Journal of Taibah University Medical Sciences (2024) 19(4), 816–822

Taibah University

Journal of Taibah University Medical Sciences

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Review Article

Applications of 3D-printed teeth in dental education: A narrative review

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Received 2 April 2024; revised 9 June 2024; accepted 24 July 2024; Available online 1 August 2024

الملخص

أهداف البحث: يحث عصر التعليم المعاصر على الحاجة إلى الابتكارات التي تسهل التعلم الشامل والشامل للطلاب. تقدم الطباعة ثلاثية الأبعاد أو التصنيع الإضافي على شكل أسنان مطبوعة ثلاثية الأبعاد بديلا لا يقاوم للأسنان المقلوعة ونماذج الأسنان القياسية، حيث توفر المساواة التعليمية والمحاكاة الواقعية للأسنان الطبيعية، وبذلك تصبح جزءا أساسيا من نظام تعليم طب الأسنان. تم توثيق تطبيقات الطباعة ثلاثية الأبعاد في مجموعة واسعة من المجالات. تهدف هذه المقالة المراجعة إلى تلخيص الابحاث التي أثبتت دور وفعالية الأسنان المطبوعة ثلاثية الأبعاد في تعليم طب الأسنان.

طريقة البحث: تتبع مقالة المراجعة هذه إرشادات مقياس تقييم مقالات المراجعة السردية. تم استخدام قاعدتي بيانات بحثية إلكترونية، بيميد وغوغل العلمي، للبحث عن الدراسات ذات الصلة. تم تضمين الدراسات التي تناقش تطبيقات الأسنان المطبوعة ثلاثية الأبعاد في تعليم طب الأسنان.

النتائج: تم التحقق من صحة الدور الإيجابي والقيم للغاية للأسنان المطبوعة ثلاثية الأبعاد في تعليم طب الأسنان بسبب طبيعتها الممكنة. كما تم إثبات التحسن في ثقة طلاب طب الأسنان والمهارات السريرية وخبرات التعلم.

الاستنتاجات: يمكن أن تكون الأسنان المطبوعة ثلاثية الأبعاد بمثابة بديل مناسب وسهل الوصول إليه لنماذج طب الأسنان المستخرجة والقياسية لتعليم طب الأسنان.

الكلمات المفتاحية: أسنان مطبوعة ثلاثية الأبعاد؛ طلاب طب الأسنان؛ تعليم طب الأسنان؛ الطباعة ثلاثية الأبعاد؛ تخصصات طب الأسنان

Abstract

Background: The contemporary era of education prompts the need for innovation that facilitates the comprehensible and immersive learning of students. Three-dimensional (3D) printing or additive manufacturing in the form of 3D-printed teeth provides an attractive alternative to extracted teeth and standard dental models, as they provide educational equality and realistic simulation of natural teeth.

Aim: This review article summarises the literature that has proven the role and effectiveness of 3D-printed teeth in dental education.

Method: This review article follows the Scale for the Assessment of Narrative Review Articles (SANRA) guidelines. Two electronic research databases, PubMed and Google Scholar, were used to search for relevant studies. Studies discussing the applications of 3D-printed teeth in dental education were included.

Results: The positive and highly valuable role of 3D-printed teeth in dental education has been validated because of their feasible nature. Improvements in dental students' confidence, clinical skills, and learning experiences have also been proven.

Conclusion: 3D-printed teeth can serve as a convenient and accessible alternative to extracted and standard dental models for dental education.

Keywords: 3D printing; 3D-printed teeth; Additive manufacturing; Dental education; Dental specialities; Dental students

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Peer review under responsibility of Taibah University.

ELSEVIER Production and hosting by Elsevier

 https://doi.org/10.1016/j.jtumed.2024.07.005

Introduction

Three dimensional (3D) printing, also known as additive manufacturing, is a creative blend of art and technology, invented by Charles Hull.[1] Stereolithography, also called rapid prototyping and manufacture or simply "3D printing" is a method by which 3D models can be produced through layering and curing of photosensitive resins in increments.[2] This technology has brought innovation because it allows better reproduction of ideas and results in its applicability across a range of disciplines.[3,4] In the recent era of technology and revolution, many countries have recognised its importance and are endlessly receiving benefits from this captivating technology.[5]

Numerous studies have reported that 3D printing is a source of improved engagement, active participation, and a tool for better understanding and learning. Evidence from the literature suggests that 3D printing has been used effectively in dentistry and anthropology[6] and in the manufacturing of medical models[7] such as acrylic models, which are used to facilitate preoperative treatment planning and intraoperative management of surgical correction of craniofacial clefts.[1] 3D printing also enables the manufacturing of aligners,[7] customised removable retainers, and occlusal splints.[8]

Several studies have also explored its application in the domain of education[4] such as teaching mechanical engineering,[9] physical and urban geography education,[10] creation of 3D-printed Bohr's atomic model, hybridisation and bond polarity model for chemistry education,[11] and studying lunar and planetary topography in geosciences education.[12]

In healthcare, the development of 3D-printing technology has helped customise models.[13] These models help in patient-specific interventions and greatly speed up the procedure by helping in patients' efficient preoperative treatment planning, less radiation exposure, and reduced surgical time.[14] Additionally, the printing of surgical instruments, custom-made and affordable prostheses such as limbs and implants is also made possible because of the 3D-printing technique.[13]

The field of dentistry has benefited greatly from this technology, which has led to the growth of clinical, experimental, and educational domains of dentistry (Figure 1).[15] Clinically, it evolves by producing customised dentures, maxillofacial prostheses, crowns, bridges, 3D-printed teeth, orthodontic appliances, and implants by utilising 3D printing. In addition to clinical success, 3D printing is also being employed to create 3D-printed teeth for educational purposes. Studies have confirmed that use of 3D-printed teeth improves learners' engagement and clinical skills.

This narrative review aims to consolidate all scientific evidence related to the educational applications of 3D-printed teeth in different specialties of dentistry.

Materials and Methods

This review was formulated according to the Scale for the Assessment of Narrative Review Articles (SANRA) guidelines.[16] Electronic databases, including PubMed and Google Scholar, were searched without any search limits using the keywords "3D-printed teeth" AND "dental students" AND "dental education" in April 2023. The studies were scrutinised based on whether they investigated the applications of 3D-printed teeth in different specialities of dentistry for dental education purposes. Articles in languages other than English, letters to the editor, systematic reviews, research reports, commentaries, and studies that did not evaluate the applications and effectiveness of 3D-printed teeth in dental education were excluded.

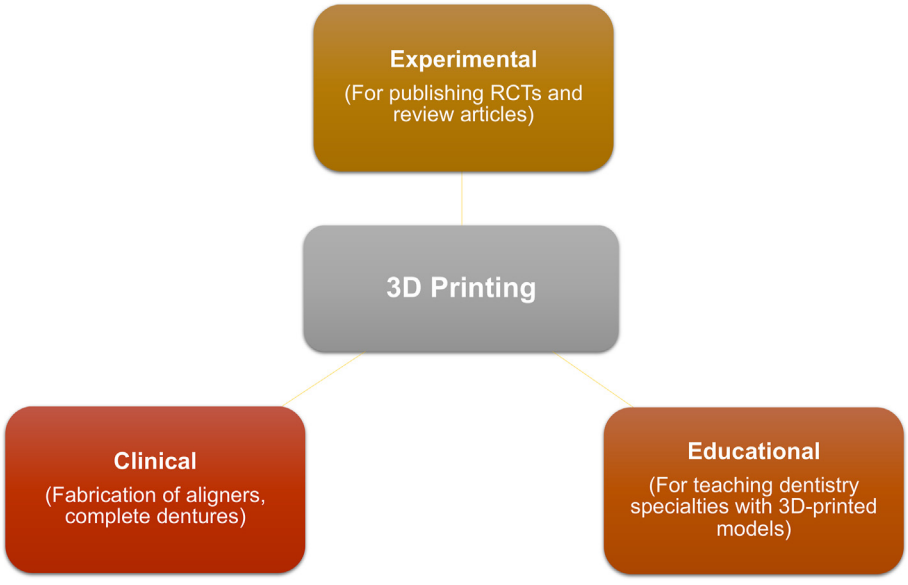

Figure 1: 3D-printing applications in different domains of dentistry.[15]

Applications of 3D-printed teeth in dentistry

There is a need for contemporary teaching methods and techniques, compared to traditional teaching methodologies, for better learning outcomes. Hence, in this situation, 3D-printed teeth can serve as preferable tools. Figure 2 briefly illustrates the use of 3D printing in dentistry and also shows 3D-printed teeth as a valuable aid in the clinical and educational aspects of dentistry.[15] Earlier studies related to its application have also determined that 3D-printed teeth greatly enhance the learning capabilities of students as they enable them to make use of their tactile sense and knowledge coherently. Studies have found that anatomically designed 3D-printed teeth can be used effectively to teach dental morphology and conservative dentistry.[17,18] 3D-printed dental models have also been used for dental trauma simulation training.[19]

Dental morphology

Wang et al. conducted a study to evaluate the application of 3D-printed tooth models in teaching dental morphology.[17] One of the two groups received a set of 3D-printed models for learning, and the student's experiences were evaluated using a questionnaire. The study revealed no marked differences in examination scores. However, a major difference was observed in the scores of the gypsum carving exercise, indicating that these dental models were helpful for students in improving their carving abilities. The majority of students favoured the use of 3D-printed tooth models for studying tooth morphology. Mahrous et al. evaluated the use of different methods for teaching dental anatomy to first-year dental students.[2] The teaching methods included the use of extracted tooth, a 3D-printed tooth, 3D virtual models demonstrated on a computer monitor, and an augmented reality (AR) application. Each of the four stations was examined by the participants randomly and their responses were recorded using an electronic survey, which concluded that the students acknowledged the extracted teeth as most beneficial for learning purposes while the 3D-printed teeth were appreciated for their handling characteristics and the AR modality was rated as the most interesting teaching aid.

Prosthodontics

Hohne et al. assessed the benefits of a 3D-printed tooth model alongside the standard artificial teeth and the real teeth for crown preparation.[20] Fourth-year dental students prepared crowns on four similar printed and standard teeth. A questionnaire was used to assess the benefits of 3D-printed teeth. Most students found 3D-printed teeth beneficial for improving their skills and felt confident by practising on these teeth.

Petre et al. assessed the teaching of different partial edentulous case scenarios using digital and 3D-printed dental models.[21] Various fixed prosthetic procedures on these dental models were performed by the students for the entire semester for their training. These 3D-printed models also served as reference tools for dental preparations. The students' perceptions evaluated using a questionnaire revealed that these dental models were found to be favourable for their training.

Hohne et al. assessed the use of multilayered 3D-printed teeth representing enamel and dentin to teach crown preparation.[22] The extracted first permanent molar was scanned and printed for this study. Fourth-year dental students and experienced dentists recorded their learning experiences using a questionnaire. Each student and expert dentist prepared four teeth and used the already prepared tooth model they received as a reference for crown preparation. They acknowledged the guidance provided by the prepared tooth and that 3D-printed teeth representing the enamel and dentine of different materials were useful for their learning experience.

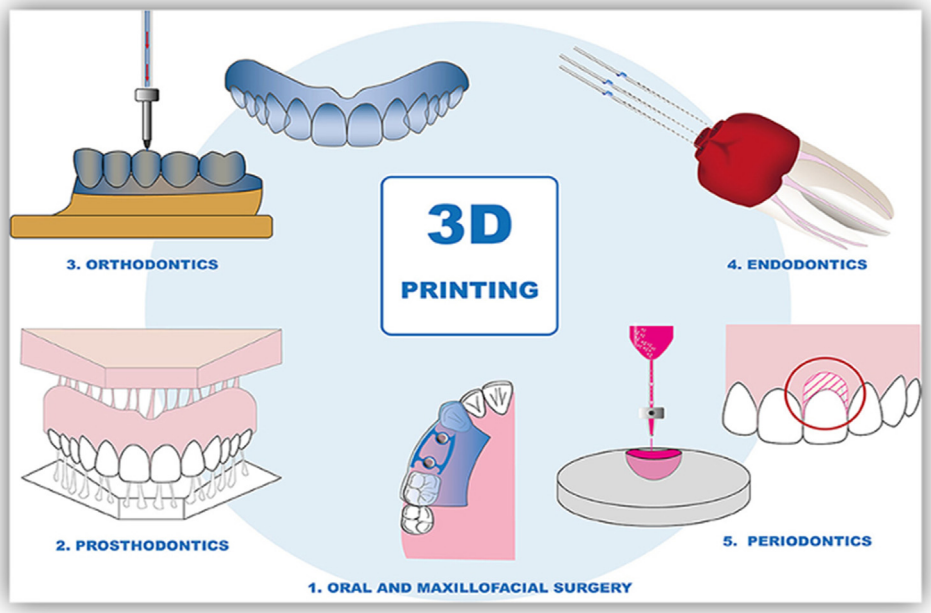

Figure 2: 3D-printing applications in dental specialities for teaching and clinical purposes.[15]

A study was conducted by Hohne and Schmitter to create anatomically designed 3D-printed teeth for use in preclinical training.[23] These teeth were used by the fourth-year dental students for training while they had standard model teeth experience during their preclinical education. Each student performed caries removal, dental pulp capping, core build-up, and preparation of crown on the three printed teeth. These exercises have been reported to be of practical relevance and useful for learning the fine skills of tooth preparation.

Hohne et al. assessed the design and practicality of an internally prepared 3D-printed tooth model for veneer preparation training.[24] Each participant prepared four printed teeth and used another correctly prepared tooth model they received as a reference. The effectiveness of the 3D-printed teeth was assessed using a questionnaire comparing them with the commercially available dental models. The students found 3D-printed teeth valuable for veneer preparations and appreciated their self-learning benefit.

Hohne et al. tested 3D-printed tooth models used for post-preparation and evaluated their relevance using a questionnaire. The participating students prepared dentin posts on four 3D-printed teeth. A comparison between real and 3D-printed teeth was made in which the latter received positive feedback from the students. The 3D-printed teeth helped the students in gaining confidence and they showed interest in doing more exercises using these 3D-printed teeth.[25]

Oral surgery

Hanisch et al. conducted a study in which two groups of students performed a root tip resection procedure also called apicoectomy on 3D-printed surgical models to gain a realistic experience in comparison to typodont model. Group 1 evaluated the industrially manufactured training models, while Group 2 evaluated the 3D-printed models. 3D-printed models provide a more life-like alternative to conventional typodont models for better student understanding.[26]

Endodontics

Kolling et al. explored the educational benefits and acceptance of 3D-printed tooth models by students for a preclinical course. The students' working experience using the 3D-printed model, extracted teeth, and resin blocks was evaluated using a questionnaire. Students did not favour 3D-printed teeth handling compared to extracted teeth but acknowledged the benefits of 3D-printed teeth in comparison with resin blocks. 3D-printed teeth offer standardisation of endodontic training and make the training of difficult root canal morphologies easier.[27]

Delfosse et al. investigated the students' experience regarding root canal treatment (RCT) preclinical training on 3D-printed primary teeth[28] and its impact on their confidence level. Each student performed two RCTs, using both manual and rotary instruments. The students were eager to use 3D-printed teeth for their practical session. The practical session using the 3D-printed teeth had a positive effect on student's confidence in performing the RCT procedure.

Kustra et al. evaluated the student's mistakes during the access cavity preparation and their learning progress using 3D-printed tooth models. Each student created an access cavity in ten 3D-printed teeth models under similar conditions. It was concluded that the use of these dental models enhances the training quality at the preclinical stage and can reduce the chances of complications while working on patients in clinical practice.[29]

Peters et al. investigated whether enhanced obturation skills were acquired by students via obturation of 3D-printed tooth replicas during their preclinical activities. The students in the four groups were randomly divided into the experimental and control groups. Experimental group students obturated the 3D-printed teeth whereas those in the control group obturated the extracted teeth. Obturation quality was independently evaluated and graded by two separate evaluators. Major differences or improvements were not found in obturation skills between the two groups.[30]

Yekta-Michael et al. evaluated the effectiveness of artificial root canal treatment models in preparing students for endodontic treatment. Both students and demonstrators evaluated these models in their initial and modified versions. Three different types of teeth (incisors, premolars, and molars) were designed for the evaluation. Both tooth models received positive ratings from the students as well as demonstrators, which confirmed their suitability for the endodontic course training purpose. Moreover, the students also felt well prepared for treating their patients after this exercise.[31]

Tsai et al. assessed students' perception in preclinical endodontic training with the introduction of a standardised teaching model (i.e., a 3D-printed tooth and evaluation system). Access opening, cleaning, shaping, and root canal filling were the procedures included in the training. Students' satisfaction was reported with the new training system as it allowed self-assessment and provided uniform training. Students found 3D-printed teeth and rubrics effective for endodontic training.[32]

Fakhr and Nagy intended to fabricate a 3D-printed tooth model to get control of errors that happen during endodontic treatment and for improved management of dental anomalies and difficult root canal morphologies. Each participant made use of clear resin models, opaque resin models, and natural teeth for doing RCT and their feedback was evaluated using a questionnaire. The clear resin models were rated higher than the other two models for clear visualisation during preparation and obturation of the canals. In addition, the 3D-printed teeth models were rated as a good learning tool for preclinical education as they refine the clinical practice of trainees.[33]

Operative dentistry

Tricio et al. investigated the dental tutors' and students' perceptions on a simulated exercise using patient-specific virtual and 3D-printed teeth models. Every student had to practice on two 3D-printed teeth models. The majority of the students favoured 3D-printed models for their hands-on skills refinement and the study confirmed the positive feedback of dental students and tutors as they found out that students were more confident after practising on these 3D-printed teeth models.[34]

Sinha et al. assessed students' perceptions regarding the 3D-printed teeth use as a teaching aid for caries removal. One tooth was given to each participant to perform cavity preparation. A questionnaire was used to assess the students'

experiences. The 3D-printed tooth was a suitable simulation for caries removal and resulted in better preparation for clinical treatment than the plastic teeth. 3D-printed teeth also cause a reduction in their stress level and proved to be a promising learning aid.[35]

Panpisut et al. prepared 3D-printed teeth for the selective caries removal (SCR) method and assessed the students' perceptions. The students received two teeth with proximal and occlusal lesions and performed the SCR technique. Afterwards, the feedback was recorded by a questionnaire. The students accepted that these modified 3D-printed teeth provide a substitute for the standard plastic teeth and are more appropriate than the extracted teeth for practising the SCR technique.

Table 1 shows the general characteristics of studies applying 3D-printed teeth in different specialities of dentistry.

Chevalier et al. used 3D-printed teeth in preclinical laboratory sessions and evaluated their effects on student anxiety, stress, confidence and knowledge, while caries and pulp

Table 1: General characteristics of studies using 3D-printed teeth in different dental specialities.

S. No.	Author(s)/year	Study design	Name of University	Place of study	Participants (n)	Dental speciality
1.	Petre et al.[21]	Cross-sectional study	Carol Davila University of Medicine and Pharmacy	Romania	Third- and fourth-year dental students (205)	Prosthodontics
2.	Delfosse et al.[28]	Randomised controlled trial	University of Lille	France	Fourth-year dental students (100)	Endodontic
3.	Panpisut et al.[36]	Cross-sectional study	Thammasat University	Thailand	Fifth-year dental students (61)	Operative dentistry
4.	Dobros et al.[18]	Cross-sectional study	Jagiellonian University Medical College	Poland	Fifth-year dental students (22)	Conservative dentistry
5.	Richter et al.[38]	Cohort study	Goethe University	Germany	Licensed dentists (12) and fifth-year dental students (27)	Conservative dentistry
6.	Tsai et al.[32]	Cross-sectional study	National Yang Ming Chiao Tung University	Taiwan	Fourth-year dental students (44)	Endodontic
7.	Kolling et al.[27]	Cross-sectional study	University of Wurzburg	Germany	Sixth-semester students (88)	Endodontic
8.	Fakhr and Nagy[33]	Cross-sectional study	Ain Shams University	Egypt	Postgraduate dental students (30)	Endodontic
9.	Tricio et al.[34]	Cross-sectional study	University of Andes	Chile	Fourth-year dental students (78)	Operative dentistry
10.	Sinha et al.[35]	Cross-sectional study	University of Leeds	United Kingdom	Fifth-year dental students (14)	Operative dentistry
11.	Chevalier et al.[37]	Randomised controlled trial	Brest Dental University and Trinity College Dublin	France	Second- and third-year dental students (108)	Operative dentistry
12.	Mahrous et al.[2]	Cross-sectional study	The University of Iowa	United States	First-year dental students (70)	Dental morphology
13.	Peters et al.[30]	Cross-sectional study	University of Queensland	Australia	First-year dental students (145)	Endodontic
14.	Yekta-Michael et al.[31]	Cross-sectional study	RWTH Aachen University	Germany	Dental students (60) and demonstrators (7)	Endodontic
15.	Kustra et al.[29]	Cross-sectional study	Jagiellonian University	Poland	Fourth-year dental students (9)	Endodontic
16.	Hohne et al.[24]	Cross-sectional study	University of Wurzburg	Germany	Fourth- and Fifth-year dental students (40)	Prosthodontics
17.	Wang et al.[17]	Cross-sectional study	Fourth Military Medical University	China	Second-year dental students (45)	Dental morphology
18.	Hohne et al.[20]	Cross-sectional study	University of Wurzburg	Germany	Fourth-year dental students (38)	Prosthodontics
19.	Hanisch et al.[26]	Cross-sectional study	University of Munster	Germany	Ninth-semester students (68)	Oral surgery
20.	Hohne et al.[25]	Cross-sectional study	University of Wurzburg	Germany	Fourth-year dental students (48)	Prosthodontics
21.	Höhne et al.[22]	Cross-sectional study	University of Wurzburg	Germany	Fourth-year dental students (38) and experienced dentists (30)	Prosthodontics
22.	Höhne and Schmitter[23]	Cross-sectional study	University of Wurzburg	Germany	Fourth-year dental students (47)	Prosthodontics

exposure management and whether students appreciate this new teaching innovation. The students were randomly distributed into two groups and their experiences were recorded by several assessments and questionnaires. A management lecture was attended by both groups, but only the experimental group was the part of laboratory session in which they performed SCR and partial pulpotomy procedure. The positive impact of 3D-printed teeth was proved as it decreased the students' anxiety and stress levels and improved self-confidence.[37]

A study made a comparison of 3D-printed teeth models to extracted teeth and standard models and investigated fifth-year dental students' perceptions. The students performed cavity preparation and filling on the 3D-printed replicated carious lesions models. The students found 3D-printed teeth as good replicas of their natural counterparts. It was demonstrated by the results of a survey in this study that rubber dam placement, caries treatment, and endodontic access preparation were a few procedures considered by the students best taught by using this teaching aid.[18]

A study compared the simulation reality and educational value of 3D-printed teeth models with commercial models. Licensed dentists and final-year dental students were divided into two groups for the study. Final-year students had prior experience related to the procedures of conservative dentistry. Each participant performed caries excavation, cavity preparation, and defect restoration on both types of models. The results from the questionnaire revealed better rating of 3D-printed tooth models by the students' group in most aspects. 3D-printed tooth models' efficacy for education purposes was acknowledged by experts as well as students.[38]

Limitations and future work

This narrative review thoroughly collected the literature findings related to the applications of 3D-printed teeth for dental education. There is a possibility that some articles might be missed or not appeared in our search because of limited databases search and keywords choice. It is a generalised narrative review without any limitations for the 3D-printing technique and the printing materials. Through this review, it is also appreciated that the sub-specialities of dentistry (e.g., oral surgery, orthodontics, and periodontics) are the areas lacking the use of this technology, as only a few studies relevant to these specialities have been found. Also, the majority of included studies took place in developed countries reflecting the use of this technology because of better funding availability. In the future, more original studies, including cross-sectional and randomised controlled trials, are warranted targeting the use of 3D-printed teeth in numerous dental specialties. Moreover, studies that concentrate on 3D-printing methods and materials will also be acknowledged.

Conclusion

Thus, it can be concluded from this narrative review that 3D-printed teeth constitute a prominent part of the education domain as they are a very helpful and impactful teaching aid, which has also been realised by the students. Apart from the students' perceptions, experts have also concluded that 3D-printed teeth can serve as a valuable aid for training purposes.

Source of funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval

There is no ethical issue.

Authors contributions

Conceptualisation, YF and MA; Data curation, YF and MA; Methodology, MSS; Writing - original draft, YF and MA; Writing - review & editing, MSS and RU. All authors have critically reviewed and approved the final draft and are responsible for the content and similarity index of the manuscript.

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How to cite this article: Fayyaz Y, Ali M, Ullah R, Shaikh MS. Applications of 3D-printed teeth in dental education: A narrative review. J Taibah Univ Med Sc 2024;19(4):816−822.