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Current state and solution proposal for plateau wastewater treatment plants: a review

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ABSTRACT

Rapid urbanization and increasing population growth rates have led to increased amounts of sewage discharge in plateau regions. The implementation of plateau wastewater treatment plants (WWTPs) is a key solution to alleviate the pressure to fragile plateau ecosystem. However, many WWTPs have difficulties achieving the required effluent quality and the encountered difficulties can be attributed to the extreme climate conditions, e.g., low temperature, low oxygen level and low pressure, as well as the quantity and the quality of the wastewater in plateau regions. The unique operational conditions result in differences in the microbial community and the structure of bacteria, archaeal, and fungi between plains and plateau WWTPs, which in turn affect the removal efficiencies of organics, nutrients and micropollutants. Measures should be used to resolve the operational problems, such as enriching oxygen contents, modifying the operational processes, and introducing bioaugmentation technology. The review specifically demonstrated the practices used in the Tibetan Plateau in China and suggested that full-scale WWTPs using activated sludge processes can be successfully implemented to treat wastewater in plateau regions. Valuable information and experience with WWTPs in the Tibetan Plateau are of significance to guide the future design of plateau WWTPs in other areas and countries.

Keywords: Plateau wastewater treatment plant; Microbial community; Engineering strategies

1. Introduction

Plateaus, also called high plains or tablelands, constitute important landforms all around the globe. Plateau regions feed important rivers on a continental scale and are crucial to the water security of downstream areas and countries. The Tibetan Plateau is one of the famous plateaus worldwide; it has an average altitude greater than 4,000 masl (meters above sea level) and occupies more than 1/3 of the land area of China together with the Yungui Plateau. Recently, rapid urbanization and increasing population growth rates have led to increased amounts of sewage discharge and are resulting in increased pressure on the fragile ecosystems in the plateau regions. For example, the population in Tibet experienced a sharp increase from 2.58 to 3.31 million during the last two decades. As a result, water pollution has become a leading environmental problem and is affecting terrestrial vegetation and even remote water resources [1–4]. There is an urgent need for effective wastewater treatment in the plateau regions.

Different types of wastewater treatment facilities have been implemented to cope with the wastewater challenge in the plateau region. Small-scale moving bed bioreactors (MBBRs) [5], wetlands [6,7] and stabilization ponds [8,9] have been used to treat wastewater in mountain areas. Full-scale wastewater treatment plants (WWTPs) are widely used in the USA, China, and Saudi Arabia [10]. Fig. 1 and Table 1 provide examples of representative wastewater treatment facilities

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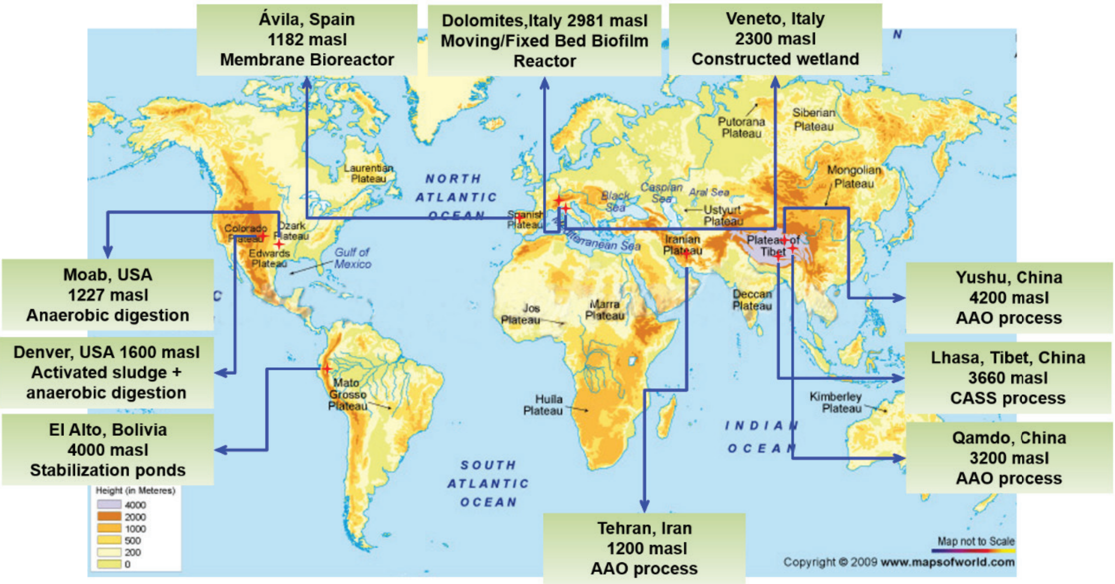

Fig. 1. Representative plateau wastewater treatment facilities around the world (original map downloaded from www.mapsofworld.com).

Table 1
Representative plateau WWTPs worldwide

	Location	Altitude (masl)	Annual average temperature (°C)	Flow (10^3 m^3 day^{-1})	Treatment process
Tibetan Plateau & Yungui Plateau (China) [13,20,53,80]	Kunming, Yunnan	1,900	15	53	AAO
	Kangding, Sichuan	2,560	7	11	Orbal oxidation ditch
	Lijiang Yunnan	2,685	6–8	1	B/L Wetland
	Xining, Qinghai	2,272	6	61	OD
	Golmud, Qinghai	2,780	–4.2	35	Modified AAO
	Changdu, Tibet	3,200	7.6	6	AAO
	Jiuzhai, Sichuan	3,496	3–5	0.45	MBR
	Kongga, Lhasa, Tibet	3,579	5-7	1	A/O MBR
	Liuwu, Lhasa, Tibet	3,658	4–6	50	CASS
	Yushu, Qinghai	4,200	3	15	AAO
Colorado Plateau (USA)	Moab Utah, USA (1)	1,387	13.8	66	SBR
	Moroni Utah, USA (2)	1,686	8.3	567	Activated sludge
	Golden, Colorado, Denver	1,600	4.1	530	Activated sludge + anaerobic digestion
Iranian plateau (Iran)	Tehran, Iran (3)	1,200	17.6	520	AAO
Meseta Central (Spain)	Ávila, Spain (4)	1,182	12.4	30	MBR

MBR: membrane bioreactor; B/L Wetland: baffled/lateral subsurface flow wetland; A/O-MBR: anaerobic/oxic-membrane bioreactor; CASS: cyclic activated sludge system; A/A/O: anaerobic/anoxic/oxic; Orbal® OD: Orbal® oxidation ditch
(1) https://moabcity.org/DocumentCenter/View/1348
(2) https://deq.utah.gov/ProgramsServices/programs/.../ugw390005-sob.pdf
(3) http://www.kuzugrup.com/en/western-tehran-wastewater-treatment-plant
(4) https://eponline.com/articles/2013/03/06/spanish-city-upgrades-wastewater-treatment-plant.aspx?admgarea=ht.water.wastewater

with different designs and operation methods in plateau regions around the world. Yet, in practice, there are problems regarding the operation, maintenance, and treatment performance of WWTPs in plateau regions due to the distinct climate and landscape features when compared with WWTPs located in the plains. Studies have shown that many WWTPs have difficulties achieving the required effluent quality and the contents of chemical oxygen demand (COD), biological oxygen demand (BOD), and the nutrient levels, e.g., total nitrogen (TN), ammonia (NH_4-N), and total phosphorus (TP), exceed the standards for effluents [8,11,12].

Evidence suggests that the encountered difficulties and poor performance of WWTPs located in plateaus (plateau WWTPs hereafter) can be largely attributed to the extreme climate conditions. The quantity and the quality of the wastewater, which predominantly regulate the performance of all types of wastewater treatment facilities, might also play an important role in effecting the efficiencies in plateau WWTPs. Table 2 summarizes the wastewater treatment performance and operational parameters of representative plateau WWTPs, taking Chinese WWTPs as examples. Unlike the influencing factors affecting WWTPs in the plains (plains WWTPs hereafter), the low temperature, low oxygen level, and low pressure are key factors limiting the performance of plateau WWTPs [12,13]. For example, the influent of plateau WWTPs generally contains less nitrogen and the biodegradability is lower than in plains WWTPs. Additionally, the wastewater quantity is much lower, too. In order to obtain an in-depth understanding of the performance of plateau WWTPs and the underlying mechanisms, it is essential to summarize the key factors governing the performance of plateau WWTPs. Suitable strategies to achieve the stable operation of plateau WWTPs are urgently needed for pollution control.

It is generally believed that the microbial community and the interactions between the microbes and pollutants play fundamental roles in controlling the biological processes and treatment efficiencies. Recently, a series of studies were conducted to determine the effects of the unique geographical properties of plateaus on the performance of WWTPs [12–14]. Differences in the microbial community and the structure of bacteria, archaeal, and fungi were observed between plains and plateau WWTPs. Plateau WWTPs also showed variations in nutrients and micropollutant removal behaviors at the phylum and genus level. These studies on the microbial composition and structure are providing fundamental engineering and scientific guides for the construction of plateau WWTPs.

This review provides details on the research and the issues associated with wastewater treatment biotechnologies in plateau regions. Key factors affecting the performance of WWTPs were summarized and discussed. The microbial community structure in plateau WWTPs is also analyzed and its relevance to the performance of WWTPs is discussed. Additionally, suitable strategies aimed at improving the performance of plateau WWTPs are proposed to cope with the issues. Valuable information and experience with WWTPs in the Tibetan Plateau are also provided to guide the future design of plateau WWTPs in other areas and countries.

2. Factors affecting performance of plateau WWTPs

Similar to plains WWTPs, the performance of plateau WWTPs is affected by different factors and operational parameters, including the influent composition, pH alteration, oxygen level, sludge concentration, and the design of the bioreactors. In addition, plateau WWTPs are facing challenges brought on by extreme climate conditions, including strong solar radiation, large temperature differences between

Table 2
Wastewater treatment performance and operational parameters of representative plateau WWTPs in China

	Altitude (masl)	Organic loading rate ($kg/m^3·d^{-1}$) of					Removal (%) of					DO ($mg\ L^{-1}$)	SRT (d)	HRT (h)	Process	pH	TC ($10^3 m^3\ d^{-1}$)	SVI ($ml\ g^{-1}$)	MLSS ($mg\ L^{-1}$)	F/M (kg BOD/ kg $MLSS·d^{-1}$)
		COD	BOD	TN	NH_4-N	TP	COD	BOD	TN	NH_4-N	TP									
GY	1,280	0.775	0.468	0.057	0.042	0.008	91.9	96.2	50.5	93.6	NA	2.7 ± 0.3	13	13.5	AO	6.5 ± 0.2	74 ± 4	91 ± 2	5,543 ± 329	0.084 ± 0.006
LZ	1,520	1.111	0.582	0.152	0.098	0.017	91.8	95.2	57.8	93.5	93.9	2.5 ± 0.3	11	7.2	AAO	7.3 ± 0.2	107 ± 8	125 ± 6	4,176 ± 258	0.139 ± 0.006
KM	1,900	0.883	0.457	0.084	0.055	0.011	91.6	96.7	45.1	91	NA	2.4 ± 0.2	12	9.1	AAO	7.1 ± 0.1	53 ± 14	113 ± 4	3,462 ± 384	0.132 ± 0.005
XN	2,272	0.384	0.203	0.044	0.037	0.003	90.3	95.8	57.1	92.8	NA	2.3 ± 0.3	13	19.1	OD	6.7 ± 0.2	61 ± 8	88 ± 2	3,516 ± 247	0.058 ± 0.002
LJ	2,400	0.563	0.318	0.103	0.063	0.006	90.1	97.5	73.1	89.7	NA	2.7 ± 0.3	11	12.3	AO	6.9 ± 0.1	58 ± 16	96 ± 5	3,428 ± 362	0.093 ± 0.003
GEM	2,780	0.536	0.291	0.058	0.05	0.006	90.8	94.6	63.2	84.5	NA	2.7 ± 0.3	14	12.6	AAO	6.6 ± 0.1	35 ± 6	101 ± 3	2,795 ± 374	0.104 ± 0.003
CDX	3,200	0.453	0.245	0.052	0.043	0.003	86.7	93.6	67.2	78.2	NA	1.9 ± 0.2	12	13.2	AAO	6.8 ± 0.1	25 ± 9	95 ± 2	2,266 ± 126	0.108 ± 0.004
LS	3,660	0.417	0.179	0.052	0.036	0.002	79.3	92.5	65	70.6	NA	1.8 ± 0.2	14	12.8	CASS	7 ± 0.1	28 ± 11	96 ± 3	1,676 ± 182	0.107 ± 0.002

All data presented are annual average values. TC: treatment capacity; F/M: food/microorganism ratio, SRT: solid retention time, HRT: hydraulic retention time, SVI: sludge volume index, MLSS: mixed liquor suspended solids.

day and night, rarefied air, low oxygen pressure, and long frozen periods [15]. The predominant influences could be ascribed to the low temperature, low oxygen level and pressure, and other characteristic problems in high-altitude regions in the following sections.

2.1. Effects of low temperature on pollutant removal and sludge bulking

Physically, the viscosity of wastewater declines at lower temperatures, retarding the diffusion of the organics in the wastewater. Sludge becomes easily bulked and washed out, resulting in elevated suspended solid contents in the effluent. The decline in the concentration of the return sludge also affects the solid contents in the biological reactors. The chemical reaction rate increases 2–4 folds with every 10°C increase in temperature [16]. The microbial activities, e.g., protein synthesis rate, the activity of enzymes, and DNA replication, are extremely low below 4°C and the low temperature accelerates the excretion of soluble microbial products. The retarded microbial activities affect the removal of organics and nutrients and result in sludge bulking, leading to the deteriorating of the effluent quality [16,17].

2.1.1. Effects on the removal of organics

Mesophilic microorganisms play key roles in degrading organic matters in municipal wastewater. The ability of the mesophilic microorganisms in metabolizing exogenous substances was inhibited when the temperature was below 10°C [17]. However, some researchers found that low temperatures had fewer impacts on the removal of organic matter in a long-term experiment [18]. Some species might have adaptive responses to lower temperatures after a period of operation, even resulting in a higher biomass than in systems operated at ambient temperatures. As a result, the system can maintain a relatively stable COD removal efficiency compared to WWTPs in plains areas [19].

In several studies, a lower COD removal efficiency in plateau WWTPs than in plains WWTPs has been observed [12,13]. Despite the potential effects of low temperatures, the relatively low sludge load and biodegradability (BOD_5/COD value less than 0.4) might be responsible for the lower COD removal performance [14,20]. At low sludge loads, the endogenous respiration is higher than at high sludge loads due to the substrate limitations. Consequently, self-digestion of sludge easily occurs and the sludge breaks down into smaller flocs, which decreases the COD removal efficiency [14]. The produced excess sludge is less liable to ferment during endogenous respiration and this occurs easily in plateau WWTPs.

2.1.2. Effects on nitrogen and phosphorus removal

The nitrification process is a key step for biological nitrogen removal and relies on autotrophic aerobic microbes including ammonia oxidizing bacteria (AOB), which oxidize NH_3/NH_4^+ to NO_2^- and nitrite oxidizing bacteria (NOB), which oxidize NO_2^- to NO_3^-) [21]. The maximum specific growth rates of species including *Nitrosomonas* (NS) and *Nitrobacter* (NB) are highly correlated to temperature [22]:

$$\mu_{\max,NS} = 0.042\exp(0.0351T–2.174) \tag{1}$$

$$\mu_{\max,NB} = 0.042\exp(0.0587T–1.13) \tag{2}$$

Low temperatures not only inhibit the specific growth rate and proliferation of nitrifying bacteria [23,24], but have also been observed to affect the distribution and activity of nitrifying bacteria, resulting in the failure of the nitrification process [25]. The rate of denitrification also decreases markedly with decreasing temperatures and stops below 5°C [16]. During the cold season, the freezing of surface wastewater often occurs and foaming has been observed in plateau regions. According to previous studies, these effects jointly resulted in the decline in the microbial activity and the productivity ratios of nitrifying bacteria and a lower effluent quality with respect to NH_4-N and TN removal [12,13,26]. For example, the TN removal efficiency in a WWTP in Lasha was only 57.8%–67.9% in our recent study [14]. To alleviate the negative effects of low temperatures on the TN removal efficiency, the addition of materials such as zeolites resulted in a superior ability in absorbing ammonia, which will be discussed in section 4.2 [27].

The removal of phosphorus in WWTPs mainly depends on the uptake and storage of excess phosphorus by phosphorus-accumulating organisms (PAOs) [28]. Fang et al. [12] evaluated the TP removal performances of representative WWTPs in plateau and plains. The results indicated that the overall TP removal in plateau WWTPs (annual temperature 3°C–8°C) were significantly lower than in plains WWTPs (annual temperature 11°C –14°C), with an efficiency of 28.7%–51.0% compared with 83.7%–88.8% [12]. The low temperature might be one of the factors affecting the TP removal efficiencies. The formation of volatile fatty acids and the activities of the PAOs are inhibited at low temperatures [16]. Mohsen Heidari et al. [2] found that the TP removal efficiency declined rapidly when the temperature decreased from 15°C to 12°C. Some other studies have reported that the capacity of the sludge to absorb phosphorus decreased when the operating temperature declined from 20°C to 10°C [29].

2.1.3. Sludge filamentous bulking

Sludge bulking is one of the problems associated with the microbial community at low temperatures. The decline in temperature usually leads to a reduction in the charge density of the sludge flocs, an increase in the hydrophilicity of the sludge surfaces, and the secretion of more viscous materials, which impedes the sludge aggregation. Consequently, lower sludge compression, settleability, and sludge-water separation efficiency are often observed [30,31]. From a microbial perspective, the sludge filamentous bulking is a result of the imbalance between the zoogloea bacteria and the filamentous bacteria. As the temperature decreased, psychrophilic bacteria (mainly *Acidobacteria*) bloomed and gradually replaced the microbes sensitive to low temperatures [32].

Bulking induced by the overgrowth of filamentous bacteria at low temperatures has been commonly observed in plateau WWTPs and results in serious problems in the solid-liquid separation and the effluent quality. To alleviate the adverse effects brought on by filamentous bulking, alternative designs in bioreactors such as a membrane bioreactor

(MBR) can be used to achieve better sludge-liquid separation efficiencies. Researchers found that limiting the filamentous bulking represents an energy-saving approach and should be used in the plateau and cold regions; this aspect will be discussed in Section 4.2. Fig. 2 illustrates the effects of low temperature on sludge property, microbial community, and nutrient removal efficiency.

2.1.4. Energy consumption of the facilities

The elevated energy consumption of biological treatment facilities has been a key problem impeding their wider applications in northern climate regions including Russia [33], Canada [34,35] and northern Europe [36,37]. The construction materials easily freeze in the cold season in plateau regions, resulting in higher energy costs [19]. In order to alleviate the negative effects resulting from low temperatures, insulated equipment and the use of electric heating cables are needed. The water pipelines should be buried. Overflow areas designed for accidents should be installed above the pipelines to prevent freezing and cracking of pipelines. Recently, a buried bio-contact oxidation constructed wetland was developed on the Tibetan Plateau and represents a potential solution to achieve good effluent quality.

As far as the authors are concerned, there is limited work available on the estimation of energy gap in response to decreased temperature and elevated altitude of treatment facilities. It is advisable to evaluate the performance at cold plateau regions and design novel mechanical devices to cope with the problems of freezing or low efficiencies. The generated scientific and engineering information is of significance to guide the future operation of WWTPs in these regions from either a technical or economic perspective.

2.2. Effects of dissolved oxygen deficiency and low pressure on nutrient removal and sludge bulking

Plateau regions suffer from oxygen deficiency and low pressure. For example, in the Tibetan Plateau, the average air pressure, oxygen level, and the density of air only account for 50%, 60%, and 66% respectively of those values in the plains. At the same aeration intensity, the oxygen supply is only around half that in the plain regions. In plateau regions, WWTPs are always facing the problems of oxygen deficit as shown in Table 2. Low DO and low pressure reduce the microbial activities and affect the internal pressure of cells, resulting in reduced nitrification/denitrification processes of the flocs, fewer nutrients, and lower organic matter removal efficiencies [16,38].

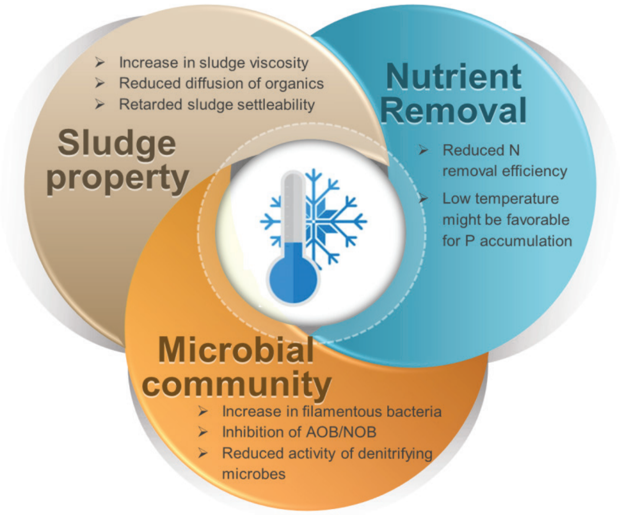

Fig. 2. Effects of low temperatures on the performance of plateau WWTPs.

2.2.1. Effects on the nutrient removal

Nitrifying bacteria are strictly aerobic microbes whose bioactivity is distinctly inhibited under oxygen-deficient and low-temperature conditions. In order to achieve the same nitrification rate, the DO concentration should be 10% higher for every 1°C decrease in temperature [39]. Although, the nitrification ceased when a conventional activated sludge plant transitioned to low DO conditions, the nitrification capacity could be restored after a period of cultivation [40,41]. For a granular sludge system, the granules broke up due to a low oxygen concentration, whereas an oxygen saturation of 40% increased the nitrogen removal efficiency [42]. There are few studies on the effects of low DO on the P removal. Carvalheira et al. [43] found that the PAO Accumulibacter had an advantage over the glycogen-accumulating organism (GAO) Competibacter, suggesting that low DO conditions may favor the PAO activity. To alleviate the effects of oxygen deficiency on nutrient removal, modifications in the biological processes such as prolonging the sludge retention time (SRT) in the bioreactor should be performed [44]. Even though limited studies were available stressing the effects of DO concentration on nutrient removals in plateau WWTPs, we believe that performance of WWTPs in these regions were largely hindered owing to the deficiency of DO and low pressure. The combined effects of low temperature and low DO content might result in a worse situation for treatment performance and microbial community, which merit future research.

2.2.2. Sludge filamentous/viscous bulking

Zoogloea bacteria, which contribute to the floc formation, are strictly aerobic microbes, whereas *Sphaerotilus natans* such as *Bacillus* and *Thiothrix* can survive in aerobic and micro-aerobic (~0.5 mg L^{-1} DO) conditions [30]. The presence of spindly hyphae in filamentous bacteria results in a larger specific area, which provides advantages with regards to the competition for oxygen against zoogloeal bacteria [45,46]. In plateau regions, the deficiency of DO is believed to be one of the major causes responsible for the filamentous growth. The growth of certain filamentous bacteria, such as *Sphaerotilus*, *Haliscomenobacter hydrossis*, *Thiobacteria*, and *Chloroflexi* is favored by relatively low DO concentrations [47–50]. For example, Martins et al. [51] observed that a low DO concentration (1.1 mg L^{-1}) had a strong negative effect on the sludge settleability and resulted in the proliferation of filamentous bacteria (*Thiothrix* spp.).

Viscous bulking usually occurs under anoxic conditions and high sludge loading. The insufficient metabolism of the organic matter results in large amounts of viscous polysaccharide materials in the extracellular regions. The adsorption of the excess organic matter onto the cells adds density to the particles. A lower negative charge density and higher hydrophilicity promoted the formation of "gelatinous" flocs, leading to deteriorated sludge flocculability and compression [31,49,51]. The lack of nitrogen in the influent is another reason for sludge viscous bulking, which commonly occurs in plateau regions. We previously reported that the TN and NH_4-N contents in plain WWTPs were 0.066–0.247 and 0.043–0.169 kg $(m^3{\cdot}d)^{-1}$, respectively whereas the values were 0.045–0.157 and 0.034–0.093 kg $(m^3{\cdot}d)^{-1}$, respectively in plateau WWTPs above elevations of 1,000 masl [13]. According to Gerardi, [30] the microbes could not utilize the carbon sources to synthesize the cellular materials and the excess carbon sources were transformed into polysaccharides as extracellular storage due to the shortage of nitrogen, which might be responsible for the observed viscous bulking phenomenon mentioned earlier.

2.2.3. *Effects on equipment and energy consumption*

Under anoxic conditions, weak thermal diffusivity always occurs in the voltage distribution cabinets in plateau WWTPs. Cooling devices such as exhaust fans and gas vents should be installed near the cabinets. Under low-pressure conditions, the compression ratios of air blowers markedly decrease, resulting in overheating, a decline in the performance of the lubricating oil, and damage to the bearings. Some analytical equipment such as DO meters does not function properly under these conditions. Compared with WWTPs in plains regions, a higher aeration is required to achieve the same oxygen supply and equipment suitable for plateau regions should be further evaluated and implemented. Fig. 3 illustrates the effects of DO deficiency and low pressure on sludge properties and the performances of plateau WWTPs.

2.3. *Other factors*

Other factors affecting the performance of plateau WWTPs include the low population density, the living conditions of residents, the lack of wastewater quantity, and the difficulty associated with water collection. The population density in plateau regions is lower than in the plains areas and most people rely on livestock farming in small communities and remote areas. Thus the amount of daily water consumption is limited, resulting in lower wastewater quantity for many plateau WWTPs [13]. The difficulty associated with the collection of waste water, which is attributed to the underdeveloped drainage facilities results in the low performance of plateau WWTPs [7,9]. In addition, the potential challenges associated with the operation of plateau WWTPs that we elaborated on may not have been taken into account in the current WWTP operations, thus the management processes may not be adapted to the difficult climate conditions and the underdeveloped facilities.

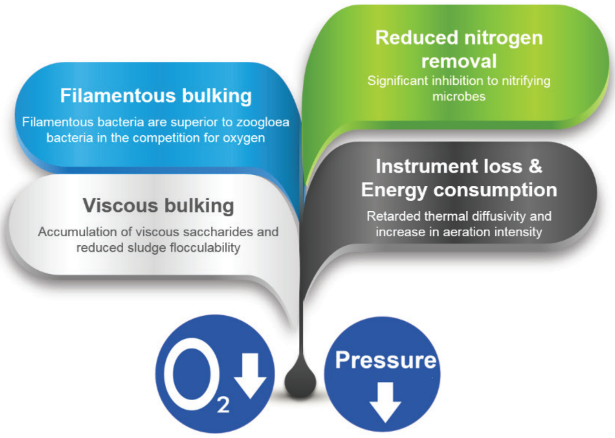

Fig. 3. Effects of low DO and low pressure on the performance of plateau WWTPs.

3. Microbial community in plateau WWTPs

Microorganisms serve as the most important component of the biological wastewater treatment process and the microbial structure and species composition is significantly affected by the operating conditions in the WWTPs [12,13]. Studies have investigated the distributions and characteristics of the microbial communities in different geographical regions. Factors including altitude, temperature, soil composition, etc. affect the distribution of the microbial communities (bacteria, archaea, and fungi) and these factors have been investigated at scales from single mountains to the continental scale [52–56]. For example, Yang et al. [57] determined that the abundance of endemic stress genes such as the σ^{24} genes increased in response to extreme temperature stress and pressure stress in the Tibetan Plateau.

Many authors have stressed that the geographical distribution has a potential effect on the microbial community in WWTPs [58–62]. Significant geographical differences were observed in bacterial communities among samples collected in WWTPs in eastern and western China and in Asia and North America [58,59]. According to Wang et al. [60] the geographical locations explained 14.7% of the bacterial community variation among 14 WWTPs located in four cities in China. Recent studies have analyzed the microbial diversity, composition, and type of microorganisms used for nutrient and pollutant removal in response to elevation, provided in Fig. 4. Differences in the microbial diversity, composition, and functions were observed between WWTPs in plateau and plains regions.

3.1. *Microbial diversity in plateau WWTPs*

Recently, 16S rRNA sequencing technology and the GeoChip technology have been employed to analyze the species composition and determine the microbial community functional structures in WWTPs [63–65]. For example, Xia et al. [66] found that the microbial community structure and diversity were consistent among reactors of various designs in China and in the United States. In contrast, the microbial diversity generally experienced a decline as the altitude increased in both natural systems and in WWTPs. Damage to the DNA and RNA in cells due to a high ultraviolet light environment resulted in a decline in microbial diversity in plateau WWTPs [15]. In addition, low temperatures were also responsible for the decline in the microbial diversity in plateau

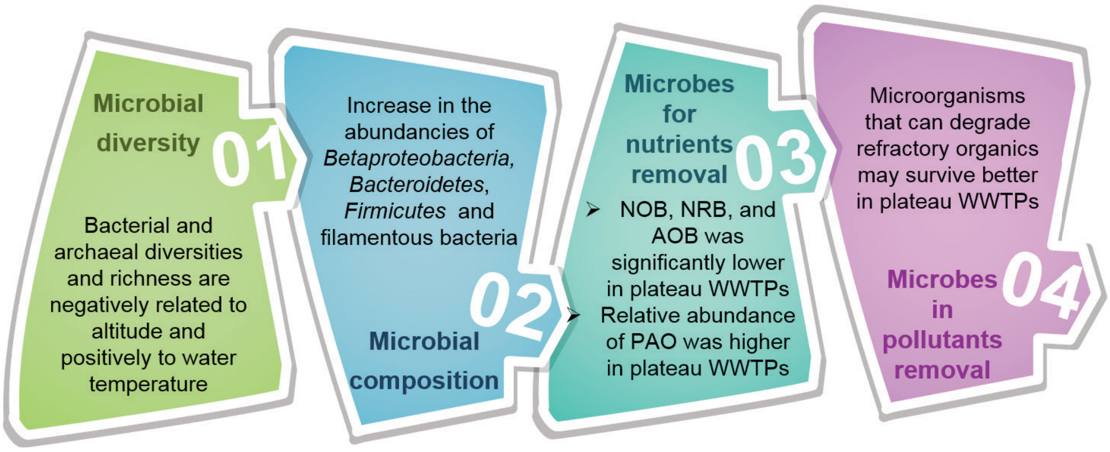

Fig. 4. Microbial community characteristics in plateau WWTPs.

areas [21,67,68]. It was observed that the microbial richness and phylogenetic diversity of planktonic bacteria, bacteria, and archaea was negatively related to altitude, implying a decreased functional resistance of the WWTP microbial communities to extreme environmental stress [69–72].

We previously compared the activated sludge bacterial community along a 3,600-m elevation gradient [13]. At lower elevations, the bacterial richness and evenness were not significantly associated with elevation. In contrast, at higher elevations, the community richness, and evenness were negatively related to altitude. Both the microbial community richness and the evenness were 2 to 3 times lower at high elevations than at low elevations. Fang et al. [12] also observed that the microbial diversity and richness were negatively associated with the altitude and positively associated with the water temperature. Similarly, the archaeal community richness and structure exhibited negative correlations with altitude at higher elevations in the plateau regions [53], whereas the archaea community richness and diversity exhibited fewer fluctuations in the plains regions [65]. These results were similar to those reported by Singh et al. [73] who analyzed elevational patterns in archaeal diversity on Mt. Fuji. The community structure was associated more strongly with the wastewater variables at higher elevations than at lower elevations [53].

3.2. Microbial composition in plateau WWTPs

Various factors were found to affect the community compositions across the entire elevation gradient, among which the influent TP, the food/microorganism ratio, the treatment process, the NH_4-N content, and the temperature were the dominant variables [13]. The changes in the microbial community structure were significantly related to elevation. In a study analyzing the microbial community along a lake elevation gradient, the nutrient concentrations and elevation were two predominant contributors to the constrained variability in microbial composition. A distance–decay relationship in the microbial community structure was observed across the lakes, suggesting that both local environmental factors and dispersal affect the community structure [74].

The dominant phyla were similar in municipal WWTPs, including *Proteobacteria, Bacteroidetes, Chloroflexi, Firmicutes,* and *Acidobacteria* [12]. *Betaproteobacteria* were generally most abundant and were largely responsible for organic and nutrient removal [75–77]. In our previous work, we found that the top five most abundant phyla in plateau WWTPs were *Proteobacteria*, *Bacteroidetes*, *Actinobacteria*, *Firmicutes*, and *Chloroflexi*. *Betaproteobacteria*, *Bacteroidetes*, and *Firmicutes* exhibited significant increases, whereas most other phyla showed decreases with an increase in altitude [13]. Fang et al. [12] reported a positive relationship between the abundance of *Chloroflexi* and the abundance of *Firmicutes*. The higher abundance of *Firmicutes*, *Bacteroidetes,* and *Betaproteobacteria* indicated that the phenotypes of some microorganisms in the plateau WWTPs had mutated under the extreme climate conditions because these species can produce spores to resist extreme environmental stress [13,78].

At the genus level, the most representative bacterial genera in plateau WWTPs were *Haliangium*, *Roseiflexus*, *Smithella,* and *Lachnospiraceae*. The majority of the dominant phyla, classes, and genera were negatively correlated with the altitude and positively correlated with the concentration of the influent pollutant, implying that a lower concentration of wastewater and a higher altitude reduced the complexity of the microbial community in the WWTPs [12]. The archaeal communities in the WWTPs were dominated by *Methanosarcinales* (84.6%). The tested WWTPs shared a core archaeal population (94.5%) composed of *Methanosaeta*, *Methanosarcina*, *Methanogenium*, and *Methanobrevibacter*. The wastewater variables were the dominant factors affecting the variations in the archaeal community structures at high altitude [53]. The assay of the activated sludge fungal communities from 18 full-scale municipal WWTPs in China suggested that *Ascomycota* and *Basidiomycota* were the most abundant phyla and were dominated by *Pluteus*, *Wickerhamiella*, and *Penicillium*. Altitude was an important factor affecting the fungal community structure based on a distance-decay relationship analysis [79].

3.3. Nutrient removal microorganisms

The abundance of and the balance between *Nitrosospira* sp. and *Nitrosomonas* sp. is of significance in the nitrification processes [24,80]. Regarding NOB, low DO levels and short SRTs favor the growth of Nitrospira sp. in WWTPs, whereas the abundance of *Nitrobacter* sp. increases in the winter when the DO levels are high [81]. Studies have shown that nutrient removal bacteria exhibited greater differences in the abundance of plateau and control groups than heterotrophic bacteria. Fang et al. [12] observed that the abundance of *Nitrospira* was significantly lower in the plateau WWTPs. Denitrifying bacteria including nitrate-reducing bacteria (NAR) and nitrite-reducing bacteria (NIR) also were less abundant in the plateau WWTPs. These lower abundances might be the reasons for the reduced nitrification/denitrification process and the poorer nitrogen removal efficiencies in plateau WWTPs [12]. Regardless of the N-utilizing organisms, a significant and positive association was observed between NH4-N and *Chloroflexi* at high elevations in this study and the latter was frequently reported in other WWTPs [13].

At the gene level, representative genes including betaproteobacteria ammonia-oxidizing bacteria (βAOB) and NIR containing the copper-containing nitrite reductase gene (*nirK*-NRB) and the cytochrome cd_1-containing nitrite reductase gene (*nirS*-NRB) involved in the nitrogen-removal process in WWTPs along a 3,600-masl altitude gradient were analyzed. The authors observed an altitude threshold at approximately 1,500 masl that was associated with the proportions of NRB to total bacteria, NRB to βAOB, and *nirK*-NRB to *nirS*-NRB. The community structure dissimilarity of βAOB, *nirK*-NRB, and *nirS*-NRB exhibited significant positive correlations with the altitudinal distance between the WWTPs. Nevertheless, wastewater and operational parameters were still dominant factors affecting the nitrogen-removal bacterial community [20].

As mentioned earlier, the ratios between the PAOs and the GAOs affect the phosphorus removal process. Although the relative abundances of the PAOs and GAOs were higher in the plateau WWTPs than in the control WWTPs, the abundance ratio of the PAOs to GAOs was lower in the plateau WWTPs than in the controls. These results suggest that the phosphorus removal bacteria were more abundant at higher altitude and the high-altitude and low-temperature conditions might favor the growth of the GAOs over the PAOs [12].

3.4. Microorganisms used for micropollutant removal

Although, the microbial diversity and richness declined in the WWTPs at a higher elevation, some species showed better survival rates in the plateau. Fang et al. [12] observed that *Holophagales* (order), *Alcaligenaceae* (family), *Holophagaceae* (family), and *Holophagaceae_g_uncultured* (genus) were enriched in the plateau samples. These species have been reported to degrade aromatic compounds, suggesting that microorganisms that can degrade refractory organics showed superior survival rates in the plateau regions [82]. Generally, the results suggested that most of the microbes were more likely to survive at lower altitudes and warmer conditions.

Kruglova and co-workers analyzed the removal of emerging contaminants such as ibuprofen, diclofenac, and estrone (E1) under low-temperature conditions similar to those in plateau regions. The results suggested that the disappearance of the contaminants such as diclofenac was related to the activity of the nitrifying bacteria and deteriorated at low temperatures [83]. The sludge in the MBR showed higher removal potential than the sludge in a conventional sequencing batch reactor (SBR) system; this was attributed to the accumulation of slowly growing specialist-degrading bacteria [37,83]. The *Delta*- and *Gammaproteobacteria* showed positive correlations with the diclofenac removal rate. Other species including *Microbacterium* sp., *Terracoccus* sp., *Terrabacter* sp., and *Luteococcus* sp. were possibly involved in the removal of pharmaceuticals and estrogens during wastewater treatment under low-temperature conditions [69]. Future work on the detection and habits of strains responsible for the distinct nutrient and micropollutant removal behaviors in plain and plateau regions is highly required.

3.5. Links between community structure and operational variables

We systematically investigated the links between microbial community structure, i.e., bacteria, archaea, and fungi and environmental & operational parameters, as shown in Table 3 [13,20,53,79]. The results suggest that various technological parameters and wastewater qualities play dominant roles in shaping the microbial community structure and that these variables generally account for more than 60% of the variance in the structure of the microbial community. The processing parameters during WWTP management were more significantly associated with the community structure than the wastewater qualities. The wastewater qualities in the study included influent COD, influent BOD, influent C/N ratio, food to microorganism (F/M) ratio, TP loading, NH_4-N loading. The operational variables included hydraulic retention time (HRT), SRT, and DO; the treatment processes were the dominant contributors to the variances in the community structures [13,20,53,79].

Geographical variables and altitude were two other important factors affecting the microbial community structure. The effects of the altitude on the community composition were gradually enhanced as elevation increased (generally 3–4 times higher than at low elevations). The experimental data implied that the operational parameters and the wastewater properties contributed more to the changes in the microbial community than the altitude. Nevertheless, the community structure showed higher correlations with the wastewater characteristics at high altitudes than in the plains regions. The results strongly suggest there is a pressing need for the optimization of wastewater quality, operational parameters, and treatment processes for enhancing the performance of plateau WWTPs.

4. Potential solutions for plateau WWTPs

To cope with the earlier-mentioned operational problems, engineering strategies and technology improvements should be implemented. The aeration strength, SRT, oxygen transfer efficiency, and excess sludge measurements should be optimized to meet the needs of the operation in plateau WWTPs. The proposed strategies include oxygen enrichment and insulation, improvements and modifications of the operational processes, and bioaugmentation technology.

4.1. Aeration and insulation strategies

Sufficient aeration is required to maintain an appropriate oxygen concentration for the biological treatment processes.

Table 3
Explanatory percentages of environmental variables for the variation in microbial community structure

	Bacteria		Nitrogen-removal bacteria						Archaea		Fungi
			βAOB		nirS-NRB		nirK-NRB				
Altitude gradient (masl)	<1,500	>1,500	<1,500	>1,500	<1,500	>1,500	<1,500	>1,500	<1,500	>1,500	
Geographical variables	14	11	9.0	10.3	8.2	13.6	5.3	10.6			
Altitude	3	11	2.0	9.2	3.0	10.6	0.3	6.4	2	6	
Wastewater & Operational variables	80.5	83.2	69.2	64.5	58.4	66.8	67.9	68.4			50
Most dominant variables	Influent C/N ratio (15%) HRT (12%) F/M ratio (9%) NH_4-N loading rate (9%) Influent TP (8%)	Influent TP (19%) F/M ratio (17%) Treatment process (13%) Effluent NH_4-N (11%) Temperature (9%)	NH_4-N loading rate (8%) Influent NH_4-N (7%) DO (5%)		C/N ratio (12%) Loading rate of COD Influent NH_4-N		C/N ratio (9%) Loading rate of COD Influent NH_4-N		SRT (12%) Influent BOD (8%) F/M ratio (8%) Treatment process (7%)	Loading rate of BOD (22%) Effluent BOD (18%) DO (9%) HRT (9%)	DO (9%) C/N ratio (8%) Influent BOD (5%) Temperature (3%)

Additionally, insulation strategies should be implemented in plateau WWTPs. For example, the aeration tanks could be installed underground if a recycling process is permitted. Rubber insulation cotton should be attached to the outside of the tank above the ground. To increase the backflow quantity in the cold season, the effective depth of the tanks should be larger to minimize the heat loss due to radiation and the highest reflux ratio should be utilized to achieve high biomass content. Heating of the inlet air is necessary to increase the temperature of the aeration tank.

4.2. Process improvements and modifications

Modifications of reactor designs are commonly used in plateau and cold regions to achieve high treatment performance. For example, cyclic activated sludge technology (CAST) is a proven design for cold and hilly regions [19,84]. The use of an MBR is an alternative approach at low temperatures due to the enhanced nitrification efficiency and the excellent sludge-liquid separation efficiency [85]. Other modifications in reactor configurations include the A^2/O-MBR and the MBBR [86]. Table 4 summarizes feasible process modifications and bioaugmentation technologies for plateau WWTPs.

Nonbiological materials, e.g., zeolite selectively adsorb ammonia and the selectivity in adsorbing ammonia is more profound at low temperatures. Miazga-Rodriguez et al. [27] found that the use of zeolite in retention ponds facilitated the removal efficiencies of ammonia. The removal efficiency was even higher in the winter than in the warm months due to the colonization of nitrifying biofilms. Thus the addition of zeolite should be attempted in plateau WWTPs.

As mentioned earlier, filamentous bulking commonly occurred in plateau WWTPs. Studies showed that limited bulking under oxygen-deficient conditions is not always negative but could be utilized as an energy-saving approach. By using limited filamentous bulking technology, energy used for aeration could be saved, pollutant removal would be enhanced, and energy consumption could be reduced by at least 10% in full-scale aerobic systems [87]. The results indicated that limited filamentous bulking could be applied in plateau WWTPs, although the reduction in the nitrification efficiency might represent a bottleneck for the application of this technique.

In addition to the above approaches, improvements in the existing biological processes are more feasible to enhance the treatment performance. Generally, a longer SRT favors the growth and functions of nitrifying bacteria, even at low temperatures [44,80]. Nevertheless, the 'younger' bacteria with high microbial activity decrease at longer SRT conditions, resulting in a decline in the overall microbial purification capacity. Modifications in the bioreactor configuration could enhance the organic matter removal efficiency, facilitate the accumulation of AOB and ammonia-oxidizing archaea (AOA), and promote nutrient removal under oxygen-deficient conditions [41,85,88–91] and at low temperature [92,93].

4.3. Bioaugmentation technology

Bioaugmentation technology refers to the practice of adding microorganism with degradation capabilities that differ

Table 4
Feasible process modification and bioaugmentation technologies for plateau WWTPs

Process		Mechanism	Performance	Reference
Modifications of reactor designs`	CAST (Cyclic activated sludge technology)	CAST system exhibits strong resistance to high load and strengthens the performance of nutrient removal due to the ability to switch between the aeration/anoxic/clarification processes. The process performs well for filamentous bulking control.	Removal rates of COD, NH_4-N, and TN were 90.3%, 83.2%, and 69.1%, respectively to treat influent at temperatures lower than 15°C.	[84]
	MBR (membrane bioreactor)	Membrane filtration offers total recovery and recycling of biomass with feasible designs and operations. MBR can achieve simultaneous nitrification/denitrification due to low oxygen transfer efficiency.	At a low DO range of 0.15–0.35 mg L^{-1}, effective removal of nitrogen and COD could be achieved treating black water with high COD and TN concentration.	[85]
	MBBR (Moving bed bioreactor)	The presence of both aerobic and anoxic processes in integrated activated sludge-biofilm system promoted a partial nitrification/anammox process and the removal efficiencies of nitrogen and micropollutants.	MBBR with attached biofilm could sustain enough biomass to allow anammox activity even at 10°C. Reactor performance was stable in ammonium conversion efficiency below 12.5°C.	[98,99]
	Upflow microaerobic sludge blanket (UMSB)	UMSB treatment is feasible to treat wastewater at low/high organic strength under low-oxygen conditions due to the high biomass concentration.	Significantly lower operational costs and effective COD removal was simultaneously achieved at a DO lower than 0.5 mg L^{-1}	[89]
Addition of nonbiological materials	Addition of zeolite	Zeolite amendment markedly enhances nitrification rates by increasing nitrifying biomass due to a high capacity of adsorbing ammonium and provide surface areas for microbial attachment.	100% nitrogen removal was achieved by adding zeolite to the retention pond water due to the accumulation of a nitrifying biofilm.	[27]
Limited filamentous bulking technology		Technically, it is feasible to use limited filamentous bulking under oxygen -deficient conditions to save energy for aeration instead of eliminating bulking sludge.	Removal efficiencies of COD, NH_4-N, TN, and SS were 85.9%, 73.0%, 73.3%, and 98%., respectively. More energy could be saved due to low aeration.	[87]
Process modifications	Increasing SRT	A higher SRT promotes the growth and functions of nitrifying bacteria, resulting in a higher nitrogen removal. In contrast, longer SRT might result in higher effluent P contents due to the excess P released in the anaerobic phase.	At a BOD_5 loading less than 0.12 kg (kg·d)$^{-1}$ and an SRT higher than 12 d, effective removal of nitrogen was achieved, even at temperatures below 10°C	[44,100]
	Accumulation of AOB by decreasing aeration	By using continuous-flow reactors with gradually declining aeration steps, an accumulation of AOB with unusually high yields was achieved at low DO conditions.	Complete nitrification was achieved at a DO concentration of 0.5 ± 0.3 mg L^{-1} in low-aeration units.	[88]
	Slow step-wise oxygen reduction	When DO was slowly reduced in bench- or pilot-scale studies, the nitrification capacity could be stored after prolonged exposure. A low-DO operation may also favor PAO activity.	Full low-DO nitrification combined with low-DO P removal was achieved at the pilot-scale at a DO concentration of 0.33 mg L^{-1}. The removal efficiencies of TKN, TAN, and TP were 96%, 98%, and 89%	[41]

(Continued)

Table 4 *(Continued)*

Process		Mechanism	Performance	Reference
	Optimization in oxygen transfer dynamics	By optimizing oxygen transfer dynamics and at SRTs, sludge with smaller floc size and less extracellular polymeric substances (EPS) was generated.	Smaller floc size and less EPS facilitated the oxygen diffusion rate and were beneficial to the nitrification process. Long-term low DO cultivation reduced the oxygen half-saturation constant of the adapted microbial population.	[101,102]
Bioaugmentation technology	Adding microbes with special degradation capacity	Addition of strains with cold resistance and low-oxygen resistance enhanced treatment efficiency, which could be potentially applied in plateau WWTPs.	Nitrobacteria strains with cold-resistance and higher activity of ammonia were isolated from aeration tanks at temperatures below 12°C and used in the bioaugmentation process.	[94]

from those of the indigenous flora. This approach has been proven to be a useful method to improve the performance of biological systems. For example, Hao et al. [94] selected five kinds of nitrobacteria strains with cold resistance and high ammonia degradation activity from aeration tanks operated at temperatures below 12°C. The addition of the selected strains alleviated the shock stress of low temperatures and shortened the start-up period of the biological processes in pilot-scale experiments [95–97]. Thus, strains that possess cold resistance and low-oxygen resistance should be obtained from hilly and cold regions and utilized in plateau WWTPs to improve the treatment efficiencies of organics and nutrients [96].

5. Summary and perspectives

Plateau regions feed important rivers on a continental scale and govern the water security of downstream areas and countries. Nevertheless, plateau regions have been witnessing unprecedented rapid urbanization and population growth, which increase the pressures on water resources, water security, and fragile ecosystems. The implementation of plateau WWTPs is of great significance in purifying wastewater and protecting fragile water resources. Owing to the extreme climate conditions such as strong solar radiation, large variation in daily temperatures, rarefied air, low oxygen pressure, long frozen periods, and lack of technical advances, plateau WWTPs are facing various types of operational problems. Thus, a better understanding of the factors governing the performance of plateau WWTPs is urgently needed.

This review highlights the influences of low temperature, low oxygen, and low pressure on the performance of plateau WWTPs. In general, low temperatures result in an increase in the sludge viscosity and a decrease in the sludge settleability. The combined effects of low temperatures and oxygen deficiency result in both filamentous and viscous bulking, which commonly occur in plateau and cold regions. Low temperatures markedly inhibit the activity of nitrifying/denitrifying bacteria and reduce the nitrogen removal efficiency. Phosphorus removal is also affected in plateau WWTPs due to the combined effects of low temperatures and low oxygen levels.

The microorganisms used in biological wastewater treatment processes fundamentally determine the performance of WWTPs. Recent studies have evaluated the microbial structures and functions in plateau WWTPs and found significant differences between the plateau and plains WWTPs. The bacterial and archaeal diversities and richness are negatively correlated with altitude. The abundances of the NOB, NRB, and AOB were significantly lower in plateau WWTPs, whereas the PAO exhibited increases at higher altitudes. It is interesting that microorganisms that can degrade refractory organics survive better in plateau WWTPs, providing an available approach for bioremediation and bioaugmentation technology. Based on the operational problems in maintaining plateau WWTPs and taking into account the unique microbial community structure, several suitable improvement strategies for plateau WWTPs are proposed.

The conclusions of this review emphasize the need for further research. Future research and engineering tasks emerging from the data gathered here are summarized as follows:

(1) The quantity and the bioavailability of wastewater are lower in the plateau regions than that in the plains regions and the plateau regions have distinct water quality. The selection of suitable technologies is taking into account the characteristics of the wastewater in the plateau regions is a key to improving the performance of the biological facilities. Moreover, technologies focused on effective aeration and insulation should be expanded in WWTPs in plateau and cold regions in the future to alleviate the effects of low temperatures and low oxygen levels.

(2) Studies on optimal designs and modifications of biological facilities, such as SRT, HRT, sludge load, wastewater quality, solid-liquid separation styles, the reactor configuration, and the operation modes are critical to the biological processes in plateau WWTPs. Appropriate approaches are required for dealing with the plateau wastewater with unique water quantity and quality. In the future, more funding and infrastructure development are suggested to improve the water collection system in plateau regions.

(3) The data in our review indicate that an in-depth survey is required on the microbial community structure and functions in plateau WWTPs. A series of studies should

be performed to investigate the effects of the extreme plateau climate on the evolution of the microbial community and the distribution of genes related to nutrient removal. Technologies such as transcriptomics and GeoChip should be used to understand the gene functions and networks in plateau WWTPs to determine the ecosystem functioning and stability in response to extreme climate conditions.

(4) Further studies on the implementation of bioaugmentation in plateau WWTPs are required. The enzymatic activity response mechanisms in specific strains isolated from plateau WWTPs should be analyzed. More information on the cold-adaptive genes and eosinophilic plasmids is needed to determine the eosinophilic molecular mechanisms. The applications of bioaugmentation of these strains in pilot- and large-scale systems are needed to achieve high treatment performance and meet the demand for higher treatment efficiency in plateau WWTPs [96].

Considering the operational problems of plateau WWTPs, the practices used in the Tibetan Plateau in China have demonstrated that full-scale WWTPs using activated sludge processes can be successfully implemented to treat wastewater in plateau regions. The engineering experience of the WWTPs in the Tibetan Plateau is of great importance to guide the future designs of WWTPs in other high-altitude countries and areas. The mixed liquor suspended solids (MLSS), aeration intensity, SRT, and oxygen transfer rate in plateau WWTPs should be optimized from a microbial perspective. Functional strengthening approaches for wastewater treatment techniques should be proposed by determining the microbial community structure and stability. Pilot-scale treatment facilities should also be implemented to evaluate the efficiencies by using cold-resistant and low-oxygen resistant species in bioaugmentation approaches. The findings of this study provide an important basis for future work to enhance the performance of high-elevation WWTPs.

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