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The use of *Bacillus* species in maintenance of water quality in aquaculture: A review

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ABSTRACT

Aquaculture effluent is often associated with increased organic carbon, suspended solids, phosphates, nitrogenous species (nitrates, nitrites, and ammonia), chemical oxygen demand and biological oxygen demand. This is regarded as a global threat to aquatic ecosystems due to its influence on surrounding waters as well as groundwater. The threat of aquaculture effluent is not confined to the aquatic ecosystems as high levels of phosphorus and nitrogen may become poisonous to plants and change their protein synthesis, enzyme activities, photosynthesis, oxidative stress response, membrane permeability, and respiratory processes. Other forms of water pollution such as the presence of heavy metals as well as pathogenic microbes are issues of concern since they can be transferred through the food chain. *Bacillus* species have demonstrated great ability in the maintenance of water quality in aquaculture which is simple and cost-effective. This review highlights that *Bacillus* modulates a wide range of water quality parameters including physical (transparency and total dissolved solids) and chemical (pH, conductivity, chemical oxygen demand, dissolved oxygen, biological oxygen demand, alkalinity, phosphates, nitrogenous species, hardness) water quality parameters, heavy metals, oil spillage as well as maintenance of microbial balance; hence reduction in pathogenic microbes. The efficiency of *Bacillus* in modulating water quality is greatly dependent on factors such as mode of application, dissolved oxygen, pH, temperature, source of nutrients, strain type, and metal ions. This review further highlights aquaculture activities that lead to pollution and the possible mechanisms used by *Bacillus* for improving water quality. It is recommended that a range of optimum conditions be established to increase the efficiency of *Bacillus* in modulating water quality. A better understanding of *Bacillus* to the genetic level and the development of new genetic tools is also recommended since the ability of microorganisms to modulate water quality is related to their genetic make-up.

1. Introduction

The intensive culture of aquatic organisms to meet the demands of the ever-growing human population has been coupled with several challenges (Edwards, 2015). Aquaculture can impact the environment negatively through the spread of diseases, wetlands and mangroves

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destruction, declined biodiversity of natural fish populations by the escape of non-native fish, and surface and groundwater pollution by effluent discharge (Ottinger et al., 2016; van Rijn, 2013; Wang et al., 2018). The contribution of aquaculture to global fish production is significant, regardless of the negative impacts, as capture fisheries have been stagnant and efforts to increase capture fisheries production have been futile (Herath and Satoh, 2015). Aquaculture activities which result in the pollution of ground and surface waters include the use of commercial feeds, accumulation of fish faeces, and decomposition of dead fish. Also, the disturbance of sediment by fish resulting in the vertical mixing of sediment into the water column, excessive use of chemicals result in pollution (Wang et al., 2018). Indiscriminate disposal of fish waste such as scales, offal, and dead fish also contribute to water pollution. The resulting effects are high concentrations of organic matter, phosphorus, and nitrogen which negatively impact the rearing water and lower dissolved oxygen (DO) levels due to the decomposition of organic substances (Farrelly et al., 2015; Herath and Satoh, 2015; Morata et al., 2015; Srithongouthai and Tada, 2017). These poor water conditions threaten the survival of aquatic organisms and render both ground and surface water unsafe for other organisms.

Deterioration of the rearing water quality is one great issue of concern as the wellbeing of aquatic organisms depends greatly on the water (Brönmark and Hansson, 2017; Hura et al., 2018). High stocking densities result in rapid deterioration of the water quality which in turn leads to stress thus increased susceptibility to diseases, suitable environment for the proliferation of pathogenic microbes, and eventually mortality of cultured species (Lieke et al., 2019; Zokaeifar et al., 2014). Typically, poor water quality induces emaciation, gill opercula malformation, and gill filament ulceration (Chen and Chen, 2001). Water pollution in aquaculture is unavoidable as the culture of aquatic organisms is accompanied by waste accumulation resulting in the pollution of receiving waters and groundwater. This is because aquaculture effluents are released into natural water bodies (Lalloo et al., 2007).

Water exchange and biofilters are traditional methods used to control toxic metabolites in aquaculture (Crab et al., 2007; Jahangiri and Esteban, 2018; Martins et al., 2010). Several systems and methods have also been proposed and used for the improvement of water quality and the treatment of aquaculture wastewater. These include recirculating aquaculture systems, biofloc technology which involve the use of microorganisms, and aquaponics (Carlberg et al., 2002; Emerenciano et al., 2017; Maucieri et al., 2018; van Rijn, 2013). The most common method used in the maintenance of aquaculture water quality is frequent water exchange which is expensive, laborious, and may introduce pathogens into the culture systems (Devaraja et al., 2013). Furthermore, several chemical substances such as Biolite plus, Bio-tuff, Geotox, Green zeolite, JV zeolite, Pontox plus (Shamsuzzaman and Biswas, 2012), Well Zeolite, and Aquazet (Faruk et al., 2008) have been used for the improvement of water quality in aquaculture. However, the complex nature of the above-mentioned systems and the bioaccumulation of these chemicals for human consumption are of great concern. Thus several studies are geared towards the use of probiotics for the management of aquaculture water quality (Hura et al., 2018). The use of probiotics for the remediation of aquaculture wastewater has gained ground as probiotics not only improve the water quality but also confer on the cultured fish other benefits. Immunostimulation resulting in resistance against pathogens, direct inhibition of pathogenic microbes, provision of nutrient and enzymes, and improved feed utilization and growth are other benefits of probiotics (Hoseinifar et al., 2018; Kuebutornye et al., 2019; Ringø et al., 2018; Van Doan et al., 2019). Water quality partly determines the growth and wellbeing of aquatic organisms thus probiotics can improve water quality making it suitable for the culture of aquatic organisms (Hura et al., 2018; Tuan et al., 2013). The recent advancement in the aquaculture industry is to use probiotic *Bacillus* to improve water quality and many supporting articles are available (Devaraja et al., 2013; Kuebutornye et al., 2019; Soltani et al., 2019). As discussed earlier (Kuebutornye et al., 2019), *Bacillus* as probiotics possess characteristics which are advantageous over other probiotics including their ability to produce spores and metabolites which are effective against a wide range of pathogenic microbes. Thus this review aimed to bring together literature in which *Bacillus* has been used in the maintenance of aquaculture wastewater and discusses the mechanisms as well as the role of probiotic *Bacillus* in the improvement of water quality in aquaculture.

1.1. *Aquaculture activities resulting in water pollution*

Lakes, ponds, and rivers are major water sources for freshwater aquaculture whiles the sea serves as water source for mariculture (Ni et al., 2018). Aquaculture uses diverse systems such as cages, pens, ponds, long-lines, rafts, and stakes (Chua, 1992). The activities of any culture system result in the release of waste into the natural water bodies and groundwater which serves a vast community of organisms including humans regardless of the source of water and the type of system. Thus activities from any aquaculture system has influences on other species. Internal and external sources can pollute aquaculture systems (Soltani et al., 2019). The followings are aquaculture associated activities that directly or indirectly result in water pollution.

1.1.1. *Feed and fertilizers*

Farmed fish, as well as crustaceans, depend on external nutrient sources including farm-made feeds, fresh feeds, or commercially manufactured feeds (Pahlow et al., 2015). The most common form of feed used in aquaculture is commercial feed. In pond aquaculture, fertilizers are often applied to promote production. The major source of waste in aquaculture is feed as significant amounts are uneaten and undigested (Amirkolaie, 2011). Fertilizers and commercial feeds contain higher phosphorus and nitrogen contents than the rearing water bodies (Schwartz and Boyd, 1994). They serve as a source of water pollution i.e. eutrophication and natural ecosystem destruction due to increased levels of nitrogen and phosphorus (Amirkolaie, 2011). Oxygen depletion in the water column, enriched nutrients as a result of the presence of cyanobacteria, influence on benthic communities and diversities, sulphur bacteria *Beggiatoa* spp. growth beneath cages, and excessive production of potentially toxic phytoplankton are the effects of eutrophication (Alongi et al., 2009; Laws, 2000; Macuiane et al., 2016). Thus uneaten feeds and fertilizers increase nutrient loads leading to eutrophication which eventually depreciates the quality of aquatic ecosystems.

1.1.2. *Metabolic wastes*

The end products of digestion of feed in fish, mainly faeces, are implicated with water pollution in aquaculture. Chen et al. (1997) stated that between 0.2 and 0.5 kg dry matter per kg feed is the amount of faecal waste generated. These wastes are released into the rearing water which later find their way into receiving waters. Excretory products contain high levels of nitrogen (Devaraja et al., 2013; Faramarzi et al., 2012). For example, higher pH values recorded in an experiment by Ling et al. (2010) were attributed to high algal growth as a result of faeces contributing to increased nutrients. In another experiment, increased phosphorus levels which led to pollution was associated with faeces (Primavera, 2006). Thus, fish faeces also increase nutrient loads in aquatic ecosystems.

1.1.3. *Fish mortalities*

Aquaculture is often associated with high fish mortalities especially during disease outbreaks as well as poor water conditions (Ananda Raja and Jithendran, 2015). Dead fish are usually disposed of indiscriminately while a greater portion of the dead fish remains in the water column and decays. Thus dead fish increase the organic matter load in the culture waters.

1.1.4. *Oil spillage*

Aquaculture involves the use of machines such as generators, automated feeders, water pumps, aerators, outboard motors, vehicles, and lawnmowers. These machines use fuel, grease or other forms of oil as source of power or for maintenance of parts. Oil spillage may sometimes occur during repairs, negligence during refilling or as a result of faulty parts of the machines. Eventually, these oils find their way into the water column causing pollution.

1.1.5. Drugs and chemicals

In an investigation by Faruk et al. (2008); Shamsuzzaman and Biswas (2012), and Ronquillo and Hernandez (2017), it was realized that fish farmers utilize a wide range of chemicals and drugs for the preparation and management of ponds, growth promotion, water and disease treatment. The common chemicals include salt, lime, potassium permanganate, malathion, formalin, sumithion, malachite green, bleaching powder. Antibiotics such as co-trimoxazoie, oxysentin, oxytetracycline, renamox, sulphadiazine, chlorotetracycline, renamycin, amoxicillin, and orgamycine are also used which come with their own threat to the aquatic ecosystem.

All in all, fish feed, fertilizers, faeces, urine, dead fish, spilled oil, drugs, and chemicals build up in the rearing water. They are subsequently released as effluents in the case of ponds or directly into the receiving waters (in the case of cages, pens and other culture systems which use the main water sources). These result in water pollution not only in areas where aquaculture is practiced but also to the far ends of the receiving waters affecting diverse organisms.

1.2. Mechanisms used by probiotic Bacillus in improving water quality

Aquaculture is associated with the accumulation of nitrogenous and organic wastes such as ammonia and nitrite as well as increased loads of organic matter. The build-up of these wastes can be toxic to cultured fish leading to stress and eventually death (Loh, 2017). Total ammonia nitrogen (TAN), N-NO_3, N-NO_2, and total Kjeldahl nitrogen (TKN) which are different forms of nitrogen are utilized by some microorganisms including probiotics for their metabolism, contributing to nitrogen removal from the water column (Martínez-Córdova et al., 2015). Nevertheless, aquaculture practices result in heavy loads of these wastes; therefore, extra measures are required to remedy the water quality.

Ammonification, nitrification, and denitrification are part of the processes involved in the nitrogen cycle. The initial form of nitrogen from the death of plants, animals or their waste products is organic. This organic nitrogen is converted to ammonium ($NH^{+}{}_4$) and ammonia (NH_3) by fungi or bacteria, including *Bacillus* species in a process called ammonification. The ammonium is converted to nitrites ($NO^{-}{}_2$) and then to nitrates ($NO^{-}{}_3$) mainly by *Nitrosomonas* and *Nitrobacter* species respectively in a process called nitrification. This is then followed by the conversion of nitrate to nitrogen gas (N_2) (denitrification), thus removing bioavailable nitrogen and returning it to the atmosphere (Bernhard, 2010). *Bacillus* species have, however, play significant roles in the nitrogen cycle through ammonification (Hui et al., 2019), nitrification (Rout et al., 2017), and denitrification (Verbaendert et al., 2011) as well as nitrogen fixation (Yousuf et al., 2017), unlike *Nitrosomonas* and *Nitrobacter* which are mainly involved in nitrification and sometimes denitrification (Liu et al., 2020). For example, *Bacillus amyloliquefaciens* DT converted organic nitrogen into ammonium (Hui et al., 2019) and *Bacillus cereus* PB8 removed $NO^{-}{}_2$−N from wastewater (Barman et al., 2018). *Bacillus* species can therefore, remove the different forms of nitrogen from aquaculture wastewater.

Gram-positive bacteria reduce the build-up of particulate and dissolved organic carbon (Balcázar et al., 2006). Heterotrophic bacteria use both organic and inorganic sources of carbon for growth. Hence, they have a profound role in the decomposition of organic matter as well as the production of particulate food materials from dissolved organics (Padmavathi et al., 2012). Probiotics optimize the decomposition of organic matter (Hai, 2015). *Bacillus* converts organic matter effectively into CO_2 (CO_2 is in turn utilized by β- and γ-proteobacteria as carbon source (Koops and Pommerening-Röser, 2001)) compared to other bacteria which covert most of the organic matter into slime or bacterial biomass (Mohapatra et al., 2013; Zorriehzahra et al., 2016). *Bacillus* are mostly used in removing the organic matter load in aquaculture thereby recycling nutrients in the water column and reducing sludge accumulation (Soltani et al., 2019). Organic matter loads in aquaculture are often associated with uneaten food, but probiotic *Bacillus* increases appetite by increasing the digestive enzymes activities of fish resulting in better feed utilization and less waste production (Hura et al., 2018).

Oxygen is consumed by microorganisms during mineralization resulting in the production of CO_2, H_2O, and nutrients in natural waters (Bokossa et al., 2014). The CO_2 and nutrients from the mineralization, favour the photosynthesis of phytoplankton, which in turn release O_2. As stated by Wang et al. (2005), DO concentration corresponds with the density of phytoplankton. Another means by which probiotics modulate DO is through reduction of the stress level of the fish as seen in the cortisol levels, hence less oxygen consumption (Zink et al., 2011). Also, photosynthetic activities use up free CO_2 and bicarbonates resulting in increased carbonates and DO, thus modulating the pH of the water as carbonates increase the pH of water on hydrolysis (Sunitha and Padmavathi, 2013). In addition, nitrification of NH_4^+ discharges hydrogen ions which contribute to the acidification process of aquaculture water (Camargo and Alonso, 2006; Gomes et al., 2008; Nimrat et al., 2012). Thus, mineralization and nitrification are the mechanisms used by *Bacillus* species to modulate pH and/or dissolved oxygen levels in water.

High levels of phosphorus lead to water deterioration and eutrophication although it is associated with the fertility of ponds. Phosphates are utilized by probiotics for metabolic activities thereby reducing this nutrient in aquaculture waters (Rao, 2002). This has translated in reduced orthophosphate concentrations observed by Sunitha and Padmavathi (2013) in probiotic treated ponds. Evidently, *Bacillus* strains were reported to efficiently remove phosphorus, nitrogen and organic matter (Choi et al., 2002).

Maintenance of pond microbial community is also an attribute of *Bacillus* species. This ensures that no one species dominates, especially the pathogenic microbial species. Hence *Bacillus* ensures the balance of the microbial community (Soltani et al., 2019).

Nonetheless, except for nitrification, researches elucidating the effects of probiotics on water quality are limited and understanding of the mechanisms of action is still in its early stages (Jahangiri and Esteban, 2018). Therefore, more research into the mechanisms used by probiotics, especially *Bacillus* in bioremediation will help optimize their role in maintaining aquaculture water quality. Fig. 1 summarises the possible mechanisms used by *Bacillus* in bioremediation.

1.3. Mode of application and factors influencing Bacillus in improving water quality

In aquaculture, several routes of administration of probiotics are used including injection, direct addition to the water, and as dietary supplements to pelleted or live feed (Jahangiri and Esteban, 2018; LaPatra et al., 2014). A suitable mode of application can increase the efficiency of probiotics in aquaculture (Jahangiri and Esteban, 2018). It was, therefore, advocated that the best mode of application of probiotics in aquaculture is the direct addition to the water. This method can be applied to all ages of fish and are more effective due to the continuous intake of water by fish (Jahangiri and Esteban, 2018; Lauzon et al., 2014; Villamil et al., 2010). Administration as a feed additive, for instance, cannot be applied to larvae because of their immature digestive system, whereas injection results in stress (Jahangiri and Esteban, 2018). Hence, the direct addition of probiotics to water is the best mode of application in terms of water quality improvement, although application as feed additives have yielded some good results. The efficiency of probiotics, in general, is affected by several factors. Water quality including dissolved oxygen, hardness, pH, temperature, mechanical

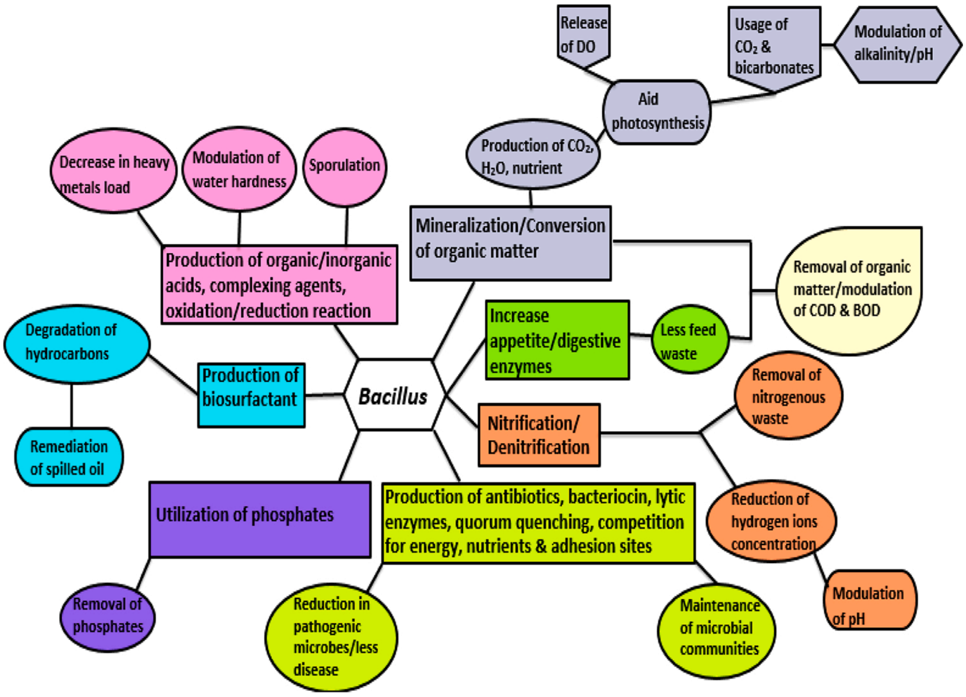

Fig. 1. Summary of mechanisms used by probiotic *Bacillus* in modulating water quality. DO = dissolved oxygen; COD = chemical oxygen demand; BOD = biological oxygen demand. Same colour represent same mechanism lane; rectangular compartments represent the first stage of the mechanisms; oval compartments represent the second stage of the mechanisms; rounded rectangles represent the third stage of the mechanisms; pointed pentagon represent the fourth stage of the mechanisms; hexagon represents the fifth stage of the mechanisms; tear drop represent intersection between two processes.

friction, strain biotype, and osmotic pressure affect probiotic actions (Cha et al., 2013; Das et al., 2008). For instance, the contrasting results observed between *Bacillus subtilis* L10 and G1 (Zokaeifar et al., 2014) and *B. subtilis* E20 (Liu et al., 2009) in improving water quality was attributed to genetics, nutrition, and environmental factors.

It can be deduced from an experiment by Rajakumar et al. (2008) that nutrient sources (cellulose, starch, sucrose, and glucose) affect the efficiency of *Pseudomonas* sp. KW1 and *Bacillus* sp. YW4. They also mentioned that temperature and pH influenced the nitrate reduction ability of the isolates. Gupta (1997) and Timmermans and Van Haute (1983) pointed out that deviation from a neutral pH can reduce the activities of denitrifying bacteria. This is supported by Liang et al. (2013) and Barman et al. (2018) who concluded from their experiment that regulating pH to a neutral condition resulted in higher efficiency of ammonium and phosphorus removal by *Bacillus* species. In another experiment, *Bacillus fusiformis*'s ability to degrade petroleum hydrocarbon was reported to be improved by low concentration of Mg^{2+}, Fe^{2+}, and Ca^{2+} (Dongfeng et al., 2011). Thus, metal ions also influence the ability of *Bacillus* species in improving water quality. Dissolved oxygen (DO) affect the efficiency of nitrification by probiotic *Bacillus.* Song et al. (2011) pointed out that the nitrification efficiency of *Bacillus* sp. YX-6 increased with increasing DO but later decreased showing a different tendency to the threshold curve. Patureau et al. (2000) also mentioned that lack of NO^{-}_{x} or O_2 resulted in the reduction of bacterial growth rate and denitrification efficiency. In another experiment, *Bacillus* W2 eliminated 97 % nitrogen under 2 mg/l dissolved oxygen, however, nitrogen elimination dropped to 85 % under 4–5 mg/l dissolved oxygen (Yu et al., 2005). An increased denitrification rate of *Bacillus cereus* PB88 was also recorded as DO increase and later declined (Barman et al., 2018) with an increasing DO. It can, therefore, be said that higher DO does not favour denitrification by *Bacillus*. Perhaps different strains of *Bacillus* may have diverse optimum conditions to carry out their roles as water quality modulators. However, a range of optimum conditions needs to be established to increase the efficiency of *Bacillus* in water quality management. The activities of denitrification bacteria are inhibited by too high or too low temperatures, thus the optimum temperature for denitrification is 25–35 °C (Maag and Vinther, 1996). Hence another prominent factor influencing the ability of probiotic *Bacillus* in improving water quality is temperature. For instance, the Nitrite-N degradation rate of *Bacillus* sp. YX-6 was up to 90 % at a temperature between 25 and 40 °C (Song et al., 2011). It was also realized by Xie et al. (2013) that 30 °C and 35 °C temperature resulted in higher ammonia-N removal by *Bacillus amyloliquefaciens* HN than 25 °C temperature. Inferentially, different temperatures influence the activities of microbes; therefore, to achieve desired results in water quality management by *Bacillus*, the optimum temperature needs to be considered.

Biotic factors, especially the presence of other microorganism also affect bacterial growth thus can affect the efficiency of probiotics. Antagonistic processes, such as competition for food, energy and adhesion sites, production of bacteriocins, antibiotics, and lytic enzymes with antibacterial and antifungal activities (e.g. chitinases, proteases, cellulases, and β-1,3-glucanases) and quorum quenching (Kuebutornye et al., 2020) by other microbes can interfere with the growth of probiotics. For instance, probiotics and other microbes use similar energy and nutrient sources thus need to compete for same available organic substrates such as carbon (Mohapatra et al., 2013). The activities of other microbes can, therefore, influence the efficiency of *Bacillus* in maintaining water quality.

1.4. *Water quality parameters modulated by Bacillus species*

Aquaculture wastewater is often associated with increased organic carbon, suspended solids, phosphates, nitrogenous species (nitrates, nitrites, and ammonia), chemical oxygen demand (COD), and biological oxygen demand (BOD) (Boopathy and Lyles, 2008). This is regarded as a global threat to aquatic ecosystems due to its influence on surrounding waters as well as groundwater (Liang et al., 2015; Othman et al., 2013). The threat of aquaculture wastewater is not confined to the aquatic ecosystems as high levels of phosphorus and nitrogen may become poisonous to plants (Li et al., 2007; Liang et al., 2015). Therefore, a sustainable approach is required for the treatment of aquaculture wastewater.

Decomposition of organic matter, reduced phosphorus and nitrogen concentrations, higher dissolved oxygen, control of nitrite, hydrogen sulfide, and ammonia and lower disease occurrence are the beneficial effects conferred on water quality by probiotics in aquaculture (Boyd and Gross, 1998; Cha et al., 2013). Relatively high transparency, proper temperature, adequate oxygen, less concentration of metabolites are characteristics of good quality water (Bhatnagar and Devi, 2013). The followings are evidences of the various water quality parameters modulated by *Bacillus* species and summarized in Table 1–3.

1.4.1. Dissolved oxygen

The most important water quality parameter is possibly dissolved oxygen (DO) with regards to aquaculture in that at low levels, aquatic animals do not grow well or feed, and are more vulnerable to disease infections (Dabrowski et al., 2018; Manahan, 2017). One of the most significant effects of aquaculture is decreased DO levels resulting from the enrichment of the aquatic systems with ammonia, phosphorous, organic matter, copper, and other nutrients (dos Santos Simões et al., 2008). Dissolved oxygen requirements for aquatic animals are species-specific; nonetheless, an optimum DO is required for the survival of most species.

Modulation of DO levels within the optimum range by probiotic *Bacillus* has been reported by a few researchers. For instance, in an experiment by Hura et al. (2018) to evaluate the effect of *Bacillus megaterium* on water quality in the culture of major carps, higher DO values were recorded relative to the control. Improved DO levels by a mixture of *Bacillus* species were recorded in aquarium stocked with tilapia larvae at high density (Hainfellner et al., 2018). In other experiments involving *Bacillus* species (*B. subtilis, Bacillus licheniformis, B. megaterium,* and *Bacillus laterosporous*) during transport of fish (Yellowfin Tuna Yolk Sac Larvae and *Carnegiella strigata*), higher DO were recorded in *Bacillus* supplemented waters (Gomes et al., 2008; Zink et al., 2011). Higher DO was also observed in the *Bacillus* treated group by Omitoyin (2016). However, no significant difference was recorded regarding DO levels using a mix of *B. megaterium* and *Streptomyces fradiae* for water treatment (Aftabuddin et al., 2013). It could be said that research on the modulation of DO by probiotic *Bacillus* is less explored compared to its effects in modulating nitrogenous species in aquaculture. As DO is an important water quality parameter, we advocate that more attention be paid to its modulation by *Bacillus* species.

1.4.2. Total dissolved solids (TDS)

Total dissolved solids (TDS) are present naturally in water and contain organic molecules and minerals that provide nutrients. They also serve as sources of contaminants such as organic pollutants and toxic metals. TDS measures organic matter, inorganic salts, as well as other dissolved substances in water by filtering the water through a filter (2.0 μm). TDS is not regarded as a primary pollutant, however, it is used as an indicator for a wide range of chemical contaminants. TDS cause toxicity via variations in the ionic composition of the water, upsurges in salinity, and toxicity of the individual ions (Barman et al., 2018). Dissolved minerals are commonly measured as TDS and are usually associated with drinking water (Devesa and Dietrich, 2018). Of course, there is a link between drinking water, groundwater, and waters used for aquaculture activities. Sources of TDS include coal mines, agriculture (which includes aquaculture), residual runoffs, and discharge from industrial or sewage treatment plants (Daniels et al., 2016; Shi et al., 2014; Wu and Maskaly, 2018). Thus, contaminants from these sources end up in drinking water if not properly treated. Not only does TDS affect drinking water quality but also influence the spatial distribution of freshwater invertebrates due to imbalances between the ions in the water and dissolvability of oxygen in the water column (Cormier et al., 2013; Mueller et al., 2017; Olson and Hawkins, 2017; Pendashteh et al., 2012).

Modulation of TDS is expensive (Olson and Hawkins, 2017), nevertheless, *Bacillus* species have been associated with the removal of TDS in aquaculture which is relatively cheaper. A mix of *Bacillus* strains (*B. subtilis, B. licheniformis* and *Bacillus pumilus*) was reported to maintain TDS within the acceptable range for the culture of tilapia (Elsabagh et al., 2018). Relatively lower TDS were observed by Hura et al. (2018) which was attributed to enhanced feed utilization, improvement in digestion, and assimilation by fish treated with *B. megaterium*. Other researchers have recorded positive effects of *Bacillus* in maintaining TDS in aquaculture. For instance, *B. cereus* PB88 (Barman et al., 2018) and *B. subtilis* HS1 (Md et al., 2015) in shrimp and *Dicentrarchus labrax* larvae culture respectively. The little evidence mentioned demonstrates the potential of *Bacillus* to be used for the modulation of TDS in aquaculture.

1.4.3. Alkalinity and pH

pH is the measure of the hydrogen ion concentrations in water. Alkalinity, on the other hand, is the ability of water to neutralize strong acids (Boyd et al., 2011). Alkalinity and pH as water quality parameters are usually confusing and sometimes regarded as same, nevertheless, Boyd et al. (2011) and Wurts (2002) have extensively distinguished between the two. Therefore the two parameters are never the same with regards to water quality. They indicated that pH is an intensity factor, whereas alkalinity is a capacity factor of water. The hydrogen ion concentration (pH) and alkalinity affect almost every biological and chemical process hence are important water quality parameters (Summerfelt et al., 2015). Some of the processes influenced by these two parameters have been previously discussed (Boyd et al., 2016; Summerfelt et al., 2015).

Bacillus species favour the modulation of alkalinity and pH by aiding in the mineralization of organic matter which promotes photosynthetic activities. The basic nature of aquaculture waters is considered better than acidic waters as Hura et al. (2018) observed beneficial effects on carp culture as a result of the maintenance of alkalinity by *B. megaterium*. Increased pH was also observed in *Bacillus* treated tilapia ponds (Elsabagh et al., 2018). Therefore, under acidic conditions, probiotic *Bacillus*

Table 1
Water quality parameters modulated by *Bacillus* through dietary administration.

*Bacillus*species	Source	Mode of application	Doses	Water quality effect	Reference
B. megaterium	Commercial	Diet	NM	BOD, DO, ammonia, TDS, COD, alkalinity and pH	Hura et al. (2018)
Sanolife PRO-F (*B. subtilis, B. licheniformis*and *B. pumilus*)	Commercial	Diet	0.2 g/kg	Ammonia, electric conductivity, salinity, total dissolved solids, pH	Elsabagh et al. (2018)
B. subtilis, B. mojavensis, and*B. cereus*	Soil	Diet	10^9 cfu/g	BOD, COD, phosphate, pH, DO, alkalinity, hardness, TAN, Nitrate-N	Reddy et al. (2018)
B. subtilis	Carassius auratus gibelio intestine	Diet	10^9 cfu/g	Lead (Pb)	Yin et al. (2018)
B. subtilis	Intestinal microflora of shrimp	Diet	1×10^{10} cfu/g	Ammonia	Cha et al. (2013)
Bacillus strains (probiotic A and probiotic B)	P. monodon intestine	Diet	10^{10} cfu/mL	pH, ammonia, nitrite, *V. harveyi*	Nimrat et al. (2012)

NM = not mentioned; NS = not specified; cfu = colony forming unit; COD = Chemical oxygen demand; BOD = Biochemical oxygen demand; TDS = Total dissolved solids; TAN = Total ammonia nitrogen.

Table 2
Water quality parameters modulated by *Bacillus* with water as a mode of application.

*Bacillus*species	Source	Mode of application	Doses	Water quality effect	Reference
B. velezensis AP193	Soil and catfish intestine	Water	NS	Total phosphorus, total nitrogen, nitrate	Thurlow et al. (2019)
Bacillus sp. YB1701	Coastal sediment	Water	1 × 10^5 cfu/mL	*Aeromonas hydrophila* and *Vibrio parahemolyticus*, COD	Zhou et al. (2018)
*B. subtilis*FY99-01	Commercial	Water	5 × 10^4 cfu/mL	pH, nitrite, phosphorus	Wu et al. (2016)
*B. licheniformisi, B. subtilis, B. polymyxa, B. laterosporus*and *B. circulans*	Commercial	Water	10^8 cfu/L	Ammonia nitrogen, total bacteria count,	Naderi Samani et al. (2016)
Ecotrax® (mix of 7 *Bacillus* species)	Commercial	Water	NS	Transparency, hardness, algae growth	George et al. (2016)
EcoAqua (*B. subtilis, B. licheniformis, B. megaterium,*and *B. laterosporous*)	Commercial	Water	15 mL/L, 1.5 × 10^6 cfu/mL	Total ammonia nitrogen, un-ionized ammonia, DO	Zink et al. (2011)
Efinol®L (*B. subtilis, B. licheniformes, L. acidophilus*and *S. cerevisiae*)	Commercial	Water	10 mg/L	DO, conductivity, pH, ammonia	Gomes et al. (2008)
Bacillus sp. (mixed with*S. cerevisiae, Nitrosomonas*sp., *Nitrobacter* sp.)	Commercial	Water	10^9 cfu/mL	Total bacteria count, DO, dissolved reactive-phosphorus, total inorganic nitrogen, COD	Wang et al. (2005)

NM = not mentioned; NS = not specified; cfu = colony forming unit; COD = Chemical oxygen demand; BOD = Biochemical oxygen demand; TDS = Total dissolved solids; TAN = Total ammonia nitrogen.

Table 3
Water quality parameters modulated by *Bacillus* through other modes of application.

Bacillus species	Source	Mode of application	Doses	Water quality effect	Reference
*B. cereus*PB88	Shrimp ponds	Denitrification medium	NS	*Vibrio harveyi, Vibrio vulnificus*, $NO^{-}{}_{2}$ −N	Barman et al. (2018)
B. subtilis, B. megaterium, and*B. polymyxa*	River and Septclean	Diesel	NS	Diesel oil	Tariq et al. (2016)
B. megaterium	Soil	Heavy metal solution	NS	Copper, iron, zinc, manganese	Stefanescu (2015)
B. subtilis	Fermented pickles	Synthetic pond water, water	10^5 and 10^8 cfu/mL	Ammonia, nitrite and nitrate ions	Zokaeifar et al. (2014)
B. amyloliquefaciens	Activated sludge of polluted river	Simulated polluted water	NS	Nitrite-N	Xie et al. (2013)
*B. cereus, B. licheniformis, B. amyloliquefaciens*and *B. subtilis*	Soil	Heavy metal solution	NS	Cadmium, zinc, copper, lead ions	Issazadeh et al. (2011)
*Bacillus*sp.	Soil	Enrichment liquid medium	3 × 10^8 cells/mL	Diesel oil	Kebria et al. (2009)
B. subtilis, B. cereus and *B. licheniformis*	Mud sediment	Synthetic pond water	NS	*Aeromonas hydrophila*, ammonium, nitrite, nitrate, phosphate ions	Lalloo et al. (2007)
*B. sphaericus, B. cereus, B. subtilis*and *Bacillus* sp.	Commercial	Heavy metal solution	16.0 mg	Cadmium, zinc, copper, lead ions	Costa and Duta (2001)

NM = not mentioned; NS = not specified; cfu = colony forming unit; COD = Chemical oxygen demand; BOD = Biochemical oxygen demand; TDS = Total dissolved solids; TAN = Total ammonia nitrogen.

can be used to increase the pH making the water suitable for the culture of fish. The opposite was observed in the case of basic pH as probiotic *Bacillus* decreased pH towards neutral (Gomes et al., 2008; Nimrat et al., 2012; Wu et al., 2016).

1.5. Nitrogenous species (nitrites, ammonia, and nitrates)

Nitrogenous species namely nitrites, ammonia, and nitrates are usually the main water pollutants associated with aquaculture in that they are toxic to aquatic life and aquatic ecosystems. Hence, they have drawn the attention of many researchers (Boopathy et al., 2015; Liang et al., 2015). Nitrogenous wastes are the key end products of protein metabolism (Faramarzi et al., 2012). Nitrogen accumulation results in stress which renders fish susceptible to infections, thus, threatens fish health and the environment (Lalloo et al., 2007). Treatment of aquaculture waters to reduce the levels of nitrogenous species is, therefore, a necessity. The use of environmentally friendly methods like the application of probiotic *Bacillus* is recommended.

Diverse modes and methods such as bead filters, rotating biological contactors, fluidized sand biofilters, and trickling filters have been adopted to treat nitrogenous wastes in aquaculture (Crab et al., 2007; Shan et al., 2016). However, biological methods which involve the use of microorganism are considered more cost-effective (Gao et al., 2018). Among the microbial agents used, results from the use of *Bacillus* are outstanding. *Bacillus* species have gained attention in the treatment of nitrogenous wastes in aquaculture because they possess both nitrification and denitrification abilities hence have an economic advantage (Kim et al., 2005; Nimrat et al., 2012).

Many researchers have reported the modulation of nitrogenous wastes in aquaculture by *Bacillus* species. In an investigation by Thurlow et al. (2019), reduced nitrate-nitrogen (75 %) and total nitrogen (43 %) levels were recorded in catfish pond water treated with *Bacillus velezensis* AP193. A similar observation was made by Lalloo et al. (2007) who recorded reduced nitrate and nitrite ions in synthetic pond water after *Bacillus* treatment. Irrespective of the form of nitrite and nitrate, relatively reduced levels have been documented. For instance, reduced nitrate and nitrite (Hura et al., 2018; Lalloo et al., 2007; Nimrat et al., 2012; Zokaeifar et al., 2014), and reduced nitrite-N (Song et al., 2011; Xie et al., 2013) have been recorded after *Bacillus* treatment. Ammonia toxicity has been reported to be reduced/modulated by *Bacillus*. For instance, *B. subtilis* (Cha et al., 2013; Zokaeifar et al., 2014), *B. megaterium* (Hura et al., 2018), and *B. amyloliquefaciens*(Xie et al., 2013) have reduced ammonia levels in aquaculture studies. Total ammonia nitrogen was reduced in carp rearing water after the addition of *Bacillus* sp. compared to the control although elevated levels of nitrate were observed (Naderi Samani et al., 2016). A similar observation was documented by Reddy et al. (2018) who recorded reduced total ammonia nitrogen. It is therefore evident that *Bacillus* is able to mineralize nitrogenous wastes through nitrification and denitrification which has resulted in the reduced nitrogen species (Nimrat et al., 2012).

1.6. Phosphates

Just like nitrates, phosphate accumulation results in algal bloom in culture systems (Lalloo et al., 2007). Phosphates are required by living organisms for physiological processes, nevertheless, eutrophic conditions have been associated with excess phosphates (Luo et al., 2016; Reddy et al., 2018). Phosphorus exists in water as phosphate ions (Querijero and Mercurio, 2016). The main sources of high phosphorus in culture waters are fish feed and fertilizers (Querijero and Mercurio, 2016; Tovar et al., 2000) suggesting that phosphate accumulation cannot be prevented but can only be controlled and modulated. Phosphate ion accumulation threatens fish health and the environment and encourages the proliferation of diseases as a result of stress (stressed fish have compromised immune systems) (Jana and Jana, 2003; Lalloo et al., 2007).

Bacillus species have demonstrated strong phosphate reduction abilities in many water quality management investigations providing an environmentally safe mode of phosphate modulation. Reduction in phosphate ions by *Bacillus* species can be dated back to the early 1990s (Porubcan, 1991a, 1991b). Recent studies have also shown that *Bacillus* can reduce phosphate ions to the acceptable range in aquaculture. For instance, 81 % reduction in phosphate ions was recorded by Reddy et al. (2018) in an experiment containing equal proportions of *B. subtilis, Bacillus mojavensis*, and *B. cereus*. In the presence of pathogens, Lalloo et al. (2007) recorded reduced phosphate ions in a water quality experiment containing *B. subtilis, B. cereus,* and *B. licheniformis.*. In shrimp culture ponds, reduced phosphorus levels were recorded in *Bacillus* treated ponds in comparison to the control (Wang et al., 2005). Total phosphorus reduction was also documented in catfish ponds treated with *B. velezensis* (Thurlow et al., 2019).

1.7. Transparency

Transparency is an easily recognized water quality parameter as transparency is an indicator of suspended inorganic and organic matter and phytoplankton populations (Mahmud et al., 2016). Good and quality water is associated with adequate transparency (Bhatnagar and Devi, 2013). Transparency is, therefore, a primary indicator of good quality water for aquaculture. For instance, low transparency is indicative of high levels of nutrient loads as well as suspended particles thus, transparency is an important water quality parameter.

Many probiotics water quality studies seem to ignore this particular parameter; few studies, however, have documented insignificant effects of *Bacillus* species on transparency. For instance, relatively high transparency was recorded in probiotic *Bacillus* and sand filter treatments (Mahmud et al., 2016). Hura et al. (2018) also recorded relatively high transparency in major carp culture ponds after *B. megaterium* treatment. A similar observation was documented by Chen and Chen (2001) who mentioned that *Bacillus* species maintained the transparency between 30–50 cm in recirculated aquarium water. Reduction in organic matter leading to optimum transparency was also reported (Dalmin et al., 2001). Higher water transparency was observed in *Bacillus* treated ponds at the initial stage of shrimp culture (Matias et al., 2002). *Bacillus* maintains good transparency in aquaculture through the modulation of organic and inorganic matter resulting in the reduction of nutrient loads (the contributing factors to phytoplankton population).

1.8. Temperature

The body temperature of fish depends on their environment since they are ectotherms thus water temperature is one most important parameter in aquaculture (Fernandes et al., 2018). Activities such as metabolism and feed conversion ratio, growth, morphometric characteristics, condition index, and excretion patterns of fish and microbial activities (nitrogen transformation) are all influenced by temperature (Fernandes et al., 2018; Martinez et al., 2018; Paudel et al., 2015). Food consumption by fish is favoured by relatively warmer temperatures but lower temperatures compromise the immunity of fish making them susceptible to diseases caused by bacteria and fungi (Fernandes et al., 2018). Temperatures ranging between 25–30 °C favour microbial activities resulting in better nitrification and denitrification rates. Lower temperatures below 10 °C however, decrease microbial activities significantly corresponding with a drastic reduction in their nitrification and denitrification abilities (Klotz and Stein, 2011; Paudel et al., 2015). Keeping temperatures within the optimal range for fish growth and microbial activities is therefore necessary.

Literature search did not reveal significant modulation of temperature by *Bacillus* species except in one experiment by Zink et al. (2011) who recorded higher temperatures in the control than *Bacillus* (*B. subtilis, B. licheniformis, B. megaterium,* and *B. laterosporous*) treated groups in a transport system containing yellowfin tuna *Thunnus albacares* yolk sac larvae. They mentioned that the relatively reduced temperature in the probiotic treatment benefited NH_3 reduction. However, the change in temperature was thought to be associated with human errors or the positioning of the boxes relative to the air conditioning vent but not probiotic activities. In contrast, no significant effect of *Bacillus* species on temperature was recorded by several other authors (Banerjee et al., 2010; Ghosh et al., 2008; Nimrat et al., 2012). Perhaps as mentioned by Velmurugan and Rajagopal (2009), temperature is not affected by biological processes as it is a conservative parameter.

1.9. BOD and COD

Biochemical oxygen demand also known as biological oxygen demand (BOD) measures the amount of dissolved oxygen needed by microbes to breakdown organic matter present in a given water sample. It evaluates the influence of decomposing organic matter on species in a specific environment. When organic matter from diverse sources enters water, they are broken down by microbes which use up the available DO in the process, thereby depriving the water of dissolved oxygen subsequently resulting in fish kills due to low oxygen. Higher BOD is, therefore, an indicator of poor water quality, as low BOD implies less DO is removed from the water (https://www.watereducation.org/aquapedia-background/biochemical-oxygen-demand). Chemical oxygen demand (COD) on the other hand measures the oxygen needed to oxidize particulate and soluble organic matter in water. Thus unlike BOD, COD measures all substances that can be chemically oxidized, instead of just biodegradable organic matter.

The use of *Bacillus* species as water quality modulators in aquaculture has resulted in lower BOD and COD in many investigations compared to the controls. This can be associated with better feed utilization by fish, thus less organic matter is decayed using DO and also perhaps *Bacillus* species require less DO to effectively decompose organic matter. For instance, *B. megaterium* was effective at lowering the BOD of major carps pond water relative to the control (Hura et al., 2018). Reduced BOD (above 90 %) was again recorded by Reddy et al. (2018) in *Bacillus* (*B. subtilis, B. mojavensis*, and *B. cereus*) treated ponds. Similarly, a mix of *B. cereus* and *Aeromonas vernoii* resulted in decreased BOD after effluent treatment (Divya, 2015). Reduced levels of COD were recorded in *B. subtilis* (Wen-jun, 2011), *B. megaterium* (Hura et al., 2018), and *Bacillus* sp. YB1701 (Zhou et al., 2018) treatments.

1.10. Hardness

The hardness of water in most cases is the measure of magnesium and calcium ions dissolved in water but sometimes involves other ions namely iron, manganese, zinc, aluminum, strontium, and hydrogen ions

(Swann, 1997). Magnesium and calcium are the principal divalent cations in almost all pond waters (George et al., 2017). Usually, agricultural lime is used in softening hard aquaculture waters, however, probiotics have also been used to soften hard water (George et al., 2016). For example, Ecotrax® (a mix of 7 *Bacillus* species) was found to significantly reduce the total hardness of treated white leg shrimp pond water relative to the non-treated ponds (George et al., 2016). A similar observation was made by Reddy et al. (2018) who recorded significantly lower total hardness in aquaculture ponds treated with *B. subtilis, B. mojavensis*, and *B. cereus.* However, contrasting observations have been made where ponds treated with *B. megaterium* resulted in higher total hardness although in the tolerable range (Hura et al., 2018). Less literature is available on water hardness modulation by probiotic *Bacillus* and the contrasting results in the available few literatures warrant more research. It is noteworthy that the ions contributing to the hardness of water stimulate the sporulation of *Bacillus.*

1.11. Organic matter

High concentration of organic matter as a result of uneaten feed is a common water quality problem associated with aquaculture. Increased appetite and digestive enzyme activities, and more feed intake resulting in reduced organic matter loads in aquaculture have been reported in many studies (Hainfellner et al., 2018). *Bacillus* species can improve the quality of pond water through the decomposition of organic matter into smaller units (Das et al., 2017; Loh, 2017). Earlier investigations revealed that *Bacillus* spp. reduced organic matter loads in treated ponds relative to the control resulting in better water quality (Dalmin et al., 2001).

1.12. Salinity

An important factor that determines many aspects of water chemistry and biological processes is salinity. Not many investigations have been conducted to evaluate probiotic *Bacillus* effects on the modulation of salinity. The available few researches demonstrate that *Bacillus* species have no significant influence on salinity as a water quality parameter except Elsabagh et al. (2018) who recorded a significantly higher salinity in the probiotic *Bacillus* (*B. subtilis, B. licheniformis,* and *B. pumilus*) treatment than in the control. For instance, Zink et al. (2011) recorded an insignificantly lower salinity in control transport bags than in the probiotics (mix of *B. subtilis, B. licheniformis, B. megaterium, and B. laterosporous*) treated transport bags. *B. pumilus* (Banerjee et al., 2010; Sreenivasulu et al., 2016) and a mix of *B. megaterium* and *Streptomyces fradiae* (Aftabuddin et al., 2013) did not show any significant influence on salinity. *Bacillus* inability to modulate salinity observed by the majority of researchers is confirmed by Velmurugan and Rajagopal (2009) who stated that salinity is not easily affected by biological processes because it is a conservative water quality parameter.

1.13. Conductivity

Conflicting results are available on the modulation of conductivity as a water quality parameter by *Bacillus* species. For instance, Bhatnagar and Lamba (2017, 2015) did not find any significant modulation on conductivity by *B. cereus* in their experiment. Likewise, no significant difference was observed in conductivity between treatments during the transport of cardinal tetra, *Paracheirodon axelrodi* (Schultz) by Gomes et al. (2009) when probiotic Efinol®L (*B. subtilis, B. licheniformes, LactoBacillus acidophilus,* and *Saccharomyces cerevisiae*) was used. However, Hainfellner et al. (2018) observed improvement in conductivity after *Bacillus* spp. mixture (a commercial probiotic) treatment. Elsabagh et al. (2018) also recorded significantly higher conductivity in *Bacillus* ($0.2\ \mathrm{g\ kg^{-1}}$ diet) (*B. subtilis, B. licheniformis,* and *B. pumilus*) treated ponds. These contrasting observations need further clarification thus more research is needed to ascertain whether *Bacillus* could effectively modulate conductivity.

1.14. Heavy metals

Lead, cadmium, silver, chromium, mercury, cobalt, zinc, iron, and copper are heavy metals which pollute the environment and are especially associated with anthropogenic activities. Their presence in the soil, atmosphere, and water can cause hazards to all organisms, thus poses a great threat to food quality, crop growth, and environmental health (Issazadeh et al., 2011; Niu et al., 1993; Silver, 1991; Stefanescu, 2015). Aqueous effluents from industries such as electroplating, steel, and mining contain high levels of heavy metals which find their way into water bodies which are used for aquaculture activities (Chatterjee et al., 2010; Stefanescu, 2015). These heavy metals accumulate in fish tissues which are then transferred to humans upon eating. Heavy metals intake by humans through the food chain and inhalation is an issue of great concern. The removal of heavy metals and/or reduction in their toxicity from aquatic systems and effluents is therefore a necessity (Chatterjee et al., 2010; Issazadeh et al., 2011; Stefanescu, 2015).

Among all the proposed methods of heavy metals removal, the use of microbes is considered more cost-effective (Chatterjee et al., 2010). Bacteria use their metabolic processes to mobilize heavy metals via the production of organic and inorganic acids, complexing agents excretion, and reduction or oxidation reactions (Stefanescu, 2015). Both dead and live microbial cells, as well as their products, can bioaccumulate particulate and soluble forms of metals (Chatterjee et al., 2010). Typically, heavy metals stimulate the sporulation process of *Bacillus* species implying that *Bacillus* species use up heavy metals to produce spores thereby decreasing the heavy metal concentration (Kolodziej and Slepecky, 1964; Stefanescu, 2015). Effective remediation of heavy metals by *Bacillus* species has been reported. For instance, *B. subtilis* at a concentration of 10^9CFU/g was found to effectively combat lead poisoning in *Carassius gibelio* culture experimentally (Yin et al., 2018). *B. subtilis* and *B. cereus* have also been documented to effectively bioaccumulate cadmium, zinc, copper, and lead ions (Costa and Duta, 2001; Issazadeh et al., 2011). Similarly, *B. megaterium* bioaccumulated copper, iron, zinc, and manganese in an experiment conducted by Stefanescu (2015). It is, therefore, evident that *Bacillus* can be applied to combat heavy metals accumulation in aquaculture.

1.15. Oil spillage

As mentioned earlier, aquaculture activities sometimes may result in oil spills. Also, pollution resulting from the manufacture and transport of oil and refinery products is a challenge since oil remains a major source of energy (Banerjee and Ghoshal, 2016). These oil spills are detrimental to aquatic life as in most cases the spills end up in aquatic ecosystems (Edet et al., 2018; Joo and Kim, 2013). Joo and Kim (2013) affirmed that oil pollution in aquatic and terrestrial ecosystems is a common phenomenon that results in significant social and ecological problems. This places aquaculture at a risk, thus effective and cheap methods of getting rid of spilled oils in aquaculture are essential.

Other methods used in combating oil spills can cause toxic problems and secondary contaminations; therefore, the use of microbes is considered the best alternative. They are non-toxic and are environmentally friendly and are relatively simple with high efficiency (Joo and Kim, 2013; Kebria et al., 2009; Singh et al., 2008). Microbes use oils as a source of food and energy thereby breaking down oils into simpler and harmless substances (Joo and Kim, 2013). Specifically, many microbes use hydrocarbons as a carbon source resulting in the production of CO_2, H_2O, and biomass (Cunha and Leite, 2000).

There are extensively published articles on the use of *Bacillus* species for the bioremediation of spilled oil although not directly related to aquaculture. *B. subtilis, B. megaterium,* and *Bacillus polymyxa* were effective at utilizing diesel oil by producing biosurfactants through emulsification process (Tariq et al., 2016). Likewise, *B. cereus* and

Bacillus thuringiensis were reported to effectively degrade hydrocarbons making them the best candidates for the remediation of oil-polluted environments (Kebria et al., 2009; Maddela et al., 2015). Crude oil utilization by *B. subtilis* JK-1 (Joo and Kim, 2013) and *Bacillus* sp. (AL-Saleh et al., 2009) have also been reported. These evidence are indicative that *Bacillus* can be applied in aquaculture for the bioremediation of spilled oils.

1.16. Lower disease occurrence

The onset of diseases is preceded by the interaction between the host, disease-causing agents, and environmental stress (Lalloo et al., 2007). Persistent infections may be as a result of bad water quality. The presence of disease-causing agents is not a characteristic of good quality water (Zokaeifar et al., 2014). In vitro methods have proven that *Bacillus* species can reduce or prevent the proliferation of pathogens via the production of bacteriocins (Al-Thubiani et al., 2018; An et al., 2015; Compaoré et al., 2013; Grubbs et al., 2017; Yi et al., 2018), quorum quenching (Chu et al., 2014; Torabi Delshad et al., 2018; Wee et al., 2018), production of lytic enzymes (Biziulevièius and ûukaitë, 2002; Urdaci and Pinchuk, 2004), production of antibiotics (Stein, 2005; Urdaci and Pinchuk, 2004), competition for adhesion sites, nutrients and energy (Lalloo et al., 2010; Luis-Villaseñor et al., 2011). This results in the elimination of pathogens such as *Aeromonas, Vibrio, Streptococcus,* and *Pseudomonas* species in aquatic ecosystems (Kuebutornye et al., 2020). For instance, *B. velezensis*'s ability to inhibit the growth of *Aeromonas hydrophila*, *Vibrio parahemolyticus, Lactococcus garvieae, Aeromonas salmonicida*, and *Streptococcus agalactiae* was attributed to its bacteriocins and antimicrobial secondary metabolite-related genes (Yi et al., 2018). *B. cereus* was reported to degrade AHL signal molecules, thus disrupting the quorum sensing of *A. hydrophila,* thereby reducing its pathogenicity (Wee et al., 2018). Additionally, *B. cereus* outcompeted *A. hydrophila* and inhibited its growth due to competition for the available energy (Lalloo et al., 2010). Therefore, *Bacillus* species lower the occurrence of diseases in aquaculture thus, maintaining water quality.

2. Conclusion

Bacillus has presented a great potential to be used for bioremediation of aquaculture waters as discussed in this review. It also presents the potential of aquaculture waters to be reused after probiotic *Bacillus* treatment. *Bacillus* modulates a wide range of water quality parameters namely alkalinity, pH, COD, DO, BOD, TDS, phosphates, nitrogenous species, hardness, transparency, heavy metals, oil spillage and reduction in the occurrence of diseases. However, the efficiency of *Bacillus* in the bioremediation process is affected by factors such as dissolved oxygen, metal ions, pH, temperature, salinity, mode of application, and source of nutrients. Thus, to achieve maximum results in bioremediation by *Bacillus,* these factors need to be considered and kept at an optimum.

The bioremediation ability of microorganisms is related to their genetic make-up, hence to enhance the bioremediation efficiency of *Bacillus*, a better understanding to the genetic level and the development of new genetic tools is highly recommended. Perhaps different strains of *Bacillus* may have diverse optimum conditions to carry out their roles as water quality modulators, however, a range of optimum conditions need to be established to increase the efficiency of *Bacillus* in water quality management. Also, more research into the mechanisms used by *Bacillus* species in the bioremediation process is necessary in order to understand and improve these mechanisms. Finally, search through literature revealed that current studies seem to ignore *Bacillus* in water quality management despite their potentials. It is, therefore, advocated that more research be conducted in order to bring to light the full potential of *Bacillus* in the bioremediation of aquaculture waters.

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