Research Journal of
Microbiology

ISSN 1816-4935

Academic
Journals Inc.

www.academicjournals.com

Research Journal of Microbiology 9 (4): 199-207, 2014
ISSN 1816-4935 / DOI: 10.3923/jm.2014.199.207

Microbial Quality of Sachet and Bagged Drinking Water: A Case Study in Kumasi, Ghana

[1]Esi Awuah, [2]Samuel Fosu Gyasi, [3]Helen K. Anipa and [3]Agnes Adjei

[1]University of Energy and Natural Resources, Sunyani, Ghana

[2]Department of Energy and Environmental Engineering, University of Energy and Natural Resources, Sunyani, Ghana

[3]Department of Civil Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

Corresponding Author: Samauel Fosu Gyasi, Department of Energy and Environmental Engineering, University of Energy and Natural Resources, Sunyani, Ghana Tel: +233 (26) 8189473

ABSTRACT

Water is the most common and important chemical compound on earth. However, only ~2.6% of the global water supply is freshwater (1.4×10-9 km^3) and available as drinking water. In hot climates, one cannot do without a sip of water especially when working in the humid and hot conditions. Sachet and bagged water have thus become very popular products and is highly patronized by the public, especially in Kumasi, Ghana. However, the quality of these sachets drinking water in Kumasi is yet to be fully explored. In this study, the quality of sachet and bagged water sold on the market was assessed to determine its suitability for consumption. Water quality analysis was performed on 50 brands of sachet water and 20 bagged water sampled at random selected for the study. Eighty two percent (82%) of the sachet water samples and all the bagged water samples were found to be contaminated with either *E. coli, Salmonella,* other coliforms and enterobacteriaceae. The analysis revealed that even though most of the physicochemical parameters were satisfactory, the biological parameter was poor. These bacteria are capable of causing diseases like typhoid, cholera and other gastrointestinal disorders thus posing a serious health risk to consumers.

Key words: Sachet water, bagged water, pathogens, water quality, *E. coli*

INTRODUCTION

Water is the most common and important chemical compound on earth. However, only ~2.6% of the global water supply is freshwater (1.4×10-9 km^3) and available as drinking water (Szewzyk *et al.*, 2000). Historically, groundwater supplies were believed to be free of microbial pathogens due to the natural filtering ability of the subsurface environment (Davidsson, 2005). A clean and constant supply of drinking water is therefore essential to every community. People in large cities frequently drink water that comes in packaged either in bottles or large dispensers. Sometimes these sources could be polluted especially in developing countries where proper environmental sanitation is a challenge (Dapaah-Siakwan and Gyau-Boakye, 2000). In either case, when you think about where your drinking water comes from, it's important to consider not just the part of the river or lake that you can see but the entire watershed and how it is presented (Appoh *et al.*, 2011). It is in the light of this that the quality of drinking water sold in our open markets in a selected town in Ghana needs to be assessed.

Kumasi, the capital city of the Ashanti Region of Ghana and the second largest city has a population of over about 2,035,064 according to the 2010 population census. The people in the metropolis are highly business oriented and engage in a lot of commercial activities. On a typical hot day, temperatures in the metropolis can rise to about 38°C or more, causing raging thirst and generating a high demand for cool drinking water (Peavy *et al.*, 1985). In a study conducted in Ghana in 2003 to assess the environmental impacts associated with activities in the Central Market Kumasi, it was established that about 92% of the people in the central market (Kumasi, Ghana) drink sachet water to quench their thirst (http://www.kma.ghanadistricts.gov.gh /?arrow=atd&_=6&sa=5475). The various business districts in Kumasi did not have adequate standpipes to meet the demand for drinking water by the populace. The few standpipes available had been commercialized and people paid as they fetched. In the past, to meet the drinking water needs of the public, water was cooled with ice blocks, refrigerated or kept in earthenware pots and sold in cups to anyone in need of water with all the health hazards (Ackah *et al.*, 2012).

These cups were used by all and sundry and thus posed a risk of transferring diseases from one user to the other. In 1986, the Environmental Health Department (Kumasi Metropolitan Assembly, KMA) recommended the sale of water in packaged plastics with volume ranging between 200 and 500 mL, popularly known as “Panin de Panin”. Unhygienic bagging procedures were practiced by those involved in its production. As part of its production, air was blown into the 500 mL capacity transparent polythene bags from the mouth to open them up before filling with water. This action contaminated these plastic bags even before water was introduced into them. There were also complaints of odour, colour and taste from some consumers as well as the incidence of enteric diseases.

To improve the situation, sachet water was introduced into the market about 5 years ago, where the filling of the plastic bags is done hygienically by an automated sachet water packing machine. Currently, the Kumasi Metropolis has over 190 different brands of sachet water and new ones keep spring up. In spite of these improvements in drinking water delivery in recent times, there has been complains of taste, odour, colour and reported cases of enteric diseases after oral consumption. This has therefore warranted the urgent need for the quality of water sold to the public to be assessed to ascertain its suitability for drinking purposes. In this study, the quality of bagged water sold by water vendors on the market in the Kumasi Metropoli in the Ashanti Region of Ghana was assessed to evaluate its impact on the health of consumers.

METHODOLOGY

An in-depth interview were conducted with selected executives of the Kumasi Sachet Water Association (KSWA) during the study period based on the different brands bagged water on the market, mode of operations, behavioral sanitation practices as well as the sources of water used in manufacturing. This study was conducted between September and December, 2009 within some selected communities systematically selected from Sub-Metro areas of Kumasi (Fig. 1b) in the Ashanti Region of Ghana (Fig. 1a) as shown in Fig. 1.

In this study, 70 samples comprising 20 bags of plastic bagged water “Panin de Panin” (Fig. 2a) and 50 different brands of sachet water (Fig. 2b) were purchased randomly in triplicates from different areas within the Kumasi Metropolis (Fig. 2b). The samples were analyzed for the following water quality parameters: pH, total dissolved solids, turbidity, nitrite, nitrate, chloride, iron, total hardness, faecal coliforms (*E. coli*), salmonella and other enterobacteriaceae. Physicochemical parameters were analyzed according to the Standard Methods for the Examination of Water and

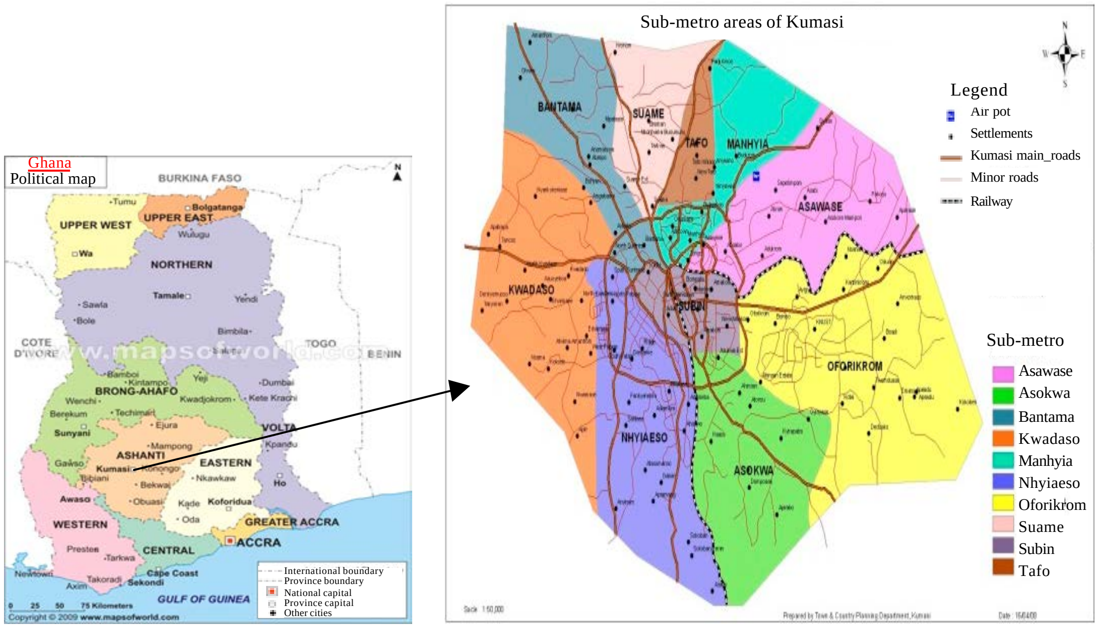

Fig. 1: A Regional Map of (a) Ghana and (b) Kumasi in the Ashanti Region and that of Kumasi Sub-Metro with other suburbs

Fig. 2(a, b): (a) Sachet water and (b) Bagged drinking water “Panin de panin”

Wastewater (AWWA/APHA, 1992). Bacteriological analysis was conducted according to Byamukama *et al*. (2000) with slight modifications. These were repeated for confirmation of the results.

Fig. 3: Workers busily packaging sachet water after production prior to consumption

General manufacturing process for sachet water: The manufacturing process involved taping from a source, filtering, disinfection and bagging as shown in Fig. 3. In this study, the raw water source could be a well with depth ranging from 2.5-6 m, boreholes >50m or ordinary tap water from Ghana Water Company Limited (GWCL). Water from well and borehole source was pumped mechanically into overhead poly tank reservoirs and stored for several hours at ordinary atmospheric temperature to allow sedimentation to occur. Tap water was usually filtered directly upon collection in a designated reservoirs.

The filtration process involved the passage of water through five sediment filters of pore sizes 5-1μm to remove all colloidal particles. Some microorganisms were eliminated during this filtration process. The filtered water was then passed through an activated carbon filter for the removal of taste and odour that it was made to go through an ultraviolet unit for disinfection. The water was then packaged into plastic bags and sealed with the aid of a electricity powered locally manufactured automated bagging machine. The filters were cleaned by washing and in some cases, changed after 100-300 batch production.

Reports gathered from the respondent interviewed showed that, at the time of going to the press, approximately 400 people had registered and formalized their activities with the association. Sources of raw water and manufacturing processes employed for this water industry were also assessed as part of the study and the study showed that wells, boreholes or tap water stored in poly-tanks reservoirs were the main sources used by the manufacturers of the sachet water. In most cases, the manufacturing process involved filtration through micro filters, UV light disinfection and packaging by machine. Untreated tap water was used as the main source for "Panin de Panin". Some people also used shallow wells as sources for this type of bagged water. The water was poured through a funnel lined with and filtered through a foam into plastic bags which were opened by blowing air through the mouth and then sealed by tying with the hand.

RESULTS AND DISCUSSION

Assessment of in-depth interviews with selected leaders of the Sachet Water Sellers Association (SWSA) during the study showed that there were about 200 different brands of sachet water with an average of 3 new members joining the association every month. There were, however, several other producers who worked during the time of the study without permit from the Food and Drugs Board (FDB), Ghana. Analysis of the quality of these bagged drinking water were assessed relative to some physicochemical parameters and the results generated showed that, for all samples collected for the study, pH values fell between the WHO recommended guidelines for drinking water (i.e. pH 6.8-8.5) as shown in Table 1. This was consistent with a study conducted by Abdul-Razak *et al*. (2009) that the water quality of drinking water from the Oti river in Ghana was assessed.

This result was also seen when the turbidity was assessed with all the values falling below the WHO (WHO/UNICEF, 2012) guideline value and that of Ghana Standard of 5 NTU (http://www.who.int/water_sanitation_health/dwq/2edvol2p1). Results from the study showed that sachet water had turbidity values ranging from 0.06-1.98 NTU whiles "Panin de Panin" samples had values between 0.3 and 3.66 NTU as shown in Table 1.

As part of this study, nitrate levels was analysed with respect to drinking water and the study showed that bagged drinking water "Panin de Panin" samples had levels that fell below the WHO recommendation as shown in Table 1. Twelve percent (12%) of the sachet water samples, however, had nitrate levels that exceeded the WHO and Ghana guidelines. Two percent (2%) of the sachet water samples also had nitrite levels above the guideline values (Table 1). The "Panin de Panin" water samples however had acceptable nitrite levels. Consistent with recent study, it was revealed in an earlier study that high nitrate levels in water could cause methemoglobinemia or blue baby syndrome, a condition found especially in infants under 6 months (Self and Waskom, 2013).

Total dissolved solid contents for both the sachet water and "Panin de Panin" when analysed during the study showed that, the samples collected did not exceed the maximum acceptable level 1000 mg L^{-1} and this came with much relief (Table 1). Results of recent epidemiological studies suggest that low concentrations of TDS in drinking-water may have beneficial effects, although adverse effects are yet to be reported and this was consistent with this present study (Wilson *et al*., 2014).

Assessment of the level of some metals was conducted as part of this investigation relative to Fe and the results showed that, all sachet water samples had acceptable levels whiles only 5% of the "Panin de Panin" water samples had levels above guideline values as shown in Table 1. Study has shown that, Fe is a harmless, though sometimes annoying, elements present in public and private water supplies and this was in concert with the study (Colter and Mahler, 2006). It must further be noted that high concentrations of dissolved Iron (Fe) however can result in poor tasting, unattractive water that stains both plumbing fixtures and clothing. When iron-rich waters mix with tea, coffee or alcoholic beverages, it assume a black, inky appearance with an unpleasant taste (Ackah *et al*., 2012).

It was further investigated to assess the hardness of these bagged drinking water and much to our expectations, all samples collected for the study had hardness values below the recommended limit of 200 mg L^{-1} by the WHO and GWCL recommendations for drinking water as shown in Table 1. Hardness of water is commonly not known to present any health hazards to human consumption and is apparently beneficial to human cardiovascular system. In fact, there is no health based standard for the hardness of drinking water and this was in support of our study (Peavy *et al*., 1985). It has further been reported that, water with a hardness of value of 200 mg L^{-1} or higher could produce scale and soft water with a value of 100 mg L^{-1} or less could also have a low buffering capacity and thus become more corrosive to pipes. This was in support of the study (Thomas *et al*., 2011).

Table 1: Results of some water quality analysis for different brands of sachet water collected from the Kumasi Metropoli

	Parameters											
	pH	TDS ($mg\ L^{-1}$)	Turbidity (NTU)	*E. coli* (No./100 mL)	Other coliforms (No./100 mL)	*Salmonella* (No./100 mL)	Bacteriaceae (No./100 mL)	Nitrite ($mg\ L^{-1}$)	Nitrate ($mg\ L^{-1}$)	Chloride ($mg\ L^{-1}$)	Iron ($mg\ L^{-1}$)	Total hardness ($mg\ L^{-1}$)
WHO guide	6.5-8.5	1000	5	0	0	0	0	0.1	10 (as N)	250	0.3	200
Sample*												
1	7.09	62.8	0.06	6	Nil	Nil	540	0.008	14.7	14	0.02	36
2	7.59	215	0.39	62	Nil	144	Uncountable	0.006	1.5	16	0.01	97
3	7.16	33	0.21	65	Nil	Nil	3060	Nil	1.8	14	0.02	31
4	7.91	223	0.29	Nil	Nil	Nil	Uncountable	0.002	5.5	31	Nil	12
5	7.16	112	0.31	25	Nil	Nil	Uncountable	Nil	4.4	11	0.01	48
6	6.96	65	0.25	32	Nil	Uncountable	Uncountable	0.003	7.4	11	0.02	47
7	7.01	140.6	0.28	Nil	8	50	Uncountable	0.006	Nil	21	0.07	31
8	7.18	193	1.93	Nil	Nil	Nil	Uncountable	0.006	12.4	14	0.01	80
9	7.11	72	0.42	Nil	8	Nil	Uncountable	0.006	Nil	12	0.04	4
10	7.51	74.7	0.26	Nil	3	Nil	Uncountable	0.01	2.9	13	0.01	39
11	7.44	191.5	0.77	3	Nil	Nil	198	0.011	9	21	0.34	57
12	6.78	241	0.29	6	Nil	21	1300	0.007	7.8	22	0.05	72
13	7.48	212	0.17	21	Nil	6	360	0.006	2.1	18	0.04	86
14	6.17	59.2	0.32	305	Nil	Nil	Uncountable	0.007	2.2	7	0.04	56
15	7.36	172.5	0.42	9	Nil	Nil	Uncountable	0.007	16	12	0.11	79
16	7.48	217	0.22	13	Nil	Nil	Uncountable	0.001	Nil	16	0.05	12
17	7.54	65.9	0.24	Nil	Nil	25	393	0.01	Nil	13	0.16	37
18	7.49	212	0.13	Nil	Nil	Nil	408	0.006	29.3	17	0.09	5
19	7.81	200	0.3	6	Nil	21	Uncountable	0.009	1.2	15	0.02	92
20	5.82	60	0.3	Nil	Nil	Nil	1092	0.006	2.2	19	0.09	35
21	7.6	171.8	0.37	18	Nil	Uncountable	Uncountable	Nil	0.7	14	0.01	9
22	7.18	170.1	0.31	Nil	Nil	Nil	20	Nil	1.6	11	0.01	15
23	7.72	189.3	0.3	51	Nil	Nil	1080	0.008	1.6	15	0.1	70
24	7.47	173	0.4	Nil	32	Nil	Uncountable	0.002	2	12	0.17	7
25	7.74	188.9	0.27	13	Nil	Nil	120	0.015	1.6	9	0.04	108
26	7.6	200	0.22	Nil	Nil	10	Uncountable	0.005	1.3	15	0.01	9

Table 1: Continued

	Parameters											
	pH	TDS (mg L^{-1})	Turbidity (NTU)	*E. coli* (No./100 mL)	Other coliforms (No./100 mL)	*Salmonella* (No./100 mL)	bacteriaceae (No./100 mL)	Nitrite (mg L^{-1})	Nitrate (mg L^{-1})	Chloride (mg L^{-1})	Iron (mg L^{-1})	Total hardness (mg L^{-1})
WHO guide	6.5-8.5	1000	5	0	0	0	0	0.1	10 (as N)	250	0.3	200
Sample*												
27	6.99	155.9	0.26	Nil	2	1	15	0.003	5.7	29	0.01	6
28	7.08	49	0.68	264	Nil	Nil	3662	0.02	9.8	10	0.02	31
29	6.98	52.4	0.27	Nil	Nil	Nil	5	Nil	2.8	12	Nil	8
30	7.68	231	0.36	3	Nil	Nil	Uncountable	0.004	2.9	16	0.02	12
31	7.98	342	0.36	Nil	36	Uncountable	Uncountable	>0.3	4.9	17	0.02	10
32A	7.64	280	0.56	81	Nil	1	Uncountable	0.025	5.3	21	0.03	95
32B	7.64	280	0.56	Nil	Nil	Nil	Uncountable	0.025	5.3	21	0.03	95
33	7.56	205	0.43	40	183	Nil	Uncountable	Nil	1.8	15	0.02	8
34	6.63	75	0.33	26	Nil	Nil	1513	0.022	10.8	14	0.04	34
35	7.28	199.5	0.09	3	5	Nil	2140	0.005	Nil	14	0.02	87
36	7.83	257	0.3	13	34	35	Uncountable	0.003	1.1	27	0.02	11
38	7.14	89	0.48	Nil	6	Nil	31	0.004	11.8	9	0.05	64
37	7.27	214	0.19	1	4	Uncountable	43	0.01	5.7	26	0.05	59
38	7.67	44.3	0.12	Nil	Nil	Nil	6	0.009	1.8	5	Nil	51
39	7.68	54.5	0.27	2	Nil	Nil	Nil	0.001	2.8	10	0.01	7
40	7.29	184.4	0.68	40	Nil	Nil	Uncountable	0.005	1.6	15	0.02	86
41	7.41	220	1.98	39	Nil	Nil	Uncountable	0.002	24.3	19	0.06	77
42	7.45	194.9	0.22	108	Nil	Nil	Uncountable	0.006	1.5	14	0.06	75
43	6.92	469	1.56	Nil	2	Nil	335	0.001	2.8	82	Nil	84
44	6.99	120	0.29	28	Nil	Nil	1365	0.006	11.9	10	0.02	47
45	7.68	46	0.26	7	Nil	Nil	Uncountable	0.005	16.4	18	0.03	10
46	7.28	209	0.53	378	Nil	Uncountable	Uncountable	0.009	6.7	19	0.05	89
47	6.47	204	0.41	Nil	Nil	Nil	Uncountable	0.001	1.4	18	0.02	84
48	6.23	54.9	0.61	Nil	Nil	Nil	27	0.007	Nil	10	0.14	36
49	6.47	168.8	0.75	16	Nil	Nil	Uncountable	0.01	16.2	11	0.04	34
50	7.58	237	0.41	89	16	Nil	100	0.004	1.1	16	0.01	10

*Brand names with held

Analysis of the sampled water showed that levels of chlorine was low with none of the samples recording values greater than the recommended levels in drinking water (250 mg L^{-1}) as shown in Table 1. It is an undeniable fact that over-chlorinated drinking water exerted adverse effects manifested as an increased percentage of death losses in all production categories of animal (pig) husbandry (Tofant *et al*., 2011).

Biological parameters: Results of bacteriological analysis performed on the 50 sachet water samples showed that only 9 samples out of the total 50, representing 18% of the total were not contaminated (Table 1). Infact 82% of the samples were contaminated with either E-coli, salmonella or other coliforms as well as enterobacteriaceae. Similarly, all the "Panin de Panin" samples were also microbially contaminated. These bacteria contamination have the ability of causing diseases including typhoid fever, cholera, dysentery and other gastrointestinal. Factors that significantly have contributed to contamination could possibly include short distance of sanitary facilities from wells, shallow depth of the wells, irregular changing of water filters and unhygienic environment for some of the manufacturing sites among many others. The "Panin de Panin" i.e., bagged water contamination could mainly be due to unhygienic handling and bagging practices.

In an earlier study conducted in Ghana and published in 2007, it was established that, some sachet water on the Ghanaian markets could serve as possible routes of transmission of protozoan parasites. The study further suggested that, epidemiological and risk assessment approaches will undoubtedly boost one's understanding of the occurrence, survival and transport of these organisms. Regardless of these measures, the possibility for contaminated water to cause significant diseases in our communities still remains due to problems associated with water purification and distribution. This was consistent with the present study (Kwakye-Nuako *et al*., 2007).

In addition, unattended pipe burst in the main distribution system was a common sight in the Kumasi Sum Metro. This could have introduced impurities including microbes into the water distribution system and end upto consumer homes. This could be the major source of contamination for the pipe borne water. It appears no value was added and one is equally not safe when the source of drinking water was sachet water. In a related study conducted by Bosompem *et al*. (2014), it was established that, where water distribution system were laid among drainage channels, there was the likelihood of microbial contamination. This was consistent with this study (Bosompem *et al*., 2014).

CONCLUSION

Even though water quality analysis of the sachet water and bagged water showed satisfactory physical and chemical characteristics, the bacteriological quality of the water was very poor. The bacteriological quality of drinking water is very important and no level of pathogens should be tolerated. The presence of these pathogens in the samples poses health risks and appropriate steps should be taken to ensure wholesome water is sold to the public. The regulatory agencies such as the Food and Drugs Board ought to carry out strict monitoring of the operations. In addition, manufacturing premises of these water producers need to ensure they are operating under hygienic conditions. Periodic sampling of the water on the market should also be carried out for water quality analysis to ascertain its suitability for drinking. The Food and Drugs Board should be given adequate resources to carry out this function. Members of the Sachet Water Sellers Association should be given education on water treatment, disinfection and storage to protect public health.

REFERENCES

AWWA/APHA, 1992. Standard Methods for Examination of Water and Wastewater. 18th Edn., American Water Works Association, American Public Health Association, Washington, DC., USA.

Abdul-Razak, A., A.B. Asiedu, R.E.M. Entsua-Mensah and K.A.A. de Graft-Johnson, 2009. Assessment of the water quality of the Oti River in Ghana. West Afr. J. Applied Ecol., Vol. 15.

Ackah, M., A.K. Anim, E.T. Gyamfi, J. Acquah and E.S. Nyarko *et al*., 2012. Assessment of the quality of sachet water consumed in urban townships of Ghana using physico-chemical indicators: A preliminary study. Adv. Applied Sci. Res., 3: 2120-2127.

Appoh, R.K., L.K. Doamekpor, E.K. Hayford, R.K. Klake and V.K. Nartey, 2011. Assessment of mercury pollution in rivers and streams around artisanal gold mining areas of the Birim North District of Ghana. J. Environ. Prot., 2: 1227-1239.

Bosompem, M.O., E.A. Agyapong, S.F. Gyasi and E. Awuah, 2014. An empirical perspective of water quality in appeadu: A suburb of Kumasi in the Ashanti region, Ghana. Trends Applied Sci. Res., 9: 144-152.

Byamukama, D., K. Kansiime, R.L. Mach and A.H. Farnleitner, 2000. Determination of *Escherichia coli* contamination with chromocult coliform agar showed a high level of discrimination efficiency for differing faecal pollution levels in tropical waters of Kampala, Uganda. Applied Environ. Microbiol., 66: 864-868.

Colter, A. and R.L. Mahler, 2006. Iron in drinking water. A Pacific Northwest Extension Publication, University of Idaho, Oregon State University, Washington State University in Cooperation with University of Alaska, USA.

Dapaah-Siakwan, S. and P. Gyau-Boakye, 2000. Hydrogeologic framework and borehole yields in Ghana. Hydrogeol. J., 8: 405-416.

Davidsson, P., 2005. Paul D. Reynolds: Entrepreneurship research innovator, coordinator and disseminator. Small Bus. Econ., 24: 351-358.

Kwakye-Nuako, G., P.B. Borketey, I. Mensah-Attipoe, R.H. Asmah and P.F. Ayeh-Kumi, 2007. Sachet drinking water in accra: The potential threats of transmission of enteric pathogenic protozoan organisms. Ghana Med. J., 41: 62-67.

Peavy, H.S., D.R. Rowe and G.T. Tchobanoglous, 1985. Environmental Engineering. 7th Edn., McGraw Hill Higher Education, New York, ISBN-13: 9780071002318, pp: 589-592.

Self, J.R. and R.M. Waskom, 2013. Nitrates in drinking water. Fact Sheet No. 0.517, Colorado State University. http://www.ext.colostate.edu/pubs/crops/00517.pdf.

Szewzyk, U., R. Szewzyk, W. Mauz and K.H. Schleifer, 2000. Microbiological safety of drinking water. Annu. Rev. Microbiol., 54: 81-127.

Thomas, K.S., T. Dean, C. O'Leary, T.H. Sach, K. Koller, A. Frost and H.C. Williams, 2011. A randomised controlled trial of ion-exchange water softeners for the treatment of eczema in children. PLoS Med., Vol. 8. 10.1371/journal.pmed.1000395

Tofant, A., M. Ostovic, S. Wolf, A. Ekert Kabalin, Z. Pavicic and M. Mikulic, 2011. Association between over-chlorinated drinking water and suckling, nursery and fattening pig death losses. Vet. Med., 56: 358-361.

WHO/UNICEF, 2012. Estimates for the use of improved drinking-water sources: China. World Health Organization, Geneva, Switzerland.

Wilson, J., Y. Wang and J. VanBriesen, 2014. Sources of high total dissolved solids to drinking water supply in southwestern pennsylvania. J. Environ. Eng., Vol. 140. 10.1061/(ASCE)EE.1943-7870.0000733.