Advances in Biopolymer Tribology

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Abstract In the current scenario, biopolymer and biopolymer composites are getting considerable interest in sustainable industrial development. Biopolymers produced from living organisms possess unique molecular and functional properties. The precise 3D structure of biopolymer makes them active molecules that are potentially applied in various industries like pharmaceutical, food, and nutraceutical, etc. The most commonly used biopolymers are chitosan, silk fibroin, poly tetra fluoro ethylene (PTFE), polyacetal (PA), various cross-linked polythenes, and ultra-high molecular weight polythenes (UHMWP). The most successful application of biopolymers may be considered as active materials for biomedical engineering, along with materials for food packaging, water purification, and the packaging sector. The term tribology is associated with the friction and wear properties of certain materials. Industrial advancement with the improvement of the tribological behavior of biopolymer is an emerging area in view of the wide applicability of biopolymer in modern engineering. The present paper will comprise industrially significant biopolymers, their tribological properties concern with efficiency improvement, and sustainable development. Further, it will elaborate on current challenges and future aspects of the tribological study of biopolymers for modern engineering.

Keywords Biopolymer · Biopolymer composites · Tribology · Biomedical engineering

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1 Introduction

In form of macromolecules, polymers are composed of monomeric units linked to each other in different conformations (Mills and White 2012). Polymers are broadly classified into two groups, i.e. synthetic and natural (Deb et al. 2019). Natural polymers termed as biopolymers have drawn key attention to the researchers due to their cellular adhesiveness, biocompatibility, and biodegradability (K. Numata and Kaplan 2011). Biopolymers may be defined as polymers originated from living organisms, like plant cells, microbial systems, or chemically synthesized from biological systems (Rebelo et al. 2017). However, heavy dependence upon synthetic polymer may not be overlooked (Buggy 2016). A longer utilization of synthetic polymer may cause a hazardous effect on human health along with the environment (Kaushik et al. 2016). These toxic effects of synthetic polymer lead to the preferable application of biopolymer in medical devices, packaging material, cosmetics, water treatment chemicals, food additives, tissue engineering, biosensors, industrial plastics, pharmaceuticals, and the food industry, etc.(Rebelo et al. 2017). Various classes of Tribology and their key applications are given in Table 1.

In the biomedical industry, the application of different biopolymers, i.e. collagen, chitin, gelatin, starch, and xanthan gum, etc. are very significant with the aspect of biocompatibility, biodegradability, nontoxicity, mechanical durability, low immunogenicity, nonmutagenicity, nonirritant nature, and self-healing property along with economically easy availability (Jacob et al. 2018). Such "biomimetic" characteristics of biopolymers offer great applicability of these materials in the biomedical sector as wound healing products, implantable devices, drug delivery systems, and tissue engineering scaffolds (Davidenko et al. 2014; SSD Kumar et al. 2018a, b). Food industries may be considered as another largest sector, in which biopolymers are widely utilized as natural ingredients to enhance texture, stability, and physicochemical properties, etc. (McClements et al. 2009). As a natural macromolecule, biopolymers are playing a vital role as a gelling, emulsifying, thickening, and stabilizing agent for food processing (Qin et al. 2018). As an eco-friendly, renewable raw material, biopolymers are widely utilized as packaging material for the sustainable development of the food industry (Qureshi et al. 2020). Some major classes and types of biopolymers currently in use are given in Fig. 1.

The biopolymer-based functional ingredients interact with other food molecules to improve the design of novel food (Qureshi et al. 2020). In the food industry, alginate, starch, chitosan, and gelatin are considered important ingredients in replace of synthetic polymers (Qin et al. 2018). In the present scenario, the pharmaceutical industry may be considered as a very important sector with the wide application of many biopolymers, i.e. alginate (Lee and Mooney 2012), pullulan (Dailin et al. 2019) for controlled drug and gene delivery, tissue engineering, medical imaging, antimicrobial activity, and plasma expander, etc. Additionally, several industrial sectors, i.e. textile, cosmetics, and paper industries show a great dependency upon biopolymers as natural macromolecules (Anwunobi and Emeje 2011). Overall biopolymer tribology-based research areas and applications are given in Fig. 2.

Table 1 Classification of various biotribology representations and their major applications

S.N	Tribology area	Major areas for application
1	Animal Tribology	Animal locomotion; ants; beetle, butterfly's wing; earthworm; feather of birds; gecko adhesion; pangolin scale; seashell; skin shark or fish; Snails; water strider; etc.
2	Artificial articular joints	Artificial cartilage, bioscaffolds, corrosion and wear in implants, explant analysis, spinal discs, total and partial joint replaccements (hip and knee), etc.
3	Biomimetics	Bioinspired tribology, insect tribology, etc
4	Haptics	Ergonomics, surface texture, Tactile perception, etc.
5	Joint tribology	Articular cartilage; Hip joint; implant interfaces; joint fluid; knee joint; restorative joint materials; etc.
6	Medical devices	Artificial cardiovascular system, gastroscope, medical gloves, operation forceps, scalpel, urinary catheters, etc.
7	Natural Joints	Articular cartilage, biochemical and mechanically induced damage, meniscus, synovial joints, etc.
8	Ocular tribology	Contact lenses,ocular surfaces, dry eye syndrome, tear lubrication, etc.
9	Oral tribology	Dental restorative materials, mandibular joints, natural teeth, saliva, swallowing, teeth implants, tongue, toothpaste, etc.
10	Plant tribology	Diatoms; lotus leaf; etc.
11	Prosthesis tribology	Prosthetic human interfacing and coupling, tribological function, etc.
12	Skin tribology	Medical and cosmetic treatment; skin care; skin friction-induced perception and grip of objects; skin connects with the articles (tactile texture, socks, shoes, shaving devices, etc.) for daily use, skin irritation and discomfort; sport devices, synthetic skin; etc.
13	Sports tribology	Deterioration and testing of sport surfaces, equipment design and development, grip, gait analysis, players interaction, etc.
14	Tribology of the other human bodies or tissues	Bone; capillary blood flow; cells; contact lenses; hairs; ocular surfaces; etc.

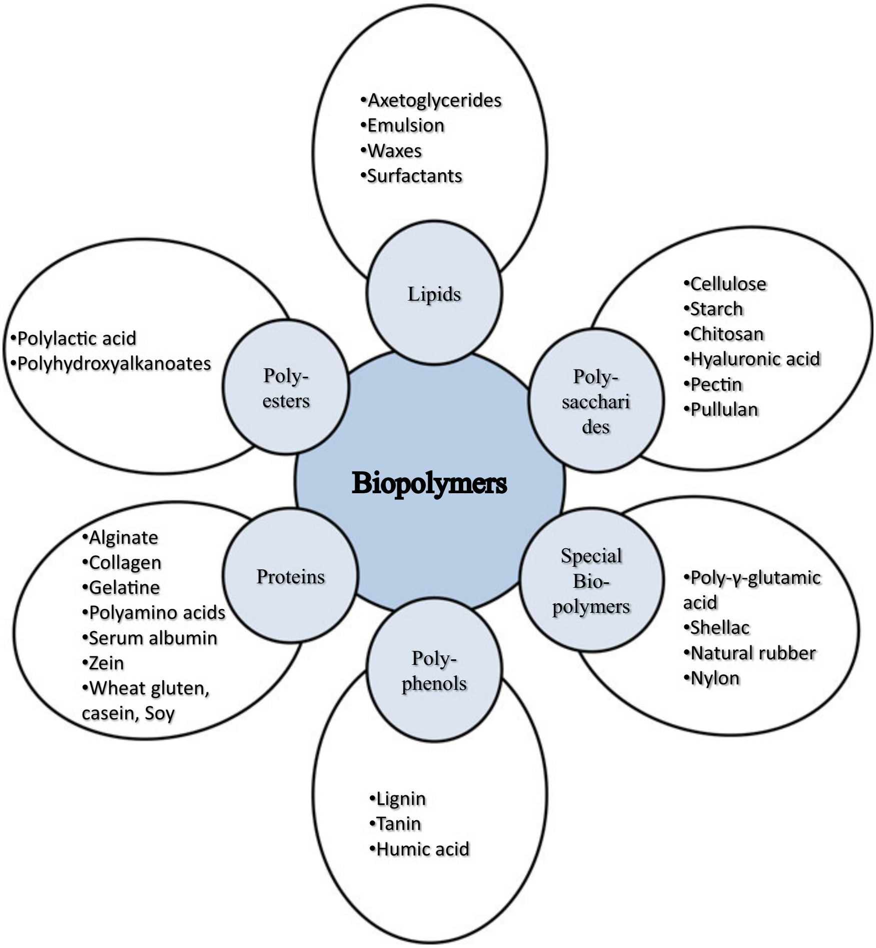

Fig. 1 Classification of different biopolymers based on their functional and structural properties

Nowadays, industries are more concerned about adopting a sustainable long-term approach without any negative effect on the environment and human health (Laine et al. 2013). This aspect put great efforts to develop materials from natural polymers rather than direct utilization of toxic, nondegradable, and mutagenic synthetic polymers (Souza et al. 2009). As per consumer demand, sustainable development of food and health industries depends upon continuous enhancement in the mechanical performance of biopolymer-based products. Tribological studies of employed biopolymers play a vital role to understand the mechanical aspect with better performance. The present chapter will help to develop the basic understanding of 'tribology' or specially termed, 'biotribology' concerned with biopolymers applied in some specific areas, i.e. biomedical, food, and packaging industry (Fig. 3). Further, it will focus on the improvement of biopolymer-based products in terms of standard design

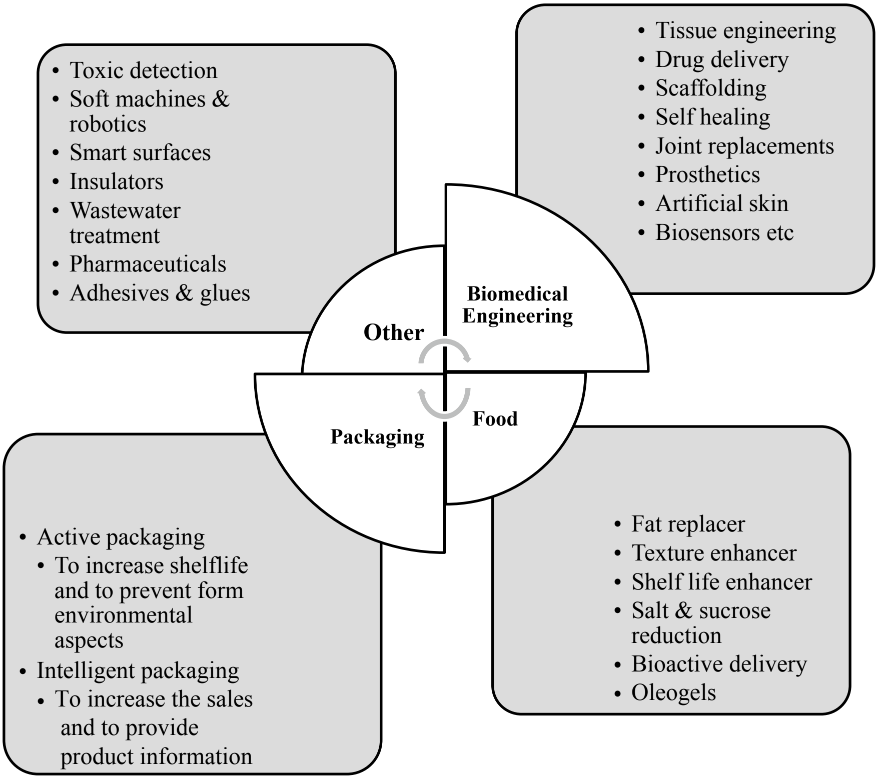

Fig. 2 Major sectors and different usage of biopolymers

as well as mechanical performance. Tribological studies will definitely show a significant impact on energy conservation issues that is one of the biggest challenges for the sustainable development of bio industries.

2 Tribological Study in Bio Industries

Tribology is the phenomena concerned with the surface of a solid or the interface between two surfaces (Sahoo et al. 2019). The most crucial components of tribological study may be considered as friction, wear, and roughness. Friction may be considered as a force resisting the relative motion between two solid surfaces or fluid layers or material elements sliding against each other. The frictional force is independent of the area of contact surfaces and is directly depends upon the applied force. The frictional force may be recognized as a non-conservative force (Cuffari 2019). Whereas, Wear is defined as surface damage, loss of material, or deformation of a

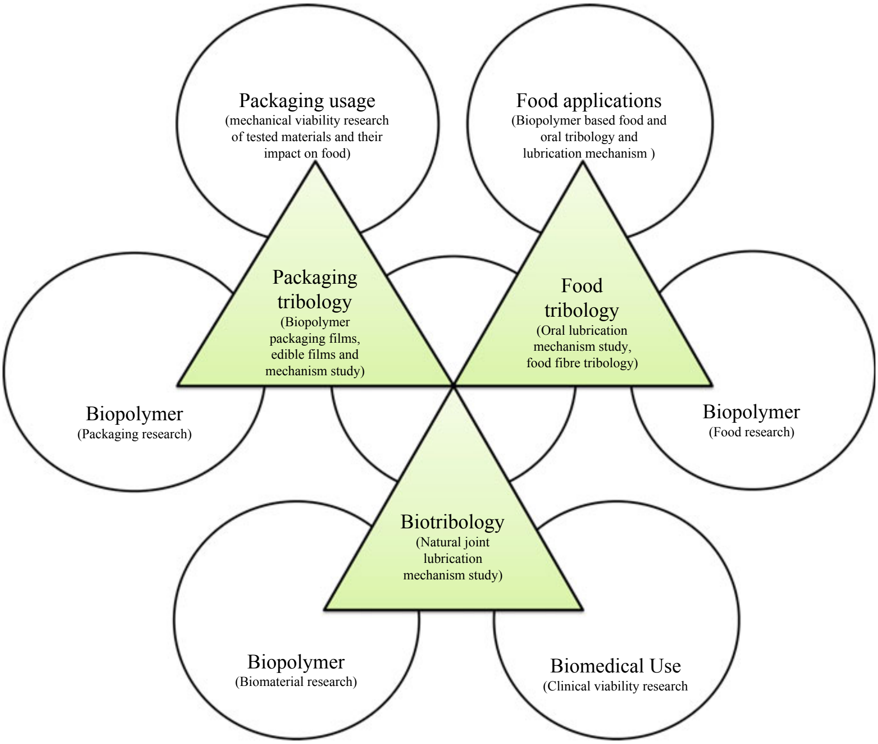

Fig. 3 Biopolymer tribology; different sectors and research baseline

body when two surfaces in contact have relative motion between them. Wear causes continuous degradation of the functional surface with the ultimate loss of functionality. The wear rate depends upon the type of loading, nature of relative motion between the contact surfaces, and temperature (Cuffari 2019). Wear may be classified into different types, as; (i) Abrasive wear (ii) Erosive wear (iii) Adhesive wear (iv) Fretting wear (vi) Corrosion and/ or oxidative wear (v) Surface fatigue. It is very clear that among these two degradation phenomena, friction is the force that occurs between two contact surfaces in relative motion, however, wear dictate material loss due to mechanical and/or chemical damage between the two surfaces in contact. Roughness in terms of surface roughness is another very important characteristic of tribology. In physics view, surface roughness plays a crucial role to determine the contact area of a surface and the contact stresses on a surface. However, the chemical perspective of surface roughness shows a major impact on shear strength, chemical compatibility, and lubrication properties of a surface (Critchley 2018). The synergistic approach to study and apply all three parameters (friction, wear, and surface roughness) jointly as a ‘tribology’ plays a significant role to enhance mechanical performance, efficiency, and reliability of a system. The tribological aspects are closely concerned with the techno-economic feasibility of industries. Further, tribological study and processes can positively handle the losses due to energy dissipation and material wear by improving standard design and optimizing energy efficiency (Sahoo et al. 2019).

As an interdisciplinary study concerned with biomechanics, physiology, biochemistry, clinical medicine, pathology, biology, etc., biotribology is emerging as a sister branch of tribology in the study of biological systems. Biotribological studies focus on all the aspects of tribology within the biological system (Zhou and Jin 2015). The domain of biotribology is very vast which covers the mechanical and tribological study of tissue-engineered cartilage, development of wear-resistant materials, preclinical testing to improve the implants and wear modeling of artificial joints, etc. by applying biocompatible prostheses, therapeutic medical devices, medical imaging equipment as magnetic resonance imaging (MRI), electroencephalography (EEG), etc.(Sahoo et al. 2019).

3 Tribology of Biopolymer and Biopolymer Composites Applied in Biomedical Engineering

The main perspective of biomedical engineering is to apply interdisciplinary engineering principles and design concepts for diagnostic and therapeutic purposes. In these applications, medical implants become an integral part of the living system of the patient by sustaining normal body functions (Dutta et al. 2020). The most common types, i.e. bones, hips, heart, knees, breasts, ears, eyes, and cardiovascular implants are either made of synthetic metals, ceramics, and polymers or preferably by using a biopolymer (Rowland et al. 2019). Traditional synthetic materials as Tantalum, gold, Co-Cr, NiTi, and stainless steel lead to a number of disadvantages as immunological rejection, cell and tissue necrosis, cytotoxicity, and implant loosening (Rawat and Saxena 2019). These limitations are the root cause to develop more research for biopolymer-based implants with advantages listed as biocompatibility, bioadhesion, functionality, low friction, high strength, and corrosion resistance, etc. (Rawat and Saxena 2019).

3.1 Essential Characteristics of Biopolymer-Based Implants

It is required to understand the nature of biopolymer-based implants for tribological studies. These biomaterials are supposed to fit with living tissue or any other organic matter without any adverse effect. The essential characteristics are listed below:

(i) Biocompatibility: The medical implant must be compatible with the living tissue. In this regard, biopolymer-based implants exist within the living system without any negative effect (Rawat and Saxena 2019).

(ii) Mechanical properties: The best thing with biopolymer-based implants is low modulus with high strength to elongate the life of such implants inside the body without any loosening effect (Sahoo et al. 2019).

(iii) High wear resistance: High wear resistance with a low friction coefficient is another desirable attribute for biopolymer over metallic implants.

(iv) High corrosion strength: Metal-based implants may suffer a highly corrosive atmosphere due to 37 °C, body temperature (Hansen 2008), along with the abundant presence of chlorine ions in the body fluid. At this point, biomaterial-based implants best suit with less corrosion resistance (Sahoo et al. 2019).

(v) Long fatigue life: Human joints are used to suffer additional weight and show cyclic motion. The implant material is required to sustain high loading to stop implant failure and stress shielding from fatigue fracture.

(vi) Osseointegration: Topography of the surface, chemistry, and roughness may be considered as a major parameter for good osseointegration as proper integration of the implant with the bone and other tissues is required to minimize the implant loosening risk (Rawat and Saxena 2019). In view of these essential characteristics, biopolymers may be considered more preferable over synthetic metals for proper integration of the implant with the bone and other tissues (Sahoo et al. 2019). Poly tetra fluoro ethylene (PTFE) may be considered the first biopolymer, studied by the late Sir John Charnley for total hip replacement design (Charnley et al. 1969). In recent years, ultra-high molecular weight polyethylene (UHMWPE) and new types of polythene, cross-linked polyethylenes (XLPE) showed promising clinical results with improved wear resistance (Joyce 2009). Including these biomaterials, polylactic acid (PLA), chitosan and silk are also explored as implant materials possessing characteristics of non- cytotoxicity, biocompatibility and biodegradation (Rebelo et al. 2017).

3.2 Biopolymers Employed in Biomedical Engineering

Among the most promising biopolymers, polylactic acid (PLA) is applied as an intravascular dilator in patients (Rebelo et al. 2017). PLA is a bioabsorbable and high-strength biopolymer that can be derived from natural bioresources as potatoes, rice, and corn starch (Tamai et al. 2000). In this direction, PLA-based biodegradable stents were developed by a group of researchers and applied in human models (Tamai et al. 2000). Further, the PLA composite scaffolds were studied as a carrier for the recombinant bone morphogenetic protein 2 (Chang et al. 2007). Nanocomposites of PLA with improved Young's modulus and hardness show better performance in tissue engineering (Zhang et al. 2011).

The next commonly used biopolymer for implantable devices is silk. The β-sheet structure of silk fibroin generates a matrix of high mechanical strength with thermodynamic stability (Rebelo et al. 2017). In this direction, Altman et al. (2003) utilized the patient's adult stem cells with silk to develop autologous tissue-engineered anterior cruciate ligaments. The highly versatile scaffolding of silk fibroin is also potentially applied to the musculoskeletal system (Meinel and Kaplan 2012).

Chitosan may be considered a widely applicable biopolymer in the medical field. Deacetylation of chitin may produce chitosan which is mostly used in medical implants as ligament, bone, liver, tendon, cartilage, neural, and skin regeneration (Rebelo et al. 2017). Chitosan-based matrices are widely studied for bone applications. To improve the mechanical strength of these scaffolds, chitosan—alginate biocomposites are developed for better performance in different medical fields (Rebelo et al. 2017). Recent studies have proved that the development of advanced materials in form of biopolymers reinforced with fillers or nanofillers have the potential to show improved performance inside the living system.

3.3 Tribological Studies in Biomedical Engineering

In the biomedical domain, tribological studies may be considered a very challenging aspect because of the continuous up-gradation of implant material (Zhou and Jin 2015). 'Biotribiology', 'Nanotribology', and 'Green tribology' may be considered as a newly established term to evaluate the tribological phenomenon of biomaterials for economical stability, ecological balance, and energy savings efficacies (Luigi 2018). Tribology may be considered an important tool to conserve energy by reducing the coefficient of friction and wear rate between the implant and adjacent surface (Zhou and Jin 2015). In this regard, eco-friendly materials as biopolymers and biodegradable lubricants may play an important role to develop an energy-efficient process with tribological concern also (Shafi et al. 2018).

3.3.1 Tribiology of Biopolymer and Biopolymer Composites

Biopolymer composites are composed of two or more constituent materials with better mechanical performance than biopolymer alone (Rebelo et al. 2017). The use of fiber-reinforced polymer (FRP) in the biomedical field especially in orthopedics offers many characteristics as low young modulus, high tensile strength, mechanical strength, and stiffness to improve their functionality as an implant to be used in bone fracture repair, dental application, and replacements of total hip, knee, ankle, and other joints (Rawat and Saxena 2019). The tribo—performance of such composites may be evaluated to test their compatibility as a biomedical implant (Yousif and Tayeb 2007). In this direction, several studies regarding the tribology of biopolymer composites are reported (Sahoo et al. 2019). Yousif and Tayeb (2007) have reported the tribological performance of oil palm fiber reinforced polyester (OPRP) composites. In continuation of that, wear and friction characteristics of these composites were tested and compared with polyester alone at different sliding distances (0–5 km), sliding velocities (1.7–3.9 m/s), and applied loads (30–70 N) under dry contact condition. The tribo—performance result concluded that

Table 2 Different materials combinations and their tribologival properties

S.N	Material combination	Friction factor	Volumetric wear (mm^3/million cycles)
1	Ceramic on ceramic	0.002–0.07	0.1
2	Eramic on metal	0.002–0.7	0.1
3	Metal on metal	0.22–0.27	1
4	UHMWP on ceramic	0.06–0.08	25
5	UHMWP on metal	0.06–0.08	40

the presence of oil palm fiber in the polyester increased the wear property by about three to four times compared to polyester alone. While the friction coefficient of these polymers was decreased by 23% than the polyester alone. The wear testing of OPRP is based on debonding, bending, tear of fibers, and deformation (Yousif and Tayeb 2007). In another study, date palm leaf reinforced polyvinyl pyrrolidone (PVP/DPL) composites were tested to determine the correlation between the fiber content of these composites and wear performance (Mohanty et al. 2014). Further, it is concluded that the addition of date palm leaf fibers (10- 40% based on the weight of fibers) leads to improve wear resistance of composites with optimum fiber content (26 wt %). With the increment of applied load specific wear rate increases at different sliding speeds for both neat PVP (0 wt %) and the friction coefficient decreases with increasing applied load. These studies conclude that the mechanical and tribological properties of biopolymer composites are correlated with each other and directly affected by fiber loading (Mohanty et al. 2014). Different materials combinations used in biomedical engineering are given in Table 2.

3.3.2 Tribology in Joint Replacement

Several studies have been evaluated to show the tribological features of articular cartilage which is defined as an aneural and avascular connective tissue that protects the end of synovial joints (Ingham and Fisher 2000). These joints minimize friction and wear during the relative motion between the joint surfaces (Lentini 2018). In this direction, Lentini (2018) investigated the tribological performance of adult bovine articular cartilage based on frictional changes due to load and static loading time. He concluded that measured friction increases as loading time elapse due to interstitial fluid exudation (Luigi 2018).

The field of tribology is surrounded by the subject knowledge of fluid mechanics, material science, lubricant chemistry, solid mechanics, and heat transfer (Jin and Fisher 1966). As a surface phenomenon, tribology includes surfaces both microscopic surface topographies as well as macroscopic bearing geometries (Zhou and Jin 2015). In biomedical, tribological studies are very significant in the functioning of artificial joints (Joyce 2009). Tribology becomes very significant in arthroplasty especially in knee and hip joint studies, dental implants, and artificial hearts where the incorporation of friction and wear between two surfaces plays a major role to

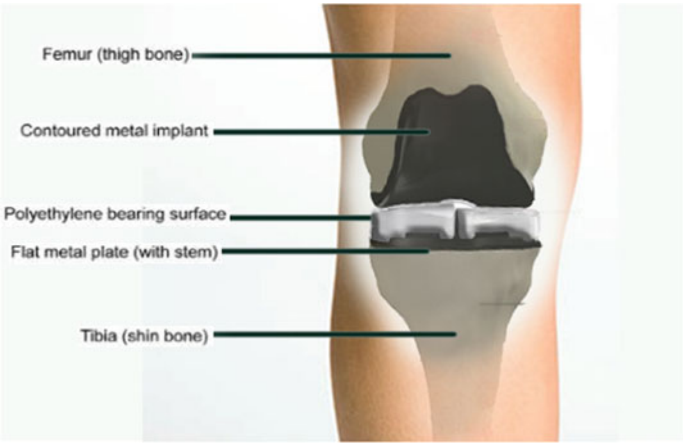

Fig. 4 Artificial knee joint (Sahoo et al. 2019)

predict the performance of medical implants within the living system (Sahoo et al. 2019). The tribology of joints depends upon biomechanical studies, i.e. structure–function relationship of joint motion and the mechanical behavior of materials that make up the joint (Mow et al.1993). In the case of synovial joint, tribology includes lubrication by synovial fluid, synovial joints friction, the mechanisms of joint lubrication, analysis of cartilage wear and damage, joint mechanics, and artificial joints development (Sahoo et al. 2019). A typical artificial knee joint is shown in Fig. 4.

3.3.3 Hip Joints

Hip joints (Fig. 5) are subjected to a large dynamic load about few times of body-weight (Jin and Fisher 1966). Friction and wear are two significant parameters as friction is involved with designing low-friction arthroplasty and wear is concerned with the integration of the prosthetic component. However, biological reactions may be adversely affected due to wear debris. Lubrication plays an important role to reduce the parameters, friction as well as wear. Low friction arthroplasty was extensively studied by Sir John Charnley with the fact that friction and the design of artificial hip joints are correlated to each other (Jin and Fisher 1966). In the early arthroplasty research, Mckee- Farrar hip replacements were clinically evaluated for long-term survival (Higuchi et al. 1997; Zahiri et al. 1999). It was observed that aseptic loosening may be the main cause of implant failure in McKee–Farrar hip replacements in both metals- on- metal and metal-on-plastic bearings (Ingham and Fisher 2000). However, general considerations as wear resistance of the bearing, implant design, and biomechanics of the reconstruction are reported to improve the surgical implantation of hip replacement (Ridzwan et al. 2007) (Fig. 6). Tribological evaluation of friction, wear and lubrication between the contact surfaces along with

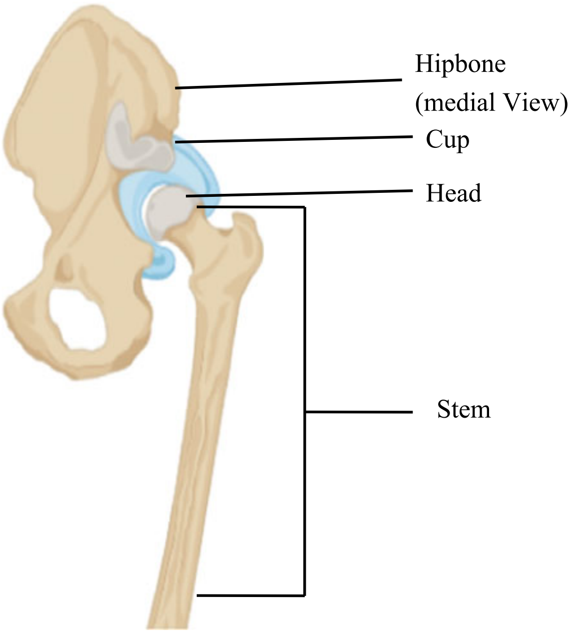

Fig. 5 Illustration of typical hip joint cup implant. (Sahoo et al. 2019)

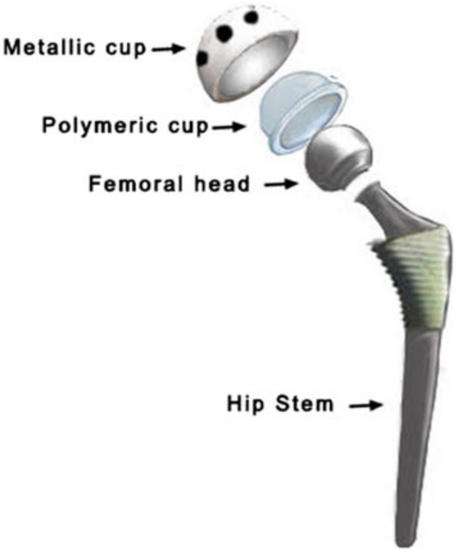

Fig. 6 Individual components required for the complete Hip implant (Sahoo et al. 2019)

contact mechanics modeling (Jin et al. 1999; Bartel et al. 2016) and study of design parameters of the femoral head radius (Plank et al. 2006) may positively impact the total hip replacements with increasing survivorship.

The theory of hip replacement is based on a ball and socket joint, in which the femoral stem and ball fit into each other and relatively move against the cup or acetabular component (Sahoo et al. 2019). Mostly used combinations of materials for hip arthroplasty are listed as metal on plastic, metal on metal, ceramic on plastic, and ceramic on ceramic. At present time, as a metal on plastic material, a very stable and reliable material, UHMWPE is usually applied as hip replacement implants due to a lower risk of wear (Sahoo et al. 2019). However, traditionally, metals on metal bearings, titanium alloy, chromium alloy, or stainless steel were applied in hip arthroplasty. Further, ceramic on ceramic may be chosen as a very good combination due to high strength and ultra low wear ceramic bearing for longer survival. The combination of two reliable materials as Ceramic on UHMWPE may be seen as a very good alternative due to scratch-resistant implant material with a very less wear rate (Sahoo et al. 2019).

4 Food Industry

Biopolymers are simple sugars, fermented products, or, amino acids. We are consuming a wide variety of food from ages to fulfill our apatite and our food includes several carbohydrates, proteins, sugars, and organic acids. Biopolymer consumption in food is escalating at a rapid pace due to a plethora of reasons as they can be used as food, gelling agent, a shelf life enhancer, or as a delivery agent of a certain compound (Fig. 7).

Besides, this class of molecular blocks also offers easy availability, biodegradability, biocompatibility, antibacterial activity, low immunogenicity, less procurement, and processing cost (Jacob et al. 2018). The most common biopolymers utilized in the food industry are listed in Table 3.

Friction is a force and wear is a process of removing material from the surface during relative motion while lubrication is the process of application of fats and oils or saliva in case of human oral tribological studies to reduce the friction and eliminate the wear (Fig. 8).

As a major component of tribology, friction, wear, and lubrication promotes the understanding of the underlying food texture and structure relationship (Axen et al. 2001; Prakash et al. 2013). During tribological studies, a friction stribeck curve is made which is generally divided into 3 sections hydrodynamic, mixed, and boundary regime (Fig. 8). In the hydrodynamic regime, friction is affected by the viscosity and sliding speed while in a mixed regime sliding speed decreases the friction. However, in the boundary regime friction remains constant and hardly affected by any change in viscosity and friction (Nguyen et al. 2017). Friction, wear, and lubrication between the machine parts was the initial concern in tribological studies till 1948 with later advancement and first study in biopolymer tribology dealing with knee

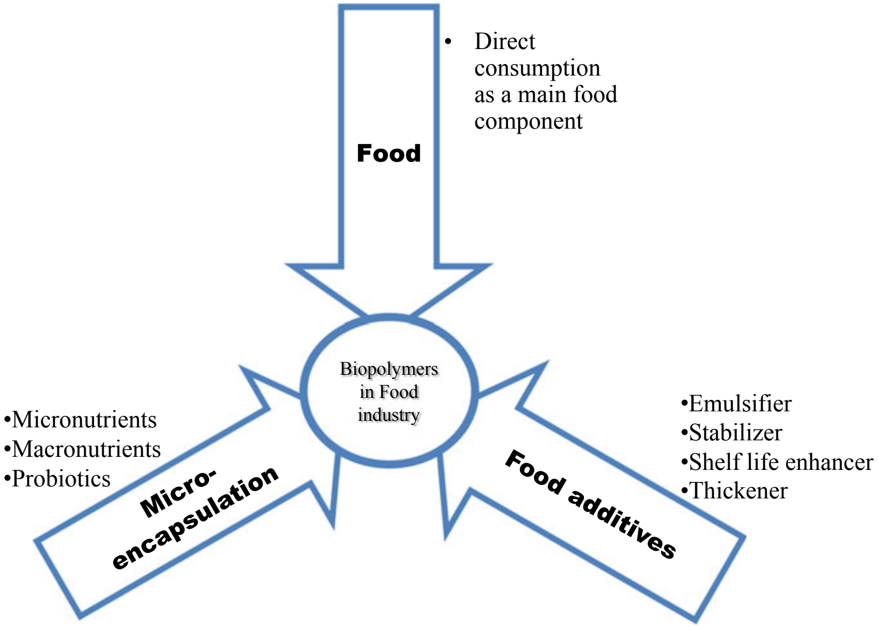

Fig. 7 Different use of biopolymers in food industry and their path of consumption

Table 3 Different Biopolymers used in food industry and their properties

S.N	Biopolymer	EC number	Molecular weight (g/mol)	Density (g/cm^3)	Melting point (°C)
1	Alginate (sodium salt)	232–680-1	216.12	1.601	263.33
2	Casein	232–555-1	2062	1.0632	280
3	Cellulose	232–674-90	342.3	1.5	260–270
4	Chitosan	618–480-0	1526.5	0.15–0.3	203
5	Collagen (type IV alpha I)	295–635-5	1587.8	0.2–0.4	160
6	Gelatine	232–554-6	20–220	1.3–1.4	35 <
7	Lignin	232–682-2	1513.6	1.39	170
8	Pectin	232–553-0	194.14	1.1–105	6.1
9	Starch	232–679-6	359.33	1.5	256–258

joint meniscectomy removal (Fairbank 1948). However, food tribology research was initiated with the first study on the effect of shear on wheat protein got published (Bernardin 1978).

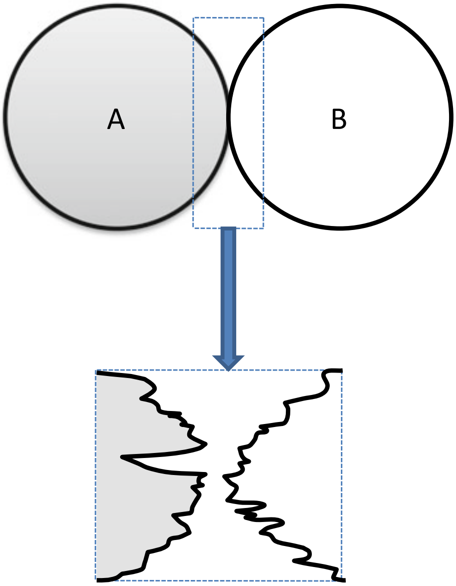

Fig. 8 Schematic view of 2 different particles interacting each other and their uneven rough surfaces causes wear

Static tribology is entirely different than the in-vivo (in-mouth) and any relation between both the situation cannot be found (Vardhanabhuti et al. 2011). The tribological study between food fibers and between food and host (sensory studies) are two major study aspects. During oral processing, we attempt mastication, salvation, aggregation, bolus formation in-mouth, and swallowing (Fig. 10).

The food tribology and rheology depend upon the firmness, hardness, melting, roughness, smoothness, and thickness of food and their impact on sensory and taste perception is in light since the 1970s (Braud and Boucher 2019). Food continuously got broken into subtly pieces to form an aggregate by blending with the saliva that forms a thin layer around the oral surfaces present in the vicinity just before, after, and during the eating. So, during oral processing, the tongue palate contact tribology dominates the rheological aspects of food for texture sensation (Anvari et al. 2018). The structure and function of food were not been assessed by the early rheometrical studies, however, recent tribological research is dealing with all these interactions along with the in-mouth sensory assessment and influence of different types of colloids on the lubrication (Farrés et al. 2014).

Frictional conditions inside the mouth suggest insights about some important food attributes such as slipperiness, mealiness, roughness, astringency, and smoothness. In the human mouth, food faces saliva which is important to prevent xerostomia (Wijk and Prinz 2005). Saliva is required in speaking, bolus formation, lubrication of mouth and in breaking of starch to facilitate food transport through the body, masticated food aggregation, and for the protection of internal bio surfaces from

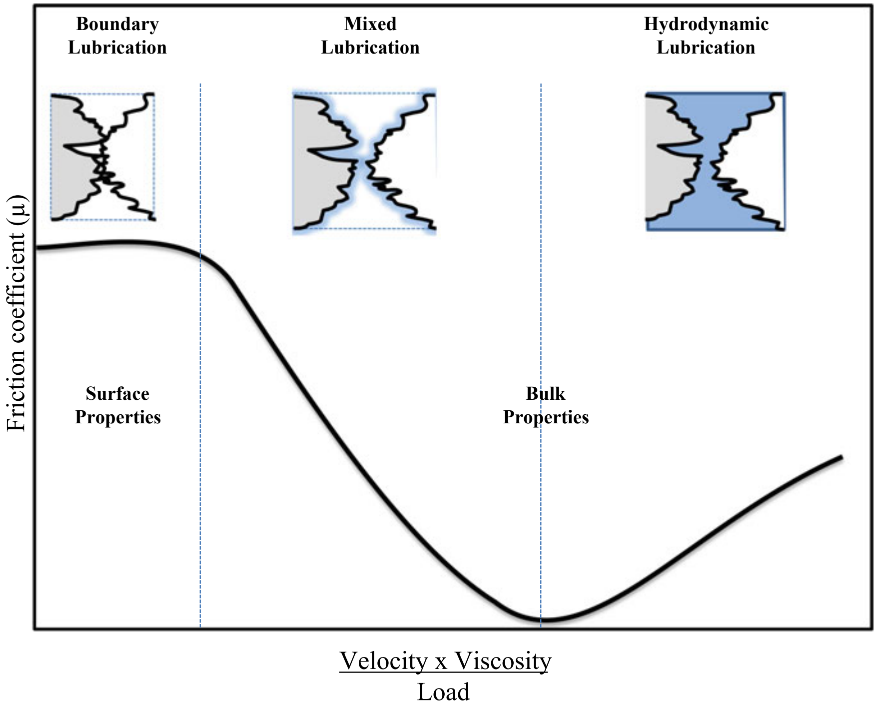

Fig. 9 Typical stribeck curve along with the lubrication conditions. (Prakash, 2017)

wear and abrasion. The human whole saliva (HWS) shows the boundary friction 2 order higher than the water (Bongaerts et al. 2007). Physicochemical properties, and mechanical processing or food mastication also affects the oral Tribology (Fig. 11).

During tribological studies, In-vivo studies against the behavior of foods in presence of oral mucosa under normal function are done on the basis of sensory evaluation through a panel while mechanical aspects of food are generally studied by different tribological testing apparatus (Prinz et al. 2007). However, Olsson and his colleagues have developed a device for measuring the sailometry and dryness based on the sliding friction principle and proved that friction values on the lips are higher as compared to the friction values in the buccal mucosa (Olsson et al. 1991). This method was required to know the status and function of the food if it wears the teeth. So that, we can avoid that food to prevent our tooth from wear (Prinz 2004). Prinz and his colleagues conducted a set of experiments and demonstrated the effect of fats on friction and lubrication. This study has concluded that fats and oils act as a lubricant but not limited to because some biopolymer gels also show good lubricating properties. The size of fat droplets significantly affects the degree of lubrication (Prinz et al. 2005). It is estimated that the fat content of food directly affects the lubricating, rheological, structural, and viscoelastic tribological properties of food but the interaction between protein and fat with the tribo-pair system requires an

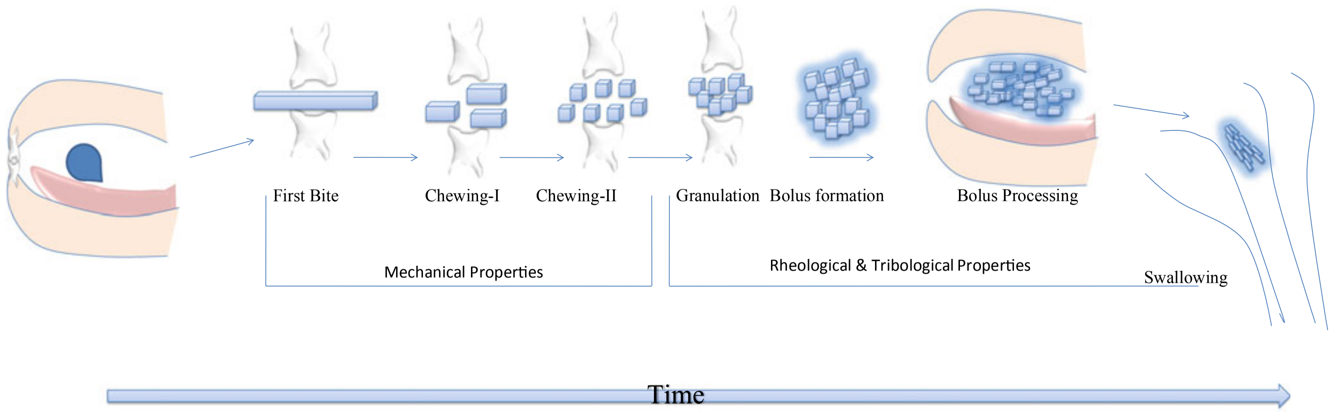

Fig. 10 Depiction of major key stages occur during oral processing of solid food. In addition figure also indicates the steps where mechanics, tribology,and rheology are important. (Stokes et al. 2013)

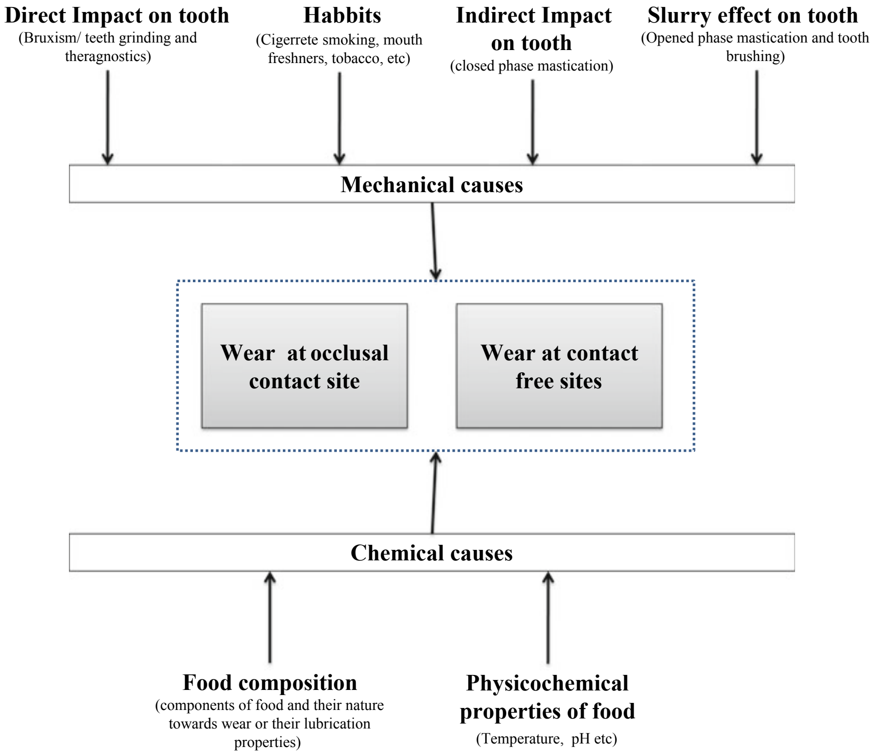

Fig. 11 Parameters influencing food tribology: the food's physico-chemical properties, route and modes of food consumption and the oral physiological properties of human mouth. (Prakash 2017; Zhou and Jin 2015)

investigation to provide some insights into the protein-fat coalescence and texture perception methods (Ningtyas et al. 2017). Among the food rheology and tribology, oral tribology is one of the least studied areas for sensory textural perception (Chen and Stokes 2012).

In earlier days, structural and textural properties of food were assessed by the typical "chew and spit" method in which food samples were given to some people for chewing for different time durations and aggregate was removed and analyzed for different rheological properties (Helkimo et al. 1978). However, the chewing strength and size of the mouth cavity could not be the same. This nonuniformity or variation in individual chewing requires more development to cover all the natural aspects that can replicate the human mouth for the tribological study (Foegeding et al. 2016).

Various attempts to study the masticating effect, salivary friction, and teeth wear were done while the study was zeroing to the soft tissues' ensalivation, function, and role in bolus formation were less. In 2007, Mazari has experimented with 2 different colored chewing gums to study the mixing inwards the bolus and inputs of teeth in the process and concluded that cheeks help in mixing, shortening the bolus, and pushing the food to swallow (Mazari et al. 2007). Tan and his colleagues have developed a numerical model to estimate the behavior of fats and also to characterize their wear interaction with different crystalline networks (Tan et al. 2019). Creep and wear recovery principle-based methods can also be utilized in new food product development and its tribological characterization (Tan and Joyner 2019). However, for different polymers or food samples, the process must be optimized because the depth of creep, loss mass, sliding speed, temperature, and fat content in the food sample varies drastically (Seighalani et al. 2021). Different traction devices have been developed for tribological studies till date and some of the instruments provide comparable conditions to the human mouth (Isschers 2008; Vardhanabhuti et al. 2011; Rodrigues et al. 2016; Stee et al. 2017; Feng et al. 2020).

A recent and more realistic study based on the polydimethylsiloxane (PDMS) disks has revealed the process of interaction and lubrication of the system with soft tribological surfaces. Besides it also stated that heavy and complex food molecules that are large for the cavities increase the friction (Taylor and Mills 2020). Another similar study has concluded that friction forces developed during oral processing are the function of food composition. The study also has stated that friction forces development depends upon the saliva quantity and size of boli (Fuhrmann et al. 2019). Biopolymer-based functional foods i.e. high internal phase emulsion (HIPE) possess ultralow friction properties and show more smoothness and creaminess as compare to commercial mayonnaise and have a potential alternative to becoming a plant-based egg (Ruan et al. 2019). An increase in protein concentration results in high heterogeneous microstructures that increase in proportion to the friction and yield stress. However, Sensory properties (creaminess and smoothness) of food decrease with an increase in protein concentration (Laiho et al. 2017). An increase in hydrocolloid concentration lowers the friction coefficient, increases the viscosity, causes phase separation, and lowers the protein stability (Zhu et al. 2019). A variety of Biopolymers is used in the food industry direct as food, as an aggregate or shelf life enhancer (Fig. 7).

4.1 Major Biopolymers and Their Tribological Properties

Biopolymers are widely used in the food industry as a gelling agent, stabilizing or thickening agent, encapsulating agent, food coating agent, fat replacer, anti-freezing, anti-aging agent, smooth texture, etc. due to their properties of viscosity increment, gelling, and film formation ability (Qin et al. 2020). Alginate ($C_{12}H_{20}O_{12}P_2$, M.W. 418.23 g/mol) has a significant impact on textural and rheological properties of food by increasing the storage modulus (G’) along with the water holding capacity of the food to enhance cohesiveness, smoothness, softness, and chewingness of the food (Kumari et al. 2017, 2018). Alginate can be used as a fat replacer it also positively affects the tribology of food, protein release, and its disintegration while negatively affects protein retention during In-vitro digestion (Kumari et al. 2019). It is perceived and proven that the oral processing and friction properties of food depend upon the fracture properties of the bolus, bolus viscosity, bolus tribology, and initial and late oral processing stages (Krop et al. 2019). That indicates the relation between rheology and oral tribology of food to its sensory properties.

Casein is a rheomorphic protein that is stable during drying, heating, and freezing which makes it valuable. However, change in ionic strength, pressure, pH, temperature, and type of solvents can modify the structure and functions of casein (Ranadheera et al. 2016). Casein cannot bear shear on low pH (2.0–4.6) and reduced in size while at normal pH (6.7–7.5) it has no effect of high shear. It shows orthokinetic aggregation and fragmentation (Ranadheera et al. 2019). Friction reduction depends upon the viscosity and the addition of hydrocolloids increases the protein solution lubrication quality and viscosity. However, frictional reduction in proteins not only dependent on the viscosity increment but also depends upon the size of molecules (Zhu et al. 2019). Wear depends upon the aging time, fat content, normal load, sliding speed, and temperature. Overall strain, depth of creep, and mass loss enhance with the addition of fat content in casein (Tan and Joyner 2019). A lower concentration of casein and casein salts for gelling effectively reduces the average gel particle's size that consequently reduces the friction while higher addition causes higher friction due to the increase in firmness (Pang et al. 2020).

Cellulose and its derivatives are used in the food industry copiously because these are very effective as rheology modifiers, thickener, moisture binders, stabilizers, and viscofiers. Different cellulose derivatives, their properties, and their application in food are given in Table 4. The addition of a small amount of cellulose gum often increases the zero shear viscosity massively and this enhanced zero shear viscosity further leads to the increment in homogeneity and dispersion stability (Jimenez et al. 2020).

Ethylcellulose (EC) or hydroxypropyl methylcellulose (HPMC) is also used as oleogels for the rheological modifications in food. An increase in EC and HPMC concentration causes an increase in flow behavior index and reduces the shear viscosity while concentration decrease causes the decrement inconsistency index. These oleogels affect the food quality and their concentration is directly proportional to the food hardness and causes loss in volume. In the bakery, a reduction in aerated volume directly hampers the texture, taste, and consumer mouthfeel. Therefore this is one of the technical challenges in their bakery use (Demirci and Lee 2020). Oils are a very important part of our food style and a combination of cellulose or its derivatives with oils shows higher lubrication, suitable thermal, mechanical and rheological properties (Sagiri and Rao 2020).

Gelatin is used as biodegradable edible films, thickening agents, emulsifiers, wetting agents, stabilizers, refined material, and microencapsulation agents. Gelatin has a unique property as compared to other biopolymer gelling agents in that it is thermal-reversible and melts in the mouth (Said 2020). Tribological behavior of food depends upon the type and dosage of fat. Gelatin is a proven best hydrocolloid due to its lubrication, gel strength, increase texture, viscosity, and synergy decrement. It is an excellent fat replacer and even increases the sensory properties in comparison to full-fat food. The addition of gelatin reduces the food viscosity and storage (G'), loss

Table 4 Different types of cellulose, their physical and tribological properties and food applications

S.N	Name	Physical properties	Rheological and tribological properties	Food applications	Listed
1	Carboxymethyl cellulose (CMC)	Tasteless, odorless, hygroscopic and white tan powder	Water Soluble	Beverages	Generally recognised as safe food food by US and listed in Food chemical codex by FAO/WHO
			Viscous	Tortillas	
			Easy dispersion and dissolution	Bread	
			Thixotropic	Cakes	
			Water holding capacity at lower solubility	Instant noodles	
			Maintains the viscosity over wide pH change	Meat analogues fomulation	
			Tolerant to salt	Syrup	
			Synergistic with other hydrocollooids	Sauces	
			Makes CMC-protein complex	Soup	
2	Methyl cellulose, Methylhydroxypropyl cellulose (MHPC) or hydroxypropylmethyl cellulose (HPMC)	Light coloured, neutral odor, neutral taste, less hygroscopic powder	Soluble in cold water	Shows thermogelation	Generally recognised as safe food food by US and listed in Food chemical Codex by FAO/WHO
			Shows thermal geling	Bakery stable sauces	
			Little thixotrophic	Bakery stable fillings	
			Pseudoplastic	Ice creams	
			Emulsifier	Whipped creams	
			High salt causes salting out	Whipped toppings	
			High sugar causes low temperature below gelling point	Formed foods	

(continued)

Table 4 (continued)

S.N	Name	Physical properties	Rheological and tribological properties	Food applications	Listed
3	Hydroxypropyl cellulose (HPC)	Neutral taste, neutral odor, water soluble, odd white compound, may be powder or in granular form	Not thixotrophic	Whipped creams	Listed in FOOD chemical Codex by FAO/WHO
			Thermoplastic	Whipped toppings	
			Insoluble in water above 45 °C	Food emulsions	
			Sugar and salt decreases the pprecipitation temperature		
			Emulsifier		
4	Ethyl cellulose (EC)	Soluble in wide range of solvants but not in water	Hydrophobic	Food encapsulation	Listed in Food chemical codex by FAO/WHO
			Ethanol soluble		
			pH change resistant		
			Stabiliser		
			Reduces moisture migration		

modulus (G”) of food significantly (Nguyen et al. 2017). Gelatin decreases the higher degree of friction coefficient of the food sample in comparison to other biopolymers and due to its unique property of melting it produces the boundary conditions (Zhu et al. 2020). The blending of gelatin with other polysaccharides e.g. chitin whiskers (CHWs) etc. develops nano-composite hydrogels. These hydrogels are more effective in terms of fracture strain, fracture stress, hardness, recovery, and increased gelling temperature (T_g). In addition to these characteristics, nanocomposite hydrogels are more stable as compare to pure gelatin gels (Ge et al. 2018).

Chitosan ($C_{56}H_{103}N_9O_{39}$, M.W. 1526.5 g/mol) is a polycationic polymer of glucosamine having some antioxidant properties and biologically adhesive with homeostatic effects that are used in clarification, encapsulation, preservation, and as an active packaging ingredient (Morin et al. 2019). Lignin is the most abundant biopolymer after cellulose. Although lignin shows high resistance to digestion as compared to other natural compounds, it is still used in food items due to its wide functions (Jha et al. 2017). Lignin is used as an egg alternate in bakery and other foods as it also gives a fluffier texture to the food (Gil-chávez 2019). Suberin is also an extracellular biopolymer mostly used as an additive in the baking industry (Mudgil 2017). Further, the Starch-lipid complex resembles the fat structure with properties such as; creaminess, glossiness, and smoothness and is used in producing low-fat mayonnaise, ice-cream, and other food items (Agyei-amponsah et al. 2019). A study has concluded that the breaking of starch molecules by the salivary α-amylase reduces friction by increasing the lubrication. After the breakdown, the small fat molecules migrate to the surface of the bolus and started acting as a lubricant (Wijk and Prinz 2005). The starch granule imbibes the water and swells to several times its initial size and releases the simple linear glucose chains. However, starch granules don’t get completely dissolved and pertains to a highly swollen state, and highly deformable starch paste further plays a vital role in the rheology, texture, and viscosity of starch (Zhang et al. 2017).

5 Packaging

Biopolymer-based food packaging has become an active packaging due to its various features like shelf life enhancement, biodegradability, eating ability, etc. (Versino et al. 2016). Several biopolymers are used in packagings such as alginate, biopolyesters, carrageenan, casein, cellulose, chitosan, collagen, curdlan, gelatin, gellan gum, lignin, pectin, polyglycolic acid (PGA), polyhydroxybutyrate (PHB), polylactic acid (PLA), pullulan, soy proteins, starch, wheat proteins, xanthan, zein, etc. not only in packaging films but these biopolymers are extensively used in producing barrels, bottles, boxes, buckets, cans, caps, closures, coatings, cups, drums, food containers, household refuse bags, jars, packaging bags, pails, vials, etc.

Polylactic acid (PLA) or polylactide is preferred in food packaging as it is a bacterial cellulosic material. PLA is brittle and can’t resist oxygen permeation up to a satisfactory level. It's blending with starch may develop materials of commercial-grade (Muller et al. 2017). PLA-Lignin films can bear high tenacity. However, PLA-starch-lignin composite films show excellent elastic modulus and tensile strength (Yang et al. 2016).

Biopolymer films are a good alternative to plastic films or cellophane. However, the addition of some compounds such as tannic acid (Luqman et al. 2018), nanoparticles (S. Kumar et al.2018a, b; Tang et al. 2018; Amjadi et al. 2019), metal–organic frameworks (Zhao et al. 2020), curcumin (Musso et al. 2017), polyvinylpyrrolidone (Gregorova et al. 2014), etc. shows an unprecedented upsurge in its mechanical, tribological, thermal, antimicrobial properties, retarded lipids extraction, shelf life, and decrease in microbial load.

Biopolymer based packaging films generate garbage after use until it's fully degradation takes place. So, researchers started focusing on zero wastage and developed edible packaging. Natural edible biopolymers are the major source of edible packaging films and also a sustainable and eco-friendly alternative to plastic packaging waste (Shit and Shah 2014). Edible films are very advantageous because they also provide indirect insights about the spoilage of food just by simply measuring the pH and also enhance the shelf life of food by its antioxidant property (Musso et al. 2017). Edible films are not only produced zero discharge but also enhance the organoleptic properties of food (Wittaya 2008).

The biodegradability of a biopolymer film can be increased drastically by increasing the starch content of up to 10% (Arvanitoyannisa et al. 1998). Carboxymethylcellulose and rice starch-based packaging films are flexible, antimicrobial, thermally stable, and antioxidant (Suriyatem et al. 2018). The biopolymer films show low oxygen permeability and good strength. However, their low elasticity and higher moisture sensitivity of some biopolymer-based films can be enhanced and desired mechanical and film properties can be achieved by adding some hydrocolloids into them (Liang and Luo 2020). Some advance biopolymer-based packaging materials such as thermoplastic starch (TPS), thermoplastic corn starch (TPCS), thermoplastic sugar palm starch (TPSPS), bacterial cellulose nano whickers (BCNW), polyhydroxy butyrate (PHB), etc. have been developed with excellent tribological properties and shown the potential of combining with the modified atmospheric packaging.

Hydroxypropyl methylcellulose (HPMC) has high formability and moisture resistance and it is used in the pharmaceutical and food industry as an outer protective layer. HPMC shows substantial wear resistance and lubrication characteristics. HPMC's shorter life span limits its use in packaging. However, its short life extends a tremendous increase in its tribological properties with the addition of Molybdenum disulfide (MoS_2) (Shi et al. 2016). Friction and wear reduction can be achieved by the addition of some nano-additives to improve the tribological properties of the polymer compound because it increases the load-bearing capacity of the composite (Shi et al. 2020). Ultra-high molecular weight polyethylene (UHMWP) is already used in packaging due to its high shear, tension, temperature, and abrasion bearing capacity, and it is proven that the addition of lignin up to 13wt. % doesn't affect its mechanical and tribological abilities. It has a proven eco-friendly packaging material production process (Gupta et al. 2016). UHWMP is a self-lubricating biopolymer having high wear, friction, and corrosion-resistant along with excellent mechanical strength and tribological properties (Guofang et al. 2004). It is estimated that nanoclay loaded UHMWP composite sheets can bear more than 100,000 cycles at 9 N load and linear sliding speed of 0.1 m/s that is advantageous because of its very low friction, wear, cost, and ease in fabrication (Azam and Samad 2018).

6 Challenges and Future Aspect of the Tribological Study of Biopolymers and Biopolymer Composites

Biopolymers and biopolymer composites have proved to be a great success in versatile fields as biomedical implants, food processing material, textile material, and packaging material. In this regard, biopolymer tribology has become very significant in order to enhance mechanical performance as well as the service life of biopolymer composed product. Tribological studies become very crucial in the biomedical field to find suitable arthroplasty materials to minimize wear. The wear minimization of biopolymers is very crucial to extend the longevity of implants. In this way, a great deal of hope for the improvement of bioimplant exists by mitigation of challenges in tribological studies. The selection of appropriate lubricant is one major area of concern for biopolymer wear testing. In this direction, a bovine serum is recognized as a suitable lubricant; however, its properties differ from synovial fluid in specific aspects (Joyce 2009). Besides UHMWPE, a relatively soft polymer polyurethane offer enhanced elastohydrodynamic lubrication as present in natural synovial joints (Dowson et al. 1991). Biopolymers employed in the biomedical application must possess a number of characteristics listed as zero or neutral inflammatory response, suitable mechanical properties according to the application, non-toxic biodegradation of end products for easy resorption or excretion, and suitable permeability and easy processability of design implant. Many parameters like material chemistry, hydrophobicity, molecular chemistry, surface charge, adsorption, degradation, erosion mechanism, etc. play a significant role to execute these characteristics. So, here, a key challenge exists to screen out suitable biomaterial from a cluster of the huge amount of biopolymers for further synthesis or composite formation to best find material as per desired application (Ulery et al. 2011). The future perspective of biopolymer tribology in the orthopedic area is concerned with the search for lubricant which is safer and economic than bovine serum for biopolymer wear testing. Further, optimum protein content determination and finding suitable additives are other challenging aspects (Joyce 2009). Extensive study is still required for better applicability of ‘High-performance polymer’ such as polyaramids (Kevlar), polyetheretherketone (PEEK), and polybenzimidazole (PBI) holding a higher level of physical properties, higher melting points, and high level of degradation resistance (Friedrich 2018). As a novel research area, ‘Green tribology’ may cover all tribological problems concerned with emerging technologies for surface characterization and better regulation of friction and wear to meet energy balance as well as environmental aspects of lubrication and surface modification techniques (Michale and Bhushan 2012). The future challenges of biopolymer application in medicine involve advanced drug loading, better encapsulation, and more controlled drug release. Better adsorption of biopolymer depends upon chemical and mechanical modification. Recent research studies explored that more flexible and durable liposome coated biopolymer may be considered as an ideal ingredient in food and therapeutic supplement. In this direction, the tribological study of biopolymer will aid new ideas to design newer materials, upgraded from the existing ones for versatile biological applications (Dutta et al. 2020).

7 Conclusion

Tribology may be considered as an umbrella to cover a close relationship between scientists, engineers, and clinicians to address the problems concerned with the interdisciplinary area of mechanical surface, materials, biology, physics, chemistry, and engineering, etc. The tribological evaluation provides a new dimension for the research and development of biopolymers in versatile industrially significant fields as biomedical, food, packaging, pharmaceutical, and textile, etc. Additionally, tribological studies show suitability to incorporate various biopolymers for controlled drug release with enhanced performance and better efficiency in drug or nutraceutical delivery. In the biomedical field, tribology is gaining significant importance by employing biopolymers such as UHMWPE, VE-UHMWPE, and polyurethane, etc., as best arthroplasty materials with minimum wear. The future research in biomedical engineering is concerned with biopolymer implant designing not only with the engineering aspect but also viewing the real biological system to obtain a desired biological response with minimization of implant failure. Further, advanced research is needed to search for novel biopolymers as the best arthroplasty materials to meet tribological aspects along with biological phenomenon for longer and qualitative patient life. Undoubtedly, the advancement in methods and techniques of tribology, as well as biotribology, will provide sustainability and reliability of biopolymer-based products for the overall wellbeing of human life with economic growth.

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