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The Impact of Post-Processing Procedures on the Characteristics of the Additively Manufactured Resins: A Systematic Review

Sara Benfaida[1], Mouna Hamza[2], Ahmed Benabdelaziz[3], EL Mehdi Jouhadi[1]

[1]Fixed Prosthesis Department, Faculty of Dentistry of Casablanca, Hassan II University of Casablanca, Casablanca, Morocco
[2]Laboratory of Community Health Epidemiology and Biostatistics, Faculty of Dentistry of Casablanca, Casablanca, Morocco
[3]Faculty of Medicine of Sousse, University of Sousse, Research Laboratory LR19SP01 (Tunisia), Sousse, Tunisia
Email: sarabenfaidafmdc@gmail.com

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Abstract

Aim: The aim of our study was to evaluate the impact of post-processing procedures on the characteristics of additively manufactured resins. Method: Literature was searched on MEDLINE (PubMed) using Anglo-Saxon keywords. Papers meeting the eligibility criteria were identified after reading their titles, abstracts, and full text. The Critical Skills Appraisal Programme (CASP) was used to assess the quality of the studies selected. **Results:** Among the 186 references initially found, 22 articles met the inclusion criteria. According to the found data, our results confirmed the effectiveness provided by the post-processing procedures on the biological and physico-mechanical properties but the effect on the surface roughness is still ambiguous. The influence was provided by increasing the light intensity and temperature. The duration between 5 and 20 minutes of the post-curing time is recommended by the studies. The types of post-curing affect the final properties but the lack of a standardized protocol within the studies precludes a definitive conclusion. **Conclusions:** Based on the results of our study, the effectiveness of the post-processing procedures on the properties of the additively manufactured resin dental devices was confirmed. Additional studies with standardized protocols are needed to establish the optimal post-processing procedure protocol and to study the conflicting findings about the time and types of post-curing. Further investigations in conditions simulating an oral environment are also required.

Subject Areas

Impression 3D, Polymers

Keywords

Polymers, Printed Resin, Additive Manufacturing, Post Processing Procedures, Post Curing, Systematic Review

1. Introduction and Background

Due to the evolution noted in the materials and the techniques, the production of dental devices by additive manufacturing methods (AM) has increased [1] [2] [3]. The additive manufacturing technique which is also known as 3D printing, rapid prototyping, and VAT polymerization was first used in the 1980s, and it was used to create the fixed dental devices such as provisional crowns, dental splints, surgical guides and denture bases. Studies have concluded that AM has advantages compared to the milling technology, such as low material waste, cost-effectiveness, shorter fabrication time, easily reproductive prostheses with fine details, no milling burs wearing and the possibility to obtain more complex shapes [3] [4].

Various additives methods exist, due to the high accuracy and rapid processing, the most popular are stereo lithography (SLA) and digital light processing (DLP). For the materials used, different types exist but AM mainly targets polymeric constructions made from 3D printing resin [1]-[6].

For the fabrication of additively manufactured resin devices, the additive process will be carried out layer by layer, and several parameters can affect the final properties of the future printed product and must therefore be controlled. After the final shape is obtained, an additional step must take place: The post-processing procedures. The objective of this step is to complete the polymerization of the manufactured device and can be divided into four steps [7] [8]:

1) Removal of the device from the building platform;

2) Cleaning eliminates the uncured resin on the surface of the object by submerging the device in an organic solvent like isopropyl (IPA) or isopropanol alcohol;

3) Post-polymerization: to complete polymerization of the device using a UV-polymerization machine;

4) Removal of supporting structures which can be performed using a cutting device, a diamond disc, or an ultrasonic tip [9] [10].

In a nutshell, the last decade has seen a surge in technological advances in materials and techniques, associated with the impression 3D. Current literature data confirm the role of these different steps in the final product. All these steps allow the polymerization of the manufactured device and define the final properties and performances of the 3D-printed resins [6] [7] [8] [9] [10]. However, it is still uncertain how the post-processing procedure affects… On the other hand, it is still uncertain how the post-processing procedure affects the quality of the printed product, and what is the exact protocol to follow to obtain a quality print. What is the best material for rinsing, which post-curing machine should be used: an atmospheric post-curing chamber, pressure post-curing chamber or treatment combining light and heat? With what intensity? At what temperature? And for how long? The studies conducted have investigated the effect of the protocol in a general way but few studies have focused on the effect of the post-processing procedure. The real link between the post-processing procedure and performance must be studied. In addition, all the studies carried out used different protocols, preventing the adoption of a standardized protocol for the physical post-processing of 3D-printed resins. Therefore, to understand the mechanisms and to find answers to all these questions, we conducted a systematic review. The objective was to evaluate the impact and mechanism of action of post-processing procedures on the characteristics of additively manufactured resins.

2. Methodology

2.1. Focused Question

Our present study is a systematic review concerning the impact of post-processing procedures on the final characteristics of the additively manufactured resins. This systematic review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [11]. The methodology was submitted to the PROSPERO International Registry of Systematic Reviews under number: 391,993. Our problematic was constructed according to the Participants Intervention Comparison Outcome and Study (PICOS) strategy. The PICO Question and Boolean search strategy are presented in **Table 1**.

Table 1. The PICOS protocol devised for the review.

Criteria	Description
P (problem or population)	**P** (problem or population) comprised specimens of dental resins printed 3D devices.
I (intervention)	**I** (intervention), assessment of the properties of 3D-printed dental resins. Including mechanical properties, biocompatibility, cell viability, surface characteristics, and other properties in *in-vitro* or *in-vivo* studies.
C (comparison)	**C** (comparison), was determined as milling/subtractive manufacturing procedures or conventional procedures. Comparisons of different dental resins printed 3D after the application of the manufacturing process variations, such as post-curing temperatures, duration and intensity.
O (outcome)	**O** (outcome), corresponded to the assessment of all characteristics and properties of the polymer printed dental devices Studies included in the review reported on these outcomes in either *in-vitro* laboratory settings or *in-vivo* biological contexts.

2.2. Eligibility Criteria

The following inclusion criteria were defined and applied to select articles:

❖ Original articles studying the effect of post-processing procedures on the characteristics of the additively manufactured resins

❖ Articles studying the final properties of the additively manufactured resins (mechanical, biological, color…)

❖ Experimental research, *in vitro* studies, randomized controlled trials, clinical studies, clinical trials, nonclinical trials, observational studies, systematic and narrative reviews, and meta-analysis

❖ Published articles after 2000 (the end of research has been limited to February 2023)

❖ English language articles

While review articles, letters to the editor, commentaries, grey literature, expert's opinion, case reports and articles outside the research period were excluded.

2.3. Search Methodology

To conduct this study, literature was searched through PubMed/MEDLINE, Science Direct, Scopus, and Web of Science databases. 10 Anglo-Saxon keywords from recent publications that deal with the topic were used. The medical subject heading (MeSH) terms were: additive manufacturing, vat polymerization additive, 3d printing, three-dimensional printing, prototyping process, rapid prototyping, polymers, printed resin, post processing procedures, post curing. To make an exhaustive search, all the synonyms corresponding to the main categories have been searched. The articles published in the years 2000 to 2023 were targeted.

The influence of post-processing procedures of the polymer vat-polymerized dental devices was studied by two calibrated reviewers (S.B. and EL.M.J). In order to retain only the papers with a high level of evidence, the content of the articles finally selected was then critically read. After a first selection based on the content of the titles and abstracts, a second reading of complete content of the selected articles was carried out, eliminating articles that did not meet the inclusion criteria. Both reviewers were present to discuss and validate the results and disagreements were resolved by consensus and other examiners (M.H.) (A.A) were consulted to ensure the validity of the review's findings. The relevant articles were enlisted. For extraction of pertinent results, we read full texts of the included studies and the findings were recorded.

2.4. Quality Assessment of Included Articles

Critical Skills Appraisal Programme (CASP) was used to analyze the publication selected and to assess the quality of the studies included in our work. CASP assessment tools are based on guides produced by the Evidence-Based Medicine Working Group and published in different studies [12] [13]. All the reviewers used the predefined consideration criteria to analyze every selected article and any ambiguity was settled by discussion and agreement. The final number of publications validated by the reviewers represented a database for the systematic analysis explored in the results and discussion section.

3. Results

3.1. Search Results

Initially, the primary search identified 186 studies based on key terms, from which we selected 29 articles based on the contents of the titles and abstracts. The remaining 29 full-text articles were assessed for eligibility. From these articles selected, we eliminated 7 publications that did not meet our inclusion criteria. The 22 relevant articles were finally included and analyzed in the review The PRISMA flow diagram for the literature search strategy is described in **Figure 1**.

3.2. General Characteristics of Included Studies

The general characteristics of the included studies are summarized in **Table 2**. The 22 references selected were written in English by researchers from different countries and ranged from the year 2000 to 2023. All the studies included were *in vitro* studies, only one study was literature review [14]. The summarized data were extracted from articles concerning the following template: authors' identity, year of publication, type of study, protocol used (the parameter studied, the resin used and the post curing) and the study outcome (**Table 2**).

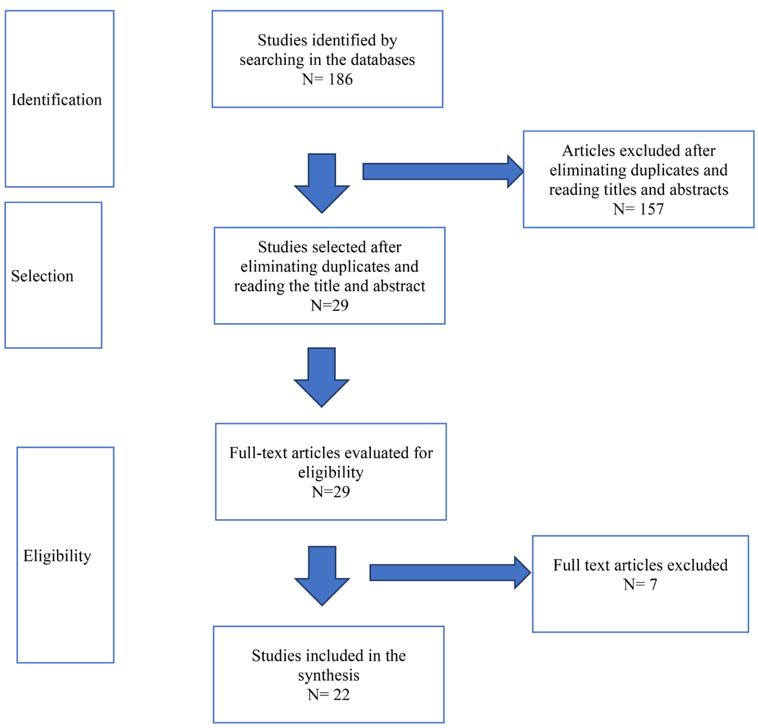

Figure 1. Flow diagram illustrating the study selection process.

Table 2. Description of studies evaluating the influence of post-processing procedures according to PICO criteria.

Author, year and type of study)	Protocol (Parameter studied, Resin used, Post curing used)	Outcome
L. Perea-Lowery *et al.* [10], 2021 *In vitro* study	**Parameters studied:** Flexural strength, elastic modulus, fracture toughness, work of fracture, water sorption, and water solubility **Resin used:** 3D-printing denture base (Imprimo®), heat-polymerizing acrylic resin (Paladon® 65), an auto polymerizing acrylic resin (Palapress®) **Post curing used:** Imprimo Cure® and Form Cure®).	Increased post-curing temperature may enhance the flexural properties of resin monomers used for 3D-printing dental appliances.
Wenceslao Piedra-Cascón *et al.* [14], 2021 Narrative review	**Parameters studied:** The surface roughness, printing accuracy, and mechanical properties **Protocol:** Collection of published articles related to vat-polymerization technologies in Three search engines: Medline/PubMed, EBSCO, and Cochrane.	The post-processing techniques significantly influence the surface roughness, printing accuracy, and mechanical properties of the manufactured dental device.
Yousif A. Al-Dulaijan *et al.* [15], 2021 *In vitro* study	**Parameters studied:** The surface roughness and hardness **resin used:** One conventional heat-polymerized (HP) resin and two 3D-printing resins (Next Dent (ND) and ASIGA (AS) **Post curing used:** Different orientations (0-, 45-, and 90-degree) and each orientation group was subjected to four post-curing times (30, 60, 90, 120 min).	The hardness of AS and ND improved when increasing post-curing time to 120 min. The printing orientations and post-curing time did not affect the surface roughness.
Min-Jung Kang *et al.* [16], 2022 *In vitro* study	**Parameters studied:** The flexural properties, Vickers microhardness, degree of conversion and 3D accuracy **Resin used:** (MAZIC D TEMP, VERICOM, Kangwon, Korea) was used as a material for the crown and bridge, and a DLP-type 3D printer (Asiga Max UV, Asiga, Sydney, Australia) **Post curing used: light intensities:** 1.4 - 1.6, 2.2 - 3.0, 3.8 - 4.4, and 6.4 - 7.0 mW/cm **post-curing time:** 5, 10, and 20 min.	The flexural properties and Vickers microhardness showed a sharp increase at the beginning of the post-curing and then tended to increase gradually as the light intensity and post-curing time increased. No significant difference between groups was found for the accuracy analysis.
Gun Song *et al.* [17], 2021 *In vitro* study	**Parameters studied:** The volumetric change, degree of conversion, and cytotoxicity **Resin used:** Dio C&B **Post curing used:** Under three different times conditions: 5 min, 30 min, and 24 h.	The post-curing duration was found to have an insignificant influence on the degree of conversion and cell viability. A post-curing duration of 5 min is considered to be clinically acceptable and can thus be applied in clinical practice.
Ahmed Altarazi *et al.* [18], 2022 *In vitro* study	**Parameters studied:** The microhardness, the flexural property, Sorption and solubility, the degree of conversion **Resin used:** 3D-printed denture base resin specimens (Next Dent) **Post curing:** Specimens fabricated in 0˚, 45˚, and 90˚ POs, followed by three CTs (20, 30, and 50 min).	No significant difference in any of the tested properties was found when the post-curing times were increased from 20 to 50 min.
Bartłomiej Nowacki *et al.* [19], 2021 *In vitro* study	**Parameters studied:** The tensile and bending strength and surface quality. **Resin used:** Anycubic (Shenzhen, China). **Post curing:** Washing time: 5, 10 or 30 min post-curing: UV rays: 10, 30, 60 min	The post-curing time has been found to strongly affect the tensile and bending strength. Washing significantly affects the quality of the printout surface but it has an ambiguous effect on the strength of the printouts, extended washing slightly reduces the strength. The optimal washing time is no more than 10 min and the post-curing time is at least 30 min.

Continued

Junichiro Wada *et al.* [20], 2022 *in vitro* study	**Parameters studied:** Flexural strength, flexural modulus, Vickers hardness (VHN), fracture toughness, degree of double bond conversion (DC%), water sorption, water solubility, and 3D microlayer structure. **Resin used:** (KeySplint® Soft, Keystone Industries GmbH, Singen, Germany) **Post curing:** Two different atmospheric conditions (air and nitrogen gas (N_2).	The post-curing at an N_2 atmosphere significantly enhanced all of the evaluated properties except water sorption, 3D microlayer structure, and fracture toughness.
Sultan Aati *et al.* [21], 2022 *In vitro* study	**Parameters studied:** Flexural strength/modulus, fracture toughness and surface hardness, degree of conversion, water sorption, solubility, and cell viability. **Resin used:** 3D-printed PMMA-based denture material in comparison to a conventional heat-cured alternative as a control. **Post curing used:** Post-curing for 0, 5, 10 or 20 min at 200 W and light wavelength range of 390-540 nm.	Flexural strength/modulus, fracture toughness and surface hardness, degree of conversion, water sorption, solubility, and cell viability were significantly improved with the increase in light curing time up to 20 min which exhibited comparable performance as the conventional heat-cured control.
Jorge Soto-Montero *et al.* [22], 2022 *In vitro* study	**Parameters studied:** Color change, flexural strength (FS), modulus (FM) and microhardness at different depths. **Resin used:** Cosmos Temp3D (COS), Smart Print BioTemp (SM) Resilab3D Temp (RES) and Prizma 3D BioProv (PRI). **Post curing used:** five different post-curing conditions (no post-curing or 5-, 10-, 15, and 20 min of post-curing).	5 - 10 min of post-curing will result in adequate mechanical properties, without affecting the acceptability in the color of the material.
Leila Perea-Lowery [23], 2021 *In vitro* study	**Parameters studied:** Flexural strength and flexural modulus. surface hardness, fracture toughness, and work of fracture, the degree of conversion. **Resin used:** 96 bar-shaped specimens (Asiga MAX), half of them with a layer thickness of 100 µm (Group A), and half with 50 µm (Group B). **Post curing used:** Post-curing with light emitting diode (LED) and nitrogen gas; post-curing with only LED; and non-post-curing	The post-curing method plays a role in the mechanical properties of the investigated 3D Printed occlusal splints material. The combination of heat and light within the post-curing unit can enhance the mechanical properties and degree of conversion of 3D printed occlusal splints.
Ping Li *et al.* [24], 2021 *In vitro* study	**Parameters studied:** Surface characteristics, flexural strength, and cytotoxicity **Resin used**: A total of 172 specimens were additively manufactured using one denture base material (V-Print dentbase, VOCO) Polymethyl methacrylate resin (Pala Express Ultra) was used as a reference. **Post curing used:** Post-cured by different light-curing devices, including Otoflash G171 (OF), Labolight DUO (LL), PCU LED (PCU), and LC-3DPrintbox (PB), respectively.	The different post-curing methods applied did not significantly influence surface topography and roughness (Ra). Flexural strength was significantly affected by the post polymerization methods Various post polymerization methods reduced the cytotoxic effects of the 3D-printed denture base polymer.
Beom-Il Lee *et al.* [25], 2021 *In vitro* study	**Parameters studied:** The accuracy (trueness and precision) **Resin used**: 30 interim crowns were fabricated using a DLP-type 3D printer. (Next Dent C&B, Next Dent, Soesterberg, Netherlands) **Post curing used:** Three different time conditions-10-minute post-curing interim crown (10-MPCI), 20-minute post-curing interim crown (20-MPCI), and 30-minute post-curing interim crown (30-MPCI) (n = 10 per group).	In the 10-MPCI, 20-MPCI, and 30-MPCI groups, there was a statistically significant difference in the accuracy of the external and intaglio surfaces ($P < 0.05$). On the external and intaglio surfaces, the root mean square (RMS) values of trueness and precision were the lowest in the 10-MPCI group. Interim crowns with 10-minute post-curing showed high accuracy.

Continued

Marcel Reymus *et al.* [26], 2020 *In vitro* study	**Parameters studied:** Fracture load. **Resin used**: 15 specimens for each subgroup Next Dent C&B (CB), Freeprint temp (FT), and 3Delta temp (DT). **Post curing used:** Labolight DUO, Otoflash G171, and LC-3DPrint Box. The positive control group was milled from TelioCAD (TC), the negative control group was fabricated from a conventional interim material Luxatemp (LT).	The highest impact on values was exerted by interactions between 3D print material and post-curing unit ($\eta_P^2 = 0.233$, $p < 0.001$), followed by the 3D print material ($\eta_P^2 = 0.219$, $p < 0.001$) and curing device ($\eta_P^2 = 0.108$, $p < 0.001$). Post-curing has an impact on the mechanical stability of printed FDPs.
Hoyeon Kim *et al.* [27], 2020 *In vitro* study	**Parameters studied:** MECHANICAL PROPERTIES. **Resin used**: A commercial AND SLR METHODS (Clear Resin, XYZ Printing Inc.) was used as a base resin. Clear Resin consists of urethane diacrylates, acrylic monomers, and a photoinitiator. **Post curing used:** The samples were washed with isopropanol several times to remove uncured SLRs. Dual-cured samples were prepared by heating the printed objects in a convection oven for 2 h at 80, 120, or 160 °C to obtain the fully cured 3D-printed samples.	The dual-curing process significantly improved various mechanical properties of the final products, including their impact strength (by more than 300%), tensile strength (by more than 200%), storage modulus (E′), and elongation at break, which thereby reduced the brittleness of the printed object.
Edmara T P Bergam *et al.* [28], 2022 *In vitro* study	**Parameters studied:** Elastic modulus; water sorption, degree of conversion **Resin used**: Conventional PMMA (Alike, GC) - group CGC; conventional PMMA (Dêncor, Clássico) - group CD; bis-acryl (Tempsmart, GC) - group BGC; bis-acryl (Yprov, Yller) - group BY; milled PMMA (TelioCAD, Ivoclar) - group MI; 3D printed bis-acryl - (Cosmos Temp, Yller) group PY. **Post curing used:** Half of the specimens were subjected to 5000 thermal cycles (5˚C to 55˚C).	Thermal cycling significantly affected the mechanical properties of polymeric systems used for temporary dental prostheses.
Danuta Miedzinska *et al.* [29], 2020 *In vitro* study	**Parameters studied:** Strain rate **Resin used:** Resin Durable (formlabs) mixture of methacrylic acid esters, photohigh density polyethylene (HDPE). The resin is composed of a mixture of methacrylic acid esters, initiators, photo-initiators, proprietary proprietary pigment, pigment, and additive and additive packages packagesphotocurable **Post curing used:** For the tests, 5-minute and 30-min, 60 min curing times were also considered	The curing time influenced the strengthening process for each strain rate. For the static and dynamic tests, the difference in the mechanical parameters is significant with the shortest curing time of 5 min. For the times of 30 and 60 min, the change in properties is not as significant.
Mario Monzon *et al.* [30], 2017 *In vitro* study	**Parameters studied:** Anisotropy **Resin used:** Three photopolymers Castable Blend. Monomers: Acrylate/Glycol diacrylate. Photoinitiator: Phosphine oxide based/VisiJet® FTX Green. Monomers: Triethylenglycol diacrylate/Tricyclodecane dimethanol diacrylate. Photoinitiator: Phenyl oxide bis (2,4,6-trimethylbenzoyl) phosphine/Industrial Blend. Acrylate/Glycol diacrylate. Photoinitiator: Phosphine oxide based. **Post curing used:** Chamber UV lamp wavelength, 315 - 400 nm, irradiance 1350 μw/cm^2 (at 15 cm). Different post-curing times to a maximum of 60 min were tested.	post-curing can, in some cases, correct the anisotropy, mainly depending on the nature of the photopolymer.
Gustavo González *et al.* [31], 2020 *In vitro* study	**Parameters studied:** Biocompatibility **Resin used:** Asiga, Australia, commercial Digital Light Processing (DLP) 3D printer **Post curing:** 1) Sonication in ethanol for 5 min followed by sterilization under UV light for 5 min 2) Incubation in ethanol for 2h then followed by sterilization under UV light for 5 min	Both the ethanol and the UV light sterilization methods do not damage the 3D printed wells; furthermore, live and dead assay showed that cells grow in both the samples. Immersion in ethanol results in small defects in the transparency of the 3D printed wells if compared to the UV treated: the best sterilization method was UV-sterilization.

Continued

Jong-Eun Kim *et al.* [32], 2021 *In vitro* study	**Parameters studied:** Color and translucency stability **Resin used:** DT-1 A2 and A3 (HA2 and HA3; Hephzibah, Incheon, Korea), Next Dent C&B MFH N1 and Next Dent C&B A3.5 (NN1 and NA3; Next Dent, Soesterburg, The Netherlands), and DIO-navi C&B A3 (DA3; DIO Inc., Busan, Korea). **Post curing:** UV chamber (Cure M D102H; SONA Global, Seoul, Korea) with a UV intensity of 220 μ W cm^{-2} for 20 min.	The color of 3D printable dental materials changed with time, and the differences varied with the materials used. On the contrary, the changes in translucency were small
Sang-Yub Lee *et al.* [33], 2022 *In vitro* study	**Parameters studied:** The color stability **Post curing used:** Specimens were post-polymerized under different conditions of oxygen inhibition, such as on glycerin immersion (GLY), medium-low vacuum environment (VA), and oxygen contact (CON, the control group), and temperature (35˚C, 60˚C, and 80˚C).	In the post-polymerization process, increasing the temperature and GLY were effective in reducing ΔE, which was lowest at 80˚C in the GLY group.
Dong Wu *et al.* [34], 2019 *In vitro* study	**Parameters studied:** Degree of conversion **Resin used:** a mixture of 99.21 weight% (wt%) PEGDA (poly(ethylene glycol) (200) diacrylate; Sigma Aldrich, Shanghai, P. R. China), 0.69 wt% Irgacure 819 (phenylbis (2,4,6 trimethylbenzoyl) phosphine oxide; Macklin, Shanghai, P. R. China) as a photoinitiator, and 0.10 wt% photoabsorber Sudan I (Adamas-beta, Shanghai, P. R. China). **Post curing:** UV light with a constant intensity along the direction perpendicular to the surface	The post-curing UV intensity can significantly change the degree of conversion in the material.

3.3. General Outcomes of Included Studies

The various properties were studied. Physical and mechanical properties were investigated in 18 studies [10] [14]-[30], impact on biological properties was surveyed in 5 studies [17] [19] [22] [31] [24]. 3 works surveyed the effect on color and translucency stability [22] [32] [33].

The post-processing procedure has been proved to improve the various mechanical properties tested (flexural strength, elastic modulus, fracture toughness…) [10] [14] [16] [18]-[24] [26] [27] [28] [29] [30]. For the hardness, the value of Vickers hardness was improved [15] [16] [17] [19], only the study of Altarazi, A. *et al.* didn't find a significant result [18]. Different results were found for the surface roughness, the effect was confirmed by Wenceslao Piedra-Cascón *et al.* [14] but, it has not been proven efficient among the teams of Ping Li [24]. For the accuracy analysis, the positive effect was confirmed in 2 studies [14] [25], but no significant difference between groups was found in the study of Song, G. *et al.* [17].

For the biological properties, the cell viability was significantly improved with the increase in light curing time up to 20 min [22] and the various post-polymerization methods used reduced the cytotoxic effects of the 3D-printed denture base polymer [24]. Dong Wu *et al.* confirmed the positive impact of the post-curing UV intensity on the degree of conversion [34]. Only the team of Gun Song found that the post-curing duration had an insignificant influence on the degree of conversion and cell viability [17].

Teams also tested the color and translucency stability of 3D-printed polymers.

Jong-Eun Kim *et al.* found that after six months, all specimens demonstrated large color changes, and the translucency differences were not clinically perceivable for any specimen [32]. The team of Jorge Soto-Montero found that the duration of 5 - 10 min of post-curing didn't affect the acceptability in the color of the material [22]. And increasing the temperature was effective in reducing ΔE [33].

According to the studies, post-treatment can be affected by its intensity, temperature, duration and its type: For the post-curingintensity, the post-curing can be made more efficient by optimizing the light intensity [16]-[21]. Increased post-curing temperature may enhance the flexural properties of resin monomers used for 3D-printing dental appliances and were effective in reducing ΔE [10] [28] [34]. For the duration of the post curing, the teams tested different durations and concluded that the increasing post-curing time improves significantly the characteristics of 3D-printed resins. Many durations were proposed by authors: the duration of at least 30 min was recommended [34], 20 min [21] and 10 min [16] [25]. By contrast, 3 studies didn't find statistically insignificant a significant difference in any of the tested properties when the post-curing times were increased from 20 to 50 min [18]. Duration of 5 min is recommended and considered to be clinically acceptable and can thus be applied in clinical practice [17].

Other conditions were also studied such as the temperature, and it was found that increased post-curing temperature may enhance the flexural properties of resin monomers used for 3D-printing dental appliances [10]. In the study of Sang-Yub Lee *et al.*, specimens were post-polymerized under different temperature conditions (35˚C, 60˚C, and 80˚C). The team found that as the temperature increased, the ΔE decreased in the groups, and was lowest at 80˚C. [33]. The same result was found in the study of Edmara T P Bergam [28].

For the type of the post curing, Junichiro Wada *et al* compared two protocols: air and nitrogen gas (N2) and found that post-polymerization in an N2 atmosphere significantly improved the properties [22]. Different post-curing UV methods were applied and compared (Labolight DUO, Otoflash G171) studies found that the protocols applied affected significantly the properties tested with differences [24] [26]. The combination of heat and light within the post-curing unit can enhance the mechanical properties and degree of conversion [23] [27].

3.4. Results of Quality Assessment

As mentioned in **Table 3**, the quality assessment of selected studies based on the 12 criteria of the CASP reading grid was ranging from 9 to 11. A mean score of 11 was attributed to the included studies. All the studies fall in the low bias category, all the articles analyzed had a minimum score of 9/12. By searching for answers to the 12 questions, the bias assessment indicated an overall low to moderate level of bias. The results of this analysis have made it possible to validate the reliability of the evidence presented in our review and support the conclusions we have drawn from our findings.

Table 3. Assessment of study quality using the CASP reading grid.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Score
Perea-Lowery [10]	+	+	+	+	−	+	+	+	+	+	+	+	11
Al-Dulaijan [15]	+	+	+	+	−	−	+	+	+	+	+	+	10
Min-Jung Kang [16]	+	+	+	+	−	+	+	+	+	+	+	+	11
Gun Song [17]	+	+	+	+	−	−	+	+	+	+	+	+	10
Jong-Eun Kim [27]	+	+	+	+	−	+	+	+	+	+	+	+	11
A. Altarazi [18]	+	+	+	+	−	−	+	+	+	−	+	+	9
B. Nowacki [19]	+	+	+	+	−	+	+	+	+	+	+	+	11
Dong Wu [34]	+	+	+	+	−	+	+	+	+	+	+	+	11
G. González [31]	+	+	+	+	−	+	+	+	+	+	+	+	11
Sultan Aati [21]	+	+	+	+	−	+	+	+	+	+	+	+	11
Soto-Montero [22]	+	+	+	+	−	+	+	+	+	+	+	+	11
P. Li [24]	+	+	+	+	−	−	+	+	+	+	+	+	10
Beom-Il Lee [25]	+	+	+	+	−	+	+	+	+	+	+	+	11
M. Reymus [26]	+	+	+	+	−	+	+	+	+	+	+	+	11
E. Bergamo [28]	+	+	+	+	−	+	+	+	+	+	+	+	11
D. Miedzińska [29]	+	+	+	+	−	+	+	+	+	+	+	+	11
M. Monzón [30]	+	+	+	+	−	+	+	+	+	+	+	+	11
Perea-Lowery [23]	+	+	+	+	−	+	+	+	+	+	+	+	11
J. Wada [20]	+	+	+	+	−	+	+	+	+	+	+	+	11
H. Kim [32]	+	+	+	+	−	+	+	+	+	+	−	−	9
Sang-Yub Lee [33]	+	+	+	+	−	+	+	+	+	+	+	+	11

Judgment: +: Yes; −: No.

4. Discussion

3D printing has made a considerable impact on the field of dentistry. It is a powerful and dynamic technology for the production of numerous complex prosthetic devices. Diverse advantages are noted such as the high accuracy, high quality of the printed surface [1]-[9]. The purpose of this systematic review was to investigate the quality and outcome of studies on the effect of post processing procedure on the characteristics of the additively manufactured resins.

Among the studies examined, it was found that not only the selection of suitable materials, but also the development of a suitable post-printing protocol is necessary for the development of biocompatible 3D printed polymers [17] [19] [22] [24]. Furthermore, post processing significantly improved the various mechanical and physical properties tested except for hardness, accuracy analysis and surface roughness, the results were contradictory.

For the hardness, the positive results were also confirmed by 4 studies [15] [16] [17] [19], and only the study of Altarazi *et al.* didn't find a significant result

[18]. The difference in the angle of the print orientation compared with other studies could explain the results found. For the accuracy analysis, the positive effect was confirmed in 2 studies [14] [25]. Beom-Il Lee found a difference but it wasn't significant [17]. The surface roughness, the effect was confirmed by Wenceslao Piedra-Cascón *et al.* [14] but, it has not been proven efficient among 2 studies [15] [24]. A score of 9 was attributed to this study, compared with others that invalidated efficacy. Even, with the small difference in scoring, a comparison of the studies was difficult. The methodology used varied among the studies as to how the impression was conducted. Conflicting findings drive more studies. Teams also tested the color and translucency stability of 3D-printed polymers. The duration and the increasing of the temperature and type of post curing were effective in color stability. Nevertheless, the literature on the effectiveness of the post curing on the color parameter is still limited.

Various parameters explaining the mechanism of action of post treatment have been studied in the selected articles:

Duration impacts the quality of the final product among the studies, only 3 studies didn't find a significant difference. The change in properties was detected but it was not significant, the duration between 5 and 20 minutes is recommended by the majority of the studies selected. The lack of a standardized protocol within the two studies (the use of the same post-curing, same polymer adhesive system, and the same sample size…) precludes a definitive conclusion.

The post-curing is efficient by optimizing the light intensity. Different light intensities (1.4 - 1.6, 2.2 - 3.0, 3.8 - 4.4, and 6.4 - 7.0 mW/cm/at 200 W) were tested in the studies and found that the physico-mechanical and biological parameters tested showed a sharp increase at the beginning of the post-curing and then tended to increase gradually as the light intensity [15] [23]. This finding is consistent with the other studies into temperature.

For the type of the post curing method, different protocols are available: atmospheric post-curing, gas post-polymerization and the protocol combining light and temperature. The results highlighted the efficiency of the post-polymerization in an N2 atmosphere gas by comparing it with the atmospheric post-curing. The effect of the UV chambers with or without gas was confirmed, the differences between machines were found and can be explained by the different wavelengths of the post-polymerization devices [24] [26]. The combination of heat and light is more effective based on the results [23] [27].

Despite the fact that the general outcomes of reviewed studies confirmed the positive impact of the post-processing procedures, some limitations are noticed in the studies selected and can explain the conflicting findings. The results are material-dependent, and some studies tested one type of polymer, while others used multiple polymers. The differences noticed in composition, the additives of photo-initiator, filler, and matrix differ between different types of resin and different manufacturers may affect the results. The evaluation of each specific resin is advised. Differences were found in the method of impression (stereolithography, digital light processing). Others differences in protocols are noticed (types of post curing, and conditions of applications…) for example, various parameters of the UV light may affect the results, such as the irradiation direction, distance, and wavelength, furthermore, the tested specimens differ from real denture configurations and the absence of oral environments and mechanical stresses from the muscular system. A definitive detailed protocol cannot be definitively concluded.

5. Conclusions

At present, the post-processing procedure has been proven to improve the additively manufactured resins. According to the findings of this study, the following can be concluded:

- The post-curing influence significantly the biological and physico-mechanical properties, but the effect on the surface roughness is still ambiguous.
- The parameters studied were significantly improved with the increase of the light intensity and temperature.
- The increasing post-curing time may significantly improve the final properties. The duration between 5 and 20 minutes is recommended by the majority of the studies selected.
- The types of post-curing affect the final properties but the lack of a standardized protocol within the studies (the use of the same post-curing, same polymer adhesive system, and the sample size…) precludes a definitive conclusion.

Based on the results of our study some studies are suggested:

- Further studies investigating various 3D-printed materials and post-curing methods are recommended to define a standardized protocol.
- Other studies on the influence of organic solvents on 3D printed materials.
- Additionally, further investigations in conditions simulating an oral environment (clinical trials with long-term follow-up) are required to evaluate other printing technologies and parameters.

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Data Availability

The data are conserved in the Fixed Prosthesis Department of the Faculty of Dentistry of Casablanca.

Conflicts of Interest

The authors declare no conflicts of interest.

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