WATER DISINFECTION TECHNIQUES: A REVIEW

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ABSTRACT:

Water pollution, inadequate water supply and poor waste treatment facilities have greatly contributed to diarrheal and other water borne disease conditions. Regular presence of Escherichia coli and other coliforms are probable indicators of water contamination. State of the art water disinfection methods of boiling and chlorination success has been limited due to inadequate germicidal effect and health risks. Frequent outbreaks of water borne illness in the rural areas of developing nations continue to exit despite the administration of boiling, chlorination and use of herbs as water disinfection techniques among the residents. Solar water disinfection has emerged as alternative to back-up the existing water techniques. However, the acceptability and adoption potential has not been fully realized. Some of the solar water disinfection technologies have exhibited draw-backs of: Limited volume, post-disinfection regrowth, incomplete disinfection and pulsating flow rates. In addition, the experimented solar water disinfection technologies have mainly focused on indicators organism such as Escherichia coli and coliforms. The effect of solar water disinfection on diverse water borne pathogens has not been fully established. Water disinfection techniques are reviewed here in with focus on sustainable development goal 6 (SDG).

Keywords: *SODIS, Solar, Water, Disinfection, Trihalomethanes, microorganisms, Polyethylene Terephthalate.*

1.0 INTRODUCTION

Water occupies about 70 % of the earth's crust and is thus the most abundant substance in nature (Anyamene *et al.*, 2014 and Thliza *et al.*, 2015). Safe and quality water sources is one of the basic concerns for human population (World Health Organization, 2014). Increasing water scarcity remains a major challenge in different countries around the world (Mallick *et al.*, 2015). The severity of water scarcity in developing countries affects the drinking water supply, sanitation, food security, economy and transport (Faisal *et al.*,2005 and Paavola *et al.*, 2008).

In Africa and some Asian regions, water is often carried over long distances by women and children from the sources to the households (Mallick *et al.*, 2015). About 2 % of the total water mass is fresh of which only half is available for use by the over 6 billion world's population (Manhokwe *et al.*, 2013). An estimated 768 million people remain without access to potable water (Muhammad *et al.*, 2017).

Moreover, 2.5 billion remain without access to improved sanitation and hygiene facilities posing high health risk and pollution of the water sources (Admassu *et al.,* 2004). In most rural areas the utilized water sources are either ground or surface water sources (Admassu *et al.,* 2004 and Kuta *et al.,* 2014). The quality and safety of most of these water sources are unknown as they are influenced by seasons and location (Muhammad *et al.,* 2017).

Many indices rate the human health within the tropics as poor, death among the young children are water borne related diseases (Hassan *et al.,* 2009). Originating from low level of personal hygiene and inadequate water treatment facilities (Kuta *et al.,* 2014). The situation is quite different in developed nations with excellent water supplies and effective treatment facilities for waste (Hassan *et al.,* 2009). Consequently, rare water-related diseases. Water disinfection has been adopted to meet Goal 6 of the sustainable development goals (SDGs). Water supply and accessibility aims at ensuring environmental sustainability (Oludairo *et al.,* 2015). Water treatment methods such as use of herbs, chlorination and boiling as well as emerging technologies of solar water disinfection are reviewed herein.

2.0 WATER

Water is a non-calorific, essential component of the diet and the basis of life (Manhokwe *et al.,* 2013, Muhammad *et al.,* 2017 and Oludairo *et al.,* 2015). Water constitutes an integral part of the living cell (Baloch *et al.,* 2000 and Garba *et al.,* 2009). About 97 % water exists in oceans with higher salt concentration and thus not suitable for drinking (Manhokwe *et al.,* 2013). Of the 70 % water cover, only 3 % is fresh water (Anyamene *et al.,* 2014 and Thliza *et al.,* 2015). Glaciers and ice caps constitute 2.97 % out of which 0.3 % is available as a surface and ground water for human use (Manhokwe *et al.,* 2013). Safe drinking water is a necessity for healthy community. Fresh water supply and accessibility is limiting resource world over. Population increase, urbanization and climate change would further worsen the world water situation in the next century (Manhokwe *et al.,* 2013 and Essumang *et al.,* 2011).

Water is thus a vital substance for the survival of all lives (Thliza *et al.,* 2015). It is absolutely necessary for most life driven processes (Aroh *et al.,* 2013). It is one of the indispensable resources needed for the continued existence of all living things including man given its abundance on earth (Gangil *et al.,* 2013 and Onilude *et al.,* 2013). Water is unavoidable in man’s daily life, constituting a sizeable percentage of man’s daily food intake because human bodies do not have reserve supply (Anyamene *et al.,* 2014). It is also an essential requirement for drinking, domestic, industrial and agricultural uses (Isikwue *et al.,* 2014). Quality water is colorless, tasteless, odourless, as well as free from faecal contamination (Opara *et al.,* 2014).

Water is required for maintenance of personal hygiene, food production and prevention of diseases (Thliza *et al.,* 2015). Water constitutes 80 % protoplasm of many living cells and aids the metabolic processes during cell growth and development as a universal solvent (Isikwue *et al.,* 2014 and Nwosu *et al.,* 2004). In nature water exhibits the three states of solid, liquid and gas facilitating biological activities under all environmental conditions (Thliza *et al.,* 2015).

2.1 POTABLE WATER

Potable water contains less than 1000 mg/L of dissolved solids and is safe for drinking and food processing (Muhammad *et al.,* 2017). It does not contain chemical substances and microorganisms in amounts that could cause hazard to health (Oludairo *et al.,* 2015). It should be clear, without disagreeable taste, color or odor therefore fit for human and animal consumption. It is water that has been treated, cleaned or filtered to meet established drinking standards (Aroh *et al.*, 2013 and Isikwue *et al.,* 2014). It can be sourced from surface water such as river, streams or the ground water such as spring, well and borehole (Aroh *et al.,* 2013). Water quality is the physical, chemical, radiological and biological characteristics of water in relation to the requirements of human and animal need (Danso-Boateng *et al.*, 2013).

Agencies that regulate water quality worldwide rely on the World Health Organization (WHO) standards and guidelines for drinking water quality (World Health Organization, 2014) so as to ensure the highest quality of potable water in order to safeguard public health (Isikwue *et al.,* 2014). Table 1 shows the quality characteristics of potable water.

It has been a challenge accessing potable water in developing countries. Most of the water sources are polluted by sanitary sewers over-flows and animal dropping surface run-offs (Muhammad *et al.,* 2017 and Maynard *et al.,* 2005). At the rural set-up, the major water sources are; rivers, pipe borne sources, water boreholes, hand-dug well, dams and sometimes unprotected wells (Kuta *et al.,* 2014), a direct indicator of limited access to safe water. These water sources contain unhealthy harmful physical, chemical and biological agents. An estimated 80 % of ill health within the tropics by world health organization (World Health Organization, 2014), are environmental sanitation and water related (Admassu *et al.,* 2004 and Cheesbrough, 2000). Globally water and food borne diseases arising from water contamination have been a great concern (Olukosi *et al.,* 2008). Pollution by heavy metals from industrial wastes renders the available water sources unsafe for drinking and food processing, some of these metals raises the physical and chemical properties of the water to unacceptable levels (Juneja *et al.*, 2008).

Climatic changes and the trending global warming especially in the arid and semi-arid areas increase the rate of evaporation in surface water sources and hence the concentration of dissolved solutes (Simpi *et al.*, 2011, Hanasaki *et al.*, 2013, Wang *et al.*, 2014 and Bada *et al.*, 2017). Water PH, electrical conductivity, turbidity, alkalinity and water hardness among other chemical properties are greatly influenced by seasons and location (Simpi *et al.,* 2011). Agricultural activities along the river banks also contributes to high water alkalinity (Pradesh *et al.,* 2012). The agricultural inputs on the farms are washed off by surface run-off into the surface water sources where they accumulate (Shen *et al.,* 2010). Leaching through the soil occurs as rain water percolates and infiltrates through the soil profile (Pradesh *et al.*, 2012). This further contaminates the ground water.

Rural dwellers rely on surface and ground water for drinking and food processing (Muhammad *et al.*, 2017, Malik *et al.,* 2010 and Ahmad *et al.,* 2012). Due to contamination, majority of the human population do not have access to potable water and are therefore exposed to water borne health risks (Muhammad *et al.*, 2017). High alkalinity and pH of most of these water sources induces unpalatable taste as well as high salt intake that is implicated in high blood pressure and kidney stones (Muhammad *et al.*, 2017 and Anwar *et al.,* 2011). However, fluoride in optimal concentration in the drinking water is beneficial for strong teeth formation (Muhammad *et al.*, 2017

Table 1: Physico-chemical characteristics of potable water, maximum permitted level (mg/l or as stated)

Parameter	Bottled Water	Un- Bottled Water
Colour	3.0 TCU	15.0 TCU
Temperature	Ambient	Ambient
Turbidity	5.0 NTU	5.0 NTU
pH	6.5-8.5	7.0-8.0
conductivity	1000 µS/cm	1000 µS/cm
Chloride	100 mg/L	250 mg/L
Fluoride	1.0 mg/L	1.0 mg/L
Copper	1.0 mg/L	1.0 mg/L
Iron	0.03 mg/L	0.05 mg/L
Nitrate	10 mg/L	10 mg/L
Nitrite	0.02 mg/L	0.02 mg/L
Manganese	0.05 mg/L	0.1 mg/L
Magnesium	0.20 mg/L	0.20 mg/L
Zinc	5.0 mg/L	5.0 mg/L
Total dissolved solids	500 mg/L	500 mg/L
Hardness (as $CaCO_3$)	100 mg/L	150 mg/L
Hydrogen sulphide	0.01 mg/L	0.01 mg/L
Sulphate	100 mg/L	100 mg/L

TCU = True Colour Unit, NTU = Nephelometric Turbidity Unit; Source: (USESA, 2012).

2.2 WATER CONTAMINATION

Regardless of the sources, water is susceptible to microbial, toxic organic and inorganic contamination (Anyamene *et al.*, 2014). The presence of coliforms in potable water is used as indicator of microbial contamination (Opara *et al.*, 2014). *Coliform* bacteria live in the digestive tract of humans and animals and remain harmless (Opara *et al.*, 2014). Generally, *Coliforms* indicate possible contamination with pathogenic bacteria, viruses and protozoa (Anyamene *et al.*, 2014).

Escherichia coli is used as indicator of possible recent faecal contamination (Anyamene *et al.*, 2014 and Opara *et al.*, 2014). It is the first bacteria present in water when contamination occurs and will be present in larger quantities than some other pathogenic microbes. Other microbial indicators of possible faecal, soil and natural water contaminations are faecal *Enterococci* especially *Enterobacter faecalis*, *Clostridium perfringens* spores, *Clostridium sporanges*, *Salmonella typhi*, *Shigella dysenteriae*, *Vibrio cholera*, *Pseudomonas aeruginosa*, *Klebsiella* spp. *Aeromonas* spp., *Mycobacterium* spp., *Alcaligens*, *Actinetobacter*, *Chromobacterium*, *Serratia spp*, *Flavobacterium spp.*, *Proteus* spp., *Bacillus subtilis*, *B. mycoides*, *Enterobacter cloaca*, *Enterobacter aeronenes*, *Nostocida fexibacter* and *Norcardia* spp. (Onilude *et al.*, 2013, Oyedeji *et al.*, 2010 and Khaniki *et al.,* 2010). These could cause different disease conditions such as giardiasis, cryptosporidiosis, gastroenteritis, diarrhea, typhoid fever, cholera, bacillary dysentery, hepatitis and shigellosis (Thliza *et al.,* 2015, Aroh *et al.,* 2013, Isikwue *et al.,* 2014, Oyedeji *et al.,* 2010 and Akinde *et al.,* 2011). Water source microbial quality is a prominent concern especially in dispensing disinfection treatment (McGuigan *et al.,* 2012). The complexity, time and cost, limit routine pathogenic organism's test. The effectiveness of water treatment methods cannot be adequately validated given the limited resources.

2.3 SOCIO-ECONOMIC CHARACTERISTICS AND SAFE DRINKING WATER

Demographic characteristics of the population influence their water handling practices as well as the source of water. Some of the demographic factors that influence water utilization and treatment techniques are discussed in this section with reference to Isiolo County Kenya. About 66 % of the population in arid and semi-arid lands (ASALs) of Kenya have no formal education and their main occupation is livestock-keeping (70 %) (Wayua *et al.,* 2012 and Watete *et al.,* 2016). The socio-demographic characteristics of the rural population that influence water handling practices included age, size of households, level of education and gender.

2.3.1 Age and Size of Households

Safe drinking-water for human consumption cannot be considered in isolation from other issues, of which age of the households' heads is the most important. Numerous studies have shown a strong correlation between the age of the household head and water safe use accessibility and consumption (Watete *et al.,* 2016, Steg *et al.,* 2009, Arouna *et al.,* 2010 and Lamuka *et al.,* 2017). About 35 % of the world rural population are children aged below 5 years and majority of the population are youth aged above 20 years (Muhammad *et al.,* 2017). The young population, are presumed to be more cautious with regard to water safety, uses and water borne diseases (Muhammad *et al.,* 2017). Households with more residents use more water (Jeffrey *et al.,* 2006). Women and children dominate the African population, defining their role in carrying water over long distances from the sources to the households (Mallick *et al.,* 2015).

2.3.2 Level of Education

Family units with advanced education levels frequently have more grounded aims to preserve water (Gilg *et al.,* 2006 and Lam, 2006). With enhanced level of education, goals to introduce water handling proficient machines are achievable (Muhammad *et al.,* 2017). However, families with lower instruction participate in more water protection practices and utilize less water than advanced educated families (Gregory *et al.,* 2003). The unit water consumption by the educated families are always higher. However, they are more concerned about the safe utilization of the water resources in the area. Improvement in the literacy levels goes a long way to facilitate diversification of water handling practices geared towards achievement of SDG 6.

2.3.3 Source of Drinking Water

Water assets and resources will be put under further weight in coming decades as population increase with growth of economy (Vorsmarty *et al.,* 2000). Environmental change is probably going to additionally compound existing stressors on water supplies. Meeting this test will require sourcing selective water supplies and expanding the efficiency of existing water supplies (Almas *et al.,* 2013). Piped, protected dug well, unprotected dug well, and hand pump among other water sources are used for drinking. Different types of water sources are used for drinking purposes, irrespective of their safety for human health (Muhammad *et al.,* 2017). The safety of the diverse water sources in the most parts of the ASALs has not been established.

2.3.4 Method of Household Water Storage

In the world storing tap water in clean and rinsed plastic, glass, enameled metal, or fiberglass containers can extend the shelf life of water and once filled in the container, it should be tightly sealed and stored in a dark and cool location (Almas *et al.,* 2013). Method of water storage at household level is divided into seven categories i.e., container with lid, container without lid, water tank on roof, drum, jericans, water cooler and pitcher (Muhammad *et al.,* 2017). These containers are also used for storing the water at household level awaiting use for drinking, food processing and domestic use. Poor handling of the containers results into contamination of the stored water.

2.3.5 Interval of Cleaning Water Storage Vessels

Drinking water is drawn from fresh water sources, which represent only 3 % of the 1.4 billion cubic kilometers of water covering the earth (Manhokwe *et al.,* 2013). Less than 1 % of this fresh water is safe to drink without prior treatment. Drinking water storage vessels at household level are cleaned daily, once a week/month, once a year and some households never clean the storage vessels entirely in their usage lifetime. Majority of the population in ASALs of Kenya are illiterate and less sensitized on the importance of hygiene and sanitation (Wayua *et al.,* 2012, Watete *et al.,* 2016, Lamuka *et al.,* 2017). Water storage vessels cleaning schedule is necessary as a mitigation for cross-contamination. However, post treatment handling of water is critical in sustaining the disinfection technique employed. Most of the water disinfection techniques offers little protection against regrowth post-treatment. Hygienic standards need to be up-held to assure the safety of the water for household use.

2.3.6 Method of Drawing Drinking Water from The Storage Container

Many observations suggest that treating water in the home can prevent illness. In many parts of the developing world, drinking water is collected from unsafe surface sources outside the home and is then held in household storage vessels (Almas *et al.,* 2011). Drinking water may be contaminated at the source or during storage; strategies to reduce waterborne disease transmission must safeguard against both events. The methods of drawing drinking water from the storage vessels are divided into four categories: dipping a glass/jug or mug, long handle scoop, taps and others (Muhammad *et al.,* 2017). In most rural set-ups, the mug used for drawing water from the vessel is the same one used for drinking, lowering the level of hygiene and increasing the health risk associated with water contamination. Such act exposes the water to high risk of cross contamination occasioned by the frequent outbreak of water borne diseases.

2.4 METHODS OF WATER DISINFECTION

Water disinfection methods are broadly grouped into three; physical, chemical and membrane process. Chlorination among other chemical water treatment methods are the most commonly used state of the art water disinfection world over (Somani *et al.,* 2011).

2.4.1 Physical Water Disinfection Methods

Cost and non-residual effect for safeguarding disinfected water against future contamination has limited the application of these methods in water disinfection (Somani *et al.,* 2011). Boiling which is a common disinfection practice among others are discussed here.

2.4.1.1 Boiling

Boiling is a phase change process associated with very high heat transfer rates (Manickam *et al.*, 2012). Boiling is a complex process constituted by nucleation, bubble growth, bubble departure and dynamics and their influence on heat transfer from the heater surface (Dhir, 2006 and Warrier *et al.*, 2006). Bubbles slide along the heater surface after departure from their original nucleation sites propagating heat transfer (Manickam *et al.*, 2012). Studies have also shown that the sliding motion of bubbles enhances heat transfer from the heater surfaces, although the cause for this enhancement has been attributed to many sub-processes including, evaporation of thin micro-layer underneath the bubble, turbulence in the wake of the bubbles and the disruption of the thermal boundary layer due to bubble motion. Sliding bubble motion and the turbulence in the reactor causes cell disruption and induction of water disinfection (Somani *et al.*, 2011).

Disinfection by boiling is achieved when water temperature is raised to boiling point, then maintaining this temperature for about 15-20 minutes to achieve desired bacteria kill (Somani *et al.*, 2011). This method has found its application in Isiolo County for preservation of milk in the camel milk value chain (Wayua *et al.*, 2012). However, the use in water treatment by households has not been established. Heating is involved and consequently fuel requirement in form of firewood, electricity and other forms must be met. The use of wood as fuel is common at household level although it has been linked to increase in deforestation as trees are cut to meet the firewood demand.

2.4.1.2 Solar Radiation

Solar energy is radiant light and heat from the Sun that is harnessed using a range of ever-evolving technologies such as solar heating, photovoltaic, solar thermal energy, solar architecture, molten salt power plants and artificial photosynthesis (Konersmann *et al.*, 2011).

Solar water disinfection method has gained recognition following the realization of sunlight germicidal effect. Effectiveness and feasibility has been reported for small quantities of about 3l of water in solar water disinfection (SODIS) (Fadhil, 2003 and Shibu*et al.*, 2006). Exhaustive application in continuous solar water disinfection reactors has not been fully established. No taste, odour and complete germicidal destruction of target microorganisms are the reported advantages (Somani *et al.*, 2011). The full potential of solar water disinfection to inactivate a wide range of waterborne pathogens has not been fully established (McGuigan *et al.*, 2012).

2.4.1.3 Titanium Dioxide (TiO2) Films and Sunlight

(TiO_2), also called Titania. TiO_2 is a wide band semiconductor whose band-gap energy of 3.2 eV, corresponds to photons of wavelength shorter than 390 nm (UV-A) (McGuigan *et al.*, 2012). TiO_2 may be utilised in aqueous suspension or may be immobilized on a supporting solid substrate. Suspending the catalyst in the reactor has been reported to be more efficient due to large surface area available for the reaction. However, using micro-particles in suspension is the requirement for post-treatment retrieval or recycling of the catalyst, potentially making the treatment more complex and expensive (McGuigan *et al.*, 2012). Hydroxyl radicals produced as a result of Titanium dioxide dissolution in water are the primary species responsible for microorganism inactivation. The oxidative effect of TiO_2 photo catalysis occurs by direct contact of the catalyst particle with the bacteria, and the first damage occur at the outer membrane.

Reactive oxygen species (ROS) such as Hydrogen peroxide and oxygen radical (H_2O_2, $O_2^{\bullet-}$) for induced microbial inactivation. These ROS cause fatal damage to microorganisms by disruption of the cell membrane or by attacking DNA and RNA. Other modes of TiO_2 action have been proposed including damage to the oxygen transport system within the cells or increased ion permeability in the cell membrane. The capability of TiO_2 to inactivate a wide range of pathogens has been a fruitful (McGuigan *et al.,* 2012).

Titanium dioxide (TiO_2) has been used as a photo catalyst in solar water disinfection of coliform bacteria contaminated water (Silva *et al.,* 2006). Titanium dioxide is added to water at a critical concentration to increase radiation absorptivity. The photo excitation of titanium dioxide particles promotes an electron from the valence band to the conduction band thus leaving an electron hole in the valence band; in this way, electron/hole pairs are generated. The photo excited electrons produce disinfection species that induces sequential germicidal effect in the water. Increased efficiency in inactivating both total and faecal coliforms and keeping the water coliform free for seven days after sun irradiation when compared with normal solar water disinfection has been reported (Somani *et al.,* 2011). This method has however found limited use due to its high cost and the need for uniform solar radiation.

2.4.1.4 U-V Radiation

Ultraviolet disinfection of water employs low-pressure mercury lamps. They generate short-wave ultraviolet in the region of 253.7 Angstroms which is lethal to micro-organisms including bacteria, protozoa, viruses, molds, yeasts, fungi, nematode eggs and algae (Brahmi *et al.,* 2012). The mechanism of micro-organism destruction is currently believed to be due to the fact that ultraviolet causes molecular rearrangements in DNA and RNA, which in turn blocks replication (McGuigan et al., 2012 and Brahmi *et al.,* 2012). The acceptance of UV disinfection at waste water plants treating in excess of one billion gallons daily is proof that UV is no longer an emerging technology, but rather an accepted technology used routinely by engineers to safeguard human health and alleviate environmental pressures.

Several investigations have reported a relationship between suspended solid concentration and fecal coliform survival in UV irradiated wastewater samples (Oparaku *et al.,* 2011). There exists a synergistic use of UV with other forms of particle-penetrating irradiation in an integrated disinfection process with a greater disinfection potential. UV light disinfect aqueous solutions in different ways and disinfection might be accomplished more efficiently if the UV is carried out at low doses to inactivate the free microorganisms (Brahmi *et al.,* 2012).

U-V water treatment thus involve the application of U-V dose to kill or retard microbial cell growth and to an extent alter the cell DNA structure (Nicki *et al.,* 2004). A 99.99 % efficiency of disinfection is achieved with water free from suspended colloids, flowing in the form of thin sheets of about 120 mm and adequate intensity and time of exposure to U-V rays (Somani *et al.,* 2011 and Nicki *et al.,* 2004). This method has the advantages of short exposure period for disinfection, no taste and odour and complete destruction of microorganisms. However, the adoption is based on specialized technical skills that limits its use among the rural dwellers in developing nations. The installation cost is relatively high and thus unaffordable to the target users.

2.4.1.5 Electromagnetic Radiation

Relies on the use of X-rays and gamma rays sourced primarily from Cobalt 60 (Co60) which exhibit high ionization power and germicidal properties that are realized at a range of 0.2 µ to 0.3 µ and peak at 0.26 µ wavelength (Bhagwatula *et al.,* 2000). Effective disinfection requires the radiation source to be close to the medium (Somani *et al.*, 2011). This method of water disinfection is not accessible for the rural dwellers in the developing nations. It is associated with high cost and specialized technical know-how and skills for use and adoption that is visibly limited given the low literacy levels in the arid and semi-arid areas of Kenya.

2.4.2 Chemical Water Disinfection Methods.

2.4.2.1 Hydrogen Peroxide

Addition of hydrogen peroxide to turbid water, liberates nascent oxygen which induces germicidal effect. Excess hydrogen peroxide is then removed by fine filtration through a column of divided manganese dioxide and sand. The column is pre-washed with dilute $KMnO_4$ (potassium permanganate) (Somani *et al.,* 2011). Treatment of the turbid water can also be achieved at a temperature of 40 $^{\circ}$C with addition of small quantities of hydrochloric acid acidified hydrogen peroxide, then neutralizing the excess acid (Bhagwatula *et al.*, 2000). This is costly, has no residual effect and has poor germicidal properties.

2.4.2.2 Acid and Alkali

The pH dependent microbial growth is inhibited through addition of an alkali or acid that either raises or lowers the pH levels. The pH is then neutralized after the desired destruction of pathogens has been realized (Somani *et al.,* 2011). To a lay person it can be quite challenging to properly portion the acids and alkali in the disinfection procedures. There is likelihood of over portioning as well as under-portioning yielding undesirable results. Most of the acids are corrosive and thus hazardous for use by lay persons. The mild organic acids are scarce and use in commercial water treatment is costly. The health risk associated with over portioning of acids and alkali in the water disinfection procedures are so high and thus not suitable for the illiterate populations in the rural areas of the developing nations. Under portioning results into inadequate germicidal effect and consequently the prolonged prevalent of water borne diseases. The use needs frequent awareness trainings that is technical unachievable.

2.4.2.3 Metallic ions

Metallic ions of silver, mercury and copper exhibit germicidal effect. Introducing 0.05 - 0.1 mg/l dose of silver ions into the turbid water produces a bacterial kill in 15-18 min contact time (Min Cho *et al.*, 2006). This method is costly and not suited for large scale operation.

2.4.2.4 Chlorite and Chlorine Dioxide

The strong disinfection and oxidising properties of chlorite ion (ClO_2^-) and chlorine dioxide (ClO_2) has found application in secondary disinfection in full-scale water distribution systems. This method is effective against *Cryptosporidium* and five times faster in inactivating *Giardia lamblia* than chlorine (Gagnon*et al.*, 2005). Its use is however not widespread due to the high operation cost as well as odour and taste problems.

2.4.2.5 Chlorination

Chlorine is widely used for water disinfection but has one problem. In water, chlorine combines with trace amounts of naturally occurring organic matter and liberate toxic by-products on disinfection known as halogenated disinfection by-products DBPs (Clark *et al.,* 1998). Toxic trihalomethanes (THMs) represent a large fraction of these halogenated DBPs, hence need for alternative disinfection methods.

2.4.3 Membrane Process Disinfection Method

Membrane process is an emerging field in water treatment with various application in desalination, taste and colour removal as well as microbial disinfection (Fane *et al.,* 2011). The involved processes are; micro and ultra- filtrations and reverse osmosis.

Technological advances and development have shown the drawback in using chlorine as disinfectant and necessity of alternative disinfectant. Currently in the developed Nations, Ozone and UV radiation are in use for water disinfection. However, in developing Nations, use of these expensive methods is limited mainly due to their costly nature (Somani *et al.*, 2011). The installation of reverse osmosis system as well as the maintenance cost is high. However, once installed little operational skills are required thus viable for use by the semi-illiterate persons. In addition, reverse osmosis requires electricity for operation that might be limited in the rural areas.

2.4.4 Water Treatment Using Traditional Herbs

The major population world's population is living in rural areas, where these natural herbs are easily available (Tanushree *et al.*, 2013). The effective antimicrobial activity of plants leaf extracts is due to the synergistic effect of the active components present in plant leaves. According to traditional belief Tulsi leaves (*Ocmium sanctum*) and Neem leaves (*Azadirachta indica*) have the capacity to purify water (Pavithra *et al.*, 2012). Other plant species with germicidal effect are *Moringa oleifera*, *Abelmoschus esculentus (Okra)* and *Calotropis Procera* (Calotrope).

Moringa oleifera, known as Moringa, is native to north India but is now found throughout the tropics. It grows fast and reaches up to 12 m. The bark is grey and thick and looks like cork, peeling in patches. Moringa is full of nutrients and vitamins and is good food for humans and animals. Moringa helps to clean dirty water and is a useful source of medicines (Tanushree *et al.*, 2013 and Binayke *et al.*, 2013).

Abelmoschus esculentus, is vegetable crop grown in the tropics (Pavithra *et al.*, 2012). Okra gum is soluble in cold water. When added to turbid water, regardless of the Gum mucilage volume, the turbidity decreases as the pH increases. The reduction in turbidity is significant with higher mucilage dose (Binayke *et al.*, 2013). The mucilage contains natural polymer molecules that aide's flocculation from a complex chemical reaction (Nacoulima *et al.*, 2000).

Calotropis procera is a tropical shrub (Binayke *et al.*, 2013). Mostly planted as an ornamental shrub. *Calotropis procera* has been reported to contain calotropin (non-toxic proteolytic enzyme) that is traditional used in the cheese industry for milk curdling (Ahmed *et al.*, 2005 and Ahmed *et al.*, 2006). *Calotropis procera* has also been used for enzyme purification by precipitation (Kareem *et al.*, 2003). Water disinfection technique using herbs is virtually less costly approach render contaminated water fit for human consumption. However, this technique can be effective for the water obtained from water sources having low degree of contamination or else water can be given prior filtration with charcoal or fine sand to reduce the contamination load (Tanushree *et al.*, 2013). Better germicidal effect can be realized if this technique is combined with solar water treatment (Binayke *et al.*, 2013).

3.0 SOLAR ENERGY

The sun emits about 1360 Wm^{-2} of solar radiation energy. Out of which 1120 Wm^{-2} hits the earth surface (McGuigan *et al.*, 2012 and Chaichan *et al.*, 2016). The radiation energy induces electricity generation on photovoltaic cell and other portions induces thermic effect that raises the temperatures of the earth's environment (Chaichan *et al.*, 2016). Absorptivity of the solar radiation on the earth surface is greatly influenced by the angle of incidents of the radiant rays (Chaichan *et al.*, 2016, Jeng *et al.*, 2009 and Makrides *et al.*, 2009). Wavelengths of the sunrays falling on the earth surface vary depending on the prevailing weather conditions of the days as well as season (Chow, 2010 and Chakraborty *et al.*, 2014). These among other factors significantly affect the solar radiation intensity incident of the earth surface (Zell *et al.*, 2015).

4.0 SOLAR ENERGY USE IN WATER DISINFECTION PROCEDURES

Solar energy use in house-hold water treatment has grown over the recent past (Clasen*et al.*, 2007). Drinking water was placed in open trays on the sun by some Indian communities over 2000 years ago (McGuigan *et al.*, 2012). Solar water disinfection is done by filling the transparent containers with contaminated water and subjected to direct exposure to radiation from the sunlight for a duration less than 6 hours. After the minimum exposure, the water is potable and ready for use.

SODIS reactors are made either from glass or ethylene-terephthalate plastics. Plastic reactors are usually used for their robust advantage over glass (Dunlop *et al.*, 2011 and Walker *et al.*, 2004). Post exposure regrowth possibilities are minimised by consuming the solar disinfected water in a period less than 24 hours post exposure (McGuigan *et al.*, 2012). Black painted solar water disinfection containers, placing the SODIS reactors on reflective surface and filtering the turbid water prior to filling into the reactor (Pansonato *et al.*, 2011) are some advances made to enhance solar water disinfection efficiency.

5.0 SOLAR RADIATION ENERGY AND ITS EFFECT ON CELLULAR STRUCTURE OF LIVING MICROORGANISM

Thymine and cytosine base components of pyridine rings of DNA molecule of the microbial cell absorb U-V upon irradiation. The absorbed energy by the cell, facilitate formation of paired covalent linkage in the neighbouring bases of pyrimidine, consequent to dimers formation (Goodsell, 2002). Molecular DNA shape is transformed at pyrimidine dimer locus following inhibited complimentary purine-base pairing (McGuigan *et al.*, 2012). The polymerase DNA copying enzyme movement is inhibited at the dimer locus, resultant effect is confusion of nucleotide to be added and deletion of two DNA bases if by chance the polymerase enzyme skips over the locus of pyrimidine dimer.

The less energetic U-V radiation near visible light excites the cell porphyrins, flavins, quinones and among other photosensitizers, forming the DNA damaging reactive oxygen species (ROS) (McGuigan *et al.*, 2012 and Reed *et al.*, 2000). Humic acid and chlorophyls on water surface, react with oxygen upon irradiation producing disinfecting effect by ROS (Schwartzenbach *et al.*, 2003 and Bosshard *et al.*, 2010). Cellular damage induced by exposure to irradiation from sunlight continues at darkness incubation post sunlight exposure (Bosshard *et al.*, 2010). To achieve desired disinfection, the physiological stage and cell growth rate remains a microbiological concern parameter (Berney *et al.*, 2006).

Escherichia coli the main disinfection studies species regular cell operations is disrupted following termination of ATP synthesis and efflux pump activity shortly on solar radiation exposure (Berney *et al.*, 2006).

Consequently, loss of glucose uptake by the cell membrane enhances the permeability of cytoplasmic membrane and ability to culture the DNA is lost. Pathogenic water borne microorganisms especially bacteria are readily susceptible to solar water disinfection with low pace disinfection reported in faecal coliforms that occur in nature (Sinton *et al.*, 2002).

6.0 SOLAR ENERGY USE IN WATER TREATMENT

Water treatment using solar energy is not a recent development and has been practiced in ancient cultures for centuries (Keane *et al.*, 2014). Historical developments of solar water treatment in the recent past have been reviewed with focus to improve the already existing technologies (McGuigan *et al.*, 2012). It has been established that, solar water disinfection (SODIS) is one of the most practical and low-cost techniques to reduce the load of pathogenic microorganisms in water at households in low-income areas (Borde *et al.*, 2016 and Castro-Alferez *et al.*, 2016). Some of the applications of solar in water treatment include: pasteurization, distillation and solar water disinfection.

6.1 SOLAR PASTEURIZATION

Solar pasteurization involves raising the temperature of the water by heating for a period of time sufficient to destroy pathogenic micro-organisms (Pejack, 2011). An exponential inverse relationship occurs between pasteurization temperature and time (Birzer *et al.*, 2014). Pathogenic organisms such as worms and protozoa cysts are destroyed at temperatures above 55 $^{\circ}$C, whereas *Escherichia coli*, *Salmonella typhi*, *Vibrio cholera*, *Shigella spp* and Rotavirus are destroyed at temperatures above 60 $^{\circ}$C (Birzer *et al.*, 2014). Therefore, pasteurization at 60 $^{\circ}$C is sufficient to effectively eliminate pathogens of concern in water.

A 4-log reduction in *Escherichia coli* was realized within 1 hour pasteurization in aluminium foil reflectors and PET plastic bottles system (Safapour *et al.*, 1999). This system was limited to treat less than 2 litres of water. In another solar water pasteurization system consisting of flat plate collector and an automotive thermostatic valve that released water batches upon attainment of desired temperature, 95 litres and 49 litres of water per day was obtained using the reflectors and without using the reflectors respectively (Onyango *et al.*, 2009).

Konersmann and Frank. (Konersmann *et al.*, 2011) used a system constituting evacuated tubes with a thermostatic valve which was used to release batches of water once the temperature was above 82 $^{\circ}$C. The system released 500 litres per day of pasteurized water (Konersmann *et al.*, 2011). The cost of construction and maintenance of this system is relatively high thereby limiting the use.

6.2 SOLAR WATER DISTILLATION

Solar water distillation has been investigated in various research studies (Muslih *et al.*, 2011 and Koning *et al.*, 2005). Solar energy from the radiation is used to evaporate the water and the distillate collected (Birzer *et al.*, 2014). Solar distillation is effective on chemical, physical and microbial contaminants. However, water demineralization occurs lowering the quality (Birzer *et al.*, 2014 and Dev *et al.*, 2011).

6.3 SOLAR WATER DISINFECTION (SODIS)

This method has gained recognition following the realization of sunlight germicidal effect, effectiveness and feasibility on small water volumes of approximately 3 litres in solar water disinfection (SODIS) (Fadhil, 2003 and Shibu *et al.*, 2006). No taste, odour and complete germicidal destruction of target microorganisms are the reported advantages (Somani *et al.*, 2011). Conventionally, transparent water bottles are filled with contaminated water and placed in the sun for 6 hours after which the water is presumed to be safe for use (McGuigan *et al.*, 2014 and Keane *et al.*, 2014). Post exposure regrowth possibilities of microorganisms in water is minimized by using the batch SODIS disinfected water within 24 hours after disinfection (McGuigan *et al.*, 2014).

7.0 IMPROVED BATCH SODIS SYSTEMS

Batch solar water disinfection has relied heavily on cost-effective plastic bottles as reactors inspite of the limited volume of 2 litres per batch of treated water. Glass reactors have a good solar transmittance of 90

% (Navntoft *et al.,* 2008). But, are more expensive than plastic reactors. Use of low-density polyethylene solar disinfection bags has been reported (Dunlop *et al.,* 2011). However, the release of potentially genotoxic compounds into the disinfected water from the PET bottles during long time solar water disinfection exposure has raised concern (Ubomba-Jaswa *et al.*, 2009). Painting the reactors, placing the reactors on reflective surface and filtering the turbid water prior to filling into the reactor are some of the advances made to enhance solar water disinfection efficiency (Kehoe *et al.,* 2001, Reed, 2004 and Mani *et al.,* 2006).

There exist a strong synergistic association between optical and thermal inactivation at temperatures greater than 45 ˚C (McGuigan *et al.*, 1998). This synergy is not achievable under normal exposure of PET bottles to the sun. To accelerate the rate of thermal inactivation of organisms, absorption of solar radiation is enhanced by use of absorptive materials and painting reactor PET bottles black (Martin-Dominguez *et al.*, 2005). The use of solar collectors and reflectors have been reported in other studies (Kehoe *et al.,* 2001, Saitoh *et al.*, 2002 and Wegelin *et al.,* 2001). Illumination of batch PET reactors only on one side facing the sun necessitated the use of reflector mirrors to concentrate solar radiation in the reactor bottle (McGuigan *et al.,*2012). Aluminium foil attached to a SODIS reactor produced a double increase in water disinfection rate (Kehoe *et al.,* 2001 and Walker *et al.,* 2004), also reported a reflective food grade solar disinfection pouch to enhance the physiological effect of the solar radiation on microorganism on irradiation.

8.0 CONTINUOUS SOLAR WATER DISINFECTION SYSTEMS

With the limited volume of disinfected water obtained using batch SODIS systems, attempts have been made to improve on disinfected water volume by enhanced thermal inactivation using flat plate flow reactors and incorporation of titanium dioxide as aphotocatalyst (Dunlop *et al.,* 2002 and Sichel *et al.,* 2007). A PVC circuit, covered with acrylic layer and a catalyst incorporated in the system produced a 4 log coliforms reduction as well as an increase in disinfected water output (Caslake *et al.,* 2004). Continuous SODIS system despite being advanced than batch systems, they also have associated limitations (Ubomba-Jaswa *et al.,* 2009).

Solar photo-reactors fitted with compound parabolic collectors (CPCs) and recirculation systems at two flow rates of 0.033 kgs^{-1} and 0.167 kgs^{-1} were used to study the effect of the total volume of treated water and the flow rate on inactivation. Irrespective of the exposure time, flow rate and bacteria inactivation were inversely associated (Ubomba-Jaswa *et al.,* 2009). Bacteria need maximum exposure to solar radiation than being subjected to sub-lethal U-V doses repeatedly for long durations without achieving complete germicidal action (McGuigan *et al.,* 2012 and (bomba-Jaswa *et al.,* 2009). Bacteria inactivation depended on U-V dose other than irradiance (Ubomba-Jaswa *et al.*, 2009). With continuous flow systems, the lethal dose was also delivered to the bacteria but in an intermittent manner, resulting in approximately a 2 log colony forming units per milliliter concentration of residual viable bacteria remaining after the 5 hour duration of disinfection.

A single pass continuous flow reactor with a flow rate of 0.167 kgs^{-1} using a CPC reflector of 1.0 concentration factor assembled in eight panels completely inactivated 100 Cfu/ml of coliforms after a 20 minutes single pass residence time (Gill *et al.,* 2010). Similarly, a 2-log reduction in *Escherichia coli* in a 50 liters continuous pilot scale flow reactor on grey water was reported (Pansonato *et al.*, 2011). A 1.89 concentration factor CPC reflector in a continuous single pass flow reactor, achieved a reduction in residence time required for disinfection and a higher volume of disinfected water (Polo-Lopez *et al.,* 2011).

Waste heat during cooking has been used to disinfect water at the rural areas (Islam *et al.,* 2006). The treated water is continually collected, though, this system is limited on large scale water disinfection operation. A parabolic trough concentrating solar collector with a passive flow temperature regulation in a continuous flow water disinfection system has been reported (Duff *et al.,* 2005 and El-Ghetany *et al.,* 2010).

Anthony *et al.,* (2015) developed a continuous-flow, gravity-fed system with flat reflectors that used simple solar oven to heat incoming water to pasteurisation (70 ˚C) in seven minutes. The waste heat from the system was recaptured for preheating water to be treated. The solar ovens were in design of closed boxes with clear face to trap heat for incident radiation from the sun. Anthony *et al*. (2015) prototypes consisted of solar collector box made from plywood, window-insulating plastic, 33.3 m of PEX tubing, a metal absorber plate, reflective Mylar, hinges and screws. A simple shell-tube heat exchanger was built from 1.2 cm OD copper pipe mounted inside a 2.54 cm OD PVC pipe (shell). The 1 m by 1.3 m solar collector had three reflectors to maximize irradiative sunlight into the box. Water flowed through 33.3 m of PEX tubing mounted on a 1 m by 1.3 m steel plate and was sealed with a solar window (clear plastic sheet) to prevent heat loss. The metal absorber plate below the array of tubing increases heat transfer to the water flow (Cramer *et al.*, 2006) [115]. The heat exchanger, which uses the hot water exiting the solar collector to preheat the water that was about to enter the solar collector, was mounted on the side of the box. Outer connective tubing that carries hot water is insulated in order to prevent unnecessary heat loss. The optimal flow rate for reaching pasteurisation temperatures of the system was about 0.0025 kgs^{-1}. The solar thermal pasteurisation design worked at 700 Wm^{-2} and disinfection was achieved at high through puts (Anthony *et al*. 2015).

An isolated tank of 500 liters connected by 1.25 cm PVC tubing to a smaller 125 liters formed part of a continuous solar disinfection reactor designed by Khaled *et al*., (2008). The water level was controlled by a float valve and submersible pump that also served water into the PET reactors.

The reactor was held by a metal frame similar to that of flat solar water heaters. The frame was tilted at 45 ˚ for maximum radiation interception and then connected to 125 liters disinfected water storage tank. The pump was controlled by a light activated switching unit that utilized a photovoltaic cell to switch the pump on when light is available dictated by the output voltage of the photovoltaic cell (two hours after sunrise) and off when light is not available (one hour before sunset). Later Khaled and co-authors installed a flat solar water heater and a heat exchanger for water circulation in the PET reactor and regulated the temperature of out coming water from the reactor respectively. The solar water heater depended on convective circulation established from solar heating to move the water from one tank to the other (Khaled *et al*., 2008). The heat exchanger during the operation of the system was to aid in increasing the temperature of the water going into the solar disinfection reactor in order to decrease the time needed to raise the temperature of the water. The system was also equipped with a thermal one-way valve to regulate the flow of water between the solar heater and the reactor. The one-way valve opens when the temperature of the water reaches the desired temperature and thus starts the whole process of disinfection (in the morning) and closes when the temperature of the water decreases below the limit (close to sunset).

The design faced flow problems especially at elevated temperatures mainly in the form of reduction in flow rates and sometimes back flow problems. Thus, the exposure times needed to achieve the required water disinfection had to be changed slightly by decreasing the flow rate of water through the reactor (Khaled *et al*., 2008). This adjustment of flow rate provided additional exposure time. Further modifications of the design are necessary to cab the flow problems. Based on the bacterial species examined, water turbidity was a major factor influencing water disinfection by natural UV radiation. Increased exposure time or pre-filtration methods are needed to reach maximum bacterial inactivation (Khaled *et al*., 2008).

El-Ghetany *et al.*, (2010) designed a continuous flow solar water disinfection system that consisted of a 200 liters contaminated water tank, clean water tank, shell and tube heat regenerator, flat-plate solar collector, control unit fitted with measuring instruments and a frame. A 4 m head pressure was used to pass water through the collector from the contaminated water tank. Significant amount of disinfected water was obtained at different set temperatures. A flat plate collector of 160 cm by 11 cm by 0.05 cm thickness was fabricated from eleven steel fins aligned with nine copper tubes of 7 mm diameter (El-Ghetany *et al.*, 2010 and El-Ghetany *et al.*, 2007). The collector had an area of 2.34 m^2 oriented at an angle of 30 ˚. The system realized approximated 400 liters output of hot disinfected water at 60 ˚C set temperature. Volume of hot water produced increased to maximum at noon followed by a gradual decrease during disinfection hours after noon, this was attributed to solar variation trends (El-Ghetany *et al.*, 2007).

Thermo siphon solar water heating system with a single flat plate solar collector produced 3.6 liters per hour of hot water at 80 ˚C per square meter of the flat plate reactor for each kWh of incident solar energy [119]. Similarly, 2.85 liters per hour of hot water at 70 ˚C per square meter of flat reactor for every kWh incident radiation was reported by El-Ghetany *et al.*, (2005).

9.0 INFLUENCE OF TURBID WATER CONDITION ON DIRECT SOLAR DISINFECTION

Solar water disinfection kinetics is greatly influenced by presences of organic matter as well as inorganic matter in the contaminated water preceding disinfection procedures (Sichel *et al.*, 2007). Under real disinfection, river and sewage water gives a good prediction of germicidal effect (McGuigan *et al.*, 2012). Water exhibiting osmotic pressure arising from the presence of inorganic ions limit solar water disinfection, radicals of hydrogen peroxide and hydroxyl propagates the U-V induced bactericidal effect (Hoerter *et al.*, 2005). Hydrogen carbonate anions interact with the free radicals producing carbonate radical ($CO_3^{\circ -}$) whose reactivity interaction with organic molecules is low on comparison to oxygen radical (O°) (Canonica *et al.*, 2005). Side absorption of solar radiation by the hydrogen carbonate anion limit the amount of radiation incident on the microbial cells in water.

10.0 ECONOMIC VIABILITY OF SODIS SYSTEMS

At the rural set-up with limited access to various household water treatment facilities, solar water disinfection tends to be affordable. SODIS is usually selected when sufficient resources are not available to afford relatively expensive and sophisticated methods such as chlorination that require technical know-how to effectively carry out. Once the reactor for solar disinfection has been installed very minimal operational and maintenance costs are incurred (McGuigan *et al.*, 2012). Most rural households are dependent on natural energy sources such as firewood for boiling water for various domestic uses, and cannot afford any other household water treatment facilities. Solar water treatment would be more reliable for this case in order to mitigate the problems of deforestation resulting from heavy reliance on wood fuel (Harding *et al.,* 2012). Viability of solar disinfection systems is realized when enhancements offset additional costs, yield quality water and increase the efficiency of disinfection resulting in higher flow-rates and larger volumes of disinfected water obtained (McGuigan *et al.,* 2012). Use of a solar water disinfection system becomes more viable for supplying water in a large community setting consisting of several households. In this case, the relatively high initial cost of installing the large system can be offset by the large number of individuals receiving the benefit of potable water services (Gill *et al.,* 2010). However, a detailed economic feasibility study has to be conducted for each specific large scale continuous solar water disinfection systems before such a project is implemented.

11.0 CONCLUSION

Water disinfection techniques have been diversified from the traditional methods to the current improved techniques. Significantly, solar water disinfection has undergone gradual enhancements in the recent past from the batch to continuous systems. These enhancements improve on the limited access to potable water largely attributed to low level of personal hygiene and inadequate treatment facilities for water and waste. Solar is also a clean and cheap energy source whose application in solar water disinfection prevents formation and generation of certain undesirable disinfection by-products associated with chemical disinfection methods. The existing systems ranging from batch system that produces limited volume of disinfected water per day and some of the continuous systems, have not been enhanced for water disinfection for large food processing industries. Furthermore, compared to other household water treatment and storage systems, solar water disinfection has no readily available manufactured products for commercialization, hence its promotion campaigns are limited. Continuous solar water disinfection systems are effective against coliforms and various pathogens where sufficient solar energy is available. Solar water disinfection has great potential for scaling up to provide water for large food processing operations.

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