Beneficial Biofilm Applications in Food and Agricultural Industry

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Abstract Biofilm is defined as a community in which microorganisms adhere to a living or inanimate surface, embedded in a gelatinous layer in a self-produced matrix of extra polymeric substances, adhered to each other, to a solid surface or to an interface. Adverse environmental conditions caused biofilm formation by inducing transition of microorganisms from planktonic cell form to sessile cell form and altered metabolism of bacteria in biofilms. Bacteria in biofilm matrix produce the specific secondary metabolites and gain robustness. Although biofilms are often accepted as potentially destructive for clinical and other industrial fields, many biofilms are beneficial and there are several reports related to the positive use of these biofilms. Beneficial biofilms could be used for wide applications (antibacterial, food fermentation, biofertilizer, filtration, biofouling, prevention of corrosion, antimicrobial agents, wastewater treatment, bioremediation and microbial fuel cells) in food, agricultural, medical, environment and other fields. According to previous reports, certain strains including *Bacillus* spp. (*B. subtilis*, *B. thuringiensis*, *B. brevis*, *B. licheniformis*, *Bacillus polymyxa*, *Bacillus amyloliquefaciens*) *Lactobacillus* spp. (*L. casei*, *L. paracasei*, *L. acidophilus*, *L. plantarum*, *L. reuteri*) *Enterococcus* spp. (*E. casseliflavus*, *E. faecalis*, *E. faecium*), *Pseudomonas* spp. (*P. fluorescens*, *P. putida* and *P. chlororaphis*), *Acetobacter aceti*, some fungi and *Pseudoalteromonas* sp., etc. led to beneficial biofilm formation. Food and agricultural industry may mostly benefit from biofilms in terms of their biochemical, fermentative, antimicrobial and biotechnological characteristics. Microorganisms in biofilm matrix could positively affect quality characteristics of food products such as texture, biochemical composition and sensorial properties *via* the production of specific secondary metabolites. Additionally, biofilms have an importance in water and soil safety of

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A. Malik et al. (eds.), *Health and Safety Aspects of Food Processing Technologies*, https://doi.org/10.1007/978-3-030-24903-8_15

agricultural land. The present chapter highlights beneficial biofilm applications in food and agriculture industry.

Keywords Biofilms · Beneficial microorganisms · Probiotics · Food and agriculture industry

Introduction

Biofilm is multicellular and cooperative communities of microorganisms attached to biotic or abiotic surfaces and frequently embedded under the extracellular polymeric substances (EPS) (Todhanakasem 2013). Microbial adhesion to a surface is the first stage of biofilm formation and is affected by several factors including hydrophobic and electrostatic interactions, substratum surface roughness, surface charges and cell surface structures (Sarjit et al. 2015). Three-dimensional structure of adherent cells in biofilm matrix contains networks of channels for supplying of nutritional compounds and a wide range of microbial cell-to-cell communication (quorum sensing) synchronizing the activities of microbial consortium (Ayala et al. 2017). Signaling molecules provided cell to cell interactions are the main mechanism that explain colonization or adhesion of bacteria or fungi based strains on various surface. Microorganisms exhibit desirable or undesirable effects in industrial fields by using this mechanism (Velmourougane et al. 2017).

Biofilms are found everywhere, ranging from the environment to the human body. Biofilms mostly have clinical scientific interest due to pathogen infection with regard to human health (Jefferson 2004). On the other hand, biofilm formations originated from food-processing equipment, environment and staff in food industry may threat the microbiological quality and safety of food products due to cross contamination and lead to foodborne outbreaks and economic losses. Therefore, food industry prioritized food safety policies to prevent and control biofilm formation (Lindsay and Holy 2006; Houdt and Michiels 2010; Wingender and Flemming 2011). There are different types of bacteria concerning biofilm formation. Biofilm formation can be enhanced through synergistic interactions among multispecies biofilms, along with some other nutritional and environmental conditions (Berlanga and Guerrero 2016). Although biofilms were mostly considered in a negative sense, beneficial biofilms with their positive characteristics were also stated in various industrial fields (Ercan and Demirci 2015). In terms of beneficial aspects of biofilm formation, food and agricultural industry utilized biofilms in food fermentation, bioremediation, wastewater treatment, biotechnological applications and as probiotics, biofertilizers, biocontrol agents and microbial fuel cells, etc. (Qureshi et al. 2004; Qureshi 2009; Shah 2018). The high biomass density in biofilms result in quite more biochemical activities than that of planktonic cell (Marapatla 2014). Biofilm applications in these fields led to higher productivity in comparison to conventional fermentation. While industry and researchers try to degrade detrimental biofilm formation, they support the utilization of beneficial biofilms in various industrial fields with the improvement of novel biotechnological applications (Winkelströter et al. 2014).

In brief, while there are innumerable studies based on negative aspects of biofilms, there are also various favorable properties of biofilms. Especially, in recent times, researchers focused on potential strategies for the enhancement of beneficial biofilms. This chapter described several examples of beneficial biofilms in food and agricultural industry and encouraged further research in this area.

Biofilm Formation: Good or Bad

Biofilms were first observed and defined in 1684 by Anthony van Leewenhoek, however called as a term centuries afterwards. The first observation about microbial biofilms which adhere to tooth surfaces and form sessile communities were detected by using his primitive light microscope (Vos 2015; Shi and Zhu 2009). The Royal Society of London reported that the vast accumulation of microorganisms were observed in dental plaque (Jefferson 2004; Lens 2011). Although the relation between cell surface structures (mostly pili and capsules) and adhesion was detected earlier (Robertson and McLean 2015). As known, biofilms could be formed by both bacteria and fungi on natural and artificial surfaces. The flagella, fimbriae, pili, lipopolysaccharides and membrane proteins are responsible for biofilm formation (Velmourougane et al. 2017).

Biofilms are formed with aggregation of microbial strains that are enclosed in self-produced extracellular polymeric substances. Biofilm formation can be observed everywhere and most microorganisms are presently considered to be capable of biofilm formation on earth (Toyofuku et al. 2016). Microbial populations in biofilms generally differ from their planktonic counterparts in terms of nutrient uptake, nutrient cycling, respiration and overall growth and also display differences in terms of their molecular structures (Blenkinsop and Costerton 1991; Dunne 2002). Many microorganisms have ability of attachment to surfaces and thus could form biofilms in various industrial fields (Houdt and Michiels 2010). Biofilms may attach on a wide variety surfaces including plastics, metal, glass, soil particles, wood, medical implant materials, tissue, food products, food processing equipment, devices and machines, etc. Microbial adhesion is supported by fimbriae, pili, flagella and EPS that play an important role to found a bridge between microorganisms and the conditioning film (Kokare et al. 2009).

For agricultural and food industry, microbial biofilms can be detrimental or beneficial (Ercan and Demirci 2015). It is essential to aware of the mechanisms of biofilm formation in order to control deleterious biofilm formation and/or to promote beneficial biofilm formation (Sarjit et al. 2015). The formation of biofilm occurs in five stage including initial attachment, irreversible microbial attachment, early development of biofilm structure (micro colony formation), maturation and dispersion (Jara et al. 2016). Several environmental factors are effective on each stage regulating the biofilm formation process. Microbial attachment to a surface is the main process due to transformation from planktonic cell form to the biofilm form. This stage called as primary adhesion, the bacteria may embed to the biofilm or leave the surface and return to the planktonic form (Hall et al. 2004; Petrova and Sauer 2012). After reversible attachment, microbial cells undergo irreversible attachment. Here, surface proteins and EPS contribute the attachment between the cell and surface. During the transition to irreversible adhesion, an intracellular secondary messenger produced by microbial cells provide the regulation of EPS production and motility (Hinsa et al. 2003; Toyofuku et al. 2016).

The formation of biofilm is challenging for food industries such as dairy, fish processing, poultry, meat and ready-to-eat foods industries due to their resistant to antimicrobial agents. The properties of the surfaces to which microorganisms attach and species are the most important factors affecting biofilm formation (Srey et al. 2013). Biofilms formed by spoilage and pathogenic microorganisms on food processing surfaces could result in food spoilage and outbreaks in view of inappropriate and inadequate cleaning with regard to sanitation (Todhanakasem 2013). The prevention of biofilm formation is essential in order to ensure food safety and protect public health. In agricultural industry, biofilm formation has negative sense because microbial colonization in plant by biofilm could cause infections (Laranjo et al. 2017). As detrimental biofilms of pathogenic and spoilage microorganisms are robust to antimicrobial substance used in sanitation, their presence endangers human health and quality properties of food (Berlanga and Guerrero 2016). For instance, contamination of nonstarter lactic acid bacteria (*Lactobacillus curvatus*, *Lactobacillus fermentum*, etc.) into equipment surfaces used in dairy industry led to adverse biofilm formations in cheeses (Somers et al. 2001; Agarwal et al. 2006). In agriculture industry, the development of pathogen biofilm in plants causes economic losses due to damage and disease of the plants (Velmourougane et al. 2017).

In addition to detrimental aspects of biofilm, there are positive aspects related to the formation of biofilm. Beneficial biofilms could be utilized for wide applications (biocontrol agents, food fermentation, biofertilizer, filtration, biofouling, prevention of corrosion, wastewater treatment, bioremediation, nutrient mobilizer, plant growth promoter and microbial fuel cells, etc.) in food, medical, agriculture, environment and other industrial fields (Stepanovic et al. 2007; Wood et al. 2016; Velmourougane et al. 2017). Biofilm formation in the food processing industry could be beneficial, especially in fermented and probiotic food products such as vinegar and cheese (Zottola and Sasahara 1999). In agriculture industry, biofilm-based biofertilizers provide use of sustainable soil because of the utilization of less or none chemical fertilizers in farming areas. In bioremediation and waste water treatment, biofilms are used for the removal of various industrial pollutants from sewage, industrial waste streams or contaminated ground water (Sarjit et al. 2015; Vilamakis 2011; Zottola and Sasahara 1999). Another good aspect, biofilms formed mostly by *Bacillus* species were utilized in the prevention of infection from plant pathogens in plant growth promotion (Winkelströter et al. 2014). With regard to positive aspects in electrical energy, biofilms are involved in microbial fuel cells which could use microbial metabolism to produce an electrical current from organic substrates

(Sarjit et al. 2015; Vilamakis 2011). Another desirable biofilms are anticorrosive biofilms with regard to their industrial importance. These biofilms can prevent the corrosion on metal surface of equipment or devices in food and agricultural industry (Wood et al. 2010).

Beneficial Biofilm Applications

Bacteria are often referred to as harmful microorganisms; however, the human body, despite having some amounts of detrimental bacteria, is replete with beneficial bacteria that thrive and decrease the number of harmful bacteria (Rajpal et al. 2017). The economic, medical and industrial importance of biofilms required detailed and meticulous studies for the controlling of microbial attachment and subsequent biofilm formation. Similar to microbial free cell, microorganisms in biofilm matrix compete with each other. Dominant microbial cell having higher cell density in population encourage biofilm formation (Robertson and McLean 2015). Cell-to-cell communication provide the organization and differentiation of microbial strains in biofilms. Signal molecules called as quorum sensing were used in microbial cell to cell communication. As microorganisms produce signal compounds, cell density increase in biofilm matrix. As high cell density led to the great accumulation of signal molecules, biofilms produce increasing amounts of metabolites and secretes (organic acids such as lactic acid and acetic acid, hydrogen peroxide and bacteriocins) (Toyofuku et al. 2016). In recent studies, instead of focusing on killing the harmful bacteria that cause an infection, this study focuses on ways to maximize the growth of good or helpful bacteria that will thrive and destroy the detrimental bacteria naturally. Quorum sensing explains the reason of biofilm formation. The relationship between quorum sensing and biofilm formation explains pathogen inhibition by beneficial biofilms (Rajpal et al. 2017). Quorum sensing behavior in biofilm matrix is thought to offer significant benefits to bacteria in terms of biofilm community structure, defense against competitors, adaptation to environmental changes and overall host colonization (Engevik and Versalovic 2017). Biofilm specific cell signaling are generally known with the providing of communication among microbial cells and information exchange. On the other hand, cell signaling in biofilms could achieve cross-kingdom interactions defined as interactions between organisms of different kingdoms (plants, algae, fungi, human, etc.) and mediate other biofilm based formations (Lens 2011; Stavridou and Forzi 2011).

Biofilm structure as microbial community or consortia has a wide range of advantages compared to a planktonic form. Biofilms generated by beneficial microorganisms are utilized in many industrial fields due to their advantageous structure. The most widely used beneficial biofilm applications in food and agricultural industry are listed as probiotic and bacteriocin producer strain biofilms, microbial biofilms specific to certain fermented food process, bioremediation, wastewater treatment, biofilms as biofertilizer or biocontrol agent, anticorrosive biofilms and biofilm reactor.

Probiotic and Bacteriocin Producing Biofilms

Human gastrointestinal tract consists of densely colonized microbial ecosystem. Microbiota in this system allows for beneficial and complex interactions with its host (Kalkan et al. 2018). Biofilms or biofilm-like forms in the human digestive tract may influence the function of the intestinal microbiota and its interactions with the host (Vos 2015). Adhesion potential of microorganisms into gut epithelial mucosal surface to form biofilm is used as a criterion in the selection of probiotic cultures (Benarjee and Ray 2017). Probiotics are viable microorganisms intended to provide health benefits due to their contributions in prevention and treatment of various diseases when consumed (Galgano et al. 2015; Kerry et al. 2018). Previous reports proved that the beneficial effects of probiotic strains were associated with their biofilm formation which pose increased robustness to temperature, low pH, osmotic stress and mechanical forces to that of their planktonic counterparts. The biofilms originated from *Lactobacillus* strains (especially *L. rhamnosus*, *L. plantarum*, *L. reuteri*, and *L. fermentum*) are used as probiotics in food and agricultural production due to various health benefits (Jara et al. 2016). Additionally, probiotic biofilms provide a variety of technological advantages in food and agricultural industry. For example, these biofilms can prevent the growth of undesirable microorganisms such as pathogenic and spoilage microorganisms and also improve the quality properties of food products (Gomez et al. 2016). Although there were a great number of probiotic applications in food and medical field, agricultural applications of probiotic have raised gradually (Song et al. 2012).

Similar to probiotic free cell, probiotic biofilms could be applied for several purposes such as inhibition of pathogen and spoilage microorganisms in foods (—fruits and vegetables, —meat and meat products, —food processing plant and surfaces), the production of some fermented foods and animal feeding (for the prevention of disease from zoonotic and other enteric pathogens), poultry, pigs, cattle and goat (for the prevention of pathogen infections) and lastly in aquaculture as biocontrol agents (Hossain et al. 2017).

Biofilms generate intimate relationship between the human gastrointestinal system and its inhabitant microorganisms. Thus, probiotic strains develop their mechanisms associated with biofilm formation (Farahmand et al. 2013). Commensal probiotic strains inactivate enteric pathogen microorganisms and regulate host immune responses in the intestinal system, however researches evaluating specific functions of biofilms from beneficial microorganisms have been inadequate. Many treatments for bacterial infections have been focused on getting rid of the pathogenic bacteria, but recent works focuses on multiplying the nonpathogenic bacteria in the body (increasing biofilm formation) under the most favorable conditions, so these beneficial bacteria can thrive in the body and reduce the number of detrimental bacteria. *Lactobacillus acidophilus*, *Streptococcus thermophilus*, *Lactococcus lactis*, and *Leuconostoc mesenteroides* subsp. *mesenteroides*, are known as lactic acid bacteria, are gram-positive, are beneficial for the body, and are found in food products (Rajpal et al. 2017).

Lactobacillus reuteri as probiotic bacterium exhibits positive effects on human health similar to other probiotics and produce the antimicrobial agent referred as reuterin. Similarly, biofilms of *L. reuteri* present beneficial effects on human health. For instance, reuterin produced by biofilm of *L. reuteri* could inhibit foodborne pathogens which cause disease in humans (Jones and Versalovic 2009).

Bacteriocins produced by microorganisms in biofilm matrix influence microbial competition in this matrix. Researchers detected that bacteriocins had inhibitory effect on pathogenic bacteria such as *Listeria monocytogenes*, *E. coli*, *Salmonella* spp. and *Staphylococcus aureus*. As a matter of fact some bacteriocins (for example nisin) were commercially used in industrial and medical aims (Engevik and Versalovic 2017).

Similar to planktonic forms of lactic acid bacteria, lactic acid bacteria biofilms as bacteriocin producers have a potential as antibacterial agents in food industry (for instance the field of food packaging). For example, biofilms formed by *Lactobacillus plantarum* and *Enterococcus casseliflavus* as bacteriocin producers exhibited antibacterial effect on *Listeria monocytogenes*. Food industry could utilize these bacteriocin producer biofilms as an antilisterial agent (Guerrieri et al. 2009).

B. subtilis is used in food and beverage production due to beneficial properties. When *B. subtilis* is regularly consumed through foods, it notably prolongs human life expectancy and assist to eliminate the detection of age-related diseases. Especially, probiotic *B. subtilis* biofilms result in the improved lifespan and healthy longevity of *Caenorhabditis elegans*. This dual microbial-worm interaction between *B. subtilis* and *C. elegans* provide colonization and a multicellular biofilm formation in the friendly environment of the worm gut mucosa (Ayala et al. 2017).

Bacillus subtilis has recently an increasing interest due to its probiotic properties. Biofilms of probiotic *Bacillus subtilis* have more favorable properties than its planktonic form. The use of biofilms of these bacteria is beneficial approach, especially as probiotic bacteria must enter the gastric system without losing their survival. Probiotic biofilms of any beneficial bacterium protect not only its own viability but also the viability of other beneficial strain by coating this strain. For example, EPS matrix in biofilm of *B. subtilis* protect other probiotic strains (e.g. *L. plantarum*) against adverse factors throughout gastrointestinal tract (Yahav et al. 2018).

Beneficial Biofilms Specific to Certain Food Process

Biofilm formation with regard to beneficial aspects in food industry could improve biochemical quality, tastes, flavors and textural properties in food products (Jahid and Ha 2014). The microbial interactions in biofilms induced certain food process. In particular, fermented beverages production and cheese ripening or production are carried out by these microbial interactions (Qureshi 2009). Various fermented food products such as fermented dairy products (yogurt, cheese, kefir), meat products (sausages, salami) and vegetable products (vinegar, pickle) in worldwide have their own microflora. Microbial diversity in fermented food arisen from production methods and microbial ecosystems in production environment. In worldwide, various biofilmed form in fermented foods were listed as mixed biofilms associated with surfaces (cheese rinds), suspended biofilms in liquid (kombucha, kefir, and vinegar), dispersed growth in liquid (lambic beers, natural wines, and yogurt), or in semi-solid substrates (kimchi and miso) (Wolfe and Dutton 2015). The wine production has been leaded by mixture of fungi, yeast and bacteria species from ripening of grapes in vineyards to wine bottling. The cell to cell communication has a key role to produce approvable last product of the wine. On the other hand, during the cheese ripening period mixed communities have been found in the fermentation medium as well (Gulgor and Korukluoglu 2016).

In the Sicilian Protected Denomination of Origin (PDO) Ragusano cheese production, raw milk is put in a wooden vat referred as a Tina without adding starter culture. Fermentative microflora (*Streptococcus thermophilus*, *Lactobacillus lactis*, *Lactobacillus delbrueckii*, and *Enterococcus faecium*) in this cheese production arise from raw milk and Tina biofilm (Licitra et al. 2007). The Tina biofilm consists of lactic and non-lactic species and generate various flavour compounds due to proteolysis and lipolysis during the cheese ripening by these bacteria. In addition to this, lactic acid bacteria in beneficial biofilms from Tina wooden vat accelerate the processing of acidification (Lortal et al. 2009).

In the production of traditional stretched cheeses, desirable biofilms form as a result of adhesion of nonstarter lactic acid bacteria to wooden vat or wooden plank. The ripening of cheese in wooden utensil provided due to the presence of beneficial biofilms both an increasing sensorial quality and biocontrol against pathogen bacteria (*L. monocytogenes*, *Salmonella* spp.) (Scatassa et al. 2015).

Traditional Vastedda cheeses were produced in virgin wooden vat. The surface of this vat subjected to microbial colonization and formed biofilms which are responsible for fermentation and ripening process of cheeses. Biofilms microbial flora caused biodiversity in Vastedda cheeses and ensured favorable sensorial profile for consumers (Gaglio et al. 2015).

In olive production, product specific quality properties stem from biofilmed microbial flora, mostly lactic acid bacteria and yeast. Biofilms mostly form on olive skin or vessels used in production and compose the most microbial communities during olive processing (Heperkan 2013).

Another food process benefited from biofilms is black olive production. During the production of black olives by submerged fermentation, *L. pentosus* and *P. membranifaciens* attach to the surface of black olive and generate biofilm in the stomatal apertures and on the epidermis of olive. As biofilm formation enhanced quality properties of black oil with regard to organoleptic and biochemical, recent olive fermentations were based on beneficial biofilms (Grounta and Panagou 2014).

After harvesting, olive is unfavorable for consumption as a fruit due to its oleuropein content (bitter component). Fermentation process is required for olives to be suitable for consumption and thus table olive is obtained with favorable sensorial and biochemical properties. Biofilms formed by microbial flora on the skin of the olives are responsible for the fermentation in table olive production. During the fermentation of "Spanish-style" green olives, microorganisms consisting of

Enterococcus, *Pediococcus*, *Leuconostoc*, *Lactococcus*, *Candida*, *Pichia*, and *Saccharomyces* are responsible for biofilm formation on surface of green olive. These biofilms act in the preservation against undesirable microbial flora (spoilage and pathogen) and ensure textural and aromatic quality as in table olive (Berlanga and Guerrero 2016).

The nonstarter lactic acid bacteria form dominant microflora which have an impact on quality in most cheese varieties during ripening. Nonstarter lactic acid bacteria in Cheddar are responsible for typical flavor development and notes. However in some cases, these nonstarter bacteria could lead to aroma defects or losses in sensorial quality (Banks and Williams 2004).

Biofilms additionally act in conventional fermented food production ranging from solid biomaterials and proceeding to the moromi-mush, semisolid state. Koji molds, yeasts, lactic acid bacteria and acetic acid bacteria contribute to many traditional fermentations (sourdough, kefir, cacao processing, sausage, tofuyo) and brewing processes (sake brewing, wine and beer brewing, Shochu, awamori, and whiskey, vinegar brewing, soy sauce brewing). Fallen crops (for instance rice), dropped ripe fruits and vegetables are available media for the growth of such microorganisms (Furukawa et al. 2013).

The traditional Minas cheese is manufactured from raw cow's milk by employing wooden utensils which are the source of fermentative or ripening biofilm (*Lactobacillus* and *Lactococcus*) in manufacture. Such biofilms stemmed from wooden utensils synthesized enzymes, organic acids and other antimicrobial substances (peptides and bacteriocins) and thus ensure the product safety. With regard to product quality, they also improve the organoleptic and textural quality properties of the cheese (Galinari et al. 2014).

Traditional smear cheeses produced by using wood utensils were preferred because of their specific sensorial quality. These wood utensils contain biofilms formed by innumerous microorganisms which support formation of flavor compounds and otherwise affect hygienic quality in cheese (Mariani et al. 2007). As a result of cross contamination with pathogen, wood materials could subject to contamination of *Listeria monocytogenes* which is the most important risk factor during ripening of smear cheeses (Aziza et al. 2006). The spontaneous microflora stemmed from biofilms on wooden shelves were utilized in the ripening process of a soft and smear cheese and so had a potential to inactivate *Listeria monocytogenes* (Guillier et al. 2008).

During Spanish style green table olive production, microflora consisting of *Lactobacillus pentosus* and yeast led to mixed biofilms formation on both abiotic (glass slide or vessels which olives placed on) and biotic (olive skin) surfaces as a result of fermentation process. Green olive skin act as a convenient surface for the adhesion of microorganisms and induced formation of complex biofilms during controlled or spontaneous table olive manufacturing (Manzano et al. 2012). Microorganisms responsible for biofilm formation on vessels as abiotic surface were mainly *Candida* spp., *W. anomalus*, *D. hansenii, P. guilliermondii* and *L. pentosus* (Grounta et al. 2015).

'Gerles' (wooden vats utilized the production of Protected Denomination of Origin Salers cheese) provides an appropriate environment for biofilm formation. These beneficial biofilm formation inhibit the growth of pathogen bacteria and as well as contribute the improvement of favorable organoleptic characteristics (Didienne et al. 2012).

Various researchers reported that colonization of food or food contact surfaces by starter cultures was a favorable situation because such colonization by beneficial microflora prevented pathogenic or spoilage bacteria growth. As known, there is competition between beneficial and undesirable microorganisms. Starter cultures exhibits antagonistic characteristic against pathogens and spoilage bacteria. Lactic acid bacteria biofilms may be used to control the formation of biofilms by the food-borne pathogens *Listeria monocytogenes*, *Salmonella Typhimurium*, and *Escherichia coli* O157:H7. Biofilms formed by lactic acid bacteria have been stated to be a stress response and survival strategy in adverse conditions. These defensive mechanisms of bacteria were related quorum sensing, adhesion, and biofilm formation (Laranjo et al. 2017).

Nonstarter lactic acid bacteria biofilms had a potential to inhibit the growth of *Listeria monocytogenes* in soft cheeses. These antilisterial biofilms were formed by *Lactobacillus plantarum*, *Lactobacillus casei*, *Lactobacillus curvatus* and *Lactobacillus paracasei*. In future, the detection of novel nonstarter lactic acid bacteria biofilms could also ensure biocontrol against various undesirable microbial strains in various food products (Speranza et al. 2009).

In aquacultures, biofilms were used as food source and thus enhance the fish production. Microalgae and probiotic bacterial products have bioavailability in terms of their beneficial dietary composition. The utilization of probiotic biofilms in shrimp juvenile stimulated its nutrient quality as biofilms had high protein contents (Pandey et al. 2014).

Beneficial Biofilm Based Practices for Sustainable Food and Agriculture

Nowadays, there are increasing interest on the subject of sustainable food and agriculture as a result of biosecurity concern (Bhardwaj et al. 2014). According to FAO, biosecurity is associated with the sustainability of agriculture, food safety and the protection of the environment. On this sense, beneficial biofilm based approaches were offered for sustainable food and agriculture. For example, in organic farming, beneficial biofilms were practiced as biofertilizer and biocontrol agents. Additionally, for waste management, bioremediation through biofilms are seen as environment friendly method and provide degradation of environmental in water soil and other related fields (Baht et al. 2018).

Bioremediation

Bioremediation is defined as a contaminant or pollution treatment technique. In this technique, a variety of pollutants are biologically destructed or converted into less deleterious forms. Microorganisms in bioremediation process are used for degradation of the environmental contaminants (toxic heavy metals, other toxic compounds, plastic wastes and synthetic dyes) or transformation into less toxic forms of these pollutants. Bioremediation process is essential for health and environmental protection (Vidali 2001). Bioremediation could be applied in water, soil and other related fields. Great applications were commercially based on bioremediation, as the microbial bioremediation of contaminated soil or water is economic and reliable (Mueller et al. 1996; Edwards and Kjellerup 2013). Beneficial physical and physiological interactions among organisms in biofilms could be used to help degradation or transformation of environmental contaminants (Horemans et al. 2016). Biofilms are particularly applied for bioremediation of recalcitrant pollutant. High microbial biomass of biofilms facilitates the immobilization of this pollutant. The enhancement of gene transfer among microorganisms in biofilm promote the bioremediation and induce bacterial chemotaxis for degradation of bioavailable contaminants (Singh et al. 2006). Biofilm-based bioremediation is a proficient and safer alternative to bioremediation with planktonic microorganisms because biofilms are more resistant to toxic conditions and xenobiotics as well as increase bioavailability of contaminants to microbial cells for degradation. Additionally, the lipopolysaccharides and EPS in biofilm structure could act as a chelating agent facilitating the bioremediation of toxic pollutant (chlorinated organics). Therefore, microbial colony with great density on surfaces and materials are utilized in the processing of bioremediation (Sarjit et al. 2015). Biofilms mostly use substrates including straw, saw dust, or corn cobs as carbon sources to enhance degradation (Vidali 2001). Biofilms due to their great cell density and stress robustness could effectively metabolize hydrophobic and toxic substances. In general, biofilm formation is explained by quorum sensing mechanism based on a population density from cell–cell communication through signaling molecules. Biofilm signaling molecules are involved in the degradation and detoxification of pollutants. As the degradation of pollutants depend on quorum sensing signal of biofilms, biofilms with high cell signaling charge are favored for bioremediation (Mangwani et al. 2015).

Mostly aerobic microorganisms as well as fungi and anaerobic microorganisms are used in bioremediation. Aerobic microorganisms including *Pseudomonas*, *Alcaligenes*, *Sphingomonas*, *Rhodococcus*, and *Mycobacterium* have a potential for degradation of pesticides, hydrocarbons, alkanes and polyaromatic substances. These aerobic bacteria utilize these pollutants for the requirement of carbon and energy. Anaerobic bacteria are utilized in order to degrade polychlorinated biphenyls in river sediments and dechlorinate the solvent trichloroethylene and chloroform (Vidali 2001). Bioremediation by fungi are called as mycoremediation. Fungi (*Phanaerochaete chrysosporium*, *Aspergillus terreus*, *Aspergillus niger*, *Rhizopus nigricans* and *Cunninghamella*) provide degradation of wide variety toxic contaminants by secreting their extracellular enzymes (Bennett and Faison 1997). Contaminant-specific fungi are used in mycoremediation (Kshirsagar 2013).

Biofilms have been known as available for the remediation of various contaminants due to their great microbial density and ability with regard to immobilization of contaminants. Biofilm researches about ecology of soil, sand, sediments and wetland vegetation have found out that biofilms are also useful for wastewater treatment. Biofilms may be successfully applied for the bioremediation of waste waters (Das et al. 2017). In wastewater treatment, the addition of a certain chosen strains to a complex environment is referred bioaugmentation (Morikawa 2006). Some microorganisms which form beneficial biofilm in the process of wastewater purification are reported as *Enterobacter agglomerans*, *Cronobacter sakazakii*, and *Pantoea agglomerans* (Turki et al. 2017). Microbiological and chemical contamination of water from industrial areas endangers safety of drinking water. Additionally, contaminated water causes toxic effect to marine life and humans (Sarjit et al. 2015). In waste water treatment colonization of beneficial biofilms occur firstly on suspended solid particles within wastewater. Applications related to wastewater treatment were often observed in food and agricultural (mostly animal husbandry) industries. For examples, beneficial biofilms by *Pseudomonas* sp. and *P. diminuta* were applied in bioremediation of polluted wastewater with vegetable oil and grease. A biofilm sand filter system designed for removing of these pollutants exhibited high degradation activity (Masry et al. 2004).

The most commonly used wastewater treatment is a trickling filter since 1880 (Robertson and McLean 2015; Qureshi 2009). Beneficial microbial cells in the biofilm degrade various compounds including phosphorous and nitrogen-containing substances, carbonaceous materials, and trapped pathogens from the wastewater. After the removal of contaminants or mess, treated water of a biofilter is either released to the nature or utilized for agricultural and other recreational targets. The removing of the contaminants from wastewater are performed through biofilm on various filter media (Sehar and Naz 2016).

Food industry is one of the most important industrial fields with regard to the accumulation of waste water production and other pollutants. Bioremediation is recent approach to food waste management. Olive oil industry, fruit and vegetable processing industry, fermentation industry, dairy industry and meat and poultry industry produce a variety of wastes at different rate and composition, mostly solid suspensions, product specific-liquids, biological oxygen demand and chemical oxygen demand (Thassitou and Arvanitoyannis 2001; Alimoradi et al. 2018). For instance, cheese whey wastewater treated to aerobic and anaerobic biodegradation for the aim of bioremediation (Carvalho et al. 2013). Additionally, phenols as agro-industrial effluents could pose a risk in drinking water and irrigation water or in cultivated land. Removal or transformation of phenols is possible with bioremediation (Chiacchierini et al. 2004).

Agriculture industry generates wastes including pollutants (chemical fertilizer, pesticide and others) and water used in farming fields. Bioremediation process can be applied for degradation of these wastes in agriculture industry (Das et al. 2017). Contamination of the veterinary antibiotic sulfamethazine to agricultural soils through manure applications pose a risk for the ecology and human health. For this reason, researchers offered the removal of this pollutant with bioremediation. Here, beneficial biofilm formed by *Microbacterium* spp. induced the degradation of pollutants (Hirth et al. 2016).

As some of marine bacteria have ability of biofilm formation and extracellular polymeric substances production, they could be used in bioremediation process of heavy metals, hydrocarbon and many other recalcitrant compounds and xenobiotics (Dash et al. 2013).

Biofertilizers and Biocontrol Agents for Plants

For sustainable agriculture and ensuring of food safety, another approach is to apply composition of organic fertilizers and biofilm-based biofertilizer and biocontrol agents in soil. Adhesion of various microbial cells to the plant roots generates antagonism between plant and biofilms and provide robustness to detrimental conditions (Ramey et al. 2004; Hettiarachchi et al. 2014). Microbial colonization on diverse plant part surfaces of different plant species induces beneficial effects such as biocontrol and symbiosis (Rudrappa et al. 2008). Some colonized bacteria for desirable properties are as follows:

- *Bacillus subtilis*, *Pseudomonas fluorescens*, *Pseudomonas putida* and *Pseudomonas chlororaphis* based biofilms around the root of crop plants for biocontrol,
- *Microsphaeropsis* sp. based biofilms around the root of onion for biocontrol,
- *Bacillus polymyxa* based biofilms around the root of cucumber for biocontrol,
- *Rhizobium* and *Sinorhizobium* based biofilms around the root of legumes for symbiosis,
- *Azorhizobium caulinodans* and *R. leguminosarum* around the root of rice for beneficial effect,
- *Azospirillum brasilense* and *Klebsiella pneumoniae* based biofilms around the root of wheat for beneficial effect
- *Gluconacetobacter diazotrophicus* based biofilms around the endophytic of sugar cane for beneficial effect (Rudrappa et al. 2008).

There are increasing demands on beneficial biofilm practices as biofertilizers or biocontrol agents (Garcia et al. 2011). Biofilm based products as biofertilizer and biocontrol agent in plants were increasingly improved for novel applications. The regulations supporting organic farming or sustainable agriculture production will be induced the use of beneficial biofilms (as biofertilizer and biocontrol agents) and detection of a variety microbial strains forming biofilm (Seneviratne et al. 2008). Until now, beneficial biofilm applications have been performed on various crops such as soybean, chickpea, tomato, bitter gourd, radish, okra, chilli, Hungarian wax pepper, aubergine, cabbage, mungbean, wheat, maize, corn, rice, lettuce, onion, strawberry and tea. However, as a novel strategy, the discovery of more resistant biofilms to adverse environmental factors (drought, salinity, inorganic, and organic pollutant, etc.) is the purpose to improve the food quality (Malusa et al. 2012; Marapatla 2014; Seneviratne et al. 2016; Velmourougane et al. 2017; Singhalage et al. 2019).

Industrial farming used synthetic chemical fertilizers, pesticides, herbicides and other continual inputs endangers sustainable agriculture. These synthetic chemical substances could eliminate beneficial microorganisms which causes a drop in soil fertility and product yield (Seneviratne et al. 2008). Recently, as a result of boosting interest in sustainable agriculture applications, beneficial microbial strains have been utilized as biofertilizer. Biofertilizers are natural substances with microbial origin (bacteria, algae and fungi) which increase bioavailability and uptake of essential nutrients for crop plants such as rhizobia and mycorrhizal fungi. They could apply to seed, plant surfaces, soil by colonizing the rhizosphere or the interior of the plant (Gupta and Anand 2018). Biofertilizers were often called as plant growth promoting microorganisms (Rafique et al. 2015; Seneviratne et al. 2016). Microbial strains such as *Bacillus*, *Enterobacter*, *Burkholderia*, *Acinetobacter*, *Alcaligenes*, *Arthrobacter*, *Azospirillum*, *Azotobacter*, *Beijerinckia*, *Erwinia*, *Flavobacterium*, *Rhizobium* and *Serratia* are the main plant growth promoting bacteria (Kasim et al. 2016). On the other hand, plant growth promoting microorganisms are mostly divided into three class including arbuscular mycorrhizal fungi, plant growth-promoting rhizobacteria and nitrogen fixing rhizobia (Malusa et al. 2012). These microorganisms enhanced the bioavailability of phosphorus (P) and nitrogen (N) and other essential trace elements by plant (Basu et al. 2017). Nitrogen fixing and P solubilizing bacteria called as "a Plant Growth Promoting Rhizobacteria" increase the N and P uptake (essential nutrients) of the plants. Beneficial biofilms exhibited great proportions of biological nitrogen fixation and organic acid production (Babu et al. 2017). Nitrogen fixing bacteria enhances the growth and resistance of effective microbial communities in the soil by supplying N through biological nitrogen fixation. On the other hand, N fertilizers having negative impact on N2 fixers reduced soil fertility and crop yield. Beneficial biofilms with N2 fixers restored soils deteriorated by common agricultural practices in tea cultivation. Nitrogen fixing bacteria including *Acetobacter* spp., *Azotobacter* spp., *Rhizobium* spp., *Bradyrhizobium* spp. and *Colletotrichum* spp. could be used as biofertilizers in sustainable agriculture (Seneviratne and Wijepala 2011).

Plant growth promoting microorganisms are able to produce exopolysaccharides and volatile organic compounds. Interactions between plant and microorganisms were established through signal molecules from quorum sensing that induces biofilm formation, competence, sporulation, and antibiotic production (Basu et al. 2017). Rhizosphere is a region around the plant root which acts as habitat of various microorganisms such as bacteria, fungi, actinomycetes, protozoa and algae. Some of these microorganisms promote the growth of plants. Plant growth promoting bacteria consist of planktonic cell or microbial endophytes colonizing part of the interior tissues of the plant (Santoyo et al. 2016; Basu et al. 2017).

Beneficial biofilms formed by fungi and bacteria were successfully utilized as biofertilizers to increase productivity in nonlegume crops. For instance, inoculation of biofilm forms of fungal rhizobia caused more N_2 fixation in soybean than inoculation of traditional rhizobium. Wheat seedlings subjected to bacterial biofilm showed higher productivity in moderate saline soils. Additionally biofilm forms acquired robustness to microbial cells for the survival stability against adverse environments. For example, the survival of rhizobia in biofilm matrix are 105-fold more than rhizobial monoculture at great salty conditions (Malusa et al. 2012).

In maize, wheat and cereals, *Azospirillum brasilense* and other *Azospirillum* sp. (plant growth promoting bacteria) exhibit the formation of biofilm on the surface of the root. Various Agrobacterium sp. and symbiotic rhizobia strains have the ability of adhesion on root and form microbial colony or biofilms. *Agrobacterium tumefaciens* cause thick and complex biofilm formation on the surface of root (on mostly epidermis and root hairs) (Rafique et al. 2015).

Saline soils in agricultural fields have a negative effect on productivity of crop. *Rhizobacteria* ensuring plant growth under stress conditions regulate nutritional and hormonal balance. For example, biofilms from *Bacillus amyloliquefaciens* as plant growth promoting *Rhizobacteria* were also useful for ensuring of salinity tolerance in barley (Kasim et al. 2016).

In organic farming or sustainable agriculture, animal manure as source of nutrients could enhance crop productivity by improving the biochemical composition of the soil. However, the bioavailability of manure by plants depends on recover and deposition of nutrients in manure. On this sense, microbial biofilms (For example biofilms from Chlorella vulgaris, green microalga as a biofertilizer) were applied and provided the conversion of organic and inorganic components in dung into more available substances (cellular components) (Rajendran et al. 2018).

As known, plant growth in corn are promoted by biofilms. Biofilms of *Pseudomonas* spp., *Bacillus* spp. and *Aspergillus* spp. caused increased productivity in maize (*Zea mays*) (Babu et al. 2017). Similarly, biofilms formed as a result of interaction and colonization between *Azorhizobium caulinodans* and *Aspergillus* spp. around rice root acted successfully as biofertilizers (Trimanne et al. 2018). In some cases, biofertilizers are used in combination with chemical fertilizers or other natural fertilizers for higher productivity. For instance, the treatment of biofilm biofertilizer obtained from *P. fluorescens* and *R. leguminosarum* with bentonite and chemical fertilizer increased growth and productivity of wheat (Ratha and Jasim 2018). In another study, a fertilizer consisting of biofilm fertilizer (*Aspergillus* sp. and *Enterobacter* sp.) and chemical fertilizer resulted in increased strawberry yield (Singhalage et al. 2019). The practices of organic fertilizer composted with fluid biofilm biofertilizer on dry land enhanced uptake of soil nutrients and spinach productivity (Sudadi and Triharyanto 2018). As a result of all these literatures, in next studies, different biofilm combinations should be tested for more effective biofilm practices.

In addition to biofertilizer properties of biofilms, biofilms formed by microbial strains as biocontrol agents were successfully practiced in crop or plants. For example, fungal–bacterial biofilms (*Pleurotus ostreatus–Pseudomonas fluorescens*) acted as biocontrol agent in the edible mushroom and also enhanced the protein amounts of mushroom with their positive effect on nutritional product quality (Seneviratne et al. 2008). *Bacillus* spp. was mostly used as biocontrol agent in agriculture industry. Also, *Bacillus*-based pesticides, fungicides and fertilizers are commercially available (Garcia et al. 2011). *Bacillus* species such as *B. subtilis*, *B. thuringiensis* and *B. amyloliquefaciens* mostly placed on plant rhizosphere could produce beneficial biofilms prevent the infection from plant pathogens (Ayala et al. 2017; Beauregard et al. 2013). In the rhizosphere which is the area of soil surrounding a plant root system, *B. subtilis* promotes plant growth and inhibits undesirable microorganisms. Its biofilms are commercially used as biocontrol agents to overcome fungal infections in plants. Surfactin producer *B. subtilis* biofilms could prevent or restrict the colonization of other microbial free cells. Similarly, virulence of plant pathogen *Erwinia carotovora* are restricted by *Bacillus thuringiensis* with signaling molecules (Morikawa 2006). *Pseudoalteromonas tunicata* called as marine specific-endophytic bacterium is colonized through stimulation of the green macroalga (*Ulva lactuca*) and thus generates antifouling substances to prevent adhesion of harmful microorganisms. Another marine macroalgae *Delisea pulchra* with great antifouling activities restricts the colonization of detrimental bacteria. In marine aquaculture, coating of fish egg by beneficial biofilms hinders infection from harmful microorganisms and additionally provide the protection of the water quality and health of adult fish (Wesselin 2015). *Pseudomonas* sp. have also high performance as biocontrol agents because this strain forms biofilms with great mass on the surface of root. High biomass in biofilm matrix from *Pseudomonas* sp. cause too extensive biofilm network channel and signaling molecules supporting inhibitory activity (Ratha and Jasim 2018). Another beneficial biofilm practice is adhesion of *Pseudomonas chlororaphis* to wheat rhizosphere against fungal diseases. Favorable microorganisms tend to nutrients or metabolites from biotic surfaces (root, rhizosphere, leave and other surfaces of crop or plant) through chemotaxis. Accumulation of beneficial microbial colonies on the surface of crop or plant ensures the protection against pathogenic microorganisms. As a result, there is a competition among microbial communities (beneficial or detrimental) on the surface of plant and new biotechnological applications are to render beneficial microorganisms or biofilms dominant (Wesselin 2015).

Biofilm Reactors (Bioreactor)

Bioreactor are often used for innumerous productions in various industrial field. Production in bioreactors are performed economically with high yield (Qureshi 2009). Recently, researchers focused on the term of biofilm based bioreactor. Because, biofilm formation in reactor lead to higher productivity through wide surface area of biofilm structure (Ercan and Demirci 2015). The use of biofilms in reactors provides many advantages such as higher biomass density, improved productivity and stability (Cheng et al. 2010). Biofilm reactors are used for a wide range of purposes including wastewater treatment, biofuels (ethanol, buthanol), organic acid production (citric acid, lactic acid, acetic acid, succinic acid and fumaric acid, polysaccharide, alcohol production (ethanol, buthanol), enzyme production, vinegar production (Qureshi et al. 2004; Qureshi 2009; Cheng et al. 2010; Todhanakasem 2013; Ercan and Demirci 2015). Particularly, biofilms in the manufacture of vinegar have been successfully performed for a long time. Vinegar were produced by *Acetobacter* or *Gluconobacter* on free-floating wood chips with higher yield. Wide surface area of wood chips boosts the growth and activity of vinegar bacteria which convert substrate into product (Zottola and Sasahara 1999). Additionally, biofilm reactor causes more yield in the production of antimicrobial substances and pigments (Morikawa 2006).

Some of products obtained in bioreactors were presented in Table 1.

Microorganisms on the surface of marine algae compete with each other for the limited amounts of nutrients. The production of inhibitory metabolites by marine epibiotic microorganisms are more than by planktonic cell. Additionally, under in vitro conditions, microbial cells in shaking flask cease the production of antibacterial metabolites. However, Bioreactor produce more antimicrobial substances by *B. subtilis* and *Bacillus pumilus* and a red pigment by *B. licheniformis*. As a result, cell to cell communication or signal molecules in biofilms regulates the expression of pigments and antimicrobial metabolites (Morikawa 2006).

Biofilm reactors have a potential for wastewater treatment in food and agricultural industry (Sarjit et al. 2015). Decomposition of food waste could be performed

Table 1 Beneficial biofilm based productions in bioreactor (Rosche et al. 2009; Qureshi 2009; Cheng et al. 2010; Ercan and Demirci 2015)

Biofilmed microorganisms used in bioreactor	Products
Zymomonas mobilis *S. cerevisiae*	Ethanol
Acetobacter aceti	Acetic acid or vinegar
Gluconobacter oxydans	Dihydroxyacetone
Lactococcus lactic, *L. lactis*	Nisin
Acetobacter xylinum	Pyruvic acid, Bacterial cellulose
Aspergillus niger	Citric acid, cellulose, xylanase
R. oryzae	Fumaric acid
L. amylophilus, *L. casei*, *L. delbrueckii*, *Pseudomonas fragi*, *Streptomyces viridosporus*, *Thermoactinomyces vulgaris*, *Rhizopus oryzae*, *Lactobacillus plantarum*, *L. brevis*, and *L. fructivorans*	Lactic acid
A. succinogenes	Succunic acid
C. acremonium	Cephalosporin C
E. coli	Amylase
A. terreus, *Trichoderma viride*	Cellulase
P. chryosporium	Lignin peroxidase
Rhizopus chinensis	Intracellular lipase
Phanerochaete chrysosporium	Lignin peroxidase
A. pullulans	Pullulan
X. campestris	Xantan

by anaerobic microorganism in bioreactor (Khan et al. 2018). Olive mill wastes form the most important sources of antimicrobial phenolic compounds (Carraro et al. 2014). Bioremediation of olive mill wastewater is quite hard because of its high chemical oxygen demand, high phenolic content and dark color. Anaerobic reactors with high performance as well as aerobic reactors are successfully used in degradations or removal of olive mill effluents (Mcnamara et al. 2008). In terms of waste, cheese industry also generates a great amount of whey and milk permeate and this situation causes economic loss originated from waste. For the benefit of agricultural and food industry, cheese factory effluents or wastes should be converted into another valued product (Wang et al. 2009). As a matter of fact, in a previous study, cheese whey was fermented by *Clostridium acetobutylicum* to produce buthanol in biofilm reactor (Raganati et al. 2013).

Anticorrosive Biofilms

In food and agricultural industry, corrosion is undesirable situation because of both economic and processing loss (Gupta and Anand 2018). When metal surfaces in various devices, equipment, etc. subjected to any substances from processing conditions or environment, deterioration on metal surfaces could be observed. Factors led to corrosion were divided into chemical (oxygen, ammonia or hydrogen sulphide, organic and inorganic acids) and biological (enzymes, microorganisms—mostly sulfate-reducing bacteria) (Beech and Sunner 2004; Ivanova and Ivanov 2013).

Industry applies various methods to prevent corrosion and recently have preferred biological methods such as the use of microorganisms due to environmental concern. In particular, oxygen-consuming and iron-reducing bacteria (*Shewanella oneidensis*) were reported as anticorrosive (Lee et al. 2006). Although anticorrosive strategies with microbial cells are commonly used, the prevention of corrosion through beneficial biofilms is a new technique. Beneficial biofilms successfully prevent and decrease the metal corrosion. Methods used in repress of corrosion with biofilms are divided into three. In first method, bacteria removes corrosive substances (oxygen and others) with aerobic respiration. In another method, corrosive microorganisms (sulfate reducing bacteria) are inactivated by inhibitory compounds from biofilms. As third method, biofilm coats the surface of industrial equipment and act as defensing cover (Zuo 2007).

As mentioned above, sulfate reducing bacteria cause the biological corrosion of metal including iron, copper, aluminum carbon steel, stainless steel and some alloys. *Bacillus brevis* biofilms inhibit *D. orientis* known as the sulfate-reducing bacterium and *L. discophora* as the iron-oxidizing bacterium and thus achieve the reduction in mild steel corrosion (Morikawa 2006). Secretion of polyanionic chemical substances (inhibitory proteins) by microbial cell in biofilm matrix (antimicrobial proteins) destroy corrosive sulfate reducing bacteria. Aerobic bacteria, mostly *Bacillus* species such as *Bacillus Subtilis* or *Bacillus licheniformis* were utilized to suppress metal corrosion (Örnek et al. 2002; Wood et al. 2002; Narekumar et al. 2017).

Additionally, EPS synthesis by *Lactobacillus delbrueckii* and *L. fermentum* as well as biofilms from this lactic acid bacteria assist to the prevention of metal corrosion. This mean that lactic acid bacteria could have anticorrosive potential (Ivanova et al. 2009; Ivanova and Ivanov 2014; Tsveteslava and Ivanov 2014). In another report, *Acetobacter aceti* biofilms exhibited anticorrosive properties by protecting or coating carbon steel surfaces. This finding is highly interesting and novel because acid-producing bacteria have been known as corrosive until now. Briefly, biofilm structure of microbial strains protects steel surfaces against corrosion unlike planktonic cells of microbial strains (France 2016).

Conclusion

Biofilm formation is a significant problem in health, food, agriculture and other industrial fields as biofilms are commonly regarded as detrimental. On the other hand, biofilms in food and agriculture industry have recently gained attention because of their beneficial properties such as food fermentation, probiotic potential, the promoting of plant growth, prevention of corrosion, inactivation of undesirable microorganism growth, wastewater treatment, destruction of industrial pollutants, etc. In particular, production with higher yield could be possible with biofilms because biofilms as microbiota embedded in extracellular polymeric substances matrix have high biomass due to a wide diversity of microbial life and metabolic potential. Although, desirable activities of biofilms are mostly associated with their quorum sensing mechanisms that provide cell to cell interactions through signaling molecules, their function are not yet completely clear. Until now, researchers have mostly focused on detrimental biofilms, biofilm formation stages, persistence of biofilms and biofilm architecture. This chapter pointed out the importance of beneficial biofilm applications in food and agricultural industry and prompts future studies based on beneficial biofilms. Especially, in future, the discovery of beneficial biofilm formation by a variety of microorganisms will bring about novel biotechnological applications in different industrial fields.

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