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BIBLIOMETRIC ANALYSIS ON ADDITIVE MANUFACTURING FOR DENTAL IMPLANT

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January, 2023

Approval

We certify that we have read the thesis submitted by Gabriel Ayuk Ndifon titled **"Bibliometric analysis on additive manufacturing for dental implant"** and that in our combined opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Biomedical Engineering.

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Declaration

I hereby declare that all information, documents, analysis and results in this thesis have been collected and presented according to the academic rules and ethical guidelines of Institute of Graduate Studies, Near East University. I also declare that as required by these rules and conduct, I have fully cited and referenced information and data that are not original to this study.

Gabriel Ayuk Ndifon

13/02/2023

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Gabriel Ayuk Ndifon

Abstract

Bibliometric Analysis on Additive Manufacturing for Dental Implant

Gabriel Ayuk Ndifon

Prof. Dr. Terin ADALI

MSc, Department of Biomedical Engineering, January 2023, 71 pages

The teeth like other body organs maybe damage via dental diseases or lost via accident and will need to be replaced or fixed, to help in cawing of food digestion and adds to beauty of an individual. There is a projection of an increase in number of people suffing from dental disease. This study seeks to evaluate the use of additive manufacturing for dental implants as well as the trends and future prospects of this technology in the field of dentistry.

A bibliometric analysis of data extracted from Scopus database between a ten-year period (2012-2022) was carried out. A total of 383 articles met the selection criteria and were analyzed and visualized using VOSview software package. The results of the analysis showed that there is a progressive interest in the use of additive manufacturing for dental implants as there is an increase number of publications with time. It was also noted from our results that the USA is the leading county followed by China with a lot of research activities related to the topic. The results also indicated a brighter future and advancement in the field of dentistry with personalized medicine being the subject of interest via the use of AM technologies.

The use additive manufacturing for dental implants is highly recommended due to the enormous potentials the technology offers. Furthermore, sharing of knowledge and collaboration between researchers is recommended in order to overcome current challenges faced by the use of this technology. We also recommend government especially those of developing countries to make polices that promote research in this area of study.

Keywords: additive manufacturing, 3D printing, dental implant, dental materials

Özet

Dental İmplantların Katmanlı Üretimi Üzerine Bibliyometrik Analiz

Gabriel Ayuk Ndifon

Prof. Dr. Terin ADALI
Yüksek Lisans, Biyomedikal Mühendisliği Bölümü, Aralık 2022, 71 sayfa

Dişler diğer organlarımız gibi dental hastalıklar veya kaza sonucu kaybedilebilir. Değiştirilip, sabitleştirme yoluyla gıda sindirimi ve çiğnenmesine yardımcı olup kişilerin sağlık ve estetiklerinin düzeltilmesine katkıda bulunurlar. Artan sayıda kişinin dental hastalıklara maruz kaldığı gözlemlenmiştir. Bu çalışmada, dental implant yapımında, katmanlı üretimin kullanımı ve bu teknolojinin gelecekteki eğilimi ve umutları araştırılmıştır.

Scopus very tabanından on yıllık bir dönem (2012-2022) aralığında veri elde edilerek bibliyometrik analiz uygulanmıştır. Seçim kriterlerine uyan toplam 383 makale analiz edilip VOSview yazılımı ile görselleştirilmiştir. Analiz sonuçları, dental implantların katmanlı üretim kullanılarak yapılmasına ilginin arttığını ve buna parallel bu konulardaki makale sayısında zaman içerisinde artış olduğu saptamıştır. Yapılan çalışma sonucunda, Amerika Birleşk Devletleri ve onu takip eden Çin'nin lider ülkeler olduğu not edilmiştir. Sonuçlar aynı zamanda, Katmanlı Üretim teknolojilerinin kullanımıyla, kişiselleştirilmiş tıpla, diş hekimliği alanında daha başarılı bir geleceği ve ilerlemeyi işaret etmiştir.

Katmanlı üretim teknolojisinin sunduğu muazzam potansiyeller nedeniyle, dental implantlar için katmanlı üretim teknolojisinin kullanılması şiddetle tavsiye edilmektedir. Ayrıca, bu teknolojinin kullanımında karşılaşılan mevcut zorlukların üstesinden gelmek için araştırmacılar arasında bilgi paylaşımı ve işbirliği önerilmektedir. Gelişmekte olan ülkelerin katmanlı üretimi tevşiki üzerine devlet politikalarını geliştirip bu konulardaki araştırmaları desteklemelerini öneriyoruz.

Anahtar Kelimeler: katmanlı üretim, 3B üretim, dental implant, dental materyaller

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List of Abbreviations

AM: Additive Manufacturing
BJG: Binder Jetting
DED: Directed energy deposition
PBF: Powder bed fusion
CAD: Computer aided designed
CAM: Computer aided manufacturing
SLA: Stereolithography
SLS: Selective laser sintering
FDM: Fused deposition modeling
DMLS: Direct metal laser sintering
PJP: Poly-jet 3D printing
IJP: Inkjet 3D printing
LOM: Laminated Object Manufacturing
CJP: Colour-Jet-Printing
EBM: Electron Beam Melting
MJP: Multi-jet-printing
SLM: Selective laser melting
FFF: Fused filament fabrication
CIJ: Continuous inkjet
DOD: Drop-on-demand
PBF: Powder bed fusion
PBBJ: Powder bed binder jet
PMMA: Poly(methyl methacrylate)
CAGR: Compound Annual Growth Rate

CHAPTER I

Introduction

1.1 Background of Study

Teeth play a very important rule in digestion by crushing food to smaller pieces to ease digestion, it also helps in speech and also gives beauty. Therefore, like other body organs such as the heart, eyes, teeth are important for our day to day living. Unfortunately, teeth can easily be loss due to bacterial infection, poor dental hygiene, extreme damage of dental pulp, periodontal diseases: that is, infection and inflammation of gums and bone that surround and support the teeth or by accident. According to the report by the Center for Disease Control and Prevention, tooth decay is among the most predominant chronic disease in adolescents and kids between the ages of 6 to 19 years, adults as well do suffer from tooth decay and it is estimated that over 90% of the population with ages above 20, suffer from some kind of tooth decay (Chang, et al., 2017). Due to the vital functions performed by the teeth, replacement of damaged teeth is essential for a better living. However, because one can survive without teeth, tooth regeneration was not the main topic of discussion in the past years, but with recent advances in the biomedical fields, especially in organ and tissue engineering, dentists are continuously in search of ways to improve on the life of patients. With the advent of tissue engineering, there has been a lot of promise in the regeneration of damaged or lost teeth through the use of advance technologies like additive manufacturing. This has made the use of dental implants in place of damaged teeth, for some time now to be attainable, usable and thus management of teeth decay easier. According to Selvaraj et al. (2022), Osseointegration which can be describe as the complete bonding of an implant with bone where by separation cannot occur without observing a fracture, is now a common practice carried out globally with great success rate in crown implant on solitary tooth replacement. Due to the fusion of implants with bones, in the osseointegration process, materials used (mostly metals or alloy) are therefore supposed to be biocompatible in order to render the process safe and possible. There are currently three paramount set of implants designs and three types of materials widely used in dental implant. These designs include endosteal, subperiosteal and transosteal implants, whereas the materials used are Ti-6Al-4V, Co-Cr-Mo alloy and Ceramic. Endosteal are the most popular and predominantly used implants which are placed in the jawbone. On the other hand, subperiosteal are place under the gum but not into the jawbone (on or above the jawbone). It is the best choice for patients with poor jawbone or who cannot or have no intention of carrying out augmentation of the jawbone. Transosteal is the most complicate and least use and an option for patients with extreme bone resorption (Dudley, 2015; Selvaraj et al., 2022). However, there has been a continuous shift in the use of these materials with time due to some defects and biocompatibility problems associated with some of the materials. Titanium is the material of choice now due to its high success rate in the production of desirable and compatible dental implants. There is great prospect of new and better biomaterials for dental implants in the future.

Additive manufacturing is an advanced technology which can be used to manufacture dental implants. It is a technology that has existed for a couple of decades in the manufacturing industry. However, with recent advancement, the technology has been used in the health sector to produce medical equipment and for production or regeneration of damaged or lost tissues.

1.2 Dental Pathology

The diagnosis, treatment and management of dental diseases is very important. Dental pathology involves dental caries and periodontal diseases (chronic apical periodontitis (CAP) and gingivitis). Dental caries is one of the commonest infectious diseases with varying prevalence across the world as the disease is influence by the fluoride content of water. Caries is an infection caused by the acidic breakdown of the dentin and enamel during metabolic breakdown of fermentable carbohydrates by microorganisms that are found on the dental surfaces. This disease ranges from mile to severe stages: that is ranging from loss of the dentine and enamel, dental pulp decay and acute periapical involvement at the start that can become chorionic as CAP. Periodontal disease is caused by bacteria in the biofilm, a more severe inflammatory infection which affects the structures that support the teeth, it causes teeth loss. Apical periodontitis is an inflammatory injury of the tooth apex resulting from infection of the dental pulp with bacteria or from prior periodontal lesion. Gingivitis is an inflammation of the gun, not as severe as periodontitis. (Navarro et al., 2017).

Apart from the essential functions the teeth play in digestion, speech and beauty which warrants proper dental hygiene and treatment of dental diseases, it has been reported that there are some diseases associated with dental diseases. For example, some researchers have reported the cause of Necrotizing fasciitis (NF) (which is a fast progressive inflammatory disease of the fascia, with secondary necrosis of the subcutaneous tissue) via dental origin to be polymicrobial with a mixture of aerobic and anaerobic bacteria. The research by carried out by Ozdinc et al., (2015), to raise awareness about NF concluded that a simple dental infection can cause extreme and deathly infection NF despite not being very common. Furthermore, the study carried out by Novarro et al., (2017), reported that of all studied dental diseases, CAP is a risk factor associated with the development of atherothrombotic cardiovascular disease (ACVD) and patients suffering from ACVD had the poorest oral hygiene and fewer number of teeth. However more studies are needed to make better conclusion. Periodontal pathogens have been found in tissues and organs of cardiovascular system reason why in the past decades periodontitis has been linked with the start of systemic infection including cardiovascular disease (CVDs) and diabetes (Liccardo et al., 2019).

There is inconclusive evidence between pulmonary diseases and oral health and some researchers have reported positive improvement of patient's systemic health due to improved oral hygiene. Also, diabetes has shown to have a bidirectional relationship with periodontal disease (Kane, S.F., 2017).

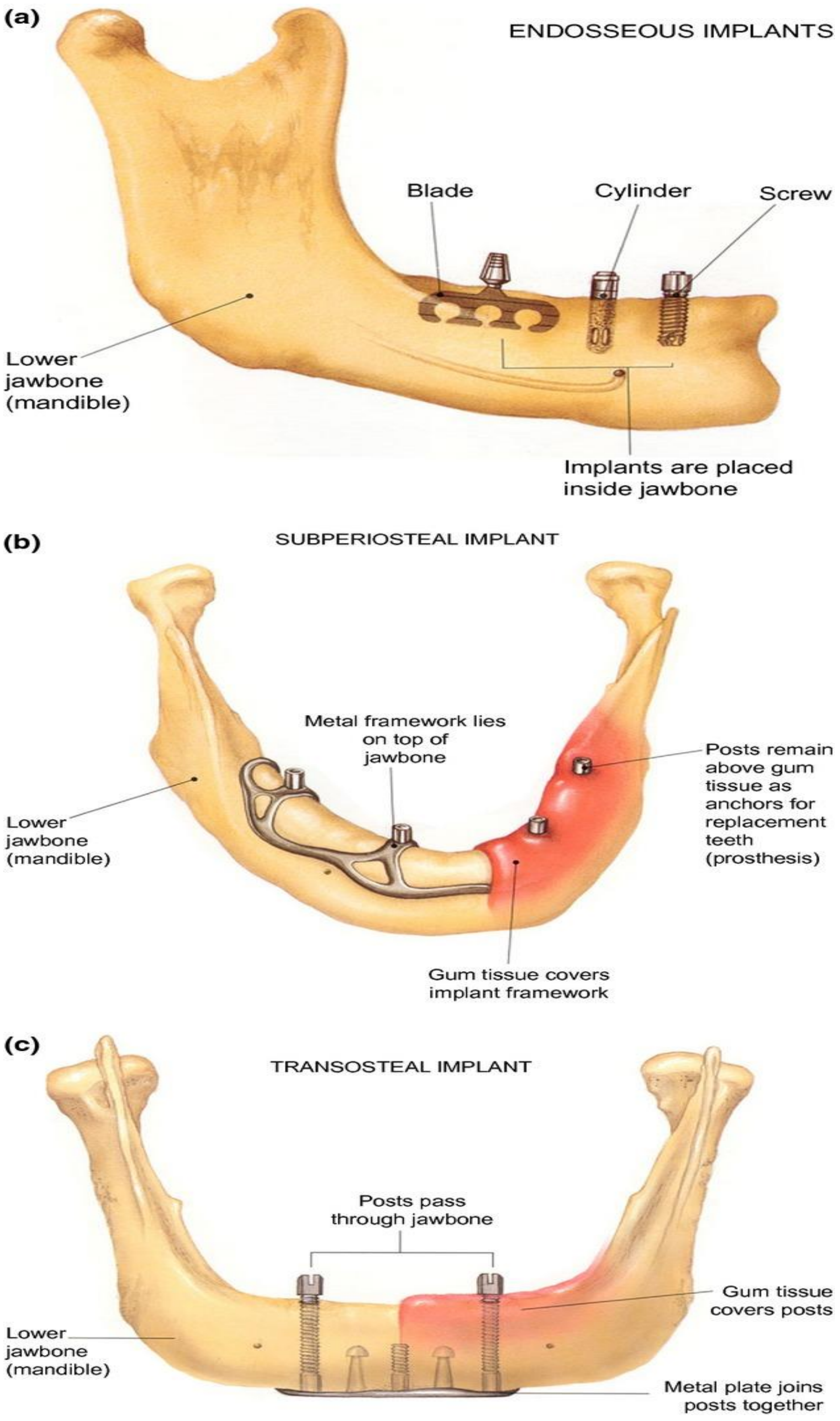
The main purpose of this research, is to evaluate the growth in scientific literature on the use of additive manufacturing technologies for making of dental implants, through the bibliometric analysis of published articles. This study will give a general view of the trends of events in the use of additive manufacturing for dental implants.

At the end of the study, we will answer the following questions:

- Is the growth in scientific literature between this10 years period?
- Which journals, institutes, countries, subject area and authors have contributed the most in research work related to additive manufacturing for dental implants?
- Is the collaboration within the scientific community in researches related to additive manufacturing for dental implants?

Figure 1.

(a) endosseous, (b) subperiosteal and (c) transosteal implants (Dudley,J 2015)



1.3 Additive Manufacturing (AM)

Additive manufacturing equally known as 3D printing is a technique that uses a layer-by-layer production process based on digital data via a computer-aided design software, to make desired structures or components of a structure, with maximization of material. This technique has a lot of advantages compared to the conventional or traditional manufacturing techniques with regards to decrease expenses, speed, ability to make complex structures with great details, accuracy and sustainability. There are various types of additive manufacturing techniques. They all have different processing requirements and outcome of the final products are based on the material used. Some will give a more accurate detailed final product than others. So due to the wide range of available technologies, so choosing the desired one for a specific material it's not easy (Vignesh et al., 2021).

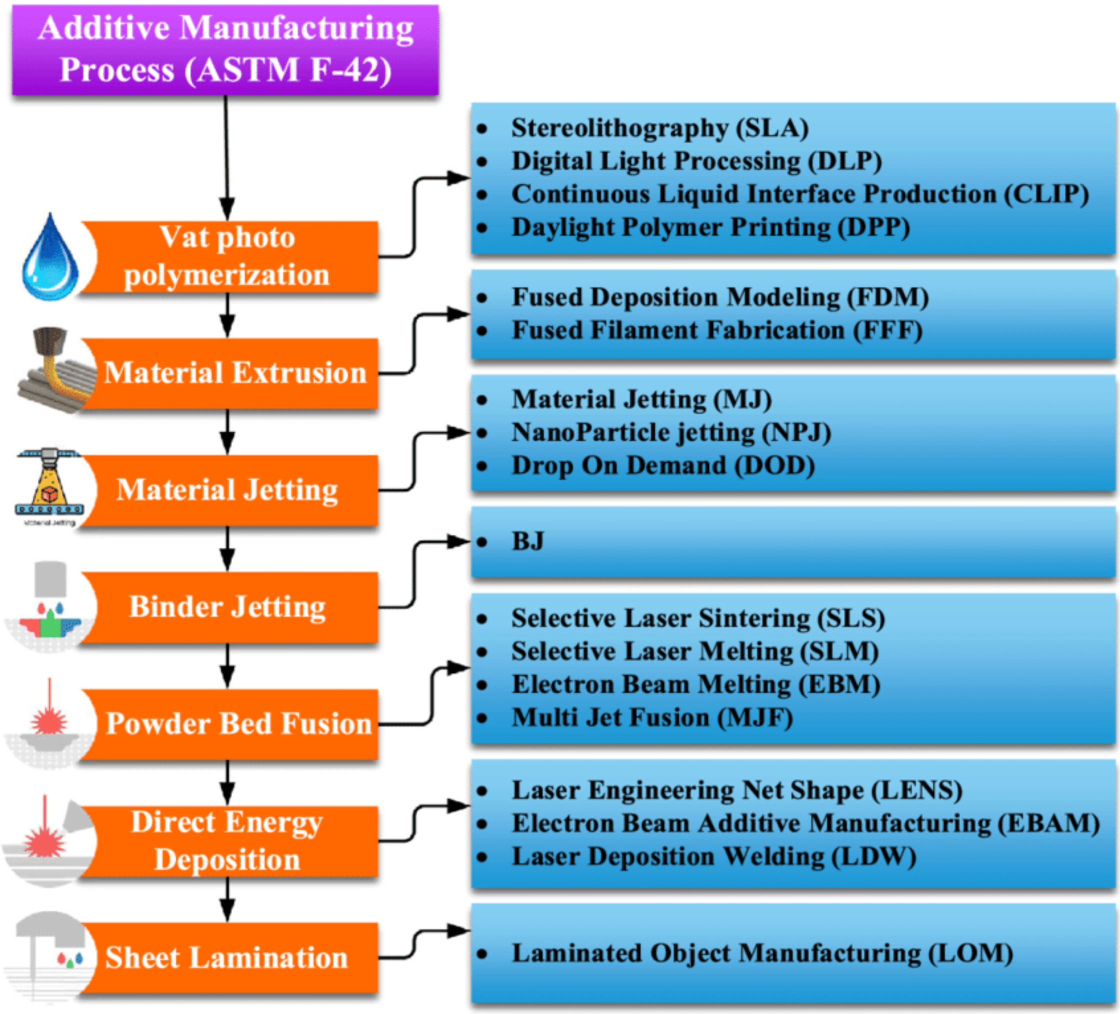
In 1971, Johannes F. Gottwald came out with the first 3D printing technology which was known as prototyping as of then. However, in 1986 stereolithographic technique was invented by Chuck Hull, this acted as pivot for the advancement of the technology. There are has been a continues advancement and development in the use of the technology due to its distinct capabilities such as time and cost effective, making of composite geometry with high accuracy, production of complete final product eliminating the assembly of different parts to make a final product. There has been an estimated 27% increase in earnings in the past 29 years. Despite the non-commercialization of aspects of the technology in the 80s, there has been a steady increase in its market value to $5.7 billion in 2014 and $21 billion in 2021. It is postulated to reach $78 billion by 2028 (Kamali et al., 2022)

Additive manufacturing is used in a lot of disciplines for example aerospace, field of medicine, energy, transportation, etc., however it has more attention in the biomedical field due to its great potentials in making economical, fast surgical equipment and patient customized implants. It is also use in the bioprinting human tissues and organs like dental implants, artificial liver, artificial cardiovascular systems and orthopedic implants as well as manufacturing of medical electronic and micro-fluidic devices (Vignesh et al., 2021). AM reduces the chances of implant failures associated with implants produce via the conventional manufacturing process thus offering great potential in the amelioration of patient's conditions.

There are a good number of additive manufacturing processes namely binder jetting (BJG) directed energy deposition (DED), material extrusion, powder bed fusion (PBF), sheet lamination, vat polymerization, material jetting etc. These processes however, have their advantages and disadvantages, and also the choice of using a particular one might be determined by the material and the properties of the desired final product.

Figure 1.

Classification of Additive Manufacturing Process (Sefene, E. M., 2022).



1.3.1 Bioprinting

Organs or tissue can lose their functioning capabilities due to damage caused for diseases. These organs or tissues can regain their functionality by undergo treatment and in extreme case, where the damage cannot be reverted, the need for a complete replacement (transplant) of the damage tissue or organ arises. Regenerating damage organs or tissues is a very costly and huge challenge in the healthcare sector.

A report by the USA agency organdonor.gov as of march 2022, stated that, around 105,800 persons (men, women and children) are on the national transplant waiting list and in every 10 minutes a person is added to the waiting list. Also, around 17 patients die every day from the waiting list. However, there are very few organ donors and a global scarcity in organ supply to meet up with the needs of recipients. This has led to increasing research in tissue and organ engineering to meet up with the needs of patients. With advances in research, the regeneration of tissues and organs like bones, skin, tendons and cartilage has been made possible through advanced innovative technologies like bioprinting (Li et al., 2016)

Bioprinting is a “technology that makes use of the layer-by-layer manufacturing process (additive manufacturing or 3D printing) where biomaterials are used as ink (bio ink), as well as live cells, extracellular matrix, growth factors, etc. for making of bioengineered structures” (Ke et al., 2022). According to Lee et al. (2018), bioprinting is defined as a process in which living and non-living matter are assembled into a needed bioengineered 2D or 3D bioengineered structure with the aid of a computer. Nevertheless, bioprinting wouldn’t have been attainable if not of the continuous development in the 3D printing technology. Bioprinting uses 3D printing technique, however, the difference is that it makes use of viable cells, growth factors etc. The first bioprinter was invented by Charles Hull in 1984 (Karzyński et al., 2018). In 1988, with the use of modified HP inkjet printer, Klebe revealed for the first time bioprinting by using cytoscribing technology (which entails the deposition of cells into substrate material with the aid of a computer-controlled inkjet printer into prearranged design). And in the years that followed (1999), Odde and Renn for the first time used laser aided bioprinting to place viable cells for fabricating analogs with complex anatomy. Some years later (2001), a bladdered shape scaffold was made by direct printing and human cells were planted in it. In the year that followed (2002), Landers et al., reported for the first time a new technology known as extrusion base bioprinting which was later make available in the market as “3D-Bioplotter”. However, in 2003 Wilson and Boland invented the first inkjet bioprinter through the modification of a standard HP inkjet printer and a year later they carried out cell-loaded bioprinting using commercially available SLA (Stereolithography) printers (Gu et al., 2020). In 2004, there was the direct print of tissues without the use of scaffolds. This event gave rise to the production of new 3D bioprinters (Novogen MMX), with a lot of commercialization. The years that followed, saw the commencement of numerous novel bioprinting products, like: scaffold-free vascular tissues (2009), skin printing and collagen infusion with hepatocytes in 2010, articular cartilage and artificial liver (2012), tissue integration with circulatory system (2014), and also heart valves in 2016 (Karzyński et al., 2018). Some researchers in 2019, successfully manufacture a perfusable scale-down heart. In the same year, a group, of researchers, using FRESH (freeform reversible embedding suspended hydrogel) technology were able to print collagen human hearts at various scales (Lee A et al., 2019). There has been a continuous advancement in bioprinting throughout the decades with new modern and better bioprinters been developed. Bioprinting has help to reduce that shortage of organs and also led to advances tissue engineering field.

Bioprinting techniques can be classified into four major classes namely (1) extrusion-based, (2) droplet-based, (3) stereolithography-based (SLA), and (4) laser-assisted bioprinting. However, out of these, the first three bioprinters are the most regularly employed, owing to their sophistication and low equipment cost. Bioprinting technologies have continue to developed as the years go by, and have gained a wide spread use in a number of fields. Bioprinting has great potential in tissue engineering and regenerative medicine to reduce the global shortage of organs and improve on the lives of patients.

1.3.2 4D printing

4D printing is an AM technology derived from 3D printing with the addition of a time dimension, where by 3D objects which are stationary are modified to response to environmental stimulus over time (that is they are able to modify their shape due to external stimuli, like temperatures, water, light). It is an advanced 3D printing. It was first demonstrated by Skylar Tibbits in 2012 at a TED conference and the first publication on 4D printing was carried out in 2013, and this technology has become popular globally among researchers and various engineering fields. This technology makes it possible to designed and fabricate time dependent products that changes their shapes or properties in response to environmental changes like temperature, pH etc. The main distinction between 3D & 4D printing is that 4D printing makes use of polymeric smart materials to fabricate structures that undergo structural changes due to outer stimuli. Also, the materials used in 4D printing are tough and are physically flexible or foldable to make complex structures that cannot be made via conventional methods (Ahmed et al., 2021; Sheikh et al., 2022). With respect to personalized medicine and therapy, 4D offer greater potentials than 3D as it makes it possible for the release of drugs at a controlled manner in response to external stimuli. 4D printing can be used in the field of prosthetic dentistry, for the fabrication of dental structures with features more or less like natural tissues in terms of hardness and softness and can withstand stress of the oral cavity. Additionally, a variety of design which are able to react to particular environmental characteristics in dentistry can be made using 4D printing (Javaid et al., 2022). 4D printing makes use of 3D printers (polyjet printers, stereolithographic principles), and materials that can undergo changes in shape, color, volume or functionality due to stimuli. The most commonly used 4D materials are shape memory polymers (SMPs), hydrogels and liquid crystal elastomers (LCEs) and hydrogels are the most commonly used materials for 4D printing (Joharji et al., 2022).

1.4 Dental Implants & Osteogenesis

The use of additive manufacturing in the field of dentistry has brought a lot of significant improvement in patients out comes thus their overall health and satisfaction. It has also given dentist and surgeons more opportunities to explore the field extensively so as to render quality service to patients. Dental implants serve as a permanent replacement of damaged or decayed teeth. However, there’s a need for osseointegration to make the implant durable.

1.4.1 Dental Implants

A dental implant is an artificial (prosthetic) object made from alloplastic material used to permanently replace missing teeth. Dental implants are fixed within oral cavity to function as normal teeth. One of the most common reasons for the wide spread usage of dental implants to replace lost or damage teeth over the years, is as a result of the benefits (such as restoration of normal function of teeth, prevention of jawbone loss and teeth movement as well as providing good facial appearance) associated with dental implants over normal dentures and bridges (Hanif et al., 2017). According to Li et al. (2020), there is an annual increase in the number of dental implant surgeries as dental implants have become a standard treatment for oral rehabilitation, with much expectations from patients and dentists for improved implants with more stability and fast healing properties.

Advanced technologies like additive manufacturing have greatly pushed dental implants to become treatment of choice for replacing lost teeth. Most commercially available dental implants are made from pure titanium (grade 1-4) or from its alloys such as Ti-6Al-4V. The success of a dental implants is dependent on the following factors; the surface, material, design and positioning of the implant, as well as the environmental conditions where the implant is placed. These parameters aid in osseointegration which is the basis for dental implant (Thakral et al., 2014)

Figure 2.

Components of a dental implant (http://www.southjerseyperiodontics.com/dental-implants.html)

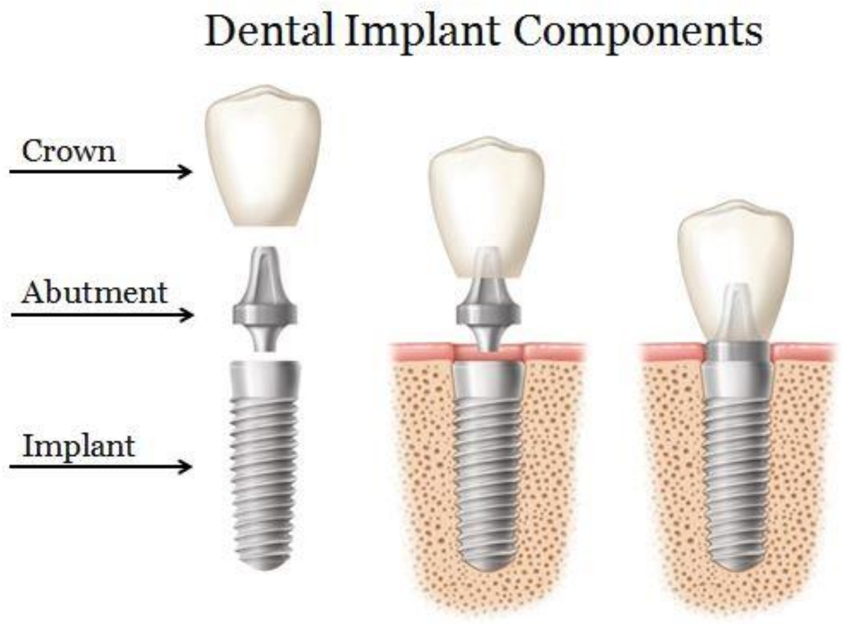


Figure 2 show that different parts of an implant: 1) implant it is the main body of the implant and serve as the root (tooth root) to anchor the abutment and crown, it is placed into the prepared hole made on the jaw bone. 2) Abutment connects the implant and the prosthetic crown (Bordenave, J. M. G., 2021).

Personalized medicine: Personalized medicine which is also known as precision medicine is the customization of medical treatment, that is making treatment or rendering of healthcare service to be patient specific. Additive manufacturing provides greater opportunities for personalized medicine especially in dentistry. It aids dentist and surgeons to make customized or personalized dental plants for patients which increase the chances of success since the implants are made base on the specific needs of the patients (e.g., anatomy of the oral cavities). Additive manufacturing technologies make implants with features (micro and nano roughness, water loving surfaces, and controlled porosity) that can easily undergo osseointegration, reducing rehabilitation time (Chen et al., 2014; Özay Önöral1 & Amr Abugofa, 2020). Furthermore, apart from offering patient specific dental capabilities, additive manufacturing gives freedom in designing, shaping and materials used in making implants which is not the case with other subtractive production technology in used (Oliveira et al., 2019; Zhang et al., 2022).

Additive manufacturing has greatly changed the field of dentistry, and has given dentist greater opportunities to render quality and satisfactory services to patients. The use of AM in the field of dentistry has continue to grow over the years as new technologies are being explored to overcome challenges faced by current AM technologies to improve on the lives of patients. This current research seeks to evaluate the various AM technologies used in dental implants, their advantages and disadvantages, the various biomaterials used and the future perspective of additive manufacturing in dental implants.

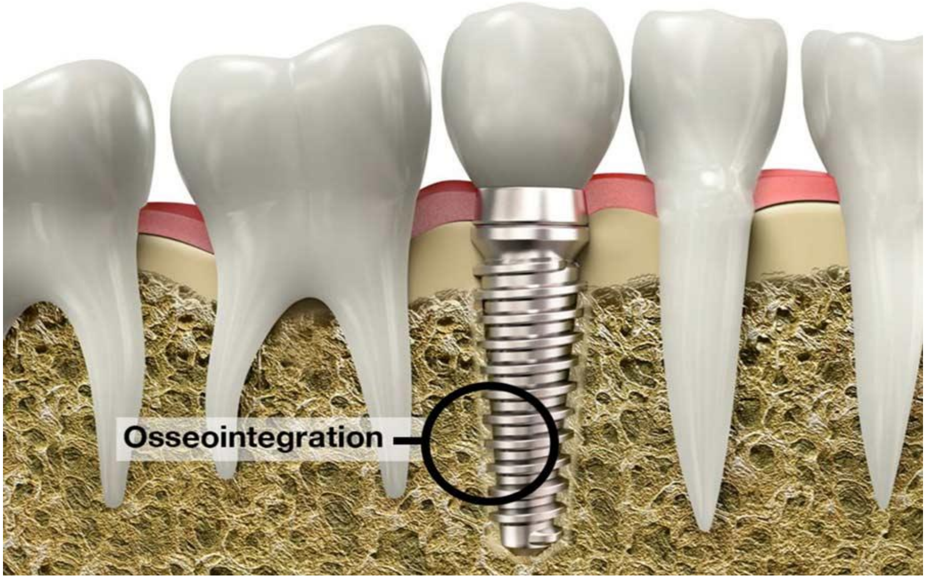
1.4.2 Osteogenesis

Bone osteogenesis or ossification is the process by which bones are formed. Osteogenesis is very vital in the success and durability of dental implants because the formation of bones on the implant or healing of the drilled bone where the implant is inserted give the implant stability. After a surgical dental implant, healing between the bone where the implant is placed and the implant, takes place via two mechanisms contact osteogenesis and distance osteogenesis. With contact osteogenesis, bone formation starts on the surface of the implant meanwhile with the distance osteogenesis, a new bone is formed on the surface of an existing bone then moves towards the implant surface (Breeland et al., 2021; Kim et al., 2021). The term osseointegration was brought forth in 1965, by Branemark to explain the interaction between a bone and an implant. In general, regeneration of bone in respect to dental implants is a complex process that can take a couple of weeks. However, despite the high survival rate of dental implant (more than 90%), some patients do experience failure which might be due to a couple of reasons like poor diagnosis and treatment plan, poor surgical placement of implant or limited information on patient medical history and poor bone conditions which reduces osteogenesis (Alghamdi, H. S. 2018). Osseointegration is defined as the fusion of an implant with the bone where the implant is placed such that separation of the implant from the bone is not possible without a fracture occurring. Osseointegration, serve as the basis for dental implantation. The implant that is osseointegrated is fixed and shows no relative movement, it gives the implant stability and durability (Hudecki et al., 2019). It is the last step in mandible reconstruction. The procedure of osseointegration has three main stages: 1) fixing of the implant into the bone with screws, 2) Adaptation of bone mass to load (lamellar and parallel fibered bone deposition); 3) Adaptation of bone structure to load (bone remodeling). Lack of osteointegration may cause fibrous tissue formation which guarantee the detachment of the implant. Properties of the implants like the design, chemical makeup, surface chemical composition and roughness of the implants, and its loading conditions are pivotal for better osseointegration. However, osseointegration is not sometimes required for temporary implants because they are removed after healing (Parithimarkalaignan & Padmanabhan, 2013; Jin & Chu, 2019; Hsieh et al., 2022).

Osseointegration is very important as it aid to prevent the loss of bone in area of missing tooth/teeth. It gives implants stability. It is therefore important when making implants to take into consideration properties such materials used, surface smoothness or roughness of implant which promote osteogenesis hence osseointegration. The use of additive manufacturing in dental implant gives freedom of production via its different technologies which makes use of different materials and offers final products with desired properties that promotes osseointegration. According to Revilla-León et al., (2020), some researchers have analyzed the use of AM technology in making dental implant and concluded that additive manufacturing gives good and controlled porosity levels as well as surface roughness which aid in formation of new bones thus enhancing the process of osseointegration.

Figure 3.

Osseointegration



CHAPTER II

Literature Review

2.1 Additive Manufacturing in Dental Implant

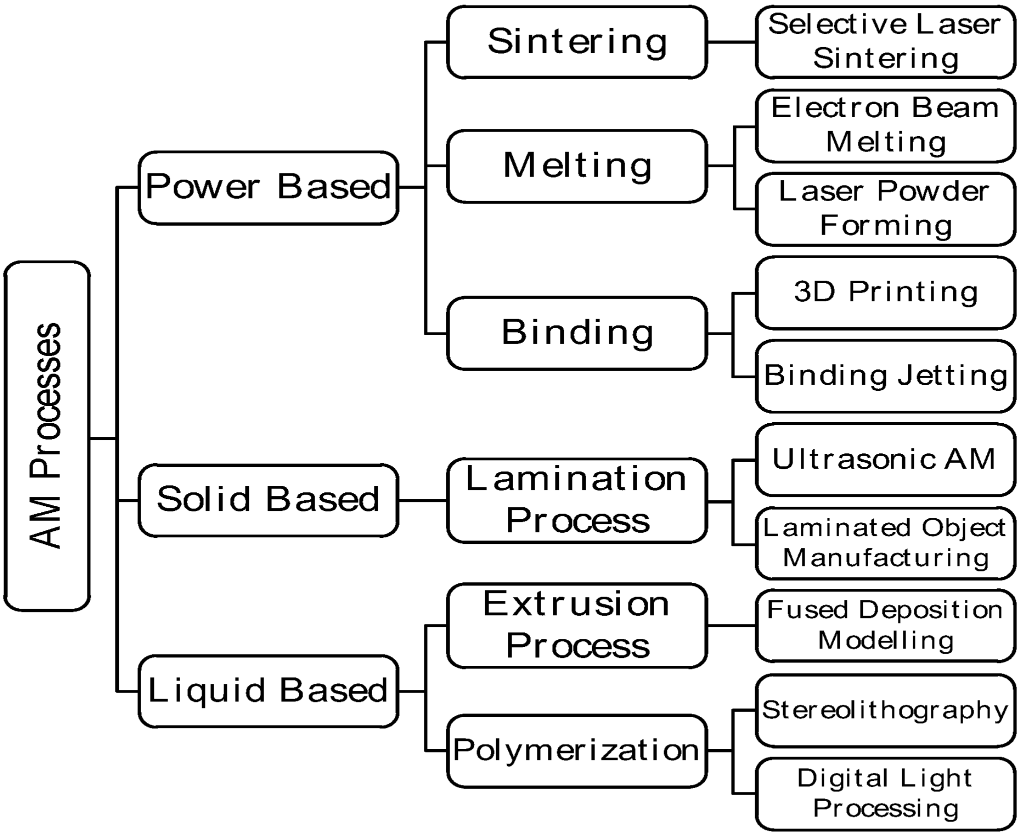
Additive manufacturing has brought a lot of innovation in the manufacturing field. It has been the topic of interest and much talked about in recent years in different fields because of its benefits and potentials such as versatility in design, ability to make personalized product, and minimum raw material utilization (Ribeiro et al., 2020). Additive manufacturing or 3D printing, is a technique by which 3-dimensional product are made through a layer-by-layer addition of material based on a model constructed using a computer aided designed (CAD) software like 3D-scanner, MRI etc. Over the years there has been a steady increase in the number of fields, that make use of this technology due to its numerous benefits compared to other manufacturing methods. The field of dentistry is not left behind as dentist are continuously looking for better ways of offering quality and satisfactory services to their patients. A variety of AM technologies such as stereolithography, selective laser sintering (SLS), fused deposition modeling (FDM), direct metal laser sintering (DLMS), poly-jet 3D printing, inkjet 3D printing, Laminated Object Manufacturing, Color-Jet-Printing, Electron Beam Melting, Multi-jet-printing table, are used to produce implants (S.K. Selvaraj et al., 2022). Each of these technologies has its own pros and cons which makes some to be used very often in manufacturing of implant than others

2.2 Types of Additive Manufacturing Technologies

There are a different types of additive manufacturing technologies. However, based on the state of material used for printing they can be classified generally into three categories namely solid, liquid and powder, based technology which can be subdivided into a number of technologies such as fused deposition modelling (FDM), selective laser sintering (SLS), stereo-lithography (SLA), electron beam melting (EBM) and binder jetting, as demonstrated in Figure 3. AM make use of materials like plastics, metals, ceramics and composites.

Figure 4.

Classification of Additive manufacturing process (Ribeiro et al., 2020)



2.2.1 Stereolithography (SLA)

It is among the earliest and most widely used 3D printing technologies, which works by a process called photopolymerization. With this technology, the 3D object is produced by selective solidification of the liquid photopolymer (resin that are sensitive to light source) when exposed to a UV laser beam. However, according to Wu et al., in Da Silva et al., (2021), other light sources that initiate polymerization can be used like radiation, high energy particle beam, normal UV light, X-ray, and electron beam. This process takes place in a bath containing liquid monomers, oligomers, and photoinitiators which, when exposed to light source, polymerization reaction occurs to form polymers that create the 3D object in a layer-by-layer fashion. However, SLA uses a CAM/CAD software to design, program and control the movement of the laser beam. After the completion of the process, the uncured resin is drained out and the 3D object under goes post processing procedure for complete polymerization of the printed object, which gives it mechanical strength. This is done by exposing the 3D printed object to UV light source.

SLA makes use of many types of materials with acrylates and epoxies being the most frequently used, having desirable mechanical toughness. Stereolithography is also good at producing objects with great accuracy and precision, this makes it the most widely used and the focus of attention compared to the other technologies. According to Da silva et al., (2021), in terms of accuracy stereolithography has accuracy of about 50 μm layer and has a production speed of about 35 m/s and in some particular occasions like microsterolithography, accuracy can reach up to 0.25 μm.

The major advantage of SLA is that it has a fast production time compared to FDM. It is able to produce very complex structures with accuracy and precision. However, it has some drawbacks like limitation in the size of structures (about 2-foot cube) made, cannot be used for mass production and the equipment are very costly (Javaid, M., & Haleem, A., 2019; Da silva et al., 2021). Stereolithography is the most used additive manufacturing technology in dentistry due to its high accuracy, resolution and unblemished surface (Khanlar et al., 2021). The mechanical and physical properties of the structure printed using SLA are determined by the thickness and orientation of the printed layer, and the depth and degree of polymerization along with any post-cure process (Della et al., 2021).

According to Robles et al., (2018), there exist approved dental devices available in the market which are made using SLA technology, and Dentca™ Denture Base II was the first approved dental device in 2015, used for the production of dental prosthetics. There is extensive literature on the application of SLA in the field of dentistry, however, there are a number of challenges to overcome in terms of materials and durability of the implants fabricated using this technology. Never the less this technology continues to be considered first in dentistry owing to the advantages elaborated above. There is an extensive use of SLA in the manufacturing of biomedical devices.

2.2.2 Selective Laser Sintering (SLS)

This technology was developed in the 1980s by Carl Deckard, unlike SLA which uses liquid photopolymer, it makes use of material in the powder form to make the layer-by-layer 3D structure (Mazzoli, A., 2013). With this technology, the laser beam is used as a heat and power source to heat and sinter powder based on the designed geometry of the object through selective laser beam scanning. There are two types of SLS namely indirect and direct selective laser sintering. Product made using indirect selective laser sintering (ISLS) are not very strong and are very porous, hence need to undergo thermal treatment. On the other hand, objects made using direct selective laser sintering do not undergo thermal treatment reducing cost and time of production (Mierzejewska & Markowicz, 2015)

Also, there has been extensive research in the past years for SLS materials (polymers, metals and composites), which reported upper hand in the production of objects with complicated configuration, DSLS makes use of a combination of various powdered materials. However, in making dense structures with ceramics, cracks are unavoidable due to the high melting point, awful thermal shock resistance and poor plasticity of ceramic materials (Chen et al., 2014). The advantage of this technique is that it provides the possibility to make objects of any shape without turning the material into liquid form however, this possesses a problem as well because improper spread of the powder can cause pores in the product (Mierzejewska & Markowicz, 2015). This technology is used in orthopedics, dental reconstructions, manufacturing of skeletal prostheses in tissue engineering. The major advantage of this technique is that it fabricates objects with great toughness and a variety of materials can be used. Furthermore, it produces durable products makes products and its less costly compared to the other AM technology in terms of mass production. Also, it is able to sinter different biocompatible polymers making it possible to make customized implants. As a drawback, objects printed with this technology are not very accurate compared to polyjet and SLA technology, however using a laser of correct specifications enhances the accuracy of the printed object with the appropriate parameters. (Mierzejewska, & Markowicz, 2015; Saffarzadeh et al., 2016).

2.2.3 Direct Metal Laser Sintering (DMLS)

It is one of the AM technologies used in dentistry to produce dental implant using metals. It is similar to SLS but makes use of metals to produce objects with greater accuracy and better mechanical toughness compared to SLS. 3D printed object is made through a layer-by-layer fusion of powdered metals using a high-powered laser beam (Javaid, M., & Haleem, A., 2019). Its major advantage is that it produces complex, accurate and durable objects but however, the machine is costly compared to other AM technology and objects produced may sometimes experience porosity, which can be controlled but not completely eliminated depending on the material (Demiralp & Yilmaz, 2021).

2.2.4 Selective Laser Melting (SLM)

This additive manufacturing technology is more like SLS and DMLS technologies but differs in that here the powered metal material used is completely melted using a very strong laser beam unlike in SLS where it is partially melted (Önöral, & Abugofa, 2020). The melting of the powdered metal materials, helps for better fusion of the materials, which eliminates porosity and gives better finished surface of the fabricated object. This technology produces objects with better densities and excellent mechanical attributes. (Demiralp & Yilmaz, 2021). Overall, products made with SLM are of good quality with little or no defects. Also, SLM is use to print complex structures, shapes, long lasting and low weight objects. There is a wide spread use of the technology in aerospace and medical orthopedics (Debdatta Ratna, 2022). Its major advantages include ability to make use of different materials, not very expensive and makes products close to the finish shape which can eliminate post production treatment of the final surface base on whether the surface roughness is tolerable. However, some of its drawbacks are that it's a somewhat time-consuming process limited by speed, it uses a lot of energy, it requires time to make good use of framework, it requires careful handling of the powder material to produce smoother surface. Furthermore, the high interior pressure during the production process can cause fractures of final product for materials that cannot withstand these conditions (Konda et al., 2017).

2.2.5 Fused Deposition Modelling (FDM)

It is also referred to as fused filament fabrication (FFF). like the other additive manufacturing technologies, FDM or FFF is the layer-by-layer addition of thermoplastic material to make a 3D object. Here, the material used is in a semi-liquid form and is released via hot nozzle (of a certain radius owing to the inability of having an excellent square nozzle) at a fixed pressure and constituent flow following a given pathway to make a layer-by-layer 3D object. The material used is heated at the extrusion head of the printer to ease the extrusion of the material from the nozzle. However, the heated material needs to be of a certain viscosity (high and low enough) to show structural support and prevent the clogging of the nozzle. The release of the material needs to be kept at fixed speed throughout the process to improve on the accuracy of the final product. The printed layers can fuse together using chemicals or temperature-controlled systems (Revilla-León & Özcan,2019). Also, there are modern printers which make used of many nozzles of different type for the simultaneous release of different materials having different properties (Mohd Javaida, & Abid Haleemb, 2019).

FDM has a lot of potentials especially in medical field and is widely use because its user friendly, works at a good speed, somewhat not expensive and makes use of a variety of materials. However, its accuracy is low in comparison to the other AM technologies, and the quality of the final printed object is a determined by the angle and width of the raster, as well as the thickness of the material layer (Önöral and Abugofa 2020)

2.2.6 Electron Beam Melting (EBM)

EBM is similar to SLS technology which makes use of material in the powder form to make the layer-by-layer 3D object with the aid of a CAD/CAM. However, the major difference being that EBM uses a strong electron beam as a source of energy unlike SLS which uses a laser beam. In addition to this, the powder bed is maintained at extreme temperatures of about 870K and after completion of fabrication process, a significant amount of cooling time is required. Also, EBM technology has a framework that requires a lot of processes (beam power, scanning velocity, pate temperature etc) which are sometimes challenging to efficiently use them, restricting it from using a variety of materials. However, its able to prevent cracking during solidification in brittle materials by choosing a good cooling temperature. The process is generally slow and expensive and is limited by size of printed object, never the less EBM prevents oxidation of the product since the process takes place in a vacuum atmosphere (Konda et al.,2017; Önöral and Abugofa 2020)

2.2.7 Polyjet 3D Printing (PJP)

It is an additive manufacturing technique which has an operating principle like that of a conventional inkjet printing but differs in that it selectively releases drops of photopolymeric resins into a built tray, after which the surfaces of the droplets are smoothen and a UV light source is passed over the resins a couple of times for proper curing of the resin. The build platform is lowered and the process is repeated for the next layer to be added, this continuous until the final 3D object is printed. (Meisel et al., 2015).

The printer is able to use many printing heads with different sources of materials and this makes it possible to print a single layer with different materials. Its main advantage is that it is able to print a variety of materials in a single layer, which gives the final end product better mechanical properties like flexibility. it also has better resolution, good finished surface quality, very high production speed and capacity compared to the other AM technologies (Murugesan et al., 2012). In the fields of dentistry and medicine, this technology gives a greater understanding of the anatomy of patients from the printed model (Javaida M., & Haleemb A., 2019). This technology also makes it possible to make colored materials that are not easy to make with SLA. On the other hand, some of its drawbacks are that it needs thick supports (requiring more material to be used) which can only be removed mechanically. Also, the shape of the final product can be changed if subjected to ambient heat, humidity, or sunlight (Meisel et al., 2014; Vanderploeg et al., 2017; Demiralp & Yilmaz, 2021)

2.2.8 Inkjet 3D Printing (IJP)

Inkjet printing was developed in the 1960s and it widely used, with its technology being the bases for some 3D printing technologies. It is a non-contact printing technology, which is versatile and make use of different materials (polymers, ceramics, metals and biomaterials) on the condition that they all meet the fluid requirements. It is use to make layer-by-layer 3D object via placement of drops of the material or spraying of photopolymric material onto a substrate which then solidifies to form the final product. The solidification of the liquid material can be carried out using solvent evaporation, cooling of low molecular weight (MW) polymers and ultraviolet curing. There are two methods of IJP namely continuous inkjet (CIJ) method and drop-on-demand (DOD) method. In the two methods, the liquid passes through a nozzle (Guo et al., 2017; Magazine et al., 2022). IJP is one of the major 3D technologies which print objects with ceramics. And makes use of two main kinds of ceramics namely wax essentials inks and liquid suspension. The quality of the final product printed using this technology is based on the size of the particle dispensed, consistency of the material, nozzle size, speed of jetting and fabrication of the ceramic. IJP can create complex structures at a lesser time and cost compared to the other AM technology. However, its drawback is that it has low resolution (Demiralp & Yilmaz, 2021).

2.2.9 Laminated Object Manufacturing (LOM)

LOM is one of the earliest 3D technologies on the market. It creates 3D objects by layer-by-layer placement and lamination of sheets of material. The material sheets are chopped mechanically or using a laser beam and then laminated to form the 3D product. This AM technology makes use of different materials like polymers composites, ceramics, paper and metal-filled tapes. Printed objects may have to undergo post processing such as subjection to hot temperature base on the material and required characteristics. It is use in different fields and its one of the best AM techniques used to produce larger and strong products with reduced production time and equipment expenses. However, it has low surface quality, accuracy and it takes time in post processing after fabrication of the object, thus not good for making complicated shapes (T.D. Ngo et al., 2018; Javaida M., & Haleemb A., 2019)

2.2.10 Multi-Jet-Fusion (MJF)

It is a kind of powder bed fusion (PBF) which uses same techniques as powder bed binder jet (PBBJ) and inkjet but uses a different binding mechanism (it uses infrared and chemical agents). With this technique, a very small amount of the powder is lay out on the print bed already heated to a uniform temperature. The bonding and detailing agents are then distributed using a print head to chosen areas of the powder bed base on the desired printed outcome. An infrared source is then used to complete the binding of powder. MJP is used to make small size parts with excellent mechanical strength, objects produce by MJP are stronger and resilient than those produce by SLS. MJF is used to make medical orthotics and prosthetics (Chin et al., 2020).

As discussed above, every additive manufacturing technique provide different dental materials and accuracy. Some are more accurate, produce quality and durable products than others and some a best suited for dentistry. Table 1 below gives a summary of the various additive manufacturing technologies, their advantages and disadvantages, the material used and the level of accuracy of the products they make. Additive manufacturing has a lot of potentials and has revolutionize the field of dentistry. With the aid of 3D printed models, dentists and surgeons are given a good picture of patient’s anatomy. Implants of a specific patient are created with geometric freedom and solve day to day challenges in dentistry.

2.3 Biomaterials for 3D Dental Implants

With dental implant becoming the routine treatment for lost teeth, there is an increase in the demand for dental implants and this has prompted research into biomaterial which can be used to make implants to keep up with the demand. Additive manufacturing makes use of different materials for dental implants. Every material has its advantages and disadvantages. However due to corrosive processes which might take place on implants, it is therefore important to take into consideration some material properties (biocompatibility, cytotoxicity,) when choosing materials for dental implants so as to prevent the release of harmful substances that may cause damage. Development in technology and material science has contributed to the understanding and use of biomaterials in dentistry. The most frequently used materials for dental implant are Titanium, Titanium alloys and Zirconia, others include ceramics and photopolymeric resins. However, titanium and its alloys are frequently used due to their resistance to corrosion, good mechanical toughness, low density and their weight ratio (Prakash et al., 2019). Therefore, dental materials must be able to deal with the stress resulting from chewing as well as chemicals in the mouth, those from food over a long period of time without causing any damaging biological response to the individual.

2.3.1 Titanium (Ti) and Its Alloys

Titanium and its alloys have long been used and is still commonly used as biomaterials for orthodontics, implantology, orthodontics, endodontics and prosthodontics because their biological, physical and mechanical properties such as their biocompatibility, good mechanical toughness, rigidity, ductility and their weight to corrosion resistance ratio (small weight with high resistance to corrosion), as well as their osseointegration properties (Romero-Resendiz et al., 2021). However, Titanium alloys compared to pure titanium (CP-Ti) has advantages for use in dental implants with the major advantages being; enhanced mechanical properties, reduced melting point of CP-Ti due to alloys and greater control of powdered titanium high chemical reactivity compared to the liquid phase (Faria et al., 2014). Furthermore, according to Liu et al. (2017) titanium is widely and successfully use as a dental implant material because of its very good biocompatibility, its ability to bind with osteoblast and its inert biological unreactive as well as its ability of withstanding corrosion. And the most commonly used titanium alloy for dental implant is Ti-6Al-4V (grade V titanium alloy made up of 6% aluminium and 4% vanadium, with a maximum 0.25% and 0.2% of iron and oxygen respectively and titanium making up the remainder part. Ti-6Al-4V has better mechanical properties and excellent ability to withstand corrosion and well as low elastic modulus than pure titanium (cp-Ti).

Titanium is a material of choice for dental implants and other biomedical implants due to its mechanical and biocompatibility properties. Also, it can be easily processed into desired shapes and sizes. However, there are some toxicity concerns with Ti-6Al-4V because of the alloys (aluminum and vanadium). Also, it does not have a good wear resistance and as such it needs surface treatment and coating. (Veiga et al., 2012)

2.3.2 Ceramics

Additive manufacturing also makes use of ceramics for fabrication of dental implants. According to Galante et al., (2019), in the years past the use of ceramic by AM as a material for dental implant was not developed because of difficulties in fabricating products with desirable finished surfaces, mechanical attributes and geometric accuracy. However, they also reported the board use of bioceramics (alumina, zirconia, calcium phosphates and ceramic composites) to make dental implants. Ceramics have attractive properties like stable color, compressive strength, thermal conductivity, aesthetics and biocompatibility, which are like natural dental properties. These properties have encouraged the use in 3D printing in dentistry.

Zirconia ceramics were first used in dentistry some decades ago. They are clinically popular with excellent mechanical properties and are easy to fabricate in the pre-sintering stage through CAD-CAM) (Denry & Kelly, 2014). Research by Shin et al. (2016), on the biocompatibility and cytotoxicity of zirconia revealed that zirconia is biocompatible with tissues of the oral cavity and osteoconductive (zirconia promotes the formation of bones when in contact with them) and also have limited cytotoxicity. Furthermore, some researchers have shown that this ceramic is not allergic and does not change the sense of taste, with respect to its mechanical attributes, it is regarded as one with a great toughness, stiffness, resistance to wear and corrosion, elastic modulus like that of steel, with thermal expansion coefficient close to that of iron. Also, among frequently used ceramics, it has the greatest breakage toughness (Galante et al., 2019). Zirconia can undergo surface treatment (surface roughening, coating of surface and surface contaminant reduction) which improve on their osteoblast adhesion and differentiation thus osseointegration (Han et al., 2017). According to Rodriguez et al. (2018), zirconia ceramic implants have good aesthetics properties (white color like natural teeth) and do not promote plaque formation, this enhances the growth soft tissues around the implant thus preventing bacterial infection.

Alumina is a ceramic material also used to fabricate dental implants with purity of ~99.99% making it a good material in dental application compared to metal alloys. It is biocompatible and resistance to wear but however not very compact, flexible in comparison to zirconia. However, their mechanical properties can be improved upon addition of zirconia. The strength and breakage resistance can be changed by the control of grain size, heating and cooling temperatures, introduction of stabilizers (zirconium oxide, magnesium oxide etc) and porosity (Khabas et al., 2014; Khorsandi et al., 2021)

2.3.3 Polymers

Polymers such as vinyl polymers, styrene polymers and polyester are used as 3D printing materials in the field of dentistry. Viny polymers such as poly(methyl methacrylate) (PMMA) is the most regularly used material in 3D print of dental implants. These polymers are biocompatible and nonbiodegradable which make them suitable for dental implants. They are largely used by sintering or photopolymerization 3D printing technologies for dental implants. PMMA is the material of choice for denture because of its easy processibility, stability in oral habitat, not expensive, not heavy and good aesthetic properties. Nevertheless, it does not have good mechanical and surface properties but can be overcome by using additives like SiO2. The addition of titanium oxide makes it antimicrobial (Stansbury & Idacavage, 2016; Khorsandi et al., 2021).

2.3.4 Metals

Metals have long been used in the field of dentistry due to their mechanical and biocompatibility properties. However, not all metallic materials are use, only those that a biocompatible are used. Stainless steel alloys made of vanadium steel are the first metal implants to be used in the 1990s. but they were not durable (losses function and requires another surgery) nor satisfactory for patients. However, with time other stainless-steel alloys with better properties were used to replace other metallic alloys with better properties (Khorsandi et al., 2021)

Table 1.

Types of Additive Manufacturing Technologies used in Dental Implants their Advantages, Disadvantages Material used and Accuracy

Types of AM	**Disadvantages**	**Advantages**	**Biomaterial used**	**Accuracy**
SLA	▪ Machine is very expensive ▪ Post-processing procedures are needed. ▪ Cytotoxicity can be caused by uncured resins and residual photo-activator ▪ Poor mechanical toughness of made structures. ▪ Limited by the size of structures	▪ High accuracy and resolution ▪ Fast production time and smooth finish surface. ▪ Ability to fabricate compounded structures with fine details ▪ Clogging of the nozzle can be circumvented due to its nozzle free technique. ▪ Used for making anatomical model, prosthetics, master patterns for injection moulding and various metal casting.	▪ Plastics ▪ Ceramics ▪ Acrylate photopolymer	≈50-55 μm
SLS	▪ Possibilities of cracks due to preheating of powder-filled tanks Sometimes, the powder-filled ▪ Post-processing is sometimes needed and tedious ▪ Porous and rough surface of objects in comparison to SLA ▪ Release of unwanted Harmful gases release during fabrication ▪ Comparatively high waste of materials ▪ Powders are costly	▪ High accuracy ▪ Does not need a supporting material ▪ Good chemical resistance ▪ Objects have excellent mechanical properties ▪ Make use of many different types of materials ▪ Different finishing potentials ▪ Protective gas in not needed ▪ Limited or no thermal stress on components ▪ Relatively quick method	▪ Ceramics ▪ Metals ▪ Wax ▪ Thermoplastics ▪ Polymer/glass composites ▪ Polymer/metal powders	≈45-50 μm
DMLS	▪ Based on material final product can be porous with rough surface ▪ Causes shrinking and warping of manufactured part	▪ High accuracy ▪ Makes objects with great toughness ▪ Make complex objects efficiently	▪ Cobalt ▪ Aluminium ▪ Titanium ▪ Bronze alloy ▪ Stainless steel ▪ steel ▪ Nickel alloy	≈20–35 μm

Table 1 (Continued).

SLM	▪Somewhat time-consuming process limited by speed ▪Uses a lot of energy to melt particles making control of process hard. ▪Requires careful handling of the powder material to produce smoother surface. ▪High interior pressure during the production process can cause fractures of final product for materials that cannot withstand these conditions ▪Base on material, parts can be porous	▪Excellent accuracy ▪Ability to fabricate complicated structures with great details ▪Better densities and excellent mechanical attributes ▪Make use of different materials ▪Not very expensive	▪Cobalt chromium alloy ▪Metals and metal alloys ▪Stainless steel ▪Titanium (Ti-6AI-4V) alloy ▪Nickel chromium alloy	≈20-35 μm
PJP	▪Needs thick supports which can only be removed mechanically ▪ Shape of the final product can be changed if subjected to ambient heat, humidity, or sunlight ▪Not good for mass production	▪Able to make use of variety of materials in a single layer, which gives the final end product better mechanical properties like flexibility ▪Better resolution ▪Good finished surface quality, ▪Very high production speed and capacity ▪Make complex structures with great details and accuracy	▪Photopolymer s	20–85 μm
FDM	▪Supports material may be needed ▪Possibility of poor finish surfaces which will need polishing ▪Delamination may occur due to temperature variation ▪Composites has to be in a filament form _to be extrudable ▪Intermittent extrusion leads to defects formation ▪Printed component may curl off the build platform because of induced thermal stress	▪Objects have great toughness ▪ Able to print Polyether ether ketone (PEEK) materials ▪Comparatively not expensive ▪Make use you of multiple materials and of different colors ▪ Good production speed ▪Fundamental for thinner layers up to 0.1 mm thick ▪Release nontoxic fumes	▪Polycarbonate ▪Composites ▪ Acrylonitrile butadiene styrene (ABS) ▪Polyesters ▪polypropylene ▪Polylactic acid (PLA)	≈35-40 μm

Table 1 (Continued).

IJP	▪Size of objects is limited ▪Machine cost is high ▪Has low resolution	▪Can create complex structures at a lesser time compared to the other AM technology. ▪Applied in health care such as print organ ▪non-contact printing technology, versatile and make use of different materials on the condition that they all meet the fluid requirements	▪Powder ▪Liquid binder ▪Polymers ▪Ceramics ▪Metals	35–40 µm
EBM	▪Needs a vacuum which is expensive and needs maintenance ▪Produces X-rays while in operation ▪Poor finish surfaces	▪Vacuumed medium prevents impurities ▪Well-fused powder may be useful in reducing residual stress in finish product and improve mechanical attributes ▪Possible to get high energy level within a small beam ▪Consumes less energy Lower as well as lower maintenance	▪Metals powder ▪Titanium	≈40-50 µm
LOM	▪ Printed objects may have to undergo post processing such as subjection to hot temperature base on the material and required characteristics. ▪It has poor finish surface quality ▪ Not good for making complicated shapes	▪Good to the Environment ▪Good strength ▪Non-hazardous to health ▪ Use of different materials ▪One of the best AM techniques used to produce larger and strong products with reduced production time and equipment expenses ▪Does not need support	▪Paper and Metal-filled tapes ▪ Plastic ▪Polymers composites ▪Ceramics	≈60–70 µm
MJF	▪High cost of material ▪Lack of variety of materials	▪Make very complex structures with fine details ▪High quality of finish surface ▪High fabrication speed ▪ No post processing proc treatments is needed ▪Is used to make small size parts with excellent mechanical properties	▪ Powder ▪ Plastics	≈25–35µm

CHAPTER III

Research Methodology

3.1 Introduction

This chapter provides the methods applied in the research, that is the design of the study, mining of data for the study, methods and data analysis tools used in the research.

3.2 Study Design

The research made use of bibliometric and visualization analysis

Bibliometric analysis: here published research articles on additive manufacturing for dental implant, were searched and analyzed. The study made use of articles between a ten-year span that is from 2012 to 2022 from Scopus database.

Visualization analysis: here, the data collected and analyzed provides information through graphs, tables, images, chats and maps. Which makes it easier to understand patterns, trends changes and growth in literature within the past years.

3.3 Bibliometric Data Collections

The data for this research was extracted and downloaded from Scopus database base articles on additive manufacturing for dental implants. Scopus is one of the largest database sources that contain more than 87 million documents ,17 million researcher, 81 million curated documents, 80,000 institutional profiles and accessible 70,000 publisher.

An extensive search for articles on the topic Additive manufacturing for dental implant on Scopus database was done using “Additive manufacturing” OR “3D printing” AND “Dental implants” OR “teeth implant” OR “Denture” as keywords, as seen in table 3, taking into consideration the selection criteria. The search results were checked manually in order to eliminate irrelevant articles that are not related to our study before analyzing the data. There are many research areas with publications related to additive manufacturing and implants in existing literature. However, in order to have publications that are relevant and specific to our subject of interest, we limited the subject area to six research area namely: dentistry, material science, engineering, medicine, biochemistry, genetics and molecular biology, and pharmacology, toxicology and pharmaceutics as shown in figure 10. The following criteria were used for the article search:

3.3.1 The inclusion criteria used were

- Types of documents: only articles were selected
- Year of publication: only articles published between 2012 to 2022 were selected.
- Subject area: six subject area were selected which were density, medicine, engineering, material science, biochemistry, genetics and molecular biology, pharmacology, toxicology and pharmaceutics.
- Language: Only article published in English were selected.

3.3.2 The exclusion Criteria used were as follows;

- Reviews, conference proceedings and books, articles published before 2012, other subject area other than those mentioned were rejected as well as article not published in English language.

A search for the various key words were also conducted as shown in table 2

Table 2.

Data Extracted from Scopus database.

Keywords	Number of Articles
Additive manufacturing OR 3D printing AND dental implant OR teeth implant OR denture	383
Additive manufacturing OR 3D printing AND dental implant	276
Additive manufacturing OR 3D printing AND denture	256
Additive manufacturing OR 3D printing AND teeth implant	130
3D printing AND dental implant	206
Additive manufacturing AND dental implant	110

3.4 Methodology and Software tools used

After extracting the data from Scopus into Microsoft Excel, the software VOSviewer was used to carry out Co-authorship analysis

VOSviewer

VOSviewer is a computer software that is available for download without any charges. It was developed at Leiden University's center for Science and Technology (CWTS) by Nees Jan Van Eck and Ludo Waltman, and launched in 2010 (Orduña-Malea & Costas, 2021) It is a worldwide acceptable bibliometric analytical tool used for bibliometric studies. It is mostly used by Researchers, institutions, companies, organization etc, to construct and visualize bibliometric web. The web consists of journals, researchers, publications, which can be establish on the bases of citation, co-citation, co-authorship relation as well as bibliometric coupling. (Contreras & Abid, 2022). VOSviewers has features (zooming, searching, scrolling) which aid in better visualization and examination of bibliometric network maps. It is also use for text mining that can be used to visualize and establish co-occurrence network for the topic.

Microsoft Excel

This is a software computer program (spreadsheet) used for data formatting, arrangement and calculations, it also graphing tools and pivot tables. Microsoft is used for the visualization of the data downloaded from Scopus, via histograms and chats.

Analysis

The study made use of VOSviewer software package to analyze and visualize the data collected from Scopus. In order to find out the growth in scientific literature in the use of additive manufacturing technologies for fabrication of dental implants, over the 10 years period (2012-2022), the number of publications per year, journals, institutions, subject area, authors and countries where the articles were published were taken in to consideration in the analysis. VOSviewer was used to visualize co-authorship analysis for authors and countries.

CHAPTER IV

RESULTS AND DISCUSSION

In this chapter, the articles extracted from Scopus database were analyzed and detailed results and explanations given base on the analyzed results. The data was extracted and analyzed on the 24 of December, 2022 from Scopus from a period of 2012 to 2022. The results are presented in two different sections below. The current status of AM for dental implants and the co-authorship analysis for authors and countries.

4.1 The Current Status of Additive Manufacturing for Dental Implant Research

In this section, a detailed view of the state of studies of application of additive manufacturing in dental implant will be given base of the articles exported from Scopus database, in term of publications made within the ten years period, citations, as well as the distribution of AM in dental implant research publications in terms of journals, countries, institutions and research areas.

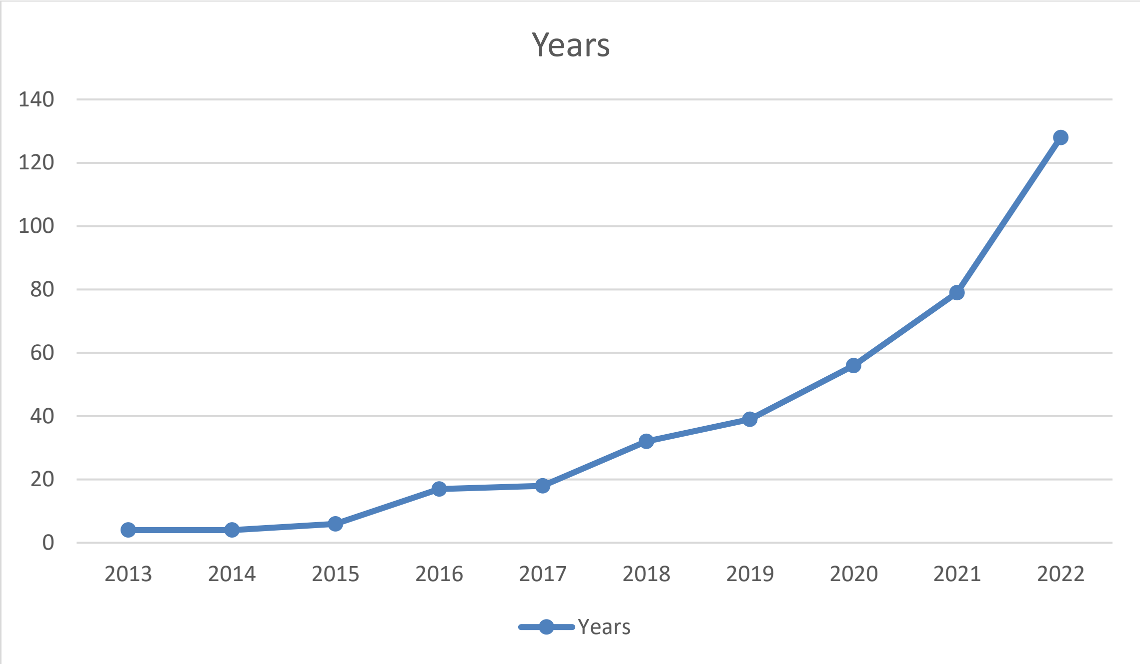
4.1.1 Number of published articles within period of study

A total of 383 articles (which met the selection criteria) on additive manufacturing for dental implant, were extracted and analyzed. The figure 6, shows the annual publication of articles within the ten years period (2012-2022) on additive manufacturing for dental implants. As illustrated in figure 6 below, between 2013 and 2014 just four articles were published per year. In the years that follows, there was gradual increase up to 2016, while in 2017 there was a slow increase in the number of publications compared to the previous years. However, there was a consistent increase up to the year 2022 (which had the highest publication).

The result of the analysis shows a significant increase in publication which shows growing interest in application of additive manufacturing in the field of dentistry. Additive manufacturing has great potentials that can be exploited to provide quality, improved and customized implants. Also, since teeth play a vital aesthetic role, there is a growing trend in care of teeth to keep these properties and improve self-esteem. In addition to these, there is a continuous increase in people suffering from dental issues with increasing world population. Thus, there is a continuous growth in research in order to develop new and innovative technologies and approach to tackle the ever-increasing needs of patients.

Figure 5.

Number of published articles within period of study

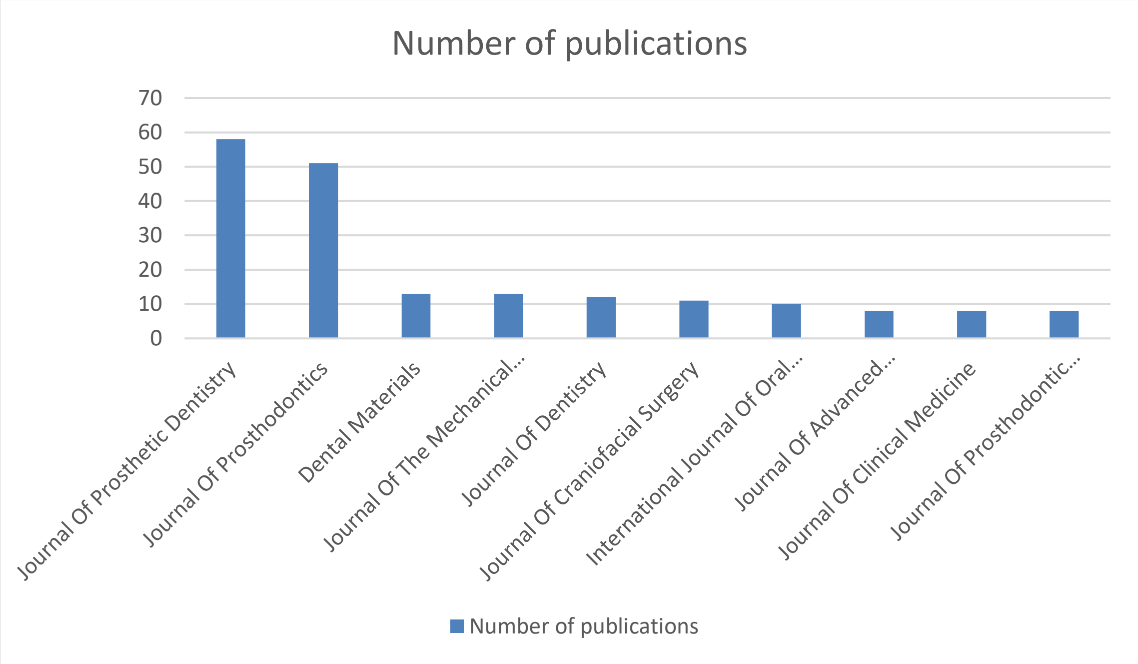


4.1.2 Top ten journals on additive manufacturing for dental implant

Out of the 383 articles extracted from Scopus, they were published by 121 journals. The figure below shows the top ten journals that publish articles related to our research topic (additive manufacturing for dental implant). A total of 50.13% publication were done by the top ten journals which sums up to 192 articles. The "Journal of Prosthetic Dentistry" had greatest number of published articles (58 articles) making 15.14% of the published articles. Also, the "Journal of Prosthodontics" had the second highest number of published that is 51 articles (13.32%), followed by "Dental Materials" journal and "Journal of the Mechanical Behavior of Biomedical Materials" with 13 publications (3.39%) each. The journals with the lowest number of publications out of the ten top journal was "Journal of Clinical Medicine" and Rapid prototyping journal and "Journal of Prosthodontic Research" with 8 articles (2.09%) each. However, as shown in figure 7, there are some journals with same number of publications.

Figure 7.

Top ten Journals with publications on additive manufacturing for dental implant

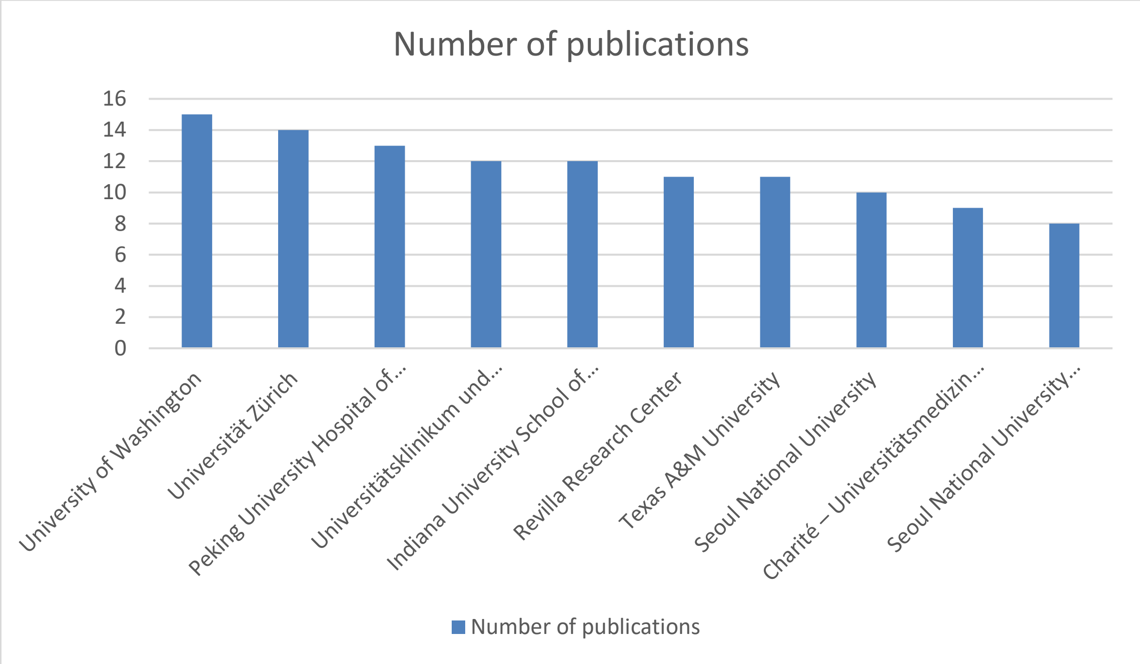


4.1.3 The top 10 Institutes with the most published articles related to additive manufacturing for dental implant

Figure 7 present the top 10 Institutes which has published most articles related to our topic of interest out of the 160 institutions involve in the publication of the 383 articles. In general, the top ten institutions made 115 publications (30.03%). The University of Washington has the greatest number of published work (15 articles) which makes up 3.92% of the total publication, next is Universität Zürich with 14 publications (3.66%), followed by Peking University Hospital of Stomatology with 13 articles (3.39%). Seoul National University School of Dentistry had the least publications (8 articles) with 2.09%. There are three institutions from USA, South Korea and Germany have two institution each and China, Spain and Switzerland have one institution each in the top 10 institutions.

Figure 6.

The top 10 Institutes with the most published articles related to additive manufacturing for dental implant

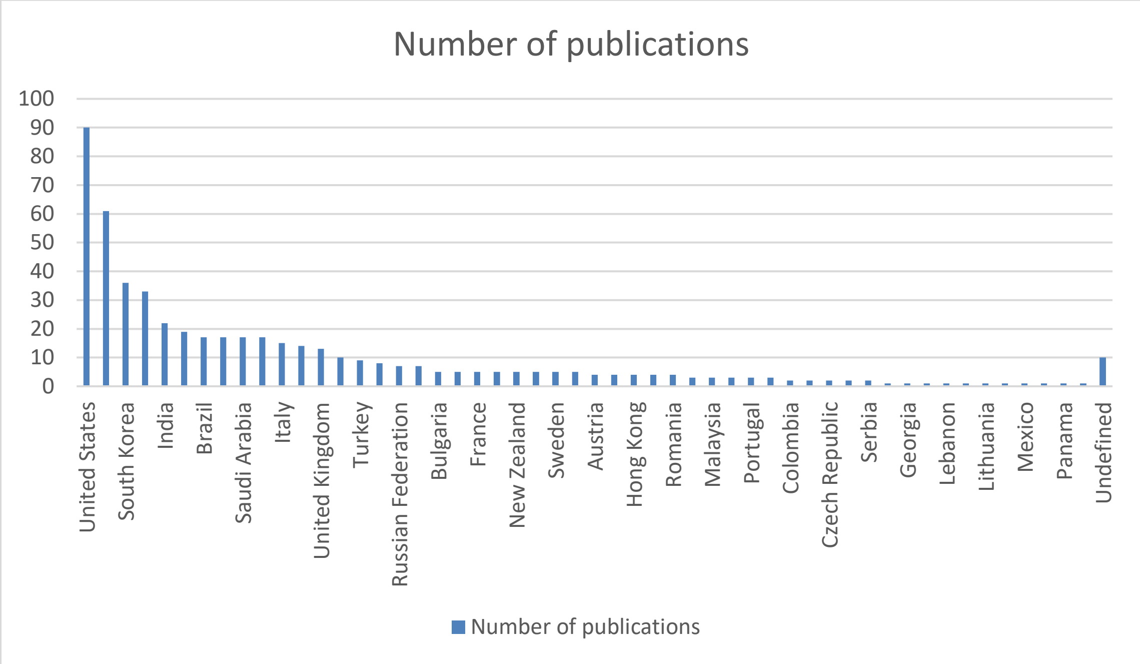


4.1.4 Number of countries with publications related to additive manufacturing for dental implants between 2012-2022

From a total of 383 articles, a total of 53 countries took part in the publication of the article whereas there were 10 publications which were undefine. Figure 9 shows the countries which have carried out research work on our topic of interest. The top ten countries with most publications make up 85.90% (329 articles) of the entire data collected, with the USA being the most productive county with 90 publications (23.50%) followed by China with 61 publications (15.93%) preceded by South Korea with 9.40% (36 articles). The other top ten countries include Germany, India, Switzerland, Brazil, Japan, Saudi Arabia and Spain in descending order of publications, with the last four countries having the same number of publications 17 article each (4.44%). Japan and Belgium have the same number of publication 20 articles each with a sum total of 10.16%. This shows that there is a lot of interest globally in the use of additive manufacturing in the field of dentistry, to provide innovative and personalize medicine to patient's dental.

Figure 7.

Number of countries with publications related to additive manufacturing for dental implants

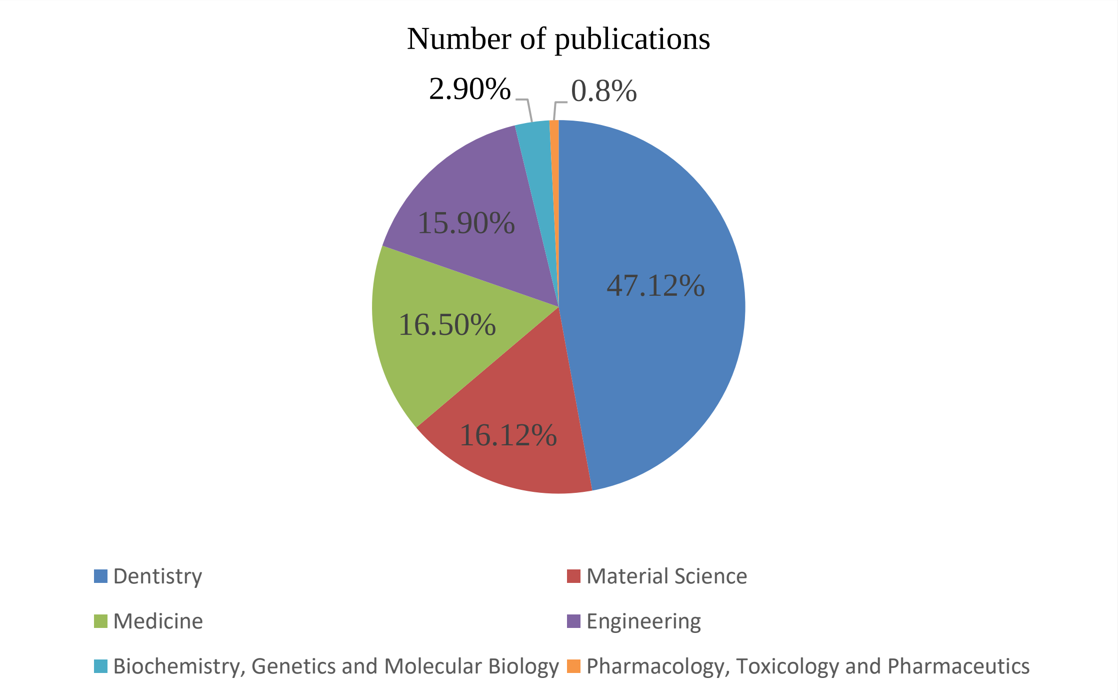


4.1.5 Subject Area of publications related to additive manufacture for dental implants

We limited the subject area to six research area namely: dentistry, material science, engineering, medicine, biochemistry, genetics and molecular biology, and pharmacology, toxicology and pharmaceutics as shown in figure 10. The field of dentistry had the greatest percentage of research publication (47.12%), followed by Material Science with 16.70%, Medicine 16.50%, Engineering 15.90%, Biochemistry, Genetics and Molecular Biology 2.98% and Pharmacology, Toxicology and Pharmaceutics 0.80%.

Figure 8.

Research Areas of published articles



4.1.6 Top ten Authors with publications related to additive manufacturing for dental implants

There are many researchers with numerous publications related to the use of additive manufacturing in the field of dentistry specifically for dental implants and other related dentary studies. Table 3 shows the top ten authors with most publications based on the data exported from Scopus (383 articles). Revilla-León, M. has the highest number of publications (14 articles) followed by Özcan, M. with12 articles. Four authors have 6 publications each and the last of the ten top authors has 5 publications. However, there a lot of authors working on the topic with many publications from different fields of studies. This illustrates that there is more interest in research on additive manufacturing and its applications in the field of dentistry and other related fields of studies such as prosthetics, general as well as personalized medicine, biomaterials and production of medical devices.

Table 3.

Top ten Authors with published work related to Additive manufacturing for dental implants

Authors	Affiliation (institute)	Country	Number of Publications
Revilla-León, M.	University of Washington	United States	14
Özcan, M.	Universität Zürich,	Switzerland	12
Spintzyk, S.	Fachhochschule Kärnten	Austria	11
Lin, W.S.	Indiana University School of Dentistry	United States	10
Sun, Y.	Peking University Hospital of Stomatology	China	7
Gad, M.M.	Imam Abdulrahman Bin Faisal university	Saudi Arabia	6
Li, P.	Southern Medical University	China	6
Morton, D.	Indiana University School of Dentistry	United States	6
Wang, Y.	Peking University Hospital of Stomatology	China	6
Beuer, F.	Berliner Institut für Gesundheitsforschung	Germany	5

4.1.7 Top five most cited publications related to additive manufacturing for dental implants

In this section, a summary of the five most cited articles within the ten years period will be given. The five most cited article are presented in table 4 below.

The most cited article is “3D printed versus conventionally cured provisional crown and bridge dental materials” published in 2018 by Dental material with 183 citations. In this article, the main objective of the researchers was to find out the printability and in-vitro performance of marketed 3D printable dental materials, to make temporary restoration (Crown & Bridge) with the use of a comparatively cheap stereolithography 3D printer (FormLabs1+) compared to CAD/CAM systems. That is, they enhanced the 3D printing of a dental material for temporary crown and bridge restorations with the use of a cheap 3D stereolithography printer; and made comparison of their mechanical properties to those made using conventional methods. They started by enhancing a couple of parameters that are needed for better 3D printing of the available dental materials, used to make crown and bridge, after which they put to test a hypothesis that 3D printing makes production of temporary restorative materials (crown and bridge) with properties compared to those of conventionally used clinical products. After carrying out the research they came up with the conclusion that despite the limitation in the accuracy of the 3D printed object using the 3D printing system, the object printed (provisional crown and bridge) had sufficient mechanical properties to be used for intraoral provisional restoration (Tahayeri et al., 2018)

The second most cited article is “Carbon fiber reinforced PEEK composites based on 3D-printing technology for orthopedic and dental applications” published in 2019 by Journal of Clinical Medicine, having 156 citations. Here the researcher’s main purpose was to examine the mechanical properties and microstructures of PEEK and CFR-PEEK samples produced using an AM technology known as Fused Deposition Model. However, they particularly focused on the effect treated surfaces has on the adhesion of cells an whether FDM process produce or introduce toxic chemicals. At the end of their research, they discovered that the objects printed with pure PEEK had mechanical properties compared to those made via traditional methods like extrusion techniques. On the other hand, those made from Carbon fibers reinforced PEEK showed significantly improved mechanical properties in comparison to those made of pure PEEK. Also, the surfaces of objects made using FDM had better roughness that couldn’t be obtained via the typical dental sandblasting processes, with surfaces more fitted for spreading and attachment of cells compared to those polished and sandblasted. Thus CFR-PEEK materials printed via FDM have good mechanical properties with a lot of potentials for used as biomaterial in dental and bone regeneration applications (Han et al.,2019)

The third most cited article is “3D-printing zirconia implants; a dream or a reality? An in-vitro study evaluating the dimensional accuracy, surface topography and mechanical properties of printed zirconia implant and discs” published in 2017 with 105 citations. The research was aimed at evaluating the surface topography and accuracy of customized zirconia dental implant printed via DLP technology and the flexure strength of the material printed. The researchers used an in-vitro experiment to check the mechanical properties and surface topography of the printed implant and used digital subtraction to technique to evaluate the dimensional accuracy. Their result showed that DLP prove to be efficient for printing customized zirconia dental implants with sufficient dimensional accuracy. The mechanical properties showed flexure strength close to those of conventionally produced ceramics. Optimization of the 3D-printing process parameters is still needed to improve the microstructure of the printed objects (Osman et al., 2017)

The fourth most cited article was "Poly(methyl methacrylate) with TiO2 nanoparticles inclusion for stereolithographic complete denture manufacturing − the future in dental care for elderly edentulous patients?" with 95 citations published in 2017 by Journal of Dentistry. The main objective of the research was to get PMMA-TiO2 nanocomposite materials with enhanced qualities like antimicrobial ones good for making 3D printed dental prosthesis. The results from the research showed that the addition of TiO2 nanocomposite enhance the structure and particular properties of PMMA, like antibacterial effects (their study showed antibacterial effect on *Candida* species) They further successfully made use of stereolithography technology for the complete fabrication of dentures with the newly gotten PMMA-TiO2 nanocomposite (0.4%) (Totu et al., 2017)

The firth most cited article is published by The Journal of Prosthetic Dentistry in 2020 titled "Printing accuracy, mechanical properties, surface characteristics, and microbial adhesion of 3D-printed resins" with over 93 citations. in this publication, the researcher's main gold was to examine the effect, printing orientation has on the accuracy, flexible strength, surface attributes and microbial response on 3D printed dentures. They postulated as their null hypothesis that printing orientation will have the same print accuracy, toughness, surface attributes, and response to C. albicans. The researchers made use PMMA to 3D print specimens (dentures) on different orientation (that is 0, 45, and 90 degrees), and then evaluation of the accuracy, flexibility, surface roughness, hydrophilicity, surface energy and response to Candida albicans were caried out. Their results showed that:

- specimens printed at 90-degree orientation had least error rates for length, those printed at 45-degree orientation had the greatest error rates for thickness
- Specimens printed at 0-degree orientation had the greatest flexibility strength, preceded by 45- and 90-degrees orientations.
- The specimens printed at 0-degree orientation had the greatest number of C. albicans on their surface, preceded by 45- and 90-degrees printing orientation thus the null hypothesis was rejected.

The findings of the top five most cited articles shows a lot of promise in the use of additive manufacturing for making of dental implants, and the great potentials and opportunities offered by this technology to improve on dental outcome of patients by providing widows of opportunities where by materials used to make dental implants can be enhanced as well as the final outcome of dental implantation. The researchers made use of two main AM technologies SLA and FDM in carrying out their research work which is in line with our findings that SLA is the most used technology in the field of dentistry.

Table 4.

Top five most cited articles related to Additive Manufacturing for Dental Implant

Ranking	Authors	Title of Articles	Journal	Year of Publications	Number of citations
1	Anthony Tahayeri, Mary Catherine Morgana, Ana P. Fugolina, Despoina Bompolaki, Avathamsa Athirasala, Carmem S. Pfeifer Jack L. Ferracane a, Luiz E. Bertassoni	3D printed versus conventionally cured provisional crown and bridge dental materials	Dental material	2018	183
2	Han Xingting, Yang Dongb, Yang Chuncheng, Spintzyk Sebastian, Scheideler Lutz, Li Ping, Li Dichen, Geis-Gerstorfer Jürgen, Rupp, Franka	Carbon fiber reinforced PEEK composites based on 3D-printing technology for orthopedic and dental applications	Journal of Clinical Medicine	2019	156

Table 4 (Continued).

3	Osman Reham B, van der Veen Albert, Huiberts Dennisb, Wismeijer Danielb, Alharbi Nawal	3D-printing zirconia implants; a dream or a reality? An in-vitro study evaluating the dimensional accuracy, surface topography and mechanical properties of printed zirconia implant and discs	Journal of the Mechanical Behavior of Biomedical Materials	2017	105
4	Eugenia Eftimie Totu, Aurelia Cristina Nechifor, Gheorghe Nechifor, Hassan Y.Aboul-Enein, Corina Marilena Cristache	Poly(methyl methacrylate) with TiO2 nanoparticles inclusion for stereolitographic complete denture manufacturing − the future in dental care for elderly edentulous patients?	Journal of Dentistry	2017	95
5	Ji Suk Shim DDS PhD, Jong-Eun Kim DDS, PhD, Sang Hoon Jeong PhD, Yeon Jo Choi DDS, PhD, Jae Jun Ryu DDS, PhD	Printing accuracy, mechanical properties, surface characteristics, and microbial adhesion of 3D-printed resins with various printing orientations	The Journal of Prosthetic Dentistry	2020	93

4.2. The Co-Authorship Analysis on additive manufacturing for dental implants.

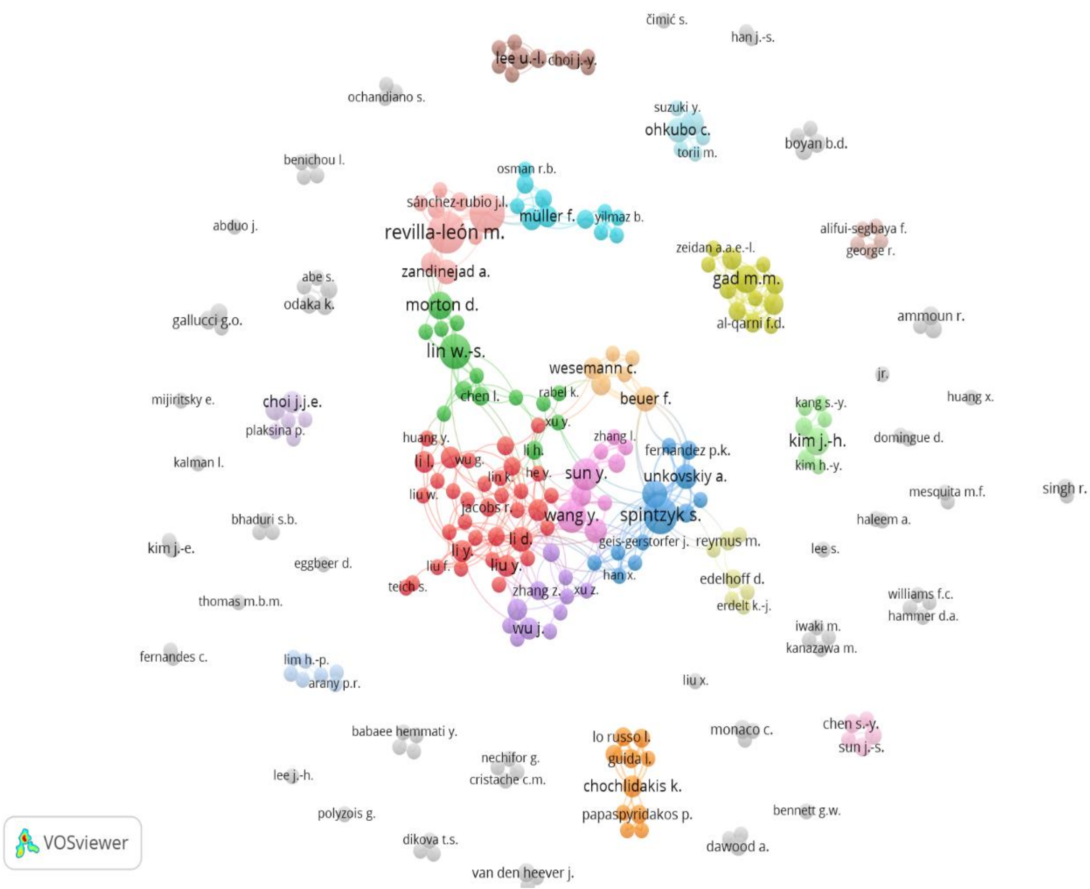
With the use of the VOSviewer software package, the data collected from Scopus was visualized though various co-authorship analysis (authors institutions and countries) to show how researchers are collaborating. The lines or circles shows the relationship or link existing between authors, institutions, countries that are carrying out research related to this topic. The strength, influence or productivity of this relationship is denoted by the size and number of circles.

4.2.1. Authors Co-authorship Analysis

In carrying out the analysis, we set the least number of documents and citation of an author at 2 and 0 respectively. With these settings, out of 1500 authors, a total of 263 fulfilled this condition and we selected for visualization. Also out of the 263 authors, 114 author had the greatest set of connected items. Figure 11 illustrates the authors co-authorship analysis of additive manufacturing for dental implant publications by the 263 selected authors, having a total of 54 clusters, 599 links and 973 total link strength. Spintzyk, S. has the greatest links (18), link strength (37) with 11 documents and 259 citations base on the map below. The circles depict authors and the lines shows the relationship between authors. From the map there are many authors working in collaboration with others, however the relationships are not very strong and interconnected.

Figure 9.

VOSviewer Authors Co-authorship Network on Published articles on Additive Manufacturing for Dental Implants.

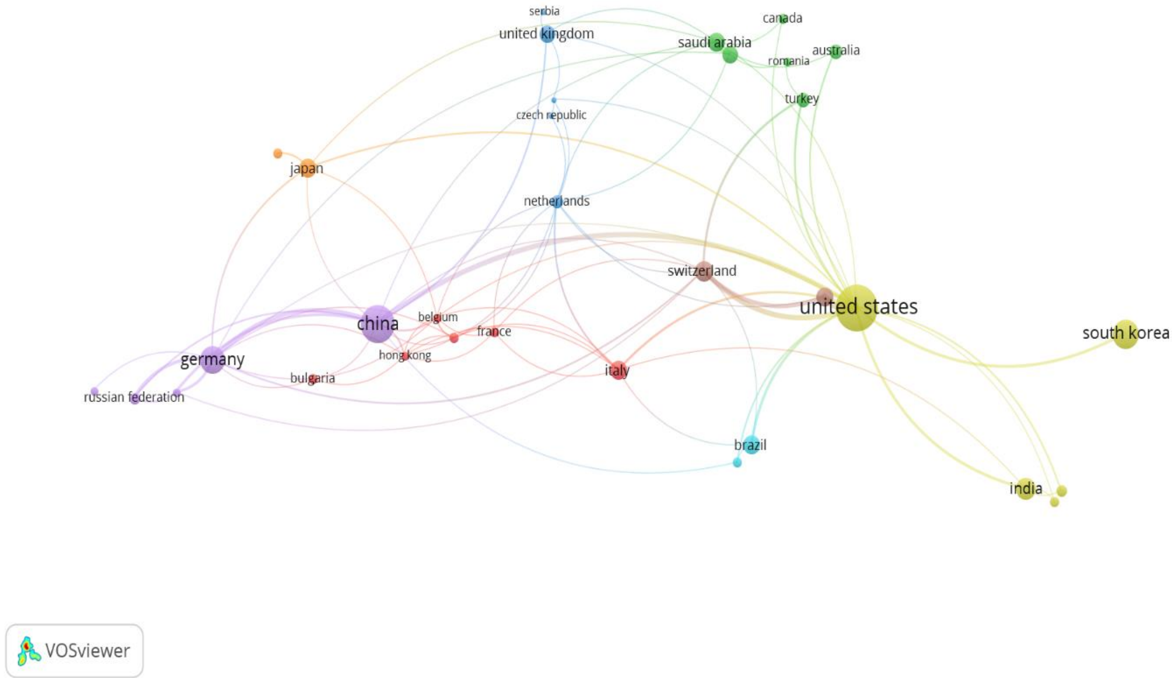


4.2.2. Countries Co-authorship Analysis

Figure 12 show the Countries co-authorship map of published articles related to additive manufacturing for dental implants. The least number of documents and citation of a country was set at 2 and 0 respectively. With these settings, out of 53 countries, a total of 42 fulfilled this condition and were visualized. The greatest connectivity was seen between 34 countries. USA being the most productive country with 20 links, 65 total link strength and 1168 citations. From the map, it can be seen that there is strong collaboration between researchers from different counties. The USA is the country with the highest link or cooperation with other countries, preceded by China, Germany and Switzerland. Nevertheless, there are some countries which are isolated in their research studies. Also from the map, it shows that most of the countries taking part in the research are from the developed countries. This might be due to the fact that in most developing countries there are other more challenging health problems where more attention is focused on and also few persons suffering from dental carries compared to the developed countries, and also the lack of finances and equipment to undertake research related to additive manufacturing. However, the map shows the wide spread of research on additive manufacturing for dental implants.

Figure 10.

VOSviewer Countries Co-authorship Network on Published articles on Additive Manufacturing for Dental Implants.



CHAPTER V

DISCUSSIONS

There has been is a growing interest in the use of additive manufacturing in various engineering fields, due to the numerous potentials this technology offers. This study aimed at appraising the various additive manufacturing technologies, biomaterials used for dental implants as well as the trends of events in researches on the use of additive manufacturing for dental implants. There has been an increasing demand for dental implants in recent years which could be as a result of the growing aging population worldwide as well as increase in dental decays and the esthetics properties that dental implants offer now. However, patients are not just in demand for dental implants, but they demand for patient specific esthetics implants. With these growing needs for personalized medicine, dentist and surgeons are constantly researching to discover new innovative technologies that will offer patients quality durable dental implants, at a relatively low cost.

Additive manufacturing is a technology capable of making patients specific dental implants with good dental and esthetic properties and accuracy compared to other conventional methods. This technology offers dentist and surgeons greater opportunities in dealing with patients' problems on basis of their specific demands. It makes the work of dentist easy by providing a wide range of techniques and biomaterials which dentist can make use of in making dental implants of different shapes and geometry base on the patients' needs. However, some techniques of AM may be more suitable for used than others as we have seen in the literature above. Furthermore, this technology makes use of different types of biomaterials separately or in combination for the making of dental implants. With a lot of research ongoing in the field of material science, it is possible that new and better biomaterials which promote dental osseointegration and healing after placement of implants with minimal post implants side effects may be discovered and utilized.

With a shift from generalized medicine to customized or personalized medicine, the field of dentistry is not left behind as dentist and surgeons are constantly carrying out research developing and providing their patients with customized implants. According to Kriegseis, et al., (2022) there is a growing demand from patients for personalized medicine in the field of dentistry. Additive manufacturing has a lot of potentials in promoting the personalized medicine since the various technologies of AM can be tailored to produce implants based on a patient specificity. Exploring the potentials of additive manufacturing will go a long way to provide safe, long lasting and comfortable implants, with good esthetic properties thus boosting self-esteem and better quality of life.

In terms of the market value, it has been reported that, 3D dental printing as of the year 2022 is valued at about 2.5 billion dollars with an expected compound annual growth rate (CAGR) of about 26.1% from 2023 to 2030 globally. This illustrates a continues increase in the growth of 3D dental printers in the market. This technology is rapidly growing as seen from our data extracted from Scopus and is currently dominating the field of dentistry specifically and other disciplines as well. The demand and adoption of this technologies stems from its ability to using in combination with other digital imaging technologies to design and fabricate excellent dental products at a fast rate with less protocol, enhancing patient comfort and satisfaction.

From our analysis of the data collected, we observed a general growth in the publication of research work related to the use of additive manufacturing for dental implant globally. In addition to this, existing literature, show a shift general to personalized or customized dental implants. Apart from increasing publications, there is also a strong research collaboration between researchers, countries and institutions in research related to additive manufacturing for dental implants. The USA is the most productive country with a lot of publications and collaboration between researchers from different intuition within USA and other countries. This shows our research results are in line with report from other researchers who reported the dominance of USA 3D dental market in the market which is postulated to continue as such till about 2030. The increasing demand for cosmetics dentistry, increasing aging population, increase awareness for the need of good of oral health as well as advancement in technology are some of the reasons for the increasing market growth. China was the second most productive country preceded by Germany. Despite the collaboration observed between researchers from different countries, there were a couple of countries like Greece, Poland, Norway etc. which do not collaborate with other countries. Also, most of the countries involve in the research are developed countries, this might be as a result of the high cost in purchasing equipment or good healthcare facilities which is not the case with developing countries. Further the growing number of citations indicates that a lot of research is been carried out on additive manufacturing for dental implants. Our results also show research funding from different organizations and state institutions. importance of additive manufacturing.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

According to our study, the USA is the leading country followed by China in research related to additive manufacturing for dental implants. Also, there is good collaboration between researchers from different universities and countries although there are some countries still working in isolation. In addition, there is an increasing number of publications as the years goes by and there are many organizations which are helping in the funding of theses researches. These are pointers that this is a topic of interest for researchers in the field of dentistry as well as other fields like material science. Thus, we can conclude that, there is a growing global adoption of the use of additive manufacturing in the field of dentistry to make dental implants and other dental products. The technology will in the future change the way dentist and surgeons perform their work, making it easier, cheaper and safer for dental placement. Also, additive manufacturing will be able to fabricate dental implants, dentures and other dental products with a variety of materials that are biocompatible at a relatively lesser cost, as well as promoting collaboration between dentist, surgeons and laboratories which will enhance development and provision personalized dentistry. Furthermore, with increasing research studies, new innovative and advanced techniques will be discovered which will go a long way to readily make available the need of patients, that are in constant increase. AM will in the future make the field of dentistry digital. The currently available additive manufacturing techniques offer special advantages for production of dental implants. They are used to fabricate implants of very complex structures with excellent resolution, accuracy, and good mechanical and rhetological properties with very little waste of materials. With the help of 3D dental scanner, the mouth of patients can be scanned and a 3D printed model is fabricated in the lab that will fit the patient thus aiding surgical implants and personalized dentistry. This technology also provides greater research and practice opportunities for dentist and surgeons before working on patients. Also, from our research, stereolithography is the most commonly used additive manufacturing technology in the field of dentistry currently. However, with continuous research and advances in the field of material science, 4D printing will be the technology of the future offering a lot of opportunities and features that cannot be provided by 3D printing.

Nevertheless, we recommend more research to be done in order to discover new techniques that will be able to overcome some of the limitations of the available techniques of AM. Also, governmental health policies that promote research in all countries should be put in place especially in developing countries. we recommend and encourage the sharing of knowledge and ideas between countries as well as put in place policies that promote research in developing countries.

Despite the compelling results, our study had some limitations: the data was sourced only from Scopus database and VOSviewer was the only visualization tool used. Subsequent studies should make use of multiple database source like PubMed, google scholar and two or more visualization tools in order to ascertain the research work been carried out.

REFERENCE

Ahmed, A., Arya, S., Gupta, V., Furukawa, H., & Khosla, A. (2021). 4D printing: Fundamentals, materials, applications and challenges. *Polymer*, *228*, 123926.

Alghamdi, H. S. (2018). Methods to improve osseointegration of dental implants in low quality (type-IV) bone: an overview. *Journal of functional biomaterials*, *9*(1), 7.

Alsalla, H. H., Smith, C., & Hao, L. (2018). The effect of different build orientations on the consolidation, tensile and fracture toughness properties of direct metal laser sintering Ti-6Al-4V. *Rapid Prototyping Journal*, *24*(2), 276-284.

Breeland, G., Sinkler, M. A., & Menezes, R. G. (2021). Embryology, bone ossification. In *StatPearls [Internet]*. StatPearls Publishing.

Bordenave, J. M. G. (2021). Zirconia Implants vs Titanium Implants.

Chang, B., Ahuja, N., Ma, C., & Liu, X. (2017). Injectable scaffolds: Preparation and application in dental and craniofacial regeneration. *Materials Science and Engineering: R: Reports*, *111*, 1-26.

Chen, J., Zhang, Z., Chen, X., Zhang, C., Zhang, G., & Xu, Z. (2014). Design and manufacture of customized dental implants by using reverse engineering and selective laser melting technology. *The Journal of prosthetic dentistry*, *112*(5), 1088-1095.

Chin, S. Y., Dikshit, V., Meera Priyadarshini, B., & Zhang, Y. (2020). Powder-based 3D printing for the fabrication of device with micro and mesoscale features. *Micromachines*, *11*(7), 658.

Contreras, F., & Abid, G. (2022). Social sustainability studies in the 21st century: A bibliometric mapping analysis using VOSviewer Software. *Pakistan Journal of Commerce and Social Sciences (PJCSS)*, *16*(1), 167-203.

Da Silva, L. R. R., Sales, W. F., Campos, F. D. A. R., de Sousa, J. A. G., Davis, R., Singh, A., ... & Borgohain, B. (2021). A comprehensive review on additive manufacturing of medical devices. *Progress in Additive Manufacturing*, *6*(3), 517-553.

Dawood, A., Marti, B. M., Sauret-Jackson, V., & Darwood, A. (2015). 3D printing in dentistry. *British dental journal*, *219*(11), 521-529.

Debdatta Ratna, (2022) Properties and processing of thermoset resin. *Recent Advances and Applications of Thermoset Resins* (Second Edition), Elsevier, 173-292.

Della Bona, A., Cantelli, V., Britto, V. T., Collares, K. F., & Stansbury, J. W. (2021). 3D printing restorative materials using a stereolithographic technique: A systematic review. *Dental Materials, 37*(2), 336-350.

Demiralp, E., DOĞRU, G., & Yilmaz, H. (2021). Additive manufacturing (3D PRINTING) methods and applications in dentistry. *Clinical and Experimental Health Sciences*, *11*(1), 182-190. https://doi.org/10.1016/B978-0-323-85664-5.00003-X.

Denry, I., & Kelly, J. R. (2014). Emerging ceramic-based materials for dentistry. *Journal of dental research*, *93*(12), 1235-1242.

Dizon, J. R. C., Espera Jr, A. H., Chen, Q., & Advincula, R. C. (2018). Mechanical characterization of 3D-printed polymers. *Additive manufacturing, 20*, 44-67.

Dudley, J. (2015). Implants for the ageing population. *Australian dental journal*, *60*, 28-43.

Feller, L., Chandran, R., Khammissa, R. A. G., Meyerov, R., Jadwat, Y., Bouckaert, M., ... & Schechter, I. (2014). Osseointegration: biological events in relation to characteristics of the implant surface: clinical review. *South African Dental Journal*, *69*(3), 112-117.

Galante, R., Figueiredo-Pina, C. G., & Serro, A. P. (2019). Additive manufacturing of ceramics for dental applications: A review. *Dental materials, 35*(6), 825-846.

Guo, Y., Patanwala, H. S., Bognet, B., & Ma, A. W. (2017). Inkjet and inkjet-based 3D printing: connecting fluid properties and printing performance. *Rapid Prototyping Journal*, *23*(3), 562-576.

Han, J., Zhao, J., & Shen, Z. (2017). Zirconia ceramics in metal-free implant dentistry. *Advances in Applied Ceramics*, *116*(3), 138-150.

Han, X., Yang, D., Yang, C., Spintzyk, S., Scheideler, L., Li, P., ... & Rupp, F. (2019). Carbon fiber reinforced PEEK composites based on 3D-printing technology for orthopedic and dental applications. Journal of clinical medicine, 8(2), 240.

Hanif, A., Qureshi, S., Sheikh, Z.A., & Rashid, H.U. (2017). Complications in implant dentistry. *European Journal of Dentistry, 11*, 135 - 140.

He, R., Zhou, N., Zhang, K., Zhang, X., Zhang, L., Wang, W., & Fang, D. (2021). Progress and challenges towards additive manufacturing of SiC ceramic. *Journal of Advanced Ceramics*, *10*(4), 637-674.

Hsieh, Y. H. B., Al Deek, N., & Wei, F. C. (2022). Oral Tongue and Mandibular Reconstruction. In Plastic Surgery-Principles and Practice (pp. 334-352). Elsevier.

https://www.grandviewresearch.com/industry-analysis/dental-3d-printing-market

Huang SH, Liu P, Mokasdar A, Hou L (2013) Additive manufacturing and its societal impact: a literature review. Int J Adv Manuf Technol 67:1191–1203. https://doi.org/10.1007/ s00170-012-4558-5

Hudecki, A., Kiryczyński, G., & Łos, M. J. (2019). Biomaterials, definition, overview. In Stem cells and biomaterials for regenerative medicine (pp. 85-98). Academic Press.

Javaid, M., & Haleem, A. (2019). Current status and applications of additive manufacturing in dentistry: A literature-based review. *Journal of oral biology and craniofacial research*, *9*(3), 179-185.

Javaid, M., Haleem, A., Singh, R. P., Rab, S., Suman, R., & Kumar, L. (2022). Significance of 4D printing for dentistry: Materials, process, and potentials. *Journal of Oral Biology and Craniofacial Research*.

Jin, W., & Chu, P. K. (2019). Orthopedic implants. Encyclopedia of biomedical engineering, 1, 3.

Joharji, L., Mishra, R. B., Alam, F., Tytov, S., Al-Modaf, F., & El-Atab, N. (2022). 4D printing: A detailed review of materials, techniques, and applications. *Microelectronic Engineering*, 111874.

Kamali, A. H., Moradi, M., Goodarzian, F., & Ghasemi, P. (2022). A discrete event simulation method for performance analysis of an additive manufacturing in the dental clinic. The International Journal of Advanced Manufacturing Technology, 118(9), 2949-2979.

Kane, S. F. (2017). The effects of oral health on systemic health. Gen Dent, 65(6), 30-34.

Ke, D., Niu, C., & Yang, X. (2022). Evolution of 3D bioprinting-from the perspectives of bioprinting companies. Bioprinting, e00193.

Khabas, T. A., Maletina, L. V., & Kamyshnaya, K. S. (2014, October). Influence of nanopowders and pore–forming additives on sintering of alumma–zircorna ceramics. In *IOP Conference Series: Materials Science and Engineering* (Vol. 66, No. 1, p. 012050). IOP Publishing.

Khanlar, L. N., Salazar Rios, A., Tahmaseb, A., & Zandinejad, A. (2021). Additive manufacturing of zirconia ceramic and its application in clinical dentistry: a review. *Dentistry Journal*, *9*(9), 104.

Khorsandi, D., Fahimipour, A., Abasian, P., Saber, S. S., Seyedi, M., Ghanavati, S., ... & Makvandi, P. (2021). 3D and 4D printing in dentistry and maxillofacial surgery: Printing techniques, materials, and applications. *Acta biomaterialia*, *122*, 26-49.

Konda Gokuldoss, P., Kolla, S., & Eckert, J. (2017). Additive manufacturing processes: Selective laser melting, electron beam melting and binder jetting—Selection guidelines. *materials*, *10*(6), 672.

Kriegseis, S., Aretz, L., Jennes, M. E., Schmidt, F., Tonnesen, T., & Schickle, K. (2022). 3D printing of complex ceramic dental implant abutments by using Direct Inkjet Printing. *Materials Letters*, *313*, 131789.

Lee A, Hudson A, Shiwarski D, Tashman J, Hinton T, Yerneni S, et al. 3D bioprinting of collagen to rebuild components of the human heart. Science 2019;365(6452):482–7.

Li, J., Jansen, J. A., Walboomers, X. F., & van den Beucken, J. J. (2020). Mechanical aspects of dental implants and osseointegration: A narrative review. *Journal of the mechanical behavior of biomedical materials*, *103*, 103574.

Liccardo, D., Cannavo, A., Spagnuolo, G., Ferrara, N., Cittadini, A., Rengo, C., & Rengo, G. (2019). Periodontal disease: a risk factor for diabetes and cardiovascular disease. International journal of molecular sciences, 20(6), 1414.

Liu, X., Chen, S., Tsoi, J. K., & Matinlinna, J. P. (2017). Binary titanium alloys as dental implant materials—a review. *Regenerative biomaterials*, *4*(5), 315-323.

Magazine, R., van Bochove, B., Borandeh, S., & Seppälä, J. (2022). 3D inkjet-printing of photo-crosslinkable resins for microlens fabrication. *Additive Manufacturing*, *50*, 102534.

Mazzoli, A. (2013). Selective laser sintering in biomedical engineering. *Medical & biological engineering & computing*, *51*(3), 245-256.

Mazzoli, A., Ferretti, C., Gigante, A., Salvolini, E., & Mattioli-Belmonte, M. (2015). Selective laser sintering manufacturing of polycaprolactone bone scaffolds for applications in bone tissue engineering. *Rapid prototyping journal*.

Meisel, N. A., Elliott, A. M., & Williams, C. B. (2015). A procedure for creating actuated joints via embedding shape memory alloys in PolyJet 3D printing. *Journal of intelligent material systems and structures*, *26*(12), 1498-1512.

Mierzejewska, Z. A., & Markowicz, W. (2015). Selective laser sintering-binding mechanism and assistance in medical applications. *Advances in materials science*, *15*(3), 5.

Munir, K., Biesiekierski, A., Wen, C., & Li, Y. (2020). Selective laser melting in biomedical manufacturing. *Metallic Biomaterials Processing and Medical Device Manufacturing*, 235-269.

Murugesan, K., Anandapandian, P. A., Sharma, S. K., & Vasantha Kumar, M. (2012). Comparative evaluation of dimension and surface detail accuracy of models produced by three different rapid prototype techniques. *The Journal of Indian Prosthodontic Society*, *12*(1), 16-20.

Navarro, B. G., Sala, X. P., & Salas, E. J. (2017). Relationship between cardiovascular disease and dental pathology. Systematic review. Medicina Clínica (English Edition), 149(5), 211-216.

Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, *143*, 172-196.

Oliveira, T. T., & Reis, A. C. (2019). Fabrication of dental implants by the additive manufacturing method: A systematic review. *The Journal of Prosthetic Dentistry, 122*(3), 270-274.

Önöral, Ö., & Abugofa, A. (2020). Advancements in 3D Printing Technology: Applications and Options for Prosthetic Dentistry. *Cyprus J Med Sci*, *5*(2), 176-83.

Orduña-Malea, E., & Costas, R. (2021). Link-based approach to study scientific software usage: The case of VOSviewer. *Scientometrics*, *126*(9), 8153-8186.

Osman, R. B., van der Veen, A. J., Huiberts, D., Wismeijer, D., & Alharbi, N. (2017). 3D-printing zirconia implants; a dream or a reality? An in-vitro study evaluating the dimensional accuracy, surface topography and mechanical properties of printed zirconia implant and discs. Journal of the mechanical behavior of biomedical materials, 75, 521-528.

Ozdinc, S., Unlu, E., Oruc, O., User, N. N., & Karakaya, Z. (2015). An unusual infection of cervicofacial area caused by dental pathology: flesh-eating syndrome. The American Journal of Emergency Medicine, 33(10), 1543-e3.

Parithimarkalaignan, S., & Padmanabhan, T. V. (2013). Osseointegration: an update. The Journal of Indian Prosthodontic Society, 13(1), 2-6.

Prakash, D., Davis, R., & Sharma, A. K. (2019, October). Design and fabrication of dental implant prototypes using additive manufacturing. In *IOP Conference Series: Materials Science and Engineering* (Vol. 561, No. 1, p. 012041). IOP Publishing.

Revilla-León, M., & Özcan, M. (2019). Additive manufacturing technologies used for processing polymers: current status and potential application in prosthetic dentistry. *Journal of Prosthodontics*, *28*(2), 146-158.

Ribeiro, I., Matos, F., Jacinto, C., Salman, H., Cardeal, G., Carvalho, H., ... & Peças, P. (2020). Framework for life cycle sustainability assessment of additive manufacturing. Sustainability, 12(3), 929.

Robles Martinez, P., Basit, A. W., & Gaisford, S. (2018). The history, developments and opportunities of stereolithography. In *3D Printing of Pharmaceuticals* (pp. 55-79). Springer, Cham.

Rodriguez, A. E., Monzavi, M., Yokoyama, C. L., & Nowzari, H. (2018). Zirconia dental implants: A clinical and radiographic evaluation. *Journal of Esthetic and Restorative Dentistry*, *30*(6), 538-544.

Romero-Resendiz, L., Gómez-Sáez, P., Vicente-Escuder, A., & Amigó-Borrás, V. (2021). Development of Ti–In alloys by powder metallurgy for application as dental biomaterial. *Journal of Materials Research and Technology*, *11*, 1719-1729.

Saffarzadeh, M., Gillispie, G. J., & Brown, P. (2016, April). Selective Laser Sintering (SLS) rapid protytping technology: A review of medical applications. In *53rd Annual Rocky Mountain Bioengineering Symposium, RMBS 2016 and 53rd International ISA Biomedical Sciences Instrumentation Symposium* (pp. 142-149).

Salmi, M., Tuomi, J., Paloheimo, K. S., Björkstrand, R., Paloheimo, M., Salo, J., ... & Mäkitie, A. A. (2012). Patient-specific reconstruction with 3D modeling and DMLS additive manufacturing. *Rapid Prototyping Journal*.

Sefene, E. M. (2022). State-of-the-art of selective laser melting process: A comprehensive review. Journal of Manufacturing Systems, 63, 250-274.

Selvaraj, S. K., Prasad, S. K., Yasin, S. Y., Subhash, U. S., Verma, P. S., Manikandan, M., & Dev, S. J. (2022). Additive manufacturing of dental material parts via laser melting deposition: A review, technical issues, and future research directions. Journal of Manufacturing Processes, 76, 67-78.

Sheikh, A., Abourehab, M. A., & Kesharwani, P. (2022). The clinical significance of 4D printing. *Drug Discovery Today*, 103391.

Shim, J. S., Kim, J. E., Jeong, S. H., Choi, Y. J., & Ryu, J. J. (2020). Printing accuracy, mechanical properties, surface characteristics, and microbial adhesion of 3D-printed resins with various printing orientations. The Journal of prosthetic dentistry, 124(4), 468-475.

Shin, H., Ko, H., & Kim, M. (2016). Cytotoxicity and biocompatibility of Zirconia (Y-TZP) posts with various dental cements. *Restorative dentistry & endodontics*, *41*(3), 167-175.

Tahayeri, A., Morgan, M., Fugolin, A. P., Bompolaki, D., Athirasala, A., Pfeifer, C. S., ... & Bertassoni, L. E. (2018). 3D printed versus conventionally cured provisional crown and bridge dental materials. Dental Materials, 34(2), 192-200.

Thakral, G. K., Thakral, R., Sharma, N., Seth, J., & Vashisht, P. (2014). Nanosurface–the future of implants. *Journal of Clinical and Diagnostic Research: JCDR*, *8*(5), ZE07.

Totu, E. E., Nechifor, A. C., Nechifor, G., Aboul-Enein, H. Y., & Cristache, C. M. (2017). Poly (methyl methacrylate) with TiO2 nanoparticles inclusion for stereolitographic complete denture manufacturing− the fututre in dental care for elderly edentulous patients?. Journal of dentistry, 59, 68-77.

Vanderploeg, A., Lee, S. E., & Mamp, M. (2017). The application of 3D printing technology in the fashion industry. *International Journal of Fashion Design, Technology and Education*, *10*(2), 170-179.

Veiga, C., Davim, J. P., & Loureiro, A. J. R. (2012). Properties and applications of titanium alloys: a brief review. *Rev. Adv. Mater. Sci*, *32*(2), 133-148.

Vignesh, M., Ranjith Kumar, G., Sathishkumar, M., Manikandan, M., Rajyalakshmi, G., Ramanujam, R., & Arivazhagan, N. (2021). Development of biomedical implants through additive manufacturing: A review. *Journal of Materials Engineering and Performance*, *30*(7), 4735-4744.

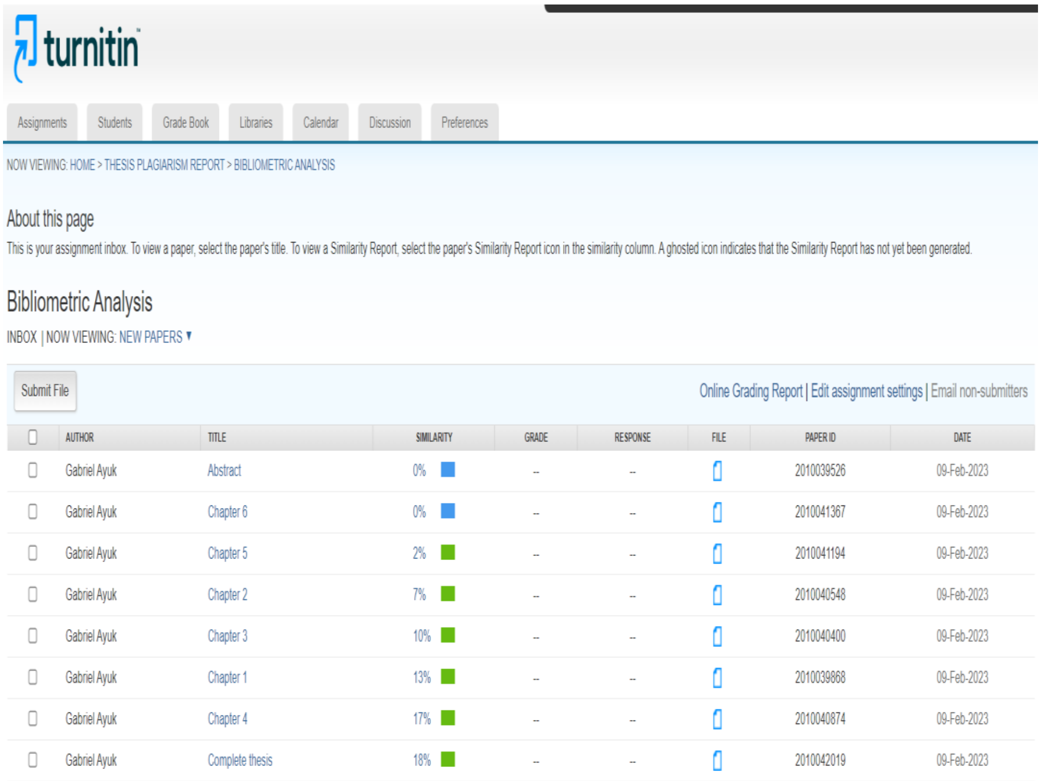
Wu H, Cheng Y, Liu W, He R, Zhou M, Wu S, Song X, Chen Y (2016) Efect of the particle size and the debinding process on the density of alumina ceramics fabricated by 3D printing based on stereolithography. Ceram Int 42:17290–17294

Zhang, F., Spies, B. C., Willems, E., Inokoshi, M., Wesemann, C., Cokic, S. M., ... & Rabel, K. (2022). 3D printed zirconia dental implants with integrated directional surface pores combine mechanical strength with favorable osteoblast response. *Acta Biomaterialia*, *150*, 427-441.

APPENDICES

Appendix A:

Turnitin Similarity Report



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