CHAPTER 1

INTRODUCTION

1. Introduction

The introduction chapter provides a quick overview of the significance of the current research on the developed bioactive composites and the various characterizations employed to describe the biocomposite system. It also briefly discusses several properties: *in-vitro* bioactivity, *in-vitro* cellular viability, antibacterial effectiveness, and biodegradation response, along with the machinability and tribological behavior of bioceramic composites. At the end of this chapter, a detailed explanation of the thesis's structure is provided.

1.1 Background

Presently, the rising incidence of road accidents and the progressive decline in the physio-mechanical characteristics of bones have spurred demand for the substitution of organs and bones with artificial components. The annual increase in cases of musculoskeletal disorders, such as osteoarthritis, rheumatoid arthritis, and osteonecrosis, further fuels this demand. Joint replacement is a common surgical intervention aimed at alleviating pain and disability in individuals with these conditions. Consequently, there is a growing need for innovative implant biomaterials that are suitable for both soft and hard tissues. The absence of appropriate biomaterial selection often leads to implant failure, necessitating revision surgery for patients (Ivanova *et al.*, 2014).

Revision surgery for joint replacement is a procedure conducted after the initial surgery, typically prompted by issues such as implant loosening, infections, and persistent pain. These revision surgeries often entail higher costs and occasionally pose greater complexity compared to the primary joint replacement procedure. Implant loosening, accounting for approximately 70% of revision surgery cases, occurs when bone implants become mechanically unstable. This instability is primarily attributed to the stress shielding effect resulting from the high Young's modulus of the chosen material. Consequently,

significant efforts have been directed toward the development of implant materials to minimize the need for revision surgeries (www.precedenceresearch.com). Continuing these efforts, zirconia, alumina, and zirconia-alumina composites have emerged as the most prevalent and suitable biomaterials within the field of bone tissue engineering. The biomaterials are not only used in bone and dental but also have applications in wound healing, neurology, plastic surgery, etc. The biomaterials market shares by application in 2022 (%) are given in Fig 1.1.

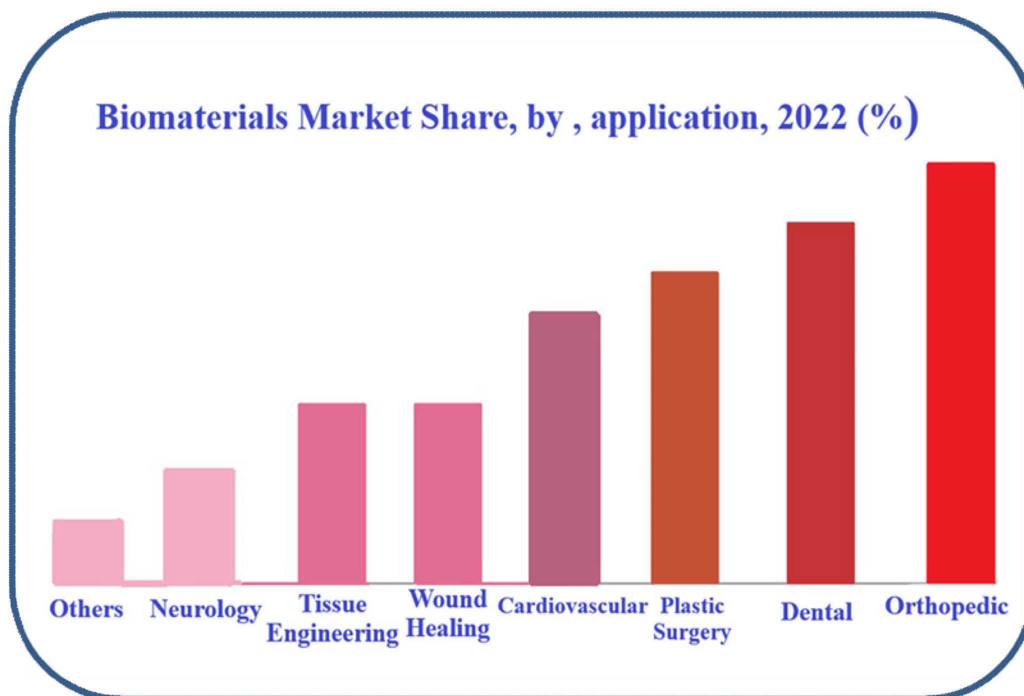

Fig.1.1 Biomaterials market share by application in different biomedical fields (www.precedenceresearch.com)

Biomaterials region-wise market share (%) in 2022 is shown in Fig 1.2. North America leads the world's biomaterials market in revenue because of many initiatives implemented by governmental and private entities. The National Institute of Standards and Technology (NIST) and the National Science Foundation (NSF) are among the institutions offering support and information about the use of biomaterials in diverse biomedical applications. On

the other hand, the Asia Pacific anticipated witnessing the fastest growth during the analysis period.

The present thesis focuses on investigating various ceramic-ceramic composites based on zirconia and alumina, which hold promise for applications in load-bearing bio-implants. This research involves reinforcing zirconia and alumina matrices with bioactive glass to enhance their properties. Consequently, it is necessary to delve into the specifics of zirconia, alumina, their composites with bioactive glass, and other biomaterials such as bioceramics, as outlined below.

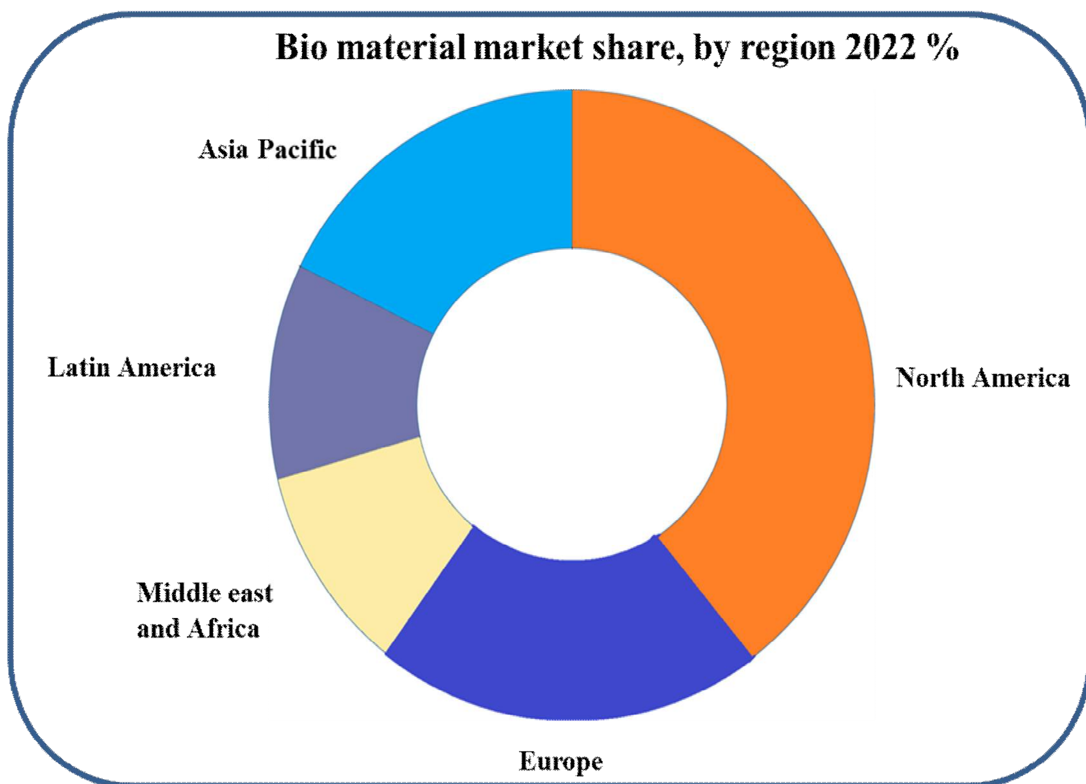

Fig.1.2 Biomaterials materials market share (%) in 2022 (www.precedenceresearch.com).

1.2 Biomaterials

A synthetic biomaterial is a purposefully engineered substance designed to interact with biological systems (Hussain *et al.*, 2019). It's defined in two classical ways: firstly, as a

material utilized to form devices that can replace or mimic body functions safely, reliably, economically, and in a physiologically compatible manner (Hench *et al.*,1982). Secondly, it refers to materials, whether synthetic or natural, that come into contact with tissue, blood, and biological fluids and are intended for prosthetic, diagnostic, therapeutic, or storage purposes without causing harm to living organisms or their components (Bruck *et al.*, 1980). The market for biomaterials is predicted to increase at a notable compound annual growth rate (CAGR) of 12.3% from 2023 to 2032, from its valuation of USD 135.87 billion in 2022 to USD 431.49 billion by 2032 (www.precedenceresearch.com), as shown in Fig.1.3.

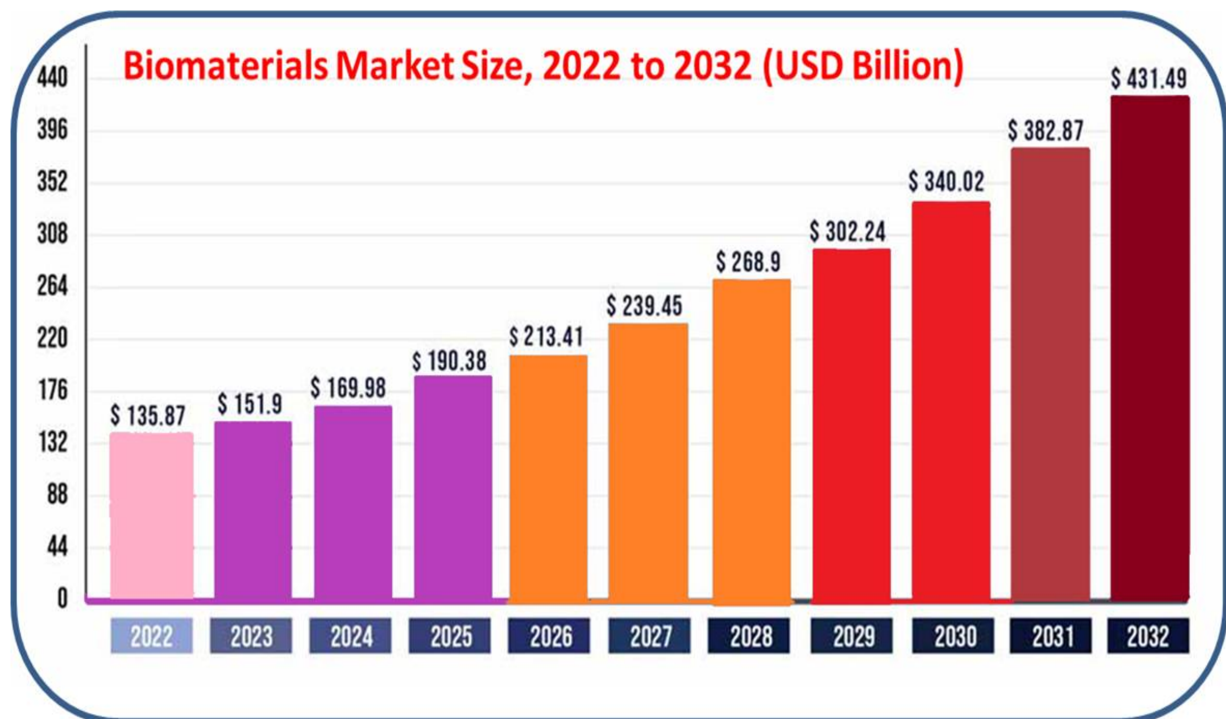

Fig.1.3 Globally forecasted growing market size trends for biomaterials development (www.precedenceresearch.com).

1.2.1 Application of biomaterials

Biomaterials play a crucial role in repairing damaged body parts by interacting with living systems. In orthopedics, these biomaterial devices are commonly referred to as implants. Examples of biomaterial implants used in the human body are given in Table 1.1.

Table 1.1 Application of biomaterials as synthetic organs (Parida et al., 2012).

S. No.	Organs	Replaced by synthetic organs
1.	Heart	Cardiac pacemaker, artificial valve
2.	Ear	Artificial stapes, cochlea implant
3.	Eye	Conatct lens, intraocular lens
4.	Bone	Bone plate, intramedullary rod
5.	Kidney	Catheters, stent, kidney dialysis machine
6.	Bladder	Catheter and stent
7.	Dental	Jaw, enamel

1.2.2 Desirable properties of biomaterials

Many unique biomaterial characteristics to be used in medical applications to optimize functional outcomes are shown in Fig.1.4. Biomaterials need to be precisely shaped and sized to match the section of the organic part that needs to be replaced. The replacement part's surface also needs to have a precise roughness to promote biological integration with the tissues or skeleton and induce cell adhesion.

For these biomaterials to be effective, they should possess the following desirable properties (Ghalme *et al.*, 2016):

- **Mechanical Properties**: It's crucial for materials to exhibit high strength to endure heavy loads while having a low modulus of elasticity to extend the service life of implants and avoid the need for revision surgeries caused by implant loosening.
- **Biocompatibility:** Materials ought to be compatible with living systems and not offer any risks to the body.
- **Wear Resistance:** To stop implant loosening, a low coefficient of friction against bodily tissues and high wear resistance are necessary. Problems may arise from any drop in wear resistance or rise in the friction coefficient.

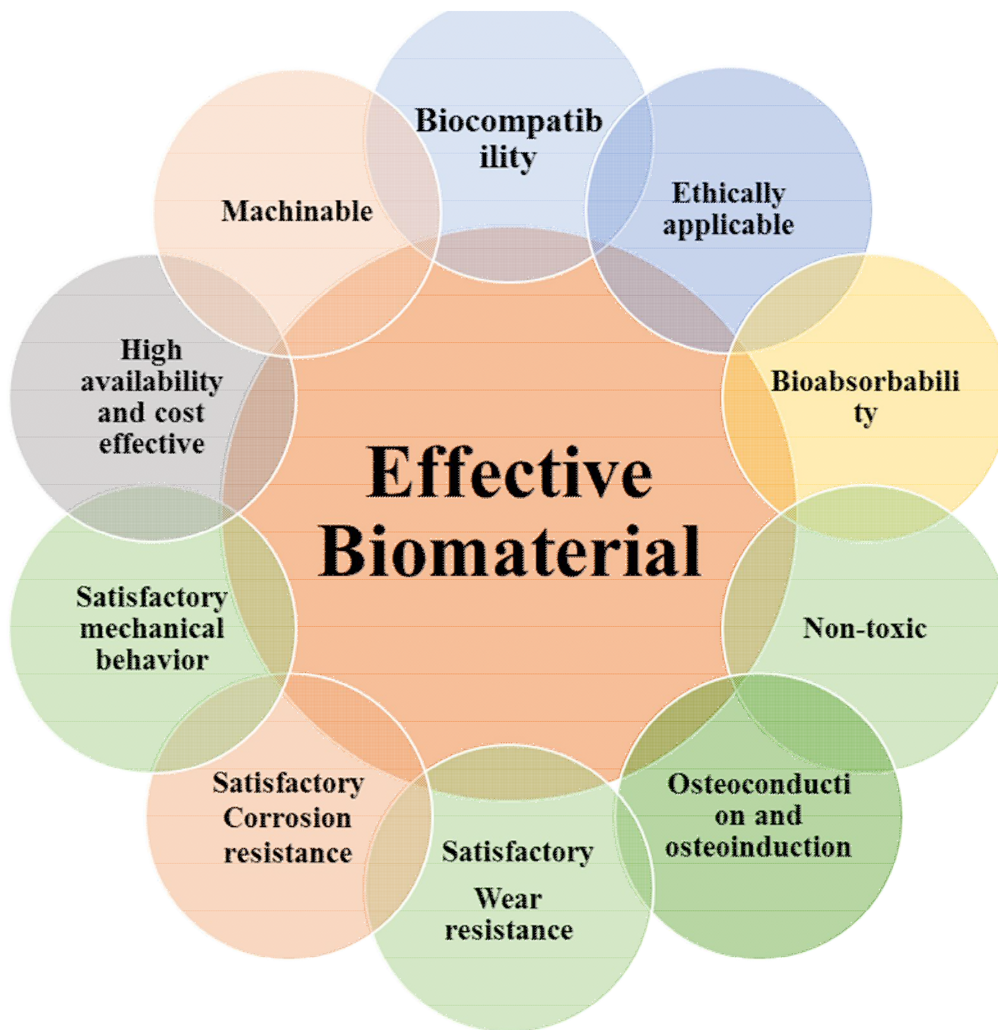

Fig.1.4 The reasoning for an effective biomaterial to be employed in the medical field (Vaiani *et al.*, 2023).

- **Corrosion Resistance:** Biomaterials need to resist corrosion to prevent the release of metal ions into the body, which could cause toxic reactions.
- **Osteoconductive:** Biomaterials should facilitate bone growth on their surfaces.
- **Osseointegration:** The material should facilitate a strong connection between the implant surface and living bone, influenced by factors like surface roughness, chemistry, and topography.

- **Non-toxic:** Implant materials must be non-toxic, avoiding harmful reactions, genotoxicity, or cytotoxicity.
- **Fatigue Life:** High fatigue resistance is necessary to prevent implant failure and fatigue fractures, which can lead to stress shielding.
- **Biotolerant:** When the material is inserted into living tissue, it shouldn't be rejected.
- **Biomimetics:** Materials are designed to mimic biological processes, enhancing the regenerative response in biological environments.

Presently, there are many types of materials used for biomedical applications, such as metal, ceramics, and polymers. In the present research, only ceramics materials are taken for the biomedical application.

1.3 Bioceramics and its types

Bioceramics are a type of ceramic material that is used to heal or replace damaged bone tissue. Depending on the application, bioceramics can interact directly with the surrounding tissue, promoting tissue growth or triggering new tissue regeneration in bioactive ceramics. It can also remain inactive at the application site and serve as a mechanical load carrier, as in the case of bioinert ceramics. Bioceramics can be broadly categorized into the following types (CaO *et al.*, 1996):

- **Bioinert ceramics:** These ceramics do not interact with the biological environment and remain unchanged after implantation. They are used for their mechanical strength and stability. Examples: Alumina (Al_2O_3) and zirconia (ZrO_2).
- **Bioactive ceramics:** These materials interact with biological tissues and can form a direct bond with bone. They are used to enhance the biological fixation of implants. Examples: Hydroxyapatite (HA), bioglass, and glass ceramics.

- **Bioresorbable ceramics:** These ceramics gradually dissolve and are replaced by natural bone tissue over time. They are particularly useful for temporary implants where gradual load transfer to the healing tissue is desirable. Examples: Tricalcium phosphate (TCP), calcium sulfate, and calcium carbonate.
- **Porous ceramics:** Designed with a porous structure to allow for tissue ingrowth and vascularization, enhancing the integration of the implant with the surrounding bone. Examples: Porous hydroxyapatite and porous alumina.

Table 1.2 Types of bioceramics (CaO *et al.,* 1996).

Type of Implant	Type of attachments	Examples
Nearly inert	Mechanical interlock (Morphological fixation)	Al_2O_3, ZrO_2
Porous	Ingrowth of tissues into pores (Biological fixation)	Hydroxyapatite (HA), HA-coated porous metals
Bioactive	Interfacial bonding with tissues (Bioactive fixation)	Bioactive glasses, Bioactive glass-ceramics
Resorbable	Replacement with tissues	Tricalcium phosphate, Bioactive glasses

Each type of bioceramic has specific applications based on its properties, making them versatile materials for various medical and dental applications, including bone grafts, dental implants, joint replacements, and tissue engineering scaffolds. Table 1.2 summarizes the classification of bioceramics and indicates that alumina and zirconia ceramics are bioinert materials, while bioactive glass and HA are bioactive materials.

1.3.1 Zirconia based bioceramic material

Zircon, historically valued as a gem, is derived from the Arabic "Zargun," meaning golden in color, originating from the Persian words "Zar" (Gold) and "Gun" (Color) (Piconi

et al., 1999). Zirconia, the crystalline dioxide of zirconium, found its first medical application in 1969 for orthopedic use, particularly in hip head replacements, offering an alternative to titanium or alumina prostheses (Helmer *et al*, 1969).

With increasing emphasis on aesthetics and concerns regarding allergic reactions to certain alloys, patients and dentists are seeking metal-free, tooth-colored restorations. This drive leads to the development of high-strength dental ceramics, offering improved durability and less susceptibility to time-dependent stress failure. These qualities are particularly desirable in prosthetic dentistry, where strength and aesthetics are crucial (Strub *et al*, 1998). Zirconia emerges as a popular bioceramic alternative to alumina, finding extensive use in dental applications such as endodontic posts, crown and bridge restorations, implant abutments, and even aesthetic orthodontic brackets (Keith *et al*, 1994).

At various temperatures, this material takes on the following three crystalline forms: cubic (c) (from 2680°C to 2370°C), tetragonal (t) (from 2370°C to 1170°C), monoclinic (m) (from 1170°C to room temperature) (Piconi *et al*, 1999), as shown in Fig.1.5. At room temperature, pure zirconia is monoclinic but transitions to tetragonal above 1170°C, and then cubic beyond that, until its melting point at 2370°C, as shown in Fig.1.6. Upon cooling, the tetragonal phase reverts to monoclinic between 1000°C and 1070°C (Piconi *et al*, 1999). The stable phase is the monoclinic (m) phase. Cubic oxides such as MgO, CaO, Y_2O_3, and CeO_2 can be added to zirconia to delay the start of the transformation phase. The zirconia crystals then remain stable at room temperature in their tetragonal or cubic configuration. These compounds are known as stabilizers (Piconi *et al*, 1999). One of the most important properties is a remarkable increase in fracture toughness of the material by hindering, but not preventing, the propagation of a crack; tensile stress concentration converts the transformation from the (t) phase to the (m) phase (Piconi *et al*, 1999).

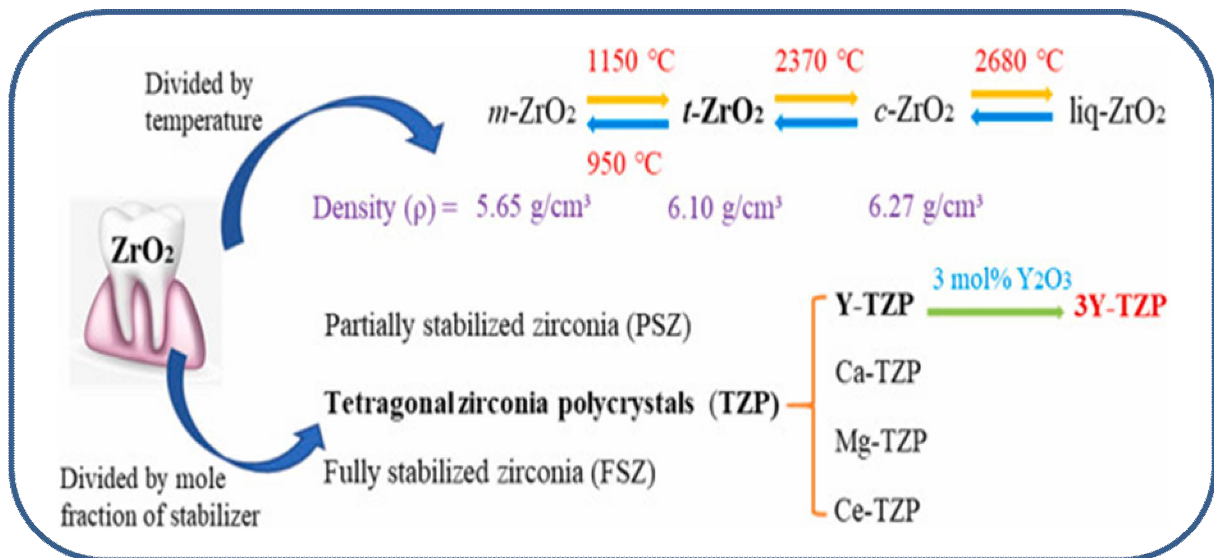

Fig.1.5 The crystal forms and transformations of ZrO_2 (Reprinted with permission from (Yin *et al.*, 2023).

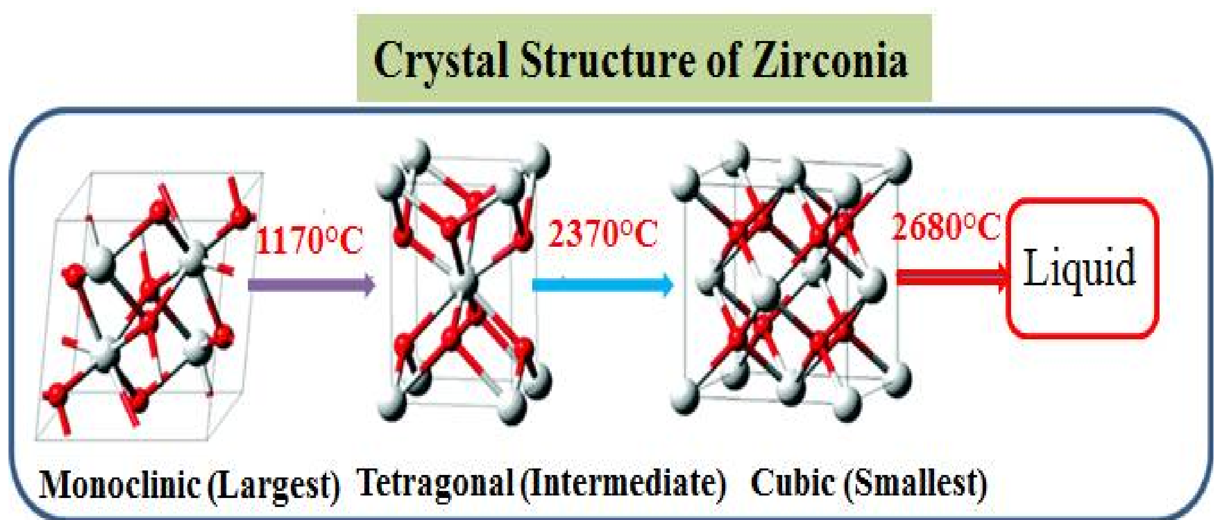

Fig.1.6 Different forms of ZrO2 at different temperatures (Gautam *et al.*, 2016).

1.3.2 Alumina-based bioceramic material

For about 20 years, alumina ceramics have been recognized as effective materials for replacing human bone. Their clinical application began in the 1960s. Through extensive research, alumina ceramics have become one of the most widely used biomaterials for bone

and tooth replacement. Their relatively high strength and excellent wear resistance make them ideal for load-bearing devices, such as the ball and socket components of hip prostheses. Additionally, they are used in prostheses for non-load-bearing situations, including dental implants, keratoprostheses, ossicular chain replacements, and maxillofacial restorations.

1.3.3 Zirconia and alumina-based bioceramic materials as the matrix

Various bioceramic materials, such as 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP), 8 mol% magnesia partially stabilized zirconia (8Mg-PSZ), and zirconia toughened alumina (ZTA), have garnered significant attention for use in biocomposites due to their exceptional biocompatibility and corrosion resistance in body fluids. Among the bioceramics based on zirconia and alumina, three stand out for biomedical applications: 3Y-TZP, Mg-PSZ, and ZTA. These materials are widely used as ceramic matrices in biocomposites (Hannink *et al.*, 2000).

1.3.3.1 3Y-TZP bioceramic

3Y-TZP ceramics are widely used in engineering applications, including engine parts, valves, cutting tools, and molds, due to their exceptional mechanical qualities, including high strength, good fracture toughness, elastic modulus, and wear resistance (Guo, 2003). Recently, 3Y-TZP has been used as an implant material in the biomedical industry due to its exceptional mechanical and chemical inertness qualities (Piconi *et al.*, 1999) (Heimke *et al.*, 2002) (Elpers *et al.*, 2014). The promising avenues for advanced zirconia ceramics lie in orthopedic and trauma surgery, where they can be utilized in prosthetic heads, skeletal fragments, and components for addressing bone defects. Similarly, in dental medicine, zirconia ceramics are found to be used in crowns and implants. Enhancing the mechanical

strength and tribological performance of ceramic products is crucial for these applications. Depending on the concentration of dopants (e.g., Y_2O_3, MgO, CaO) and temperature during thermal treatments, zirconia-based ceramics can exist in stabilized tetragonal or cubic phases. Major volumetric changes accompany the tetragonal-monoclinic (t-m) transformation of ZrO_2, underscoring the intricate nature of their structural transitions (Piconi *et al.*, 1999). Fig.1.7 shows the insertion of Yttria (Y2O3) in the zirconia (ZrO2) lattice and the creation of oxygen vacancies.

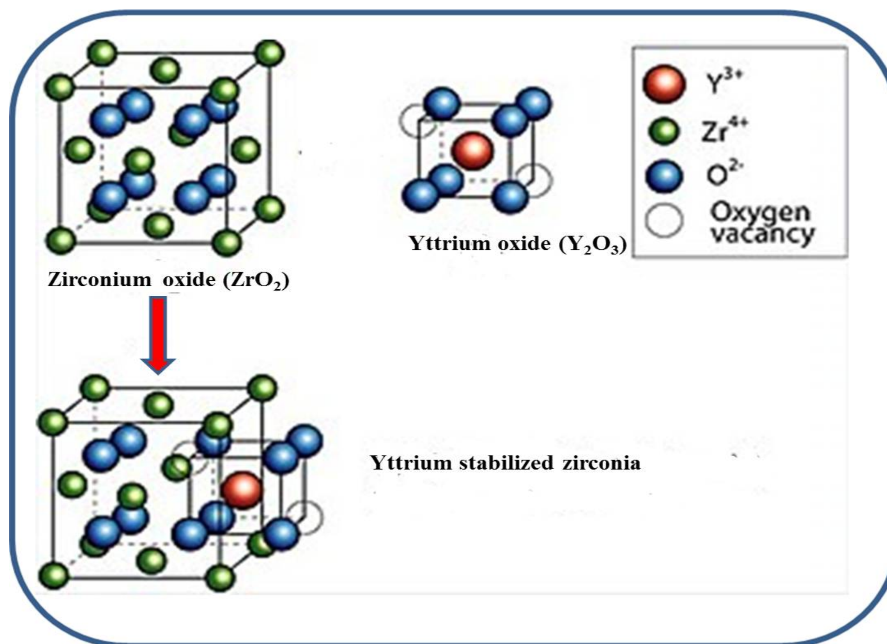

Fig.1.7 Schematic representation of the insertion of Yttria (Y2O3) in the zirconia (ZrO2) lattice and the creation of oxygen vacancies (http://www.doitpoms.ac.uk/tlplib/fuel-cells/printall.php).

1.3.3.2 8Mg-PSZ bioceramic

Magnesium oxide (MgO) partially stabilizes ZrO_2 (referred to as Mg-PSZ). In contrast to 3Y-TZP, Mg-PSZ has advantageous qualities, such as good mechanical and thermal capabilities, low-temperature degradation stability, and the same thermal expansion coefficient (TEC) (Yusuf *et al.*, 2023). The ceramic pure Mg-PSZ is bio-inert (Dehestani *et al.*, 2012). Its usage as a femur-bearing implant requires the application of bone cement. Bone

cement presents several issues, including the potential for cement breakdown and disintegration, which could result in periprosthetic edema, accelerated bone loss, and ultimately unstable implants (Rahaman *et al.*, 2008). It is, therefore, preferable to remove bone cement while maintaining a strong implant-bone bond.

1.3.3.3 ZTA bioceramic

Alumina and zirconia combine to form ZTA, a sophisticated ceramic bio-inert biomaterial. ZTA is made up of two phases: 20% of 3Y-TZP and 80% of alumina. The beneficial characteristics of monolithic alumina and zirconia are combined in this composite ceramic material. ZTA is more robust and durable than traditional zirconia and alumina. ZTA composites outperform monolithic alumina or stabilized zirconia in terms of mechanical characteristics (Sharanraj *et al.*, 2019). These characteristics are attained by a number of methods, including inhibiting the formation of cracks, regulating grain shape, managing the phase transition in the zirconia particles, and fortifying the alumina phase by regulating grain size and adding different materials. Despite its excellent hardness and wear resistance, alumina is brittle, which increases the chance of fracture. This alumina characteristic results in several limitations to the design. Although zirconia is just half as hard as alumina, transformation toughening improves fracture resistance. In comparison to alumina, the overall toughness and bending strength are higher. However, zirconia undergoes a phase shift into a metastable state, which impacts its overall stability (Sharanraj *et al.*, 2017). This phenomenon is further amplified by zirconia's low thermal conductivity. Consequently, ZTA, a material that combines the best qualities of zirconia and alumina, is the optimal ceramic.

1.3.4 Bioactive glasses as the reinforcement

Biologically active glasses can help regenerate soft and bone tissue (Hench *et al.*, 1971) (Hench *et al.*, 2013) (Brink *et al.*, 1997) (Rahaman *et al.*, 2011). The most widely used glass in biological applications is 45S5, a silicate bioactive glass (BG) (Hench *et al.*, 1971). There has been interest in using another silicate bioactive glass, termed 13–93, for biological purposes. Its composition (wt%) is 53 SiO_2, 6 Na_2O, 12 K_2O, 5 MgO, 20 CaO, and 4 P_2O_5 (Brink *et al.*, 1997). Excellent osteoconductivity and biocompatibility are also features of 45S5 BG and 13-93 BG, which are both extensively utilized in orthopedic applications (Wilson *et al.*, 1992) (Carvalho Yadav *et al.*, 2019) (Himanshu *et al.*, 2016). The hydroxyapatite layer that forms on the surface of both BGs has a chemical makeup similar to that of bone; it forms a direct bond with the bone tissue and promotes enhanced osteogenesis by timing the induction and proliferation of cells (Leonor *et al.*, 2002) (Ducheyne *et al.*, 1999) (Oonishi *et al.*, 2000). The European Medicines Agency has approved the *in-vivo* usage of 13-93 glass, while the U.S. Food and Drug Administration (FDA) has approved 45S5 glass for use *in-vivo* (Rahaman *et al.*, 2011).

1.3.5 Biocomposite materials

The heterogeneous combination of two or more materials with distinct macroscopic compositions, morphologies, and physical attributes is referred to as a composite. The goal is to create these materials with attributes that aren't possible to get from just one material (Yadav *et al.*, 2020). A "bio-composite" is defined as a composition containing one or more biological components, whereby one or more of the components are naturally occurring elements or biological components. Within the composite system, the constituent parts remain in distinct phases, retaining their own physical and chemical properties (Rajak *et al.*, 2019). The term "composite" is used in the current thesis to describe materials that are entirely suitable for biological applications.

It is important to remember that biological structural elements are practically composite in nature. Common examples include wood, bamboo, teeth, and shells. Moreover, the idea of using synthetic composite materials is not new. Bricks made of mud strengthened with straw were utilized in biblical times. In contemporary terms, this substance is referred to as an organic fiber-reinforced ceramic matrix composite. There are four categories of solid materials: carbon, metals, polymers, and ceramics. Matrix materials and reinforcements are present in all four groups. The four main types of composite materials are polymer matrix composites (PMCs), metal matrix composites (MMCs), ceramic matrix composites (CMCs), and carbon/carbon composites (CCCs) (Rajak *et al.*, 2019) (Kutz, 2002). Bone is a composite material consisting of an organic matrix mostly composed of mineralized collagen type I (hydroxyapatite). Most of the bone's outstanding mechanical qualities can be attributed to its intricate microstructure, which makes its composite design difficult to replicate (Yashas *et al.*, 2018).

Various terms are used to describe composite structures, with one method involving categorizing composites based on the geometry of the reinforcement process. Laminated materials, fiber composites, and particulate composites exemplify this approach. Fibrous composites can further be classified based on the ratio of fiber length to diameter, termed the "aspect ratio." Short/chopped fibers typically have a ratio between 5 and 200, while continuous fibers have a ratio greater than $1*10^5$ (Rajak *et al.*, 2019). The choice of matrix material is another crucial factor in classifying composites, with metal, ceramic, and polymer matrix composites being common types. In biomedical applications, all components of a composite must be biocompatible (Mishra *et al.*, 2018). Composites are heterogeneous structures composed of two or more homogeneous phases separated by interfaces. Various physical or chemical linkages hold these constituent phases together at these interfaces. Unlike conventional materials, composites offer tailored properties, including physical,

chemical, and biological attributes, to meet specific application requirements. The goal of composites is to create new materials with properties not achievable with individual components or to combine the best qualities of each component. A typical composite consists of two main phases: the matrix phase and the reinforcement phase, also known as the "second phase" or "dispersed phase." The matrix, acting as the continuous phase, surrounds and provides the overall structure to the other phases, while the reinforcement phase is dispersed more widely (Ibrahim *et al.*, 2015). Biomedical composites hold promise for various surgical applications, including total joint replacements, spinal rods, disks, plates, dental posts, screws, and ligaments.

1.3.5.1 Types of biocomposite materials

The biocomposite materials can be divided into groups based on how they are reinforced, as indicated in Fig.1.8. Three types of fillers are distinguished: particulate (powder) forms, continuous fibers, and short fibers. These reinforcing systems have been used in the development of biocomposites for biomedical applications, such as screws and stems made of short fiber reinforcements for total hip replacements and orthopedic bone plates made of unidirectional (UD) laminate.

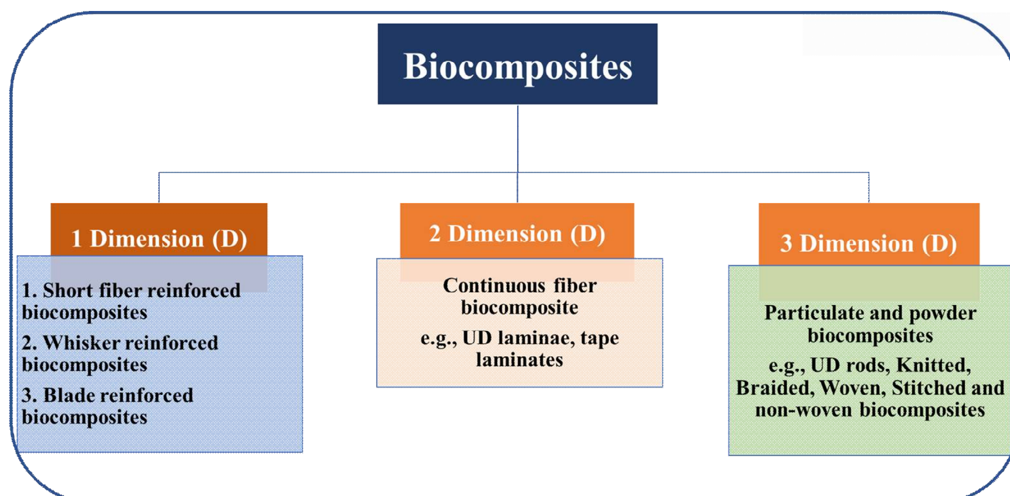

Fig.1.8 Types of biocomposites based on the reinforcement system.

1.3.5.2 Properties and applications of biocomposite materials

The primary characteristics of biocomposite materials that are needed for the replacement of bone and bone deformities are biodegradation, bioactivity, porosity, mechanical strength, and biocompatibility (Yıldızhan *et al.*, 2018). Biocomposite materials have a long history of use in a wide range of therapeutic applications. These include orthopedics, mandibular defects, cardiovascular medicine, occlusion devices for cardiac defects, dentistry, urology, gastrointestinal medicine, wound healing, ophthalmology, orbital implants, orbital floor repair, plastic surgery, drug delivery, and tissue engineering. Fig.1.9 symbolizes the optimal characteristics of biocomposite materials used in biomedical applications.

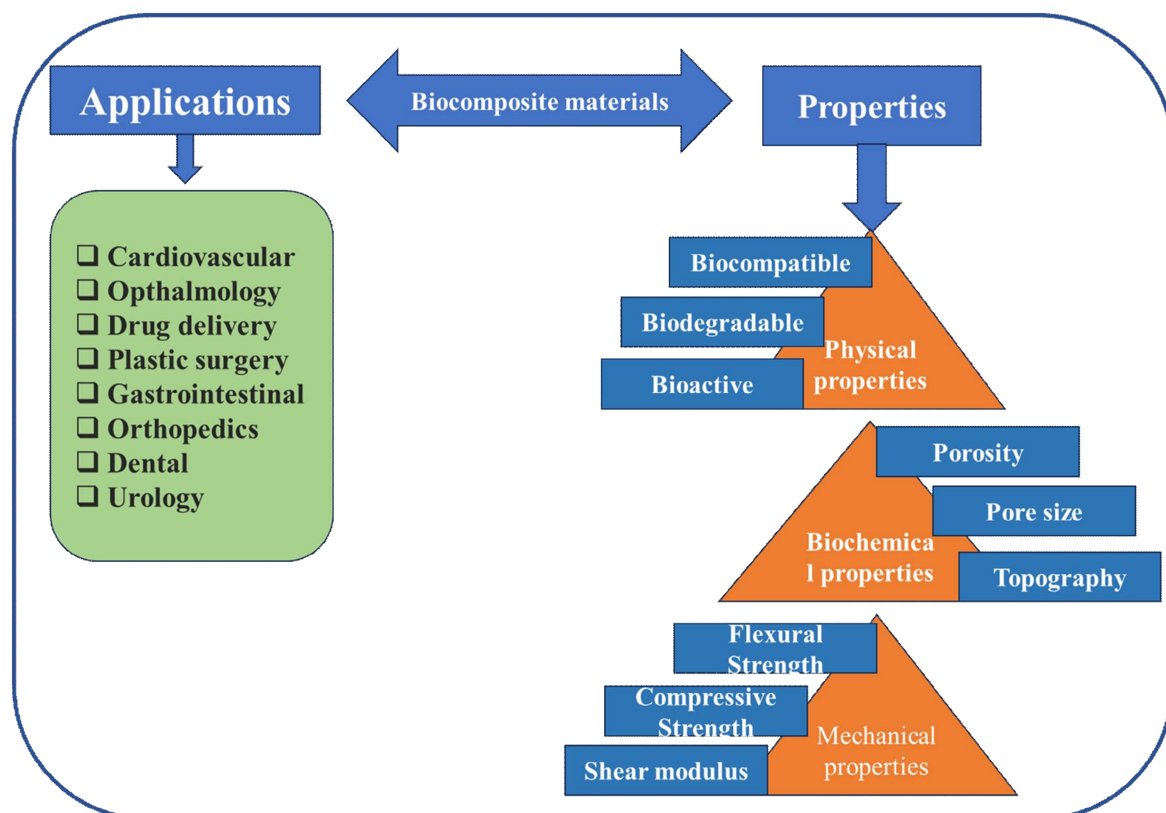

Fig.1.9 Properties and applications of biocomposite materials used as biomedical products.

1.3.5.3 Machinability/mechanical properties of biocomposite materials

For millennia, the scope of surgery was restricted to direct operations on the human body; no other devices, such as implants, were used in the procedure. Nevertheless, significant advancements in the development and testing of implants and surgical instruments have been achieved rapidly. This progress is largely attributed to a better understanding of human anatomy and the creation of materials compatible with the human body (Park *et al.*, 2007). The surgical instruments, tooling, and implant manufacturing businesses have all experienced rapid growth, averaging between 7 and 12% annually (Ramakrishna *et al.*, 2001). Naturally, with industry demands and pressure from healthcare organizations for quick and reliable surgical interventions, there is a pressing need to develop, adapt, and utilize suitable enabling manufacturing technologies. Among these, the cutting of biocompatible materials is particularly crucial.

In this context, "biocompatible materials" primarily refer to substances that interact with human tissues or organs in a way that permits their full or partial activity in relation to their structural compatibility and surface. While structural compatibility refers to the acceptance of mechanical behavior, such as stiffness, elastic modulus, and strength, which would affect the true integration between implant and tissue interface; surface compatibility of the machined surfaces primarily refers to their degree of adaptation to the host tissues in terms of biological, chemical, and surface characteristics (Ramakrishna *et al.*, 2001). Biocompatible materials are therefore widely used for implants, which require high criteria for surface and geometric accuracy throughout the machining process.

The most popular method for producing medical implants and carrying out surgical procedures is cutting. It offers high rates of material removal and is accurate (Shih *et al.*, 2008). However, when considering the target applications, which may include both implants and human tissues, cutting operations in this context can encounter a wide variety of materials. In addition, the requirements for the quality of the surface created by cutting vary

greatly depending on the specific application. Cutting for surgical operations refers to both soft and hard tissues, whereas cutting for implant manufacturing refers to metallic biomaterials (such as stainless steels, Ti/Mg, and Ni/Ti alloys), inorganic and non-metallic biomaterials (such as ceramics), and organic materials (such as polymer and polymer composites). Soft tissues include skin, fat, muscle, and soft organs. Scalpel blades and scissors are frequently used in this process. Hard tissue cutting refers to the cutting of bone structures (of varying densities) using a range of, in some way, traditional equipment (e.g., drills, taps, saws, and milling cutters). Therefore, a great number of cutting tools of various forms, sizes, and cutting-edge geometries are needed to fulfill the specific implants' functionality and medical procedures to accommodate a wide range of surgical procedures and individualized patient needs. The mechanical properties (elastic modulus, hardness, compressive strength, and flexural strength) and biological responses of bioceramic composite systems are improved by adding bioactive glass as reinforcement (Chen, 1997) (Liu *et al.*, 2002).

The modern technologies have been relied on more productive, more accurate and higher quality advanced machining processes. The reasons for utilization of advanced machining process over the traditional approach have been due to the ability of machining hard, brittle materials. On the other hand, more complex geometries can be easily machined. The advanced machining process in correlate with the energy used for machining are classified into four broad categories. The classification of advanced processes is (i) mechanical (ii) chemical (iii) electrothermal and (iv) electrochemical. Under mechanical process there are four categories namely, Water jet machining (WJM), Abrasive jet machining (AJM), Abrasive water jet machining (AWJM) and Abrasive flow machining. Similarly, under the chemical process are chemical milling and photo chemical milling. The Electrothermal processes comprises of Electric discharge machining (EDM), Wire electric

discharge machining (WEDM), Laser beam machining (LBM) and Electron beam machining (EBM). The final classification of advanced machining processes is electrochemical process and it is further subdivided into electrochemical milling, electrochemical drilling and electrochemical grinding. In the forthcoming section, the latest literatures associated with EDM and WEDM are discussed. [Jain, 2009].

1.3.5.4 Tribological behavior of biocomposite materials

Due to an increasing number of trauma cases and health issues like arthritis, there is a high need for biomedical implants Kutz *et al.*, 2007) (Singh *et al.*, 2021) (Kubiak *et al.*, 2014). In the modern world, orthopedic procedures such as joint replacement and bone mending are frequently performed (Elo *et al.*, 2017) (Ching *et al.*, 2014). Bioinert materials, such as biometals, bioceramics, polymers, and metallic alloys with innovative coatings like hydroxyapatite and calcium phosphate, are utilized for orthopedic implants (Shen *et al.*, 2018). The most widely used biomaterials have a few drawbacks, such as increased susceptibility to *in-vivo* corrosion and increased implant wear and tear that shortens implant life. The researchers have developed innovative strategies to overcome these constraints, such as modifying the material matrix to combine metals and polymers and creating new coatings to prevent surface wear (Mehta *et al.*, 2022). Over the course of use, there has been a high failure rate documented for the combination of metal and polymers. This expands the field of research on joint materials such as ceramic to ceramic and metal to metal (Chen *et al.*, 2017) (Roy *et al.*, 2015). According to multiple studies, surface topography is crucial to an artificial implant's overall lifespan (Muratoglu *et al.*, 1999) (Shi et al., 2003, so before the implants are commercialized, they should be thoroughly examined. In order to give readers insight into designing or improving artificial joints with the goal of extending the implant's life span, this review analyses and articulates the tribological performances.

1.3.5.5 Biological properties of biocomposite materials

1.3.5.5.1 *In-vitro* bioactivity

"The bonding ability with host tissue" defines the bioactivity of a material (Dubey *et al.*, 2014). This includes promoting the generation of apatite, osteoblast differentiation, and bone matrix formation. Modern bioceramics, such as hydroxyapatite, β-tricalcium phosphate (β-TCP), HAp/β-TCP composites, and bioglasses, are widely used for bone restoration due to their excellent bioactivity, which allows them to form strong bonds with host bone tissue. However, a significant drawback of these bioceramics is their relatively low mechanical strength, particularly their low fracture toughness, limiting their use to low-load-bearing areas of the body. Understanding how ceramics attach to real bone and developing methods to test bonding abilities is crucial for advancing bioactive ceramics for load-bearing bone restoration applications (Ohgaki *et al.*, 2001).

1.3.5.5.2 *In-vitro* biodegradability

To evaluate the performance of bioceramic materials for biomedical applications, it is essential to examine them *in-vitro* biodegradation in Simulated Body Fluid (SBF) (Sonohara *et al.*, 1995). SBF is a solution that mimics the ion concentrations of human blood plasma, allowing researchers to study the behavior of bioceramics under conditions similar to those in the human body. *In-vitro* biodegradation studies aim to explore the interactions between bioceramic materials and bodily fluids, particularly focusing on the formation of a physiologically active layer, such as hydroxyapatite (Frayssinet *et al.*, 1993). Additionally, determining the degradation rate of the material is crucial, especially for applications like bone grafts where slow resorption is required. This helps in understanding how long the material will remain in the body before it degrades or is replaced by natural tissue.

1.3.5.5.3 *In-vitro* cellular response

Cellular viability of bioceramics refers to the ability of cells to survive, grow, and function when in contact with or attached to these materials (Demento *et al.*, 2009). Bioceramics, which are ceramic materials used in medical applications, especially in orthopedics and dentistry, are valued for their biocompatibility, bioactivity, and mechanical properties. Assessing cellular viability is essential to determine the clinical suitability of these materials (LuO *et al.*, 2018). Factors influencing cellular viability include the composition and surface properties of the bioceramics. Different bioceramics, such as hydroxyapatite, bioactive glass, and zirconia, interact differently with cells. Surface topography impacts cell attachment, proliferation, and differentiation, while functional groups and ionic states on the surface can influence cell behaviour (Anselme *et al.*, 2000).

1.3.5.5.4 Antibacterial response

Bacterial infection at the implant site is one of the primary causes of implant failure during and after surgery (Jones *et al.*, 2008). Both gram-positive and gram-negative bacteria are associated with these infections (Goel *et al.*, 2006). Gram-positive cocci, particularly Staphylococcus aureus (S. aureus) and Staphylococcus epidermidis (S. epidermidis), are responsible for approximately 65% of bacterial infections in orthopedic implants (Berbari *et al.*, 1988). In contrast, about 11% of these infections are caused by gram-negative bacteria, notably Escherichia coli (E. coli) and Pseudomonas aeruginosa (P. aeruginosa) (Hench, 1998). To replace lost or damaged bones, various materials have been developed, including metals (such as stainless steel, titanium, cobalt, and chromium-based alloys), polymers (such as carbon fibers, glass fibers, and polymethyl methacrylate), and ceramics (such as hydroxyapatite, tricalcium phosphate, and bioglasses) (Rodrigues *et al.*, 2003) (Saini *et al.*, 2015. Despite their acceptable biocompatibility and bioactivity, these materials can still be

susceptible to bacterial infection during or after surgery. To address this significant issue, various strategies are being pursued, including incorporating antibacterial agents into current implants and using external stimuli to combat infections (Okazaki *et al.*, 2005) (Kokubo *et al.*, 2008).

1.4 Theme of the work

This research aims to explore the feasibility of incorporating bioactive glass into bioceramic materials (3Y-TZP, 8Mg-PSZ, ZTA) to address issues related to their bio-inert properties. The bioceramics 3Y-TZP, Mg-PSZ, and ZTA are optimized for their exceptional biocompatibility and corrosion resistance in body fluids. The selection of 13-93 bioactive glass as a reinforcement is explored due to its excellent biocompatibility and osteoconductivity properties. This study investigates the impact of adding 13-93 bioactive glass on the physical, structural, mechanical, *in-vitro* degradation, cell culture, and antibacterial response of the bioceramic-based biocomposite materials. Additionally, the influence of 13-93 bioactive glass on the machinability and tribological behavior of 3Y-TZP-based biocomposite materials is examined.

1.5 Organization of the thesis

The present thesis is composed of nine chapters, which are structured as follows:

- **Chapter I:** Briefly describes the biomaterials, stabilized zirconia, alumina, bioactive glass, and biocomposites with their classification, applications, and properties in the biomedical field. It also explains the theme and organization of the thesis.
- **Chapter II:** Provides a review of the current state of the art within the concerned area. The chapter explains the different methods to improve the biological properties of bio-inert ceramics along with the background information, supportive literature, and recently

published investigations. Also review the effect of bioactive glass addition on the structural, mechanical, machinability, and tribological behavior of bioceramic composites and related latest publications, considered as the objective of the present thesis.

- **Chapter III:** Offers the materials used and a detailed description of the synthesis methods employed for stabilized zirconia, alumina, and its composite with bioactive glass. Also, a description of the principles underlying the characterization techniques is given. Additionally, the standard operating procedures and protocols for assessing the cellular response, antibacterial response, and *in-vitro* bioactivity of the composites are explained.
- **Chapter IV:** Explains the impact of 13-93 bioactive glass addition on the physical, structural, mechanical, *in-vitro* degradation, cell culture, and antibacterial response of the 3Y-TZP-based biocomposite materials.
- **Chapter V:** Clarifies the influence of 13-93 bioactive glass addition on the physical, structural, mechanical, *in-vitro* degradation, cell culture, and antibacterial response of the 8Mg-PSZ-based biocomposite materials.
- **Chapter VI:** Elucidates the effect of 13-93 bioactive glass addition on the physical, structural, mechanical, *in-vitro* degradation, cell culture, and antibacterial response of the ZTA-based biocomposite materials.
- **Chapter VII:** Enlightens the impact of 13-93 bioactive glass addition on the machinability of the 3Y-TZP-based biocomposite materials.
- **Chapter VIII:** Describes the effect of 13-93 bioactive glass addition on the tribological behavior of the 3Y-TZP-based biocomposite materials.
- **Chapter IX:** Explains conclusive remarks and the future scope of the present research work.

Finally, towards the end of the thesis, a complete list of references has been included, and at last, a concise list of publications and conferences related to the present research work has been enclosed.