The advantages of applying pressure could be reaped either with a domestic pressure cooker or an autoclave [67]. The autoclave system could be a better substitute for the water-bath method, and polymerization utilizing conventional equipment requires less than 1 h.

As stated by Abdulwahhab, the mechanical properties of autoclave-polymerized samples were higher than those of the controlled curing due to the pressure [62]. These outcomes agreed with others [63] who reported that the polymerization using an autoclave revealed a considerable enhancement in the elastic modulus and flexural strength of the acrylic materials compared to the water bath system. The rapid increase in temperature generates a numerically greater number of radicals consequently, increasing the polymer chains. These chains interfere either with polymer chains or other radicals, creating a rise in branching and cross-linking of the interstitial polymer [35]. Enhanced storage modulus for the autoclave-polymerized PMMA at temperatures higher than the average boiling temperature of the monomer supports the idea of the decrease in the remaining monomer content. This finding

is consistent with other researchers who inferred that the autoclave system displayed a substantial reduction in the remaining monomer level and better hardness than the water bath method [19,64]. One viable reason for declining the remaining monomer level could be the diffusion of the unreacted molecules out of the polymer matrix by the applied pressure through autoclave polymerization. Therefore, it can be decided that the autoclave technique may be a better substitute for the water bath technique.

5.4 Gamma irradiation

Gamma rays can activate the polymerization of PMMA due to their ability to penetrate the material and change the polymer structure leading to modifying chemical bonds, the creation of free radicals, and cross-linking [14]. Although the application of gamma-activated PMMA is not new [65,69], not enough data have been found in the literature. In 2001, the curing of the PMMA denture base was introduced by Usanmaz *et al.* [65]. They studied the effect of the irradiation dose on the thermal characteristics of the resin, and a high molecular weight cross-linked polymer with low porosity is produced using this technique. Furthermore, others [66] inferred that gamma cured PMMA exhibited minimal levels of remaining monomer because of higher penetration depth of the irradiation, denoting gamma curing processes is a very efficient method for reducing the unpolymerized MMA in denture base polymers. In addition, gamma irradiation improved the biocompatibility parameters of the polymer due to the combination of oxygen and the produced free radicals [70]. Although polymerization via gamma rays and heat curing process perform a similar mechanism (free radical initiation), radiation-initiated polymerization is distinguished by producing high pure material, easy reaction control and segregation of initiation rate on temperature. Table 4 presents a short comparison between these two processes.

Table 4. A brief comparison between conventional polymerization and gamma radiation.

Polymerization process	Conventional polymerization	Radiation
No. of stages	One stage	One stage
Polymerization reaction	Additional polymerization	Additional polymerization
Curing temperature	80°C to 100°C	Ambient temperature
Curing period	Less	Very low
Degree of cross-linking	Dependent on the amount of cross-linker, reaction time, and temperature.	Affected by high-energy gamma rays and radiation dose.

6. Perspective

Chemical and physical modifications of the PMMA could lead to dramatic enhancements in the polymer attributes. When the polymerization process of heat-cured PMMA has occurred, the unreacted monomer remains after polymerization is completed [55]. Therefore, post-polymerization is essential to minimize the residual monomer at the least level, thereby promoting the mechanical characteristics. Currently, this procedure is commonly used for cold cured PMMA [3]. Moreover, developing the curing system of denture base resins by applying autoclaves and gamma irradiation produced promising results which encourage their clinical applicability.

7. Conclusions

Even though PMMA is widely used as a denture base material, this polymer does not perform ideally. Clinical failure of PMMA dentures most commonly occurs in the form of fractures due to poor strength. Although the PMMA behavior could be affected via copolymerization, none of these materials provides the exceptional aesthetic and physical properties of PMMA. Moreover, cross-linkage procedures for PMMA are employed to defeat the substantial weak points in thermoplastic PMMA like, mechanical strength, stiffness, and rigidity. Such properties could also be enhanced by heat treatment of the PMMA powder to eliminate oxygen and water absorbed on the bead's surface. Reducing the residual monomer level and improving the polymer's strength is highly dependent on polymerization conditions. Thus, the post-polymerization treatment exhibited encouraging findings for the development of PMMA performance. Using an autoclave technique, the mechanical and physical characteristics of PMMA were enhanced by reducing the remaining monomer level as the pressure increased dispersal of the unreacted MMA molecules into the PMMA matrix. Furthermore, ultrasound-assisted thermo-polymerization and gamma irradiation are good options for the processing of PMMA. The higher penetration depth of gamma irradiation is a very efficient method for reducing the unpolymerized MMA in denture base polymers.

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