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Nationwide survey of organism-related off-flavor problems in Japanese drinking water treatment plants (2010–2012)

Naohiro Kishida, Masaki Sagehashi, Hirokazu Takanashi, Naoshi Fujimoto and Michihiro Akiba

ABSTRACT

Recent trends in off-flavor problems were investigated by a nationwide questionnaire survey targeting 239 drinking water treatment plants (DWTPs) maintained by 79 regional water suppliers (RWS) in Japan. The results indicated that 43 of 79 (54%) RWS and 89 of 239 (36%) DWTPs were affected by off-flavor problems in a recent 2-year period (October 2010–September 2012). Off-flavor incidents occurred in all regions in Japan. Most DWTPs affected by off-flavor incidents take in water from closed water areas, such as dams and lakes, where phototrophic microorganisms, such as cyanobacteria and algae, can grow easily. The most common off-flavor was an earthy–musty odor, while a fishy smell was also reported in some cases. The common producers of geosmin were *Anabaena* spp., while those responsible for 2-methylisoborneol were *Phormidium* spp. and *Oscillatoria* spp. The off-flavor events frequently occurred during summer and early fall months (June–September). The water temperature and pH of raw water for the production of drinking water when off-flavor problems occurred were higher than those during normal periods. To eliminate off-flavor compounds, most DWTPs (about 58%) adopt powdered activated carbon treatment, which considerably increases operational costs.

Key words | algae, cyanobacteria, geosmin, 2-methylisoborneol, nuisance organisms

Naohiro Kishida (corresponding author)
Michihiro Akiba
Area on Water Management,
Department of Environmental Health,
National Institute of Public Health,
2-3-6 Minami, Wako, Saitama 351-0197,
Japan
E-mail: *kishida@niph.go.jp*

Masaki Sagehashi
Department of International Health and Collaboration,
National Institute of Public Health,
2-3-6 Minami, Wako, Saitama 351-0197,
Japan

Hirokazu Takanashi
Department of Chemistry, Biotechnology, Chemical Engineering,
Graduate School of Science and Engineering,
Kagoshima University,
1-21-40 Korimoto, Kagoshima 890-0065,
Japan

Naoshi Fujimoto
Department of Brewing and Fermentation,
Tokyo University of Agriculture,
1-1-1 Sakuragaoka, Setagaya-ku, Tokyo 156-8502,
Japan

INTRODUCTION

The production of off-flavor compounds by organisms in water is a problem for water utilities worldwide (Watson 2003; Giglio *et al.* 2011). In Japan, off-flavors are a serious problem in water supply systems because surface water is commonly used as raw water for drinking water (Kishida *et al.* 2013). Photosynthetic microorganisms, such as algae and cyanobacteria, which produce off-flavor compounds, often occur in water sources (Matsumoto & Tsuchiya 1988; Yano *et al.* 1988; Oikawa & Ishibashi 2004). In 1990, more than 20 million people, accounting for about 18% of the total Japanese population, were affected by off-flavors in drinking water in Japan. Although the number decreased markedly with the adoption of advanced treatment processes, more than two million people still experience off-flavors in drinking water in Japan, and the number has increased slightly in recent years (Ministry of Health Labour and Welfare Japan 2013). The Ministry of Health, Labour and Welfare, Japan, decided to include geosmin and 2-methylisoborneol (2-MIB) in the drinking water quality standards, which are the most important criteria, in 2003. Current standard values of geosmin and 2-MIB are 10 ng/L. The threshold odor number (TON) has also been adopted as a management goal, which is a second-class criterion of the Japanese water quality management system (Kishida *et al.* 2013). Even when the concentration of off-flavor compounds in finished water exceeds the standard values, water supply is normally continued. However, drinking water that does not contain off-flavor compounds is sometimes delivered

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from other drinking water treatment plants (DWTPs) to consumers by water tank trucks. In rare cases, water charges are reduced during the periods of concentration excess.

To investigate recent trends in organism-related off-flavor problems, we performed a nationwide questionnaire survey targeting 142 DWTPs maintained by 24 regional water suppliers (RWS) in Japan (Kishida *et al.* 2013). The results indicated that off-flavor incidents had occurred in all regions in Japan. Cyanobacteria were the most common organisms responsible for producing off-flavor compounds. However, the numbers of target RWS and question items were limited, and detailed information on off-flavor incidents was not available. Hence, in the present study, we performed a detailed questionnaire survey about organism-related off-flavor problems targeting a wider range of water utilities in Japan.

MATERIALS AND METHODS

The questionnaire survey was conducted in 2012. The target period of the questionnaire ranged from October 2010 to September 2012. A total of 239 DWTPs maintained by 79 RWS from all regions of Japan were targeted for the questionnaire survey. As shown in Table 1, at least 25 DWTPs were targeted from each region. The DWTPs with very small and large water treatment capacities were included, as shown in Figure 1. Total amounts of distributed water of target DWTPs accounted for about 41% of the total amount of distributed water in Japan. Most target DWTPs take in surface water.

Questionnaire items are listed in Table 2. Although the items included detailed information, such as concentrations of off-flavor compounds in raw and finished water, not all of the RWS and DWTPs analyzed and/or recorded these data. Therefore, recovery ratios were not the same for each item. However, a relatively high recovery ratio (>78%) was obtained for all items in this study. The recovery ratios were calculated using the following equations.

(Recovery ratios for 'presence or absence of off-flavor problems' and 'types of water source') = (Number of DWTPs responding to each question item)/(Number of total target DWTPs)

(Recovery ratios for other items) = (Number of off-flavor events with information on each question item)/(Number of total off-flavor events*)

*If the type of off-flavor or time of year were different, the off-flavor events were counted as separate events even for the same DWTP.

The presence of off-flavor problems was counted only if operational conditions were changed and countermeasures were taken due to the occurrence of off-flavor compounds in raw water for drinking water treatment. In general, determining whether a countermeasure is taken is decided by the individual DWTP based on concentrations of off-flavor compounds in raw water. The DWTPs normally have individual management criteria for off-flavor compounds, such as geosmin, which are stricter than the national drinking water quality standards. Only off-flavor events that would be related to organisms were included in the responses from DWTPs, and other off-flavors, such as chemical and chlorinous odors, were not counted in this survey. The 'organisms associated with off-flavor events' were those present in source and/or raw water when off-flavor events occurred and were presumed by DWTPs to be responsible for producing off-flavor compounds. The organisms were

Table 1 | Summary of target DWTPs for questionnaire survey

Region	Japanese region	Area (km^2)	Population (in thousands)	No. of target RWS	No. of target DWTPs
North	Hokkaido–Tohoku	150,347	14,842	14	45
East	Kanto	32,424	42,607	13	40
Central	Chubu	66,795	21,715	9	25
West	Kinki	33,112	22,755	17	48
Southwest	Chugoku–Shikoku	50,720	11,539	14	42
South	Kyushu–Okinawa	44,467	14,597	12	39
Total		377,865	128,055	79	239

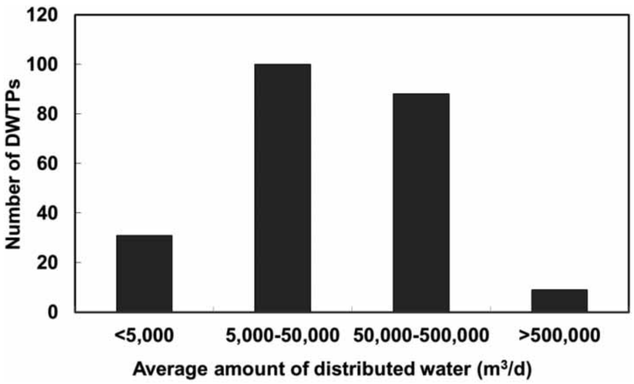

Figure 1 | Amounts of distributed water of target DWTPs.

Table 2 | Questionnaire items and recovery ratios

Question items	Recovery ratio (%)
Presence or absence of off-flavor problems	100
Types of water source of target DWTPs	100
Time of year of off-flavor events	97
Types of off-flavor	93
Types of organisms associated with off-flavor events	91
Concentration of off-flavor compounds in raw water	86
Concentration of off-flavor compounds in finished water	78
Water temperature of raw water when off-flavor events occurred	92
pH of raw water when off-flavor events occurred	92
Countermeasures against off-flavor problems	94

identified by trained staff at 85% of the target RWS, while the remaining 15% of RWS outsourced or did not perform such identification. In general, identification was performed using a microscope according to the Japanese standard manuals for the examination of water (Japan Water Works Association 2008, 2010).

RESULTS AND DISCUSSION

Proportion of DWTPs affected by off-flavor problems

The results of the questionnaire survey indicated that 43 of 79 (54%) RWS and 89 of 239 (36%) DWTPs were affected by off-flavor problems in a recent 2-year period (October 2010–September 2012). Figure 2 shows the regional distribution of the proportion of DWTPs affected by off-flavor problems. Japan has a varied climate due to the shape of the country, which stretches over 2,500 km from north to south. Typical maximum and minimum water temperatures of surface water in the north region were $20 \pm 5\,^{\circ}$C and $5 \pm 5\,^{\circ}$C, respectively, while those in the south region were $30 \pm 5\,^{\circ}$C and $12 \pm 5\,^{\circ}$C, respectively, although these were dependent on altitude and geography (Ministry of Land, Infrastructure, Transport and Tourism Japan 2013). Nevertheless, off-flavor incidents occur in all regions, although the proportion differed between regions. In this study, it was not possible to determine the reasons for these regional differences, and the eutrophication status of each water source should be investigated in future studies.

Types of water source related to off-flavors

Figure 3 shows the proportion of types of water source of all target DWTPs and the DWTPs affected by off-flavor problems. As expected, all DWTPs affected by off-flavor incidents take in surface water. In particular, most DWTPs affected by off-flavor incidents take in water from closed water areas, such as dams and lakes, where phototrophic microorganisms, such as cyanobacteria and algae, can grow easily.

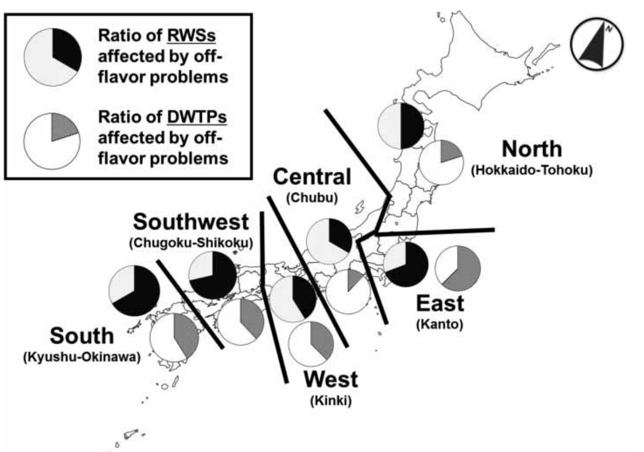

Figure 2 | Regional distribution of the proportion of RWS and DWTPs affected by off-flavor problems in Japan.

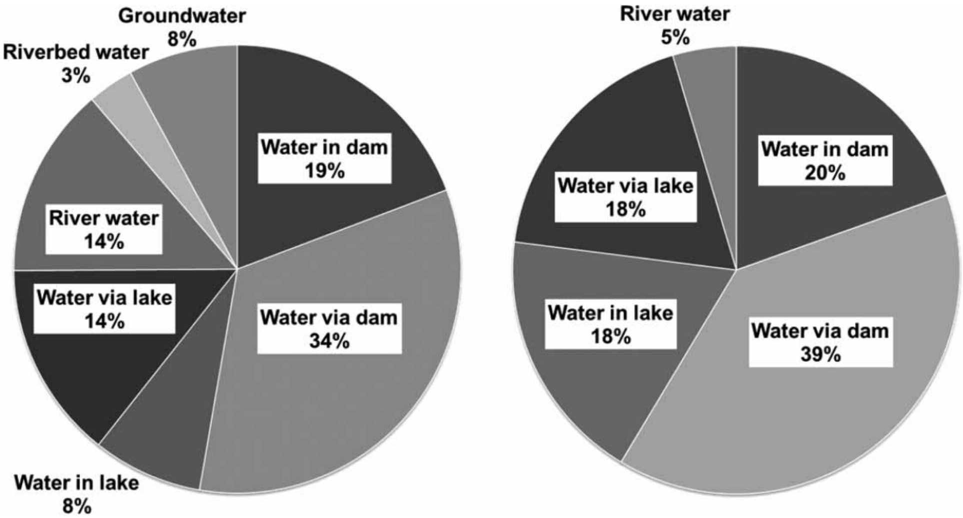

Figure 3 | Proportion of types of water source of all target DWTPs (left) and DWTPs affected by off-flavor problems (right) on the basis of the number of DWTPs. (For DWTPs that take in water from several types of water source, the main type of water source was counted.)

Types of off-flavor, concentrations of off-flavor compounds and organisms associated with off-flavor events

Table 3 shows types of off-flavor, concentrations of off-flavor compounds, and organisms associated with off-flavor events. As expected, an earthy–musty odor was the most common off-flavor encountered. There were more DWTPs with problems associated with geosmin than with 2-MIB in Japan. The maximum concentrations of geosmin and 2-MIB in raw water in some DWTPs were >500 ng/L. Although the concentrations in finished water were much lower than those in raw water due to the countermeasures implemented, the maximum concentrations in some DWTPs were higher than the Japanese drinking water quality standard values (10 ng/L). Cyanobacteria were the most common earthy–musty odor producers, although actinomycetes were also reported in some cases. *Anabaena* spp. were the most common cyanobacteria producing geosmin. It has been reported that the concentrations of geosmin and *Anabaena* spp. in water sources are significantly correlated (Uwins *et al.* 2007). *Phormidium* spp. and *Oscillatoria* spp. were common cyanobacteria responsible for production of 2-MIB. *Microcystis* spp. have not been reported to produce geosmin, and *Anabaena* spp. have not been shown to produce 2-MIB (Jüttner & Watson 2007). However, they were reported as responsible organisms in this questionnaire survey, although the number of responses was small. This indicates that the organisms associated with off-flavor events estimated by DWTPs were not always correct. This is because various organisms associated with earthy–musty odor are present in water sources, and identification requires a high level of skill. Indeed, organisms could not be identified in many cases, as shown in Table 3.

A 'fishy' smell accounted for 26% of total off-flavor events. Although the maximum TON in raw water in some DWTPs was >100, those in finished water always met the management goals of the Japanese drinking water quality management system (3 TON). Interestingly, the off-flavors that were caused by Chrysophyta and fish eggs were categorized into the same 'fishy' smell, although the off-flavor compounds would be different. It has been reported that Chrysophyta, such as *Uroglena* spp., have the potential for producing a 'cucumber' or 'fishy' smell (Yano *et al.* 1988; Watson *et al.* 2008). The large freshwater fish *Hypophthalmichthys molitrix* is known to spawn in the upper basin of the intake points of DWTPs and the eggs cause a severe off-flavor problem (Japan Water Works Association 2000). Other off-flavors such as a 'seaweed'-like smell were also reported in this questionnaire survey although the number of such events was small.

Table 3 | Types of off-flavor, concentrations of off-flavor compounds and organisms associated with off-flavor events

Types of off-flavor		Concentration of off-flavor compounds[a]				Types of organisms associated with off-flavor events			
		Raw water		Finished water				Genus	
Name	Ratio[b] (%)	Mean	Max.	Mean	Max.	Name	Ratio[b] (%)	Name	Ratio[b] (%)
Earthy–musty (geosmin)	39	30	520	3.0	13	Cyanobacteria	57	*Anabaena*	61
								Oscillatoria	16
								Phormidium	6
								Microcystis	4
								Unidentified	12
						Actinomycetes	6	–	–
						Unidentified	37	–	–
Earthy–musty (2-MIB)	29	79	1,400	3.2	14	Cyanobacteria	68	*Phormidium*	54
								Oscillatoria	42
								Anabaena	4
						Actinomycetes	18	–	–
						Unidentified	14	–	–
Fishy smell	26	130	600	1.3	3	Chrysophyta	58	*Uroglena*	97
								Dinobryon	3
						Fish eggs	29	–	–
						Cyanobacteria	2	*Oscillatoria*	100
						Unidentified	12	–	–
Others	6	18	40	< 1	1	Cyanobacteria	50	*Microcystis*	38
								Anabaena	38
								Oscillatoria	13
								Phormidium	13
						Diatom	17	*Nitzschia*	33
								Unidentified	67
						Chlorophyta	11	Unidentified	100
						Amoeba	11	*Asterocaelum*	100
						Unidentified	11	–	–

[a]Units: Geosmin and 2-MIB: ng/L; other off-flavor: TON. The means and maximum concentrations were calculated based on the maximum concentration of each off-flavor event.
[b]Ratio was calculated on the basis of the number of off-flavor events. If multiple answers were obtained, all answers were counted.

Time of year of off-flavor events and water temperature and pH of raw water when off-flavor events occurred

Figure 4 shows the time of year of off-flavor events. As expected, the events occurred frequently during the summer and early fall months (June–September). In temperate regions such as Japan, thermal stratification, which is a favorable condition for cyanobacterial growth, generally occurs seasonally (summer–fall) in water sources (Newcombe *et al.* 2010). This is one of the reasons why off-flavor events occurred during the summer and early fall months. In addition, water temperature is high in these seasons, thus promoting the growth of such organisms. As shown in Figure 5, the water temperature of raw water when off-flavor problems occurred was higher than that during normal periods. The average water temperature when off-flavor problems occurred was approximately

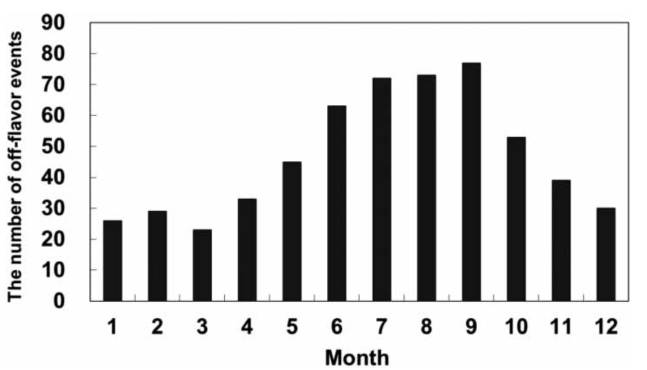

Figure 4 | Time of year of off-flavor events. (If off-flavor events stretched over a period of multiple months, all months were counted.)

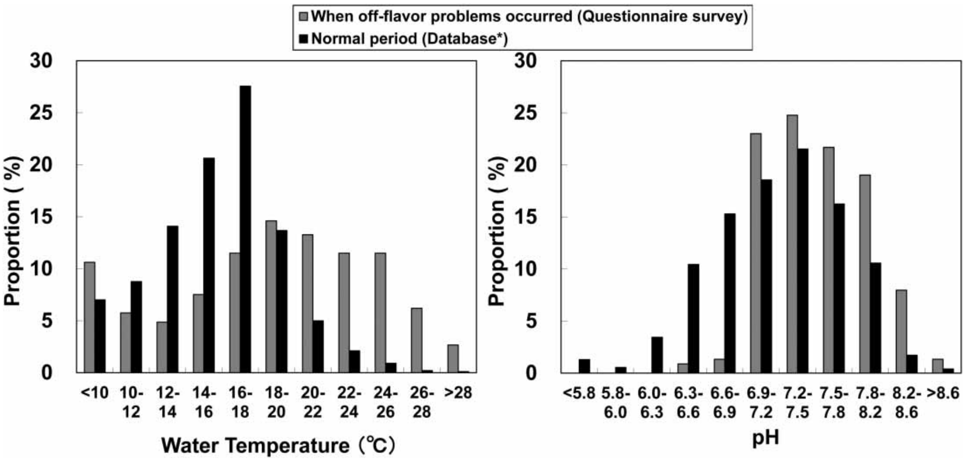

Figure 5 | Distribution of water temperature (left) and pH (right) in raw water. *Distribution data were obtained from a large database of Japanese drinking water quality (Japan Water Works Association 2013).

19 °C. It has been reported that maximum growth rates are achieved at temperatures above 25 °C for most cyanobacteria, which are the most common off-flavor producers. It has been suggested that temperature optima for cyanobacteria are higher than those for Chlorophyta and diatoms (Robarts & Zohary 1987). Meanwhile, off-flavor events were reported even if the water temperature of raw water was lower than 10 °C, as shown in Figure 4. This was mainly because Chrysophyta (*Uroglena* spp.) can grow and produce off-flavor compounds under low-temperature conditions. The average water temperature when organisms associated with off-flavor events were *Uroglena* spp. was 13 °C.

The pH of raw water when off-flavor problems occurred was higher than that during normal periods, indicating that off-flavor problems often occur when water sources are eutrophicated. It is well known that photosynthesis by cyanobacteria and algae in eutrophicated dams and lakes increases pH. The average pH when off-flavor problems occurred was approximately 7.6.

Countermeasures against off-flavors

Figure 6 shows the proportions of countermeasures against off-flavors in the questionnaire survey. To eliminate off-flavor compounds, most DWTPs (approximately 58%) adopt powdered activated carbon treatment, which considerably increases operational costs as in other countries (Cook *et al.* 2001; Giglio *et al.* 2011). All of the DWTPs determine the quantity of powdered activated carbon to add based on empirically obtained individual correlation equations or tables for the concentration of off-flavor compounds in raw water and addition quantity. A few DWTPs adopt other countermeasures, such as changes in point of chlorine addition and enhancement of coagulation.

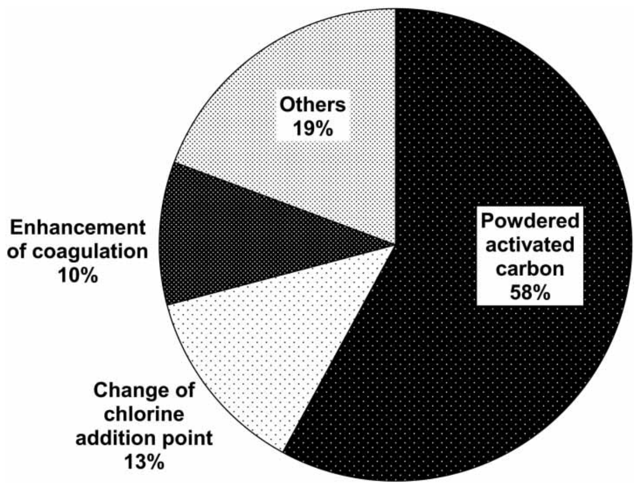

Figure 6 | Proportion of countermeasures against off-flavors in Japan on the basis of the number of off-flavor events. (If multiple answers were obtained, all answers were counted.)

CONCLUSIONS

The results of the questionnaire survey indicated that 43 of 79 (54%) RWS and 89 of 239 (36%) DWTPs were affected by off-flavor problems in a recent 2-year period (October

2010–September 2012). Off-flavor incidents occurred in all regions in Japan. Most DWTPs affected by off-flavor incidents take in water from closed water areas, such as dams and lakes where phototrophic microorganisms, such as cyanobacteria and algae, can grow easily. The most common off-flavor was an earthy–musty odor, while a fishy smell was also reported in some cases. The common producers of geosmin were *Anabaena* spp., while those responsible for 2-MIB were *Phormidium* spp. and *Oscillatoria* spp. The off-flavor events occurred frequently during the summer and early fall months (June–September). The water temperature and pH of raw water for the production of drinking water when off-flavor problems occurred were higher than those during normal periods. The average water temperature and pH when off-flavor problems occurred were approximately 19 °C and 7.6 °C, respectively. To eliminate off-flavor compounds, most DWTPs (about 58%) adopt powdered activated carbon treatment.

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