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DEVELOPMENT AND OPTIMIZATION OF IN-HOUSE 3D PRINTING PROTOCOLS FOR CLEAR ALIGNERS

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ABSTRACT
In-house three-dimensional (3D) printing has become an increasingly important approach for clear aligner fabrication by integrating digital scanning, virtual treatment planning, appliance design, printing, and post-processing within the orthodontic clinic. This workflow offers greater clinician control, shorter turnaround time, and reduced dependence on external laboratories. This review examines the development and optimization of in-house 3D printing protocols for clear aligners, with emphasis on digital workflows, software platforms, printing technologies, material properties, post-processing procedures, quality control, and emerging innovations. Relevant recent literature was reviewed to evaluate current approaches to in-house aligner fabrication, including stereolithography, digital light processing, liquid crystal display printing, direct aligner printing, thermoplastic and photopolymer materials, and major factors affecting protocol optimization. Successful in-house fabrication depends on accurate digital records, reliable virtual treatment planning, appropriate printer and material selection, controlled aligner thickness, and standardized post-processing. Directly printed aligners can simplify production and reduce material waste, while shape-memory polymers and 4D-printing technologies may further improve efficiency and adaptability. However, variability in equipment, resins, curing conditions, and workflow standardization remains a major limitation. In-house 3D printing represents a promising and increasingly practical strategy for clear aligner production. Future progress will depend on validated materials, reproducible workflows, standardized quality-control protocols, and stronger clinical evidence.

KEYWORDS: Clear aligners; In-house fabrication; 3D printing; Direct-printed aligners; Digital orthodontics

1. INTRODUCTION

Clear aligner therapy has developed significantly as compared to the initial removable orthodontic devices into a digitally powered method of treatment that can achieve progressive and guided movement of teeth. The growing need in aesthetic and comfortable orthodontic options has hastened the emerging trends of transparent removable appliances, especially in the adult population. Digital diagnosis, virtual treatment planning, computer-aided design, and custom appliance fabrication are the components of modern clear aligner therapy to provide staged orthodontic correction. Clear aligners have benefits compared to traditional fixed appliances in terms of aesthetics, oral hygiene, removability and patient comfort, but their clinical efficacy continues to rely on proper patient selection, treatment planning, and patient adherence. The persistent changes in aligner materials, attachment styles, and computer-aided planning further broadened their clinical use to include more than just simple alignment and slight crowding (AlMogbel, 2023).

The birth of in-house aligner systems is a significant shift of externally-produced appliances to orthodontic production controlled by clinicians. The orthodontist is able to handle digital scanning, virtual setup, treatment staging, model preparation, appliance fabrication and even post treatment modification in the clinical environment in an in-house workflow. This solution offers more flexibility since the chain of treatment can be amended when necessary, without relying solely on a third-party aligner service. The in-house fabrication can also minimize turnaround time and enable clinicians to make more or replacement aligners more effectively. This workflow has become more feasible to orthodontic clinics with the growing access to intraoral scanners, orthodontic planning software, low-cost desktop 3D printers, and thermoforming equipment. Notably, clinician participation during the fabrication process may offer increased control over staging, the location of attachments, and the course of the treatment and may also decrease the reliance on laboratories and the overall cost of production (Tozlu and Ozdemir, 2021).

Figure 1 represents an exemplary 3D-printed in-house clear aligner.

Figure 1. 3D-Printed In-House Clear Aligner

The use of three-dimensional printing in orthodontics has become the core of modern digital orthodontics and has changed the production process of clear aligners. Historically, aligner fabrication has been achieved by additive manufacturing of dental models (then thermoforming of plastic sheets over the printed model). More recently, direct 3D printing has made possible the production of aligners without the step of creating a dental-model. This process can streamline the manufacturing process, minimize material loss, and give better control to the geometry and thickness of the appliances. The development of vat-polymerization technologies, specifically stereolithography, digital light processing and liquid crystal display printing have helped in the manufacture of finer and finer orthodontic appliances with greater precision and efficiency. Direct 3D printing is an important field of research alongside the development of photopolymer resins and printing hardware to create customized clear aligner (Narongdej et al., 2024). Recent publications have also highlighted the opportunity to enhance workflow integration and future options in chairside and in-house orthodontic manufacturing (Slaymaker et al., 2024).
Although it has the potential, effective in-house 3D printing involves optimization of various parameters that are closely related. Technology in printing, the thickness of the layer, the thickness of the appliance, the direction of the build, the properties of the resin, the design of supports, the curing environment, the cleaning process and the aspect of dimensional accuracy may all affect the mechanical and clinical characteristics of the finished aligner. Directly printed aligners should offer a suitable stiffness, elasticity, fit, transparency, biocompatibility, and force delivery, and also retain the dimensional stability during clinical use. Systematic evidence suggests that direct-printed aligners is a new option to standard thermoformed appliances, yet differences in manufacturing guidelines and material qualities continue to be significant obstacles to predictable clinical outcomes (Torkomian et al., 2025). To that end, the standardization of protocols is crucial to the realization of a reproducible result using various printers, resins and clinical procedures. Recent developments that combine digital design, materials science, and biomechanical concepts show that optimization needs to consider the entire manufacturing process instead of only the printing step (Ki et al., 2026). Thus, this review studies the creation and streamlining of the in-house 3D printing protocols of clear aligners, especially regarding the digital workflow, printing techniques, materials, post-processing processes, quality management, and upcoming solutions.

2. Digital Workflow for In-House Clear Aligner Fabrication

2.1 Acquisition of Digital Dental Records

The e-business process of manufacturing in-house clear aligners starts with the reception of the correct patient data, such as intraoral scans, photographs, radiographs, and occlusal data. The basis of digital diagnosis, virtual treatment planning, and appliance design is based on these records. The aspect of three-dimensional scanning has gained importance especially since the operation enables accurate depiction of arches in the dentures and reduced reliance on the normal impressions. Digital records are reliable to enhance communication, repeated assessments, and efficient patient data transfer to orthodontic software to proceed with treatment planning and fabrication of the patient (Jedliński et al., 2021).

2.2 Intraoral and Laboratory Scanning

The digital aligner workflow includes intraoral and laboratory scanners as key elements, as they transform clinical dentition or physical models into 3D datasets. Intraoral scanners allow direct acquisition of scans at the chairside, but laboratory scanners can scan traditional impressions or plaster casts as needed. The files thus obtained are then moved into orthodontic design software to prepare virtual models. The in-house integration of these scanning technologies enhances efficient production, decreases the reliance on external labs, and provides clinicians with a higher level of control over the design, fabrication, and altering of the appliances during the therapy (Cousley, 2022).

2.3 Virtual Model Preparation and Scan Orientation

After digital scanning, one needs to clean, orient and prepare the acquired models before starting the treatment simulation. Virtual preparation can often involve elimination of scan artifacts, repairing incomplete surfaces, elimination of unwanted regions, and alteration of the occlusal relationship. The correct alignment of the models with reference planes is especially significant since errors at this phase can affect further planning of tooth movements. The quality of intraoral scans enhances the dependability of the virtual model preparation and offers clinically satisfactory digital models to diagnose orthodontic cases and fabricate orthodontic appliances (Alassiry, 2023).

2.4 Tooth Segmentation and Axis Adjustment

Tooth segmentation is the computerized process of isolating individual teeth against the rest of the gingival and dental structures, to allow individual teeth to be manipulated as part of a virtual treatment plan. Tooth axes are then positioned after being segmented so that they depict proper anatomical orientation and allows a controlled simulation of the planned movements. Correct division and establishment of the axis is very important since the mistakes may affect the estimated final tooth location and sequential aligner design. The accuracy of virtual setup is thus highly reliant on the quality of the digital model preparation and the accuracy of each tooth manipulation (Sereewisai et al., 2023).

2.5 Digital Treatment Planning and Staging

Digital treatment planning transforms the original model of treatment plans into a series of planned orthodontic movements. The clinician identifies the ultimate desired tooth positions and breaks down the total correction into small steps, which can be represented with successive aligners. Staging must take into account space available, magnitude of movement, anchorage, inter proximal reduction, and biomechanical constraints. It depends on the quality of the initial digital data, as the difference that appears during scanning can be transmitted into subsequent planning steps and impact the predictability of appliance fabrication and treatment (Kustrzycka et al., 2020).

2.6 Attachment Planning and Model Numbering

The virtual setup is supplemented with attachment planning to enhance the retention of the aligners and assistance with movements that may prove challenging to accomplish with the use of the aligner surface alone. Their position, form, and alignment are chosen based on the desired biomechanics and their own tooth morphology. The sequential models are then assigned numbers so that they can be identified properly when being printed and when delivered to the clinics. Planning can be further improved with the integration of other three-dimensional information such as CBCT-based anatomy information to give an understanding of the root position and surrounding structure during the design of clear aligners (Horta et al., 2026).

Figure 2. Digital Workflow for In-House Clear Aligner Fabrication

The sequential workflow of the in-house clear aligner fabrication is summarized by figure 2 as starting with the digital record acquisition and 3D scanning followed by a virtual model preparation, tooth segmentation, treatment planning and staging, attachment planning, and finally model numbering and export to fabrication. The second step is to identify the appropriate software platforms and parameters of digital design that determine the aligner geometry, accuracy, and manufacturability.

3. Software Platforms and Digital Design Parameters

3.1 Commercial and Open-Source Software

In-house clear aligner production is based on the use of digital software tools that facilitate model preparation, planning of tooth movements, superimposition, and analysis of changes in treatment. Commercial systems tend to include built-in workflows, but open-source systems can be more flexible, but might demand a higher level of technical knowledge. Digital assessment is especially required to be precise in the determination of changes in tip, torque and rotation in planning and measuring outcomes of treatment. The variability of software packages can affect the reliability of measurements, so appropriate software selection and validation in the in-house workflow is essential (Adel et al., 2022).

3.2 Aligner Shell Design

Aligner shell design translates the intended virtual tooth design into a printable appliance design. The shell is determined by the software that ensures suitable adaptation to the surfaces of the teeth and planned movements and attachments. Variations of virtual set up software can affect the end tooth positions and, therefore, shell geometry. Thus, it is the responsibility of clinicians to be aware of the impact of software-specific algorithms on treatment simulations prior to the creation of aligner shells. The comparative evidence demonstrates that virtual setup systems have the capability to yield variable planning results, which confirms the significance of quality assessment that depends on software in manufacturing clear aligners (Eliliwi et al., 2023).

3.3 Adjustment of Aligner Thickness

One design consideration is the digital control of the aligner thickness since thickness determines rigidity, force delivery, adaptation, and clinical performance. Modern software may allow shell thickness to be adjusted as needed based on treatment demands, although automated design processes should be able to recreate intended geometry. Mistakes that occur in the automated virtual setup may be carried over to the final design of the appliance to the aligner and influence its fit or mechanical characteristics. Assessment of automated models of orthodontic setups has thus been crucial to the evaluation of the reliability of digitally generated treatment setups prior to setting the thickness and shell parameters to be used in fabrication (Woo et al., 2023).

3.4 Margin Design and Retention Considerations

Aligner margins help in retaining appliances, seating, comfort, and force transmission. Clinician can adjust the extension and shape of the aligner margin using digital design software based on the anatomy of the gingivae and planned biomechanics. Since the marginal configuration is created based on the virtual configuration, the differences in the position of teeth attained with software can potentially affect the ultimate appliance adjustment. The comparative evaluation of three-dimensional tooth movement in various software systems has proven that virtual planning results are not necessarily the same, and that it is important to consider the digitally planned boundaries and retention features thoroughly before producing in-house clear aligners (Eid et al., 2025).

3.5 Support Generation and Slicing

Prior to direct 3D printing, the completed design of the aligner has to be sliced and generated into support to be manufactured. The three-dimensional appliance is sliced via software to form sequential layers that can be printed, with support structures that stabilize the object during the fabrication process, affecting quality of surfaces and dimensional accuracy. Segmentation, generation of setups and preparation of designs is also being enhanced through growing automation in orthodontic software. New AI-optimized systems can facilitate these steps, but clinical supervision is still required since the performance of the algorithms and the functionalities that they include vary across commercial systems and need relevant validation prior to implementation as a routine (Preda et al., 2025).

3.6 File Formats Used in In-House Fabrication

The orthodontics models and the aligner designs require digital interoperability to transfer the models between the scanners and the planning software, slicing programs, and 3D printers. STL, OBJ, and PLY are the most common formats, with STL still being very popular in additive manufacturing processes. Stable transfer is significant since the results of treatment rely on maintaining the geometry that was created during virtual planning. Comparisons of commercial planning systems used to plan in-house aligners in the recent past show that the software used can affect the predicted treatment outcomes, indicating that file management and the ability of digital data transfer within the entire fabrication should be compatible (Khadre et al., 2026). The summarized table 1 of the main software functions, digital design parameters and file formats used to prepare in-house clear aligners to be 3D printed are listed.

Table 1. Key Software Functions and Digital Design Parameters in In-House Clear Aligner Fabrication

Component	Main Role	Relevance	Reference
Commercial and open-source software	Digital setup and model editing	Supports treatment planning and customization	Adel et al. (2022)
Aligner shell design	Generates printable aligner geometry	Determines appliance form and adaptation	Eliliwi et al. (2023)
Thickness adjustment	Controls shell thickness	Influences stiffness and force delivery	Woo et al. (2023)
Margin design	Defines aligner borders	Affects retention and seating	Eid et al. (2025)
Support generation and slicing	Prepares design for printing	Improves print stability and manufacturability	Preda et al. (2025)
STL, OBJ, and PLY formats	Transfers 3D model data	Enables interoperability across digital systems	Khadre et al. (2026)

4. 3D Printing Technologies for Clear Aligner Production

4.1 Principles of Vat Photopolymerization

Vat photopolymerization is a popular orthodontics additive manufacturing technology whereby liquid photosensitive material is selectively solidified by regulated light irradiation to form objects in layers. The methodology allows the production of dental models and other components associated with aligners with clinically useful dimensional accuracy. Since the end appliance or model relies on the formation of the layers, resin behavior, and calibration of the printers, protocol choice has a direct impact on trueness and reproducibility. A comparative analysis of printed orthodontic models shows that various 3D-printing protocols have the potential to create quantifiable variations in accuracy (Venezia et al., 2022).

4.2 Stereolithography
Stereolithography employs a focused light source which is usually an ultraviolet laser to cure liquid resin in stages on each layer of the build. It is appreciated to create smooth surfaces, fine detailing and correct dental geometries that can be used in orthodontic works. But the speed of printing, the properties of the resin, the thickness of the layer and the post-processing may affect the final dimensional result. The accuracy of SLA needs to be evaluated based on nominal printer resolution as well as the precision of the printed dental model that would be subsequently used to form aligners (Vlasa et al., 2023).
4.3 Digital Light Processing
The difference between digital light processing and SLA is that light is projected over the whole layer at once instead of each point of the layer being traced. This enables quicker production and may enhance efficiency of production when several orthodontic models co-print. DLP systems would thus be appealing to in-house processes where turnaround time and batch capacity are relevant. However, the accuracy is related to the projector resolution, the size of the building, resin characteristics, and printing conditions. There is systematic evidence that 3D-printing technology has been gaining more and more relevance in orthodontic model production and clear aligner workflows (Tsolakis, Gizani, et al., 2022).
4.4 Liquid Crystal Display Printing
Liquid crystal display printing is a masking process that employs an LCD display as the mask to block out photopolymer resin during layer formation to ultraviolet light. The technique has gained popularity due to the relatively low cost of hardware used and its capability to create detailed dental models effectively. In the case of in-house clear aligner fabrication, its utility is determined by the acceptability of dimensional fidelity of the printed models. Direct comparisons between DLP and LCD technologies show that both technologies can be used to obtain useful accuracy, but variations in trueness and precision can appear based on the printing system and protocol used (Tsolakis, Papaioannou, et al., 2022).
The key vat-photopolymerization technologies applied in the production of clear aligners are summarized in Figure 3.

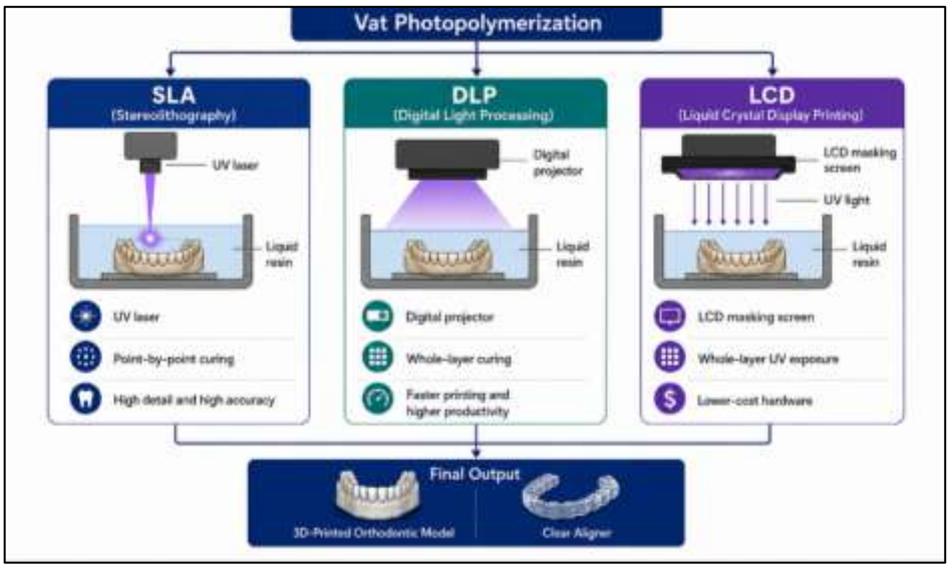

Figure 3. Comparison of SLA, DLP, and LCD 3D Printing Technologies for Clear Aligner Production

The primary differences of SLA, DLP, and LCD are the delivery of light, pattern of curing, speed, and hardware features, shape printing accuracy, productivity, and applicability in aligner fabrication in-house. Such technological variations render the choice of printers and production capacity, a significant factor in developing an effective in-house fabrication protocol.
4.5 Printer Selection and Production Capacity
When choosing the type of printer to use when producing aligners in-house, one should consider accuracy, repeatability, volume of the built, the speed of printing, ability to use a resin, how simple the calibration process is, and how many models can be printed at the same time. Large production capacity can only be beneficial when dimensional quality is constant between the various forms of dental arches and clinical conditions. Crowding and spacing can affect model geometry, and could pose different challenges to printing accuracy. Testing of printed orthodontic models specifically designed to produce clear aligner fabrication has revealed that both trueness and accuracy are important in assessing how clinically appropriate a printer is (Grassia et al., 2023).
4.6 Direct 3D Printing Versus Model-Based Thermoforming
Traditional in-house aligner manufacture typically consists of printing sequential dental models and thermoforming clear sheets over the models, but direct 3D printing does not require a printable model and the aligner itself is formed by printing a printable resin. Direct printing could eliminate fabrication steps, material scrap, and reliance on thermoforming equipment and provide a possible opportunity to control the appliance thickness and geometry better. Nevertheless, material biocompatibility, accuracy of printers, post-curing and clinical validation are critical factors to consider. Recent advances in orthodontic additive manufacturing are gradually making direct printing a significant option in the future compared to production based on models (Kangane et al., 2025).

5. Materials and Mechanical Factors Affecting Protocol Optimization

5.1 Thermoplastic Materials for Clear Aligners

Thermoplastic polymers continue to be popular in conventional clear aligner fabrication due to their ability to offer transparency, elasticity and satisfactory clinical manipulation. Included are polyurethane, polyethylene terephthalate glycol, polypropylene and multilayer polymer systems. Their mechanical performance can alter after thermoforming and intraoral exposure and affect the stiffness, relaxation, and the force delivery. The material choice must then be based on the initial properties as well as the behavior of the polymer to the oral temperature, moisture, and repeated loading during the required wear time (Can et al., 2022).

5.2 Photopolymer Resins for Direct Printing

Photopolymer resins have facilitated direct 3D printing of transparent aligners without the in-between step of making dental models to be thermoformed. These resins should be able to form a combination of printability, transparency, dimensional accuracy, biocompatibility and appropriate mechanical behavior. The shape-memory photocurable materials are especially promising since they can be able to revert to programmed geometries and produce controlled forces following deformation. They are highly dependent on temperature and material formulation to determine their thermo-mechanical properties, and selecting a resin and processing conditions carefully is crucial when establishing reliable protocols to directly print orthodontic appliances (Lee et al., 2022).

5.3 Aligner Thickness

A design variable that is critical is the aligner thickness since it influences the stiffness, flexibility, force magnitude, adaptation, and deformation resistance. Direct 3D printing can enable more control over the thickness distribution than thermoforming, where the stretching of material can form nonuniform regions. Comparison analysis has proved that there are significant variations in the mechanical properties of directly printed and thermoformed appliances, which means that the thickness should be taken into account along with the means of fabrication. Thickness can induce stiffness, and lack of enough thickness can result in reduced force delivery and structural stability in clinical practice (Shirey et al., 2023).

5.4 Elasticity and Resilience

Elasticity allows an aligner to flex in order to be inserted and then to flex back to the shape it is supposed to be in to produce orthodontic forces. The property of the material to take in and give out energy without deforming forever is called resilience. Both attributes are essential to ensuring good movement of teeth through repeated cycles of insertion and removal. More recent trends in aligner materials have been centered on enhancing elastic recovery, stress relaxation resistance, durability, and intraoral stability without compromising on transparency and comfort, especially in multifunctional material systems and polymers (Bichu et al., 2023).

5.5 Flexural Strength and Modulus

The flexural strength and elastic modulus are the factors that define the effectiveness of an aligner to resist bending and stay in the desired geometry when subjected to clinical loads. Increased modulus tends to create a more rigid appliance, and too much rigidity could lead to difficulty in inserting, removing, or fitting the appliance to tooth surfaces. Thickness and gap width are also dimensions that are important due to their influence on seating and mechanical interaction with the dentition. Comparison of micro-computed tomography has shown that there are differences in the thickness and internal adaptation between thermoformed and 3D-printed aligners, which are highly dependent on manufacturing-related material behavior (Park et al., 2023).

Figure 4 summarizes the major material specifications needed in clear aligner production, such as mechanical, optical, dimensional, biological and stability-related characteristics.

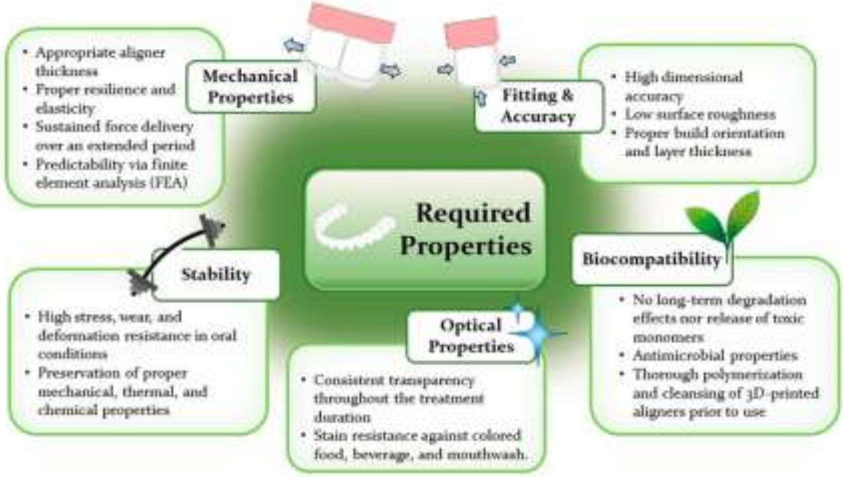

Figure 4. Required Material Properties for Clear Aligner Fabrication

All these material properties are interdependent and dictate how well an aligner can retain a sufficient fit, be transparent, mechanically stable, biocompatible, and controlled orthodontic force during clinical practice. Among these properties, force delivery and dimensional stability are involved especially in the support of the programmed orthodontic movement in the treatment.

5.6 Force Delivery and Dimensional Stability

The key to effective aligner therapy lies in ensuring that clinically acceptable forces are used and that the geometry of the programmed appliances is retained in the course of the treatment. The composition of the material, thickness, technology of the printers, the geometry of appliances, curing conditions, and deformation properties of the material influence force delivery. Aligners can be directly printed to enable control of these variables more easily, but different combinations can give significantly different mechanical responses. Recent experimental data indicate the interaction of printer type, resin formulation, thickness and aligner geometry to define mechanical performance, emphasizing that optimization of protocol-specific protocols must be used instead of focusing on a single manufacturing parameter (Oğuz et al., 2026).

The most important material and mechanical aspects influencing optimization of in-house clear aligner fabrication are summarized in Table 2.

Table 2. Material and Mechanical Factors Influencing Clear Aligner Optimization

Factor	Main Effect	Optimization Focus	Reference
Thermoplastic materials	Flexibility and force retention	Intraoral stability	Can et al. (2022)
Photopolymer resins	Printability and shape recovery	Resin selection and processing	Lee et al. (2022)
Aligner thickness	Stiffness and force magnitude	Uniform thickness	Shirey et al. (2023)
Elasticity and resilience	Deformation and recovery	Balanced flexibility	Bichu et al. (2023)
Flexural strength and modulus	Rigidity and bending resistance	Mechanical stability	Park et al. (2023)
Force delivery and stability	Maintains programmed movement	Optimize resin, geometry, and printer	Oğuz et al. (2026)

5.7 Biocompatibility of Printing Materials

Biocompatibility is vital since clear aligners are in long-term contact with teeth, saliva, gingival tissues and oral mucosa. The material of direct-printing must then have low release of residual components which may be detrimental and must be stable (chemical and mechanical) to intraoral use. The proper polymerization, post-curing, cleaning and removal of the uncured resin are part of the accomplishment of a clinically acceptable appliance. This means that there must be an optimization of any material used in terms of mechanical performance and biological safety because any increase in stiffness or shape recovery should not be done at the expense of the printed material being suitable to be used in the long term intraoral.

6. Post-Processing and Quality Control Protocols

6.1 Removal of Residual Resin

Elimination of residual uncured resin is a critical step in post-processing since partial cleaning may impact on surface quality, mechanical performance, dimensional accuracy, and biological safety. New aligners can have unpolymerized resin in surface irregularities or support-contact sites and hence effective removal is necessary prior to final curing. The cleaning procedures must reduce the amount of remaining material to the lowest level without distorting the appliance or changing its geometry. As experimental data reveal, the removal of uncured resin of directly printed dental aligners can be greatly affected by temperature and the conditions of processing (Kim et al., 2024).

6.2 Centrifugation

Centrifugation is an effective way of eliminating excess resin when using directly printed aligners and eliminating the harsh exposure of solvents that could compromise material performance. The centrifugal force forces off uncured resin between internal and external surfaces, especially on narrow anatomical areas where it could be challenging to use fingers to clean. Centrifugation time and temperature should be optimized since too little processing will leave behind residual resin, but too much treatment will unnecessarily extend the production process. The integration of standardized centrifugation procedures can thus enhance consistency and more secure, clean and reproducible in-house aligner fabrication.

6.3 Support Removal and Trimming

Following printing, support structures should be thoroughly removed to get the final appliance geometry. Inappropriate removal can form a surface defect, sharp edges, local deformation or dimensional errors that can affect aligner fit and patient comfort. The trimming should thus be done using controlled tools and with such instruments which should not destroy the pre-planned margins and structural integrity of such appliance. These supports ought to be ideally taken into account in the digital designing phase so that the post-processing phase will be made easy and the requirements of finishing are reduced as much as possible without compromising on the stability during printing.

6.4 Ultraviolet Post-Curing

Polymerization and stabilization of mechanical and biological qualities of directly printed aligners require ultraviolet post-curing to be completed. The curing period, light intensity, and environmental factors may affect the residual monomer content, stiffness, surface properties, and cytotoxicity. Poor curing can result in the presence of biologically reactive elements, and overcuring can modify performance of the material. As shown in experiments, the time of post-printing curing directly impacts cytotoxicity, and curing regimens have to be individually optimized with each resin system involved in the manufacture of clinical aligners (Iodice et al., 2024).

6.5 Ultrasonic Cleaning and Drying

Ultrasonic cleaning may be helpful in cleaning up small debris, residual resin and contaminants left following support removal and curing. This method involves acoustic agitation by cleaning intricate surfaces without a lot of mechanical interaction which preserves aligner geometry. Drying is also essential since any remaining moisture may disrupt the inspection of the surface, finishing, and further clinical application. The time spent on cleaning, bath temperature and drying must be standardized in the in-house workflow such that appliances are subject to repeat processing without introducing deformation, contamination or undue variability between production batches.

6.6 Finishing and Polishing

Surface smoothness, comfort and clinical acceptability are enhanced by finishing and polishing during printing and support removal. Unsmooth surfaces or edges can be irritating to the oral tissues and can also affect the retention of plaque and the hygiene of appliances. Imperfection elimination ought to happen via surface modification, however, without any considerable change in aligner thickness or programmed geometry. It has been demonstrated that biological analysis of directly printed aligners indicates that the material thickness and processing conditions could affect the clinical safety profile of the appliance; therefore, it is essential to complete finishing procedures without affecting the biocompatibility of the appliance (Bleilöb et al., 2025).

The entire post-processing procedure to prepare directly printed clear aligners prior to ultimate quality-control evaluation is summarized in Figure 5.

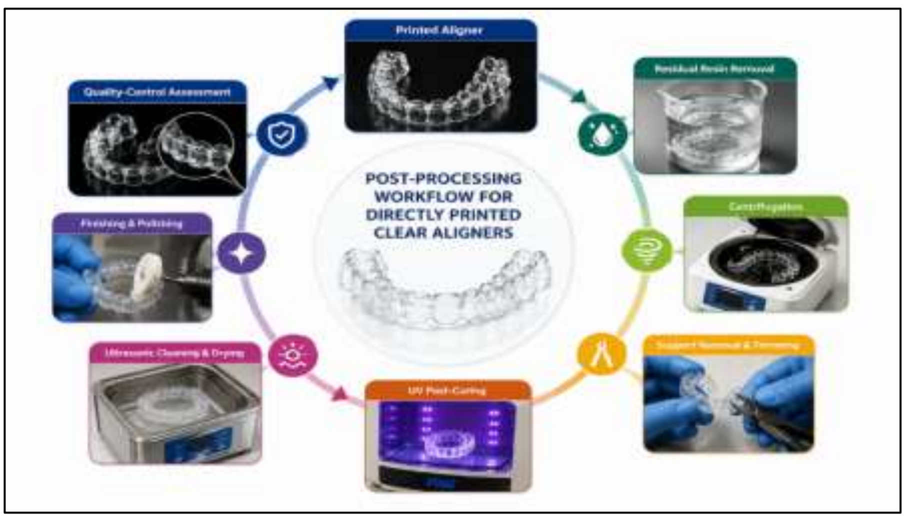

Figure 5. Post-Processing Workflow for Directly Printed Clear Aligners

All of the post-processing steps determine the quality of the surface, dimensional stability, mechanical behavior, and biological safety of the final aligner and thus standardized handling is critical prior to clinical delivery. After post-processing, a systematic evaluation of fit, dimensional precision, thickness, and quality of the surface of the completed aligner needs to be evaluated before it can be used in the clinic.

6.7 Assessment of Aligner Fit and Dimensional Accuracy

The quality control must involve the quality inspection of aligner adaption, dimensional accuracy, thickness, and surface quality prior to clinical delivery. Poor fit may cause changes in the transmission of forces and decrease the predictability of the treatment, but dimensional deviations might indicate some printing or post-curing mistakes. Mechanical, surface, and dimensional property can be affected by the type of printer used and the environment used to cure it, and therefore post-production evaluation is necessary to achieve a consistent result. Comparative evidence suggests that post-curing with nitrogen and choice of printers may have significant impacts on the final aligner properties and thus must be put into consideration during the development of the validation procedures (Kim et al., 2026).

6.8 Standardization and Reproducibility of the Workflow

To make sure that directly printed aligners have the same mechanical behavior, are biologically safe, and of clinical quality across production batches, a standardized workflow is required. Printer settings, handling of resin, cleaning, centrifugation, curing time, trimming, polishing, inspection and storage should be clearly defined in protocols. It has been established that biological testing that post-curing duration may affect the cytotoxicity of directly printed aligner materials, and it is worth noting that reproducible processing conditions are essential (Peanchitlertkajorn et al., 2026). Moreover, printed aligners could elute products that produce changes in gingivitis fibroblasts, which supports the importance of stringent validation of materials and workflow (Kim et al., 2025).

7. Optimization, Advantages, and Current Challenges of In-House Production

7.1 Reduction of Fabrication Time

Production of aligners in house can significantly reduce the fabrication pathway by incorporating scanning, virtual setup, model preparation, printing and delivery of the appliances into the clinical setting. By removing outside laboratory contact and transportation, it is possible to minimize the delays and provide fast replacement or refinement aligner production. The efficiency in the workflow is also enhanced when printing, thermoforming, trimming and finishing are done by trained personnel under the supervision of clinicians. The general time savings is based on organized digital planning and sound equipment, standard operations, and relevant delegation of laboratory processes in the orthodontic practice (Shah et al., 2022).

7.2 Cost Efficiency

One of the key possible benefits of in-house aligner fabrication is cost efficiency since clinicians will not have to pay the same commercial laboratory charges several times, and create appliances based on the real needs of the treatment. The first costs will be on the scanners, printers, software, materials, and post-processing equipment, but the expenses can be spread over a growing number of cases. Economic gain thus hinges on the frequency of use, efficiency in production, employee time, consumption of materials and equipment maintenance. Through economic analysis using thresholds, it has been shown that in-house aligners may turn out to be economically viable when the volume of treatment is enough to cover the initial investment (Kumra et al., 2026).

7.3 Greater Clinician Control

One of the biggest advantages of in-house production is that it offers a greater level of control to the orthodontist treating patient during the entire digital and manufacturing process. The clinician is able to directly establish tooth staging, attachment design, sequencing of movements, aligner thickness and make amendments to treatments without having to extensively depend on outside technicians. Such a tight collaboration of treatment planning and appliance production can enhance communication and minimize delays of duplicated external revisions. Smooth digital processes are thus high on converting clinical goals into tailored aligner designs and feasible chairside production plans more directly (Thakkar et al., 2023).

7.4 Flexibility for Treatment Modification

Home systems offer a lot of flexibility in case the treatment is not going on the way it was initially simulated in the virtual environment. Patients can be rescaned, revised digital models can be created and more aligners can be produced without re-initiating an externally managed production cycle. This adaptability is especially handy when refinement or making minor adjustments are required, or when there are unforeseen clinical developments. However, the change of treatment must be biomechanically justifiable since the presence of appliances cannot overcome challenging orthodontic movements without the aid of biomechanical reasons. Clinical experience indicates that in-house clear aligners are capable of producing useful treatment results even in relatively complex cases that are selected (Jaber et al., 2022).

7.5 Operator and Staff Requirements

Effective production of aligners in-house needs a trained clinical and technical staff. Orthodontists are required to learn about digital treatment planning, stage of tooth movement, choice of attachments, behavior of materials, and manufacturing constraints whereas trained personnel could perform the tasks of scanning, printing, thermoforming, removal of support, trimming, polishing, and organization of appliances. Poor training on any level may add flaws that influence fit or the development of treatment. It is thus imperative to establish well defined responsibilities, standard operating procedures, regular calibration and proper quality checks so as to ensure that an efficient workflow is maintained without necessarily straining clinician workload.

7.6 Equipment and Software Limitations

The production process in-house relies on various technologies that are interrelated, such as intraoral scanners, CAD programs, slicing programs, 3D printers, curing units, and finishing equipment. Systems incompatibility can disrupt the working process or loss of digital information during file transfer. The capabilities of software are also varied in terms of segmentation, staging, attachment design, thickness control and automated planning. The hardware needs to be calibrated, serviced, and replaced periodically, and the software can entail subscription fees or a license. The following are practical constraints which need to be taken into account when launching a fully integrated in-house aligner manufacturing service.

7.7 Material and Accuracy-Related Challenges

The properties of materials and precision in manufacturing are still crucial issues in direct printed aligner manufacturing. The appliance thickness, printing resolution, post-curing, resin behavior, and surface adaptation can be deviated that affects the force delivery and predictability of the treatment. The clinically obtained movement of the teeth might not be similar to the programmed position even in case the virtual setup is precise due to biological and biomechanical factors. The preliminary evaluation of 3D-printed aligners has shown the variability of the precision of various orthodontic movements, highlighting the necessity to further optimize design and production parameters (Migliorati et al., 2024).

7.8 Need for Standardized Clinical Protocols

In-house aligners require standardized clinical protocols in order to obtain reproducible results. The patient selection, scan acquisition, virtual staging, the plan of attachment, the printing parameter, the choice of material, post-processing, the delivery of the appliances, the wear schedule of the appliances, the progress assessment, and the refinement criteria should be defined in protocols. In the absence of such standardization, differences between operators and production systems can decrease the consistency of treatment. Recent appraisal of in-house aligners in minor orthodontic care has highlighted their clinical effectiveness and workflow efficiency, and it can be utilized to build evidence-based guidelines that strike a balance between customization and standardization and quality assurance (Kessler et al., 2026).

Table 3 summarizes the main benefits, existing issues, and the optimization priorities that are related to in-house production of clear aligners.

Table 3. Advantages, Challenges, and Optimization Priorities in In-House Clear Aligner Production

Aspect	Advantage / Challenge	Optimization Priority	Reference
Fabrication time	Faster production and refinements	Streamline digital and laboratory workflow	Shah et al. (2022)
Cost efficiency	Potential lower long-term cost	Balance equipment investment with case volume	Kumra et al. (2026)
Clinician control	Greater control over staging and design	Maintain direct clinical oversight	Thakkar et al. (2023)
Treatment modification	Easier rescanning and refinement	Apply biomechanically appropriate revisions	Jaber et al. (2022)
Material and accuracy	Variability in fit and movement precision	Optimize printing and post-processing parameters	Migliorati et al. (2024)
Standardization	Workflow variability may affect reproducibility	Develop evidence-based clinical protocols	Kessler et al. (2026)

8. Emerging Technologies and Future Directions

8.1 Directly Printed Clear Aligners

Direct 3D printing is becoming one of the significant innovations in the production of clear aligners since the technique eliminates the requirement to create intermediate dental models to be thermoformed. The result of this streamlined process is the ability to cut down on the number of production steps, minimize the turnaround time and enhance control of the geometry and material distribution of appliances. The latest advancements in printable orthodontic resins have transformed direct fabrication into being more possible in clinical environments. Nevertheless, additional evidence is needed to achieve a uniform performance, especially in mechanical behavior, dimensional stability over time, clinical efficacy, and uniform manufacturing requirements (Alkhamees, 2024).

Figure 6 shows the variations in the thickness uniformity and adaptation of directly printed and thermoformed aligners.

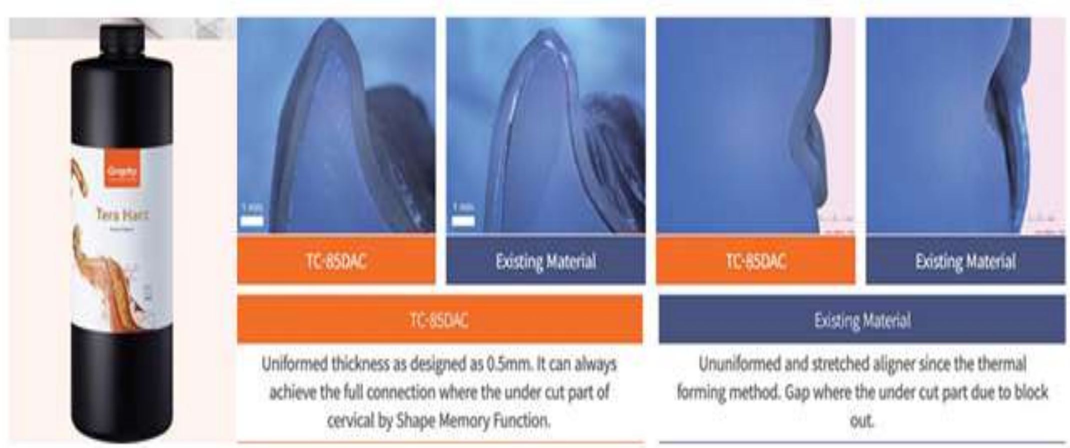

Figure 6. Thickness and Adaptation Comparison Between Directly Printed and Thermoformed Clear Aligners

Direct printing can offer a less non-uniform thickness and better adaptation in undercut areas than thermoforming, though again these benefits are also relative to the properties of the material used and to manufacturing conditions. In addition to advancements in direct-print geometry, shape-memory polymers are another potential enhancement to improve the adaptability of the aligner and controlled delivery of forces.

8.2 Shape-Memory Polymer Aligners

Shape-memory polymers are also promising material in next-generation aligner due to the ability to maintain a desired geometry following controlled deformation or thermal stimulating. This feature can enable an appliance to provide gradual orthodontic forces and have a superior adaptation during treatment. Their capability to experience significant elastic deformation without irreversible loss of shape might also save on the use of sequential appliances. Preliminary typodont studies showed promising shape-recovery performance, indicating that shape-memory materials could offer a platform to more adaptive and efficient clear aligner systems (Elshazly et al., 2021).

8.3 4D-Printed Aligner Materials

Four-dimensional printing is a further development of 3D printing in which the materials are made to be responsive to external stimuli by changing shape or behavior. In orthodontics, 4D aligner materials have the potential to enable an individual appliance to experience controlled shape change through the treatment process, and thus, create a series of tooth movement without needing to replace the aligners relatively often. The clinical development of shape-memory polymer-based 4D materials is thus based on the mechanical and physicochemical properties of the materials. Recent characterization research shows their potential with the necessity to optimize them further before they could be used widely in orthodontics (Atta et al., 2024).

8.4 Biocompatible Resins for Direct Aligner Printing

The future of directly printed aligners lies heavily in the creation of resins that are mechanically reliable and biocompatible in the long term in the intraoral environment. These substances have to offer the right degree of hardness, elasticity, transparency, dimensional stability, and controlled delivery of force and reduced the discharge of potentially harmful residual elements. The development of functional resin is progressively becoming a combination of material science and biomechanical and biological factors. The existing data show that it will take a thorough assessment of cytotoxicity, degradation performance, post-curing, and real-life performance before new resin systems can be deemed regularly appropriate (Zhang and Wu, 2026).

8.5 Sustainable and Low-Waste Manufacturing Approaches

The issue of sustainability is emerging due to the growing number of uses of clear aligners, and the resulting amount of polymer waste in terms of discarded appliances, thermoforming sheets, printed models, and packaging. Direct printing can minimize the number of waste products, such as reduction of unused thermoforming material and middle models, yet the environmental impact relies on the resin structure, its ability to recycle, and its disposal. There are still concerns about the long-term storage of aligner-produced plastics, which speaks of the necessity of recyclable materials and eco-friendly manufacturing routes (Camcı & Büyükbayraktar, 2025). The value of the study of the environmental behavior of aligner materials is also highlighted in the experimental disposal studies (Peter et al., 2025).

8.6 Future Need for Standardized Printing Protocols

The in-house direct printing practice will need to be standardized and the protocols need to define the settings of the printer, resin handling, the parameters of layers, location of support, post-curing, cleaning, dimensional control and bio-safety considerations in future clinical applications of the in-house direct printing. Currently, few systems can be compared directly due to differences in equipment, materials, and processing conditions and can lead to inconsistent clinical outcomes. Multicenter clinical trials, validated testing protocols, and manufacturing guidelines that are supported by consensus should then be encouraged to achieve standardization. It will be necessary to establish reproducible protocols to translate the new printing technologies into reliable, safe, and clinically predictable orthodontic workflows.

9. CONCLUSION

In-house 3D printing has become a significant revolution in clear aligner production, combining digital scanning, digital treatment planning, computer-aided design of appliances, additive manufacturing, and post-processing into a clinician-controlled workflow. The significant benefits of it are that it allows greater versatility in treatments, less reliance on third-party labs, shorter manufacturing time, and possibly better cost efficiency. Nevertheless, the effective application requires a thorough optimization of numerous interrelated variables, such as the type of the printers, the choice of resin, the aligner thickness, mechanical properties, dimensional precision, support design, cleaning, curing, and finishing processes. Directly printed aligners provide additional possibilities to streamline fabrication through the removal of intermediate dental models and thermoforming, yet to ensure stable clinical outcomes, validated materials and standard production guidelines are needed. New technology like shape-memory polymers, 4D-printed aligners, and new biocompatible resins can enhance further the force delivery, adaptability, and manufacturing efficiency. Meanwhile, sustainability and polymer waste minimization is becoming an important factor to be considered in future aligner development. Altogether, the further developments of in-house aligner manufacturing must be oriented towards reproducibility, biological safety, mechanical reliability and clinical predictability. Standardization of evidence-based printing and post-processing procedures will be necessary in providing assurance that the technologies could be safely and effectively integrated into orthodontic practice.

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