Sustainable wastewater management; exploring the option of greywater reuse in a developing country – Ghana



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one

Chapter one

Introduction

Due to urbanization, industrialization and population growth, the demand for water is evident so is the associated increase in freshwater pollution resulting from discharging of untreated wastewater into freshwater bodies. Meeting the water demand and wastewater management requirements has also become increasingly difficult. Although there is supposed to be enough water resources to support the functions of water, however, this assertion is defeated due to uneven distribution of this resource in both time and space. An increase in water scarcity is progressively being observed as a universal risk since nearly 4.8 billion of the world's population live in areas where there is some form of water scarcity threat (Bakker, 2012; Vorosmarty et al., 2010). It has been estimated that approximately 1.6 billion people representing approximately a fourth of the human population are already facing acute water shortages and this is expected to double in the next decade (Roson & Damania, 2017).

Many parts of the world are hit by acute water shortage, over exploitation leading to gradual destruction of these water resources and high levels of freshwater pollution resulting from anthropogenic factors (UNESCO, 2009; Vorosmarty, Douglas, Green, & Revenga, 2005). It has also been estimated that over 300 million people in Africa reside in water scarce environments and rely on close to 70% of their scarce water resources for agricultural irrigation (NEPAD, 2006; Brown, 2006). It has been established that many developing countries are faced with direct disposal of untreated sewage into freshwater resources (Vigneswaran & Sundaravadivel, 2004). These conditions have raised awareness of the state of water quality and the quantity of the water supplies within these regions. The challenges posed by water pollution has received a lot of attention and was a heavily debated subject in the United Nations conference on Environment and Development popularly known as the Earth Summit of Rio de Janeiro (UN, 1992). At this conference, it was decided that freshwater resources should be protected from contaminations in order to achieve global environmentally sustainable development. Again, this was revisited in the 2017 world water day which was dedicated to wastewater management as a means of protecting water resources (WHO, 2019). A very critical question to ask is will the available water resources be able to meet the ever-increasing demands across the globe? Where will the extra water that is required to sustain activities come from? Goal 6 of the sustainable development goals is to ensure availability and sustainable management of water and sanitation for all (UNDP, 2017). Part of the approach to achieving this is to reuse wastewater and this is where a cursory look at greywater recycling worth considering. Greywater is defined as wastewater without any contributions from toilet water (Casanova, Gerba, & Karpiscak, 2001; Ledin, Eriksson, & Henze, 2001; Ottoson & Stenstrom, 2003). This water contains a maximum of up to 95 percent water with only 5 percent being solid wastes (Tchobanoglous, Burton, & Stensel, 2002). Recycling and reusing of greywater that is being generated due to urbanization, population growth and industrialization can be a critical area that can be exploited in order to reduce the burden on the already stressed available freshwater resources.

Recycling greywater can help augment the already scarce water resources by providing alternative water sources for other uses. It plays a very key role by reducing the level of contamination to other freshwater

resources. The excessive costs incurred in treating water for potable use is also reduced due to the reduction in demand for potable water. Reuse therefore can be a supplementary source to existing water sources in areas where there is acute water crisis or in arid climatic regions. Greywater contains nutrients which can promote plant growth when used for irrigation. While the nutrients in wastewater can promote plant growth when reused for irrigation, their disposal, in extreme cases, is detrimental to ecosystems of the receiving environment. In addition, there may be concerns about the levels of other toxic pollutants in wastewater.

The major concerns with greywater reuse has been issues with public health perceptions and appropriate technology for the reuse option (Vigneswaran & Sundaravadivel, 2004). Recycled wastewater can be used to meet different water – demanding activities. The reuse option basically depends on the physical and biochemical characteristics of the wastewater. Greywater can be reused for potable or non-potable purposes because it can be used directly or treated to meet the appropriate reuse option. Among some of the non – potable uses are, agriculture, aquaculture, flushing toilets, car washing and other equally non – potable water uses. Potable reuse options require stringent treatment protocols.

Problem statement

Growth in water demand and increasing water pollution has led to acute water shortages in many parts of Africa and other developing countries. The resultant effect of this condition leads to inadequate access to sanitation and other related water use activities. The stop-gap measure has always been the provision other alternative sources of water such as development of groundwater resources, rainwater harvesting and water vending. However, all these sources are prone to some level of uncertainty in supply and availability. The current approach and existing modes of solving this and improving sanitation are not expected to lead to any major breakthrough in the near future. Many developed countries in arid and semi-arid areas have practiced greywater reuse to augment water supplies and this has been in existence for many years as part of the integrated water resource management (IWRM). Not only does this concept augment their water resources, but it also reduces the cost incurred in paying for water services. As this practice is worth adopting, developing countries and in particular sub-Saharan Africa has not yet embraced this concept of greywater reuse. People living within such water stressed communities have to walk for long distances in search of water which is used only once for a particular activity. Also, due to the non-existence of sewer systems in many developing countries, greywater generated in many households are left to join other freshwater bodies without being treated. These water bodies serve as point sources for some communities downstream and also source of water for livestock. Discharge of untreated greywater into the environment can lead to deterioration of freshwater resources due to the presence of many contaminants in greywater. However, this resource can be harnessed and reused in order to augment water supplies at the household levels. Due to the various cultural, religious and societal norms associated with many developing countries, this concept is seen as foreign and, in some instances, it may be regarded as a taboo to use 'spent water' for other water needs. Evidently, there is a need for a new approach to greywater management especially in developing countries. This thesis explores this practice of greywater reuse within a developing country by using a two-pronged approach. The first approach involved experimenting how to reduce a major contaminant from greywater using locally available agricultural waste material. The second approach involved using a socio-cognitive model to explore the

main reasons why people will be willing to adopt this practice or otherwise taking into consideration cultural, religious and societal dynamics that exists in many developing countries within sub-Saharan Africa. Research around greywater reuse has largely focused on what exists in developed countries. However, studies that explore the dynamics of greywater reuse in a developing country viz the cultural, social, religious and appropriate technology are limited. This study has been designed to inform stakeholders on how to initiate or promote this concept in a developing country. Understanding and promoting greywater reuse can support the attainment of other sustainable development goals. Irrigation with greywater can help attain food security and improve nutrition which is the focus of goal 2 on ending hunger. Reducing water born-borne and other water related diseases as well as reducing the number of illness associated with soil and water pollution which is the focus of goal 3 on ensuring healthy lives (UNDP, 2015) .

Research goal

The main aim of the research was to explore greywater reuse at the household level in the study area taking into consideration the technical and non-technical approaches.

Specific objectives

1. To explore existing literature on greywater quality, reuse, perception and treatment systems.
2. To study the environmental impact associated with discharging untreated greywater into the environment within the study area.
3. To explore the potential of two agricultural waste materials on BOD_5 and COD removal in greywater under batch conditions.
4. To study the BOD_5 and COD removal using the best performing agricultural waste under continuous condition.
5. To identify the preferred reuse application of greywater using a socio-cognitive model known as the theory of planned behaviour.
6. To assess the willingness of households to adopt a greywater treatment and reuse system using an extended theory of planned behaviour model to include personal norms.

Research questions

To be able to explore and promote the option of greywater reuse, the following questions will have to be addressed:

i. *What are the existing knowledge and gaps in greywater treatment and reuse?*
ii. *What are the pollutants of importance in regulatory discharge of greywater into the environment?*
iii. *What is the current greywater quality and generation rates within the study area?*
iv. *Which of the proposed materials have the optimum capacity for removing the important pollutants in the research?*
v. *What is the effect of process parameters in the treatment process?*
vi. *What are the factors that will determine the choice of reuse option with respect to societal, religious, educational factors?*

vii. *What are the factors that will influence willingness of households to adopt a low-cost greywater reuse system?*

Outline of the thesis

This thesis has been divided into eight chapters. Chapter 1 (current chapter) gives a brief background to the study including the problem being investigated, the objectives to be addressed and the relevance of this study to water resources.

Chapter two is a comprehensive review on the topic of greywater reuse and reviews literature on greywater characteristics, treatment systems and user perception.

Chapter three presents the quality and quantity assessment of greywater within the study area and the parameters of importance were identified to be BOD and COD.

Chapter four presents an exploration of activated carbon prepared from tropical almond shell and palm kernel shell in batch adsorption of BOD and COD. The capacity and kinetics of these materials were investigated using adsorption and kinetic models. The best performing material in this study was palm kernel shell and this was used in the next stage of the study.

Chapter four presents the performance of a fixed-bed column packed with activated carbon prepared from palm kernel shells for reducing BOD and COD in greywater. the data is evaluated using column models such as the Yoon Nelson, Thomas, BDST and Adams-Bohart.

Chapter six presents the use of socio-cognitive model known as the theory of planned behaviour (TPB) to predict the most preferred greywater reuse option that will be most appealing to users taking into consideration the cultural, social, religious, educational and gender perspectives.

Chapter seven explores the willingness of households to adopt or initiate greywater treatment and reuse systems at home using an extended model of the theory of planned behaviour with personal norm.

Chapter eight presents a general overview of the results of the study and lessons learnt and provides recommendations for future research and strategies for implementation.

two

Chapter two

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Abstract

This paper presents a literature review of the quality of greywater generated in different, especially developing, countries, constituents found in greywater, some treatment systems, natural materials for treatment, some reuse strategies and public perception regarding greywater reuse. The review shows that generation rates are mostly influenced by lifestyle, types of fixtures used and climatic conditions. Contaminants found in greywater are largely associated with the type of detergent used and influenced by other household practices. Many of the treatment systems reviewed were unable to provide total treatment as each system has its unique strength in removing a group of targeted pollutants. The review revealed that some naturally occurring materials such as *moringa oliefera*, saw dust, can be used to remove targeted pollutants in greywater. The study further showed that user perceptions towards greywater treatment and reuse were only favorable towards non-potable purposes, mostly due to perceived contamination or lack of trust in the level of treatment offered by the treatment system.

Keywords

Greywater, Reuse, Natural media, treatment systems, user perception.

Introduction

The total volume of freshwater on earth far outweighs the human demands. Out of the overall water resources on earth, about 97% can be found in the oceans while the remaining 3% remains available for direct exploitation, however, out of this 3%, the quantity of water that is available for use by humans is estimated at one-hundredth (Eakin & Sharman, 2010; Gleick, 1993). Uneven distribution of water in both time and space sways the use of water to other geographical areas depriving others of this resource. Biological survival remains one of the key factors of water use with its associated use also for household needs and for food production and other developmental needs. Many parts of the world are hit by acute water shortage, over-exploitation of water resources leading to gradual destruction of these water resources and high levels of freshwater pollution resulting from anthropogenic factors. Currently, it has been estimated that about 800 million people live under a threshold of water stress and this number is expected to reach three billion in 2025 (Qureshi & Hanjra, 2010; UNDP, 2017). Due to urbanization, industrialization and population growth, the demand for water is evident; however, will the available water resources meet the ever-growing needs in a sustainable manner? Where will the extra water that is required to sustain human activities come from? This question calls for interventions and strategies that will help address these concerns. This is where a cursory look at greywater reuse is worthwhile.

Greywater is defined as wastewater without any contributions from toilet water (Casanova et al., 2001; Ledin et al., 2001; Ottoson & Stenstrom, 2003). It is considered high volume, low strength wastewater with high potential for reuse and application. The composition of greywater is varied and depends on the lifestyle, fixtures and climatic conditions (Abedin & Rakib, 2013; do Couto, Calijuri, Assemany, Santiago, & Carvalho, 2013; Katukiza, Ronteltap, Niwagaba, Kansiime, & Lens, 2014). Reuse of greywater has been an old practice and it is still being done in areas that are water stressed. This practice if given the needed attention can help reduce the overreliance on freshwater resources and reduce the pollution caused by discharge of untreated greywater into freshwater resources. It can also be a supplementary source to existing water sources in areas where there is acute water crisis or in arid climatic regions. Recycled greywater can be used for different water – demanding activities including potable and non-potable uses such as toilet flushing and agriculture. The major concerns with greywater reuse have been issues with public health perceptions and inappropriate technology for the reuse option (Vigneswaran & Sundaravadivel, 2004). Many researchers have studied characteristics of greywater with respect to fixtures, life style patterns and type of settlement (Alsulaili & Hamoda, 2015; do Couto et al., 2013; Katukiza et al., 2014). However, the aim of this study is to assess the performance of greywater treatment system, to further review greywater reuse perceptions, to identify gaps of greywater systems with emphasis on developing countries and to identify scope for further research. This review used resources from peer reviewed journals, documents from the internet and text books. The methodological framework that guided this review is presented in figure 2.1.

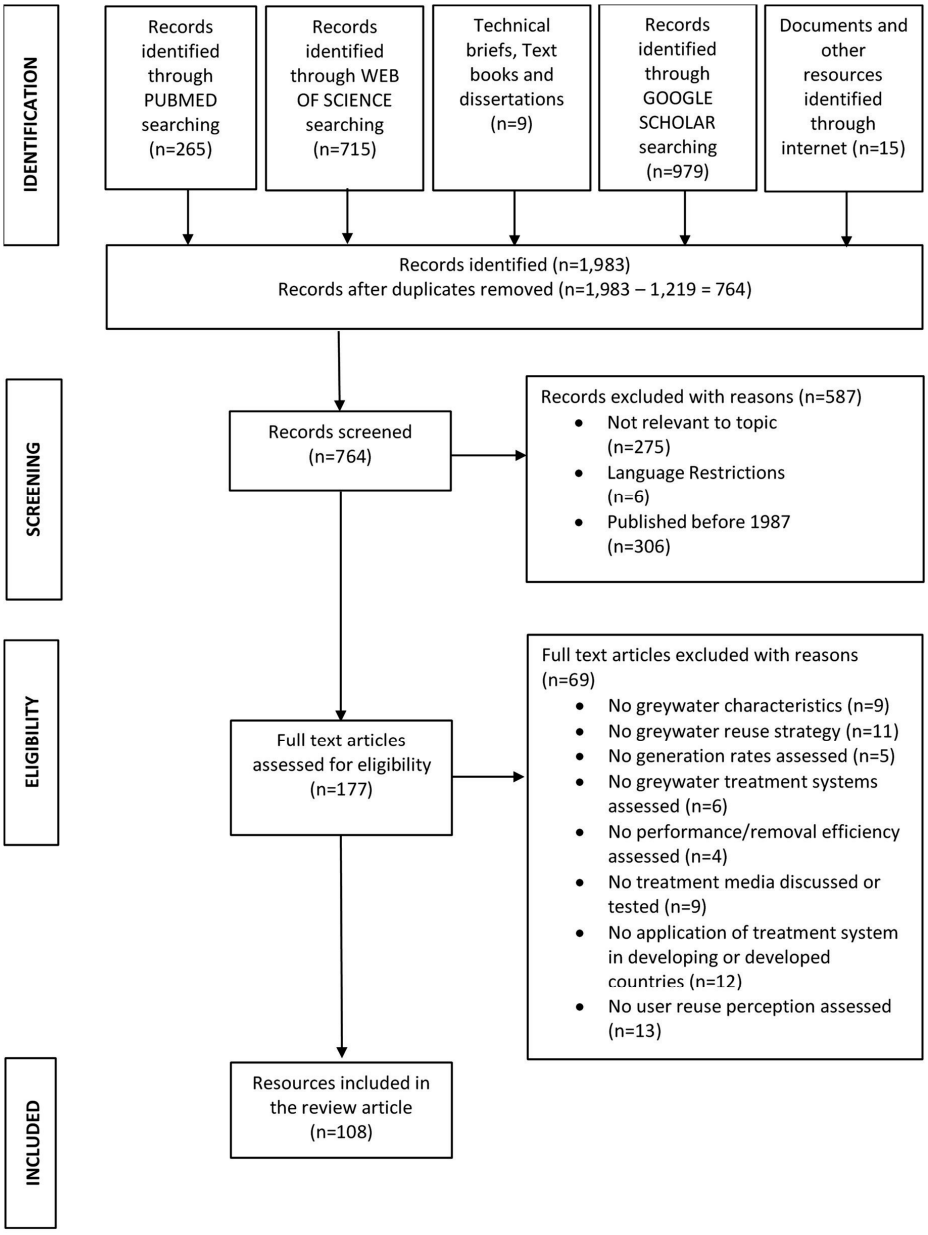


Figure 2. 1 Methodological framework

Greywater quantity

Greywater reuse has been considered as a reliable method of ensuring water security as compared to other methods of water capture such as rainwater harvesting which is dependent on hydrological conditions. The amount of greywater produced in a household can vary greatly ranging from as low as 15L per person per

day for poor areas to several hundred per person per day. Factors that account for such huge disparities are mostly attributed to geographical location, lifestyle, climatic conditions, type of infrastructure, culture, habits among others. Greywater accounts for up to 75% of the wastewater volume produced by households and this can increase to about 90% if dry toilets are used (Hernandez Leal, Temmink, Zeeman, & Buisman, 2010). It has also been estimated that greywater produced accounts for about 69% of domestic water consumption (A. Jamrah, Al Omari, Al Qasem, & Abdel Ghani, 2011). Table 2.1 presents different greywater generation rates in some reported studies in different countries.

Table 2. 1 Greywater generation rates in different studies

Location	Generation ($Lc^{-1}d^{-1}$)	Reference
Africa and Middle East	14-161	(Al-Hamaiedeh & Bino, 2010; Halalsheh et al., 2008; Morel & Diener, 2006)
Asia	72-225	(Morel & Diener, 2006)
Guateng, South-Africa	20	(Adendorff & Stimie, 2005)
Jordan	50	(Faraqui & Al-Jayyousi, 2002)
Mali	30	(M. C. Alderlieste & J. G. Langeveld, 2005)
Muscat, Oman	151	(A. Jamrah, Al-Futaisi, Prathapar, & Harrasi, 2008)
Nepal	72	(Shresta, 1999)
Stockholm	65	(Ottoson & Stenstrom, 2003)
Tucson Arizona, USA	123	(Casanova et al., 2001)
Vietnam	80-110	(Busser, Pham, Morel, & Nguyen, 2006)

Greywater composition

The composition of greywater varies and it is largely a reflection of the lifestyle and the type and choice of chemicals used for laundry, cleaning and bathing. The quality of the water supply and the type of distribution network also affects the characteristics of greywater. There will be significant variations in the composition of greywater in both place and time which may be due to variations in water usage in relation to the discharged quantity. The composition may also be affected by chemical and biological degradation of some compounds within the transportation and storage network**.** Generally, greywater contains high concentrations of easily biodegradable organic materials and some basic constituents which are largely generated from households. These include nutrients such as nitrates and all its derivatives, phosphorus and its derivatives, but others include xenobiotic organic compounds (XOC's) (Fatta-Kassinos, Kalavrouziotis, Koukoulakis, & Vasquez, 2011), biological microbes such as faecal coliforms, salmonella, and general hydrochemical constituents. Recent studies have however found pharmaceuticals, health and beauty products, aerosols, pigments, (Eriksson, Auffarth, Eilersen, Henze, & Ledin, 2003) and toxic heavy metals such as Pb, Ni Cd, Cu, Hg, Cr, (Aonghusa & Gray, 2002; Eriksson, Srigirisetty, & Eilersen, 2010) in appreciable concentrations in greywater. The presence of these contaminants in greywater is an indication of the gradual increase in the level of complexity in the composition of greywater.

Physical constituents

These are constituents that are associated with the physical appearance of greywater and include, temperature, turbidity, electrical conductivity, suspended solids, among others. Greywater normally has temperature range of between 18-35°C and the rather high temperature may be originating from warm water used for personal hygiene and cooking activities. These high temperatures may favour microbiological growth which is undesirable and may also cause precipitation of certain carbonates such as $CaCO_3$ and other inorganic salts which become less soluble at high temperatures. The concentration of total suspended solids

in greywater can range within 190-537mg/L as has been reported (Edwin, Gopalsamy, & Muthu, 2014; M. Oteng-Peprah, de Vries, & Acheampong, 2018). Greywater with much of the water originating from the kitchen and laundry accounts for the relatively high values of TSS and this may be due to washing of clothes, shoes, vegetables, fruits, tubers and many others which may contain sand, clay and other materials that could increase TSS. The ranges recorded for electrical conductivity in greywater is between 14-3000µScm^{-1} (Ciabatti, Cesaro, Faralli, Fatarella, & Tognotti, 2009; Prathapar et al., 2005). Groundwater sources and water scarce areas are mostly associated with high electrical conductivity due to dissolved materials. Poor or old plumbing materials also contribute to the increase in electrical conductivity due to leaching into greywater sources. The range of turbidity recorded for greywater is between 19 and 444NTU and it is mostly influenced by the water use activities. Greywater that has most of its sources originating from the kitchen and laundry is expected to become more turbid due to the presence of suspended matter.

Chemical contaminants

To identify the different chemical constituents in greywater, it is important to understand the sources of contaminants. Significant chemical constituents in greywater are from chemicals used for cleaning, cooking and bathing purposes. The pH in greywater to a large extent depends on the pH and alkalinity in the water supply and normally is within the range of 5-9. Greywater with most of its sources originating from the laundry will generally exhibit high pH due to the presence of alkaline materials used in detergents. The major chemical constituents found in greywater which is generated as a result of cleaning or washing activities are surfactant. These surfactants serve as the main active agent in most cleaning products. They can be either cationic or anionic in nature with a majority of cleaning and laundry products being anionic (Jakobi & Lohr, 1987). Cationic surfactants are generally salt based and they constitute a source of ammonium in the greywater. Other constituents found in greywater also include nitrates and phosphate which are reportedly from ammonium and, cationic surfactants and laundry disinfectants respectively (Eriksson, Auffarth, Henze, & Ledin, 2002). Other constituents such as sodium which is also from cooking and preservation activities in the kitchen can also be found in appreciable levels. Sodium based soaps also contribute significant quantity of sodium into greywater. Other additives such as builders control water hardness in detergents and also serve as the main source of phosphate contaminant in greywater (Lange, 1994). Nutrients such as N and P are associated with kitchen and laundry activities. Greywater sources with high nutrients concentrations are mostly made up of a high fraction of kitchen and laundry sources (Boyjoo, Pareek, & Ang, 2013). Kitchen waste are the primary source of nitrogen in greywater and range between 4-74mg/L while washing detergents are the primary source of phosphates found in grey water which also range between 4-14mg/L (Boyjoo et al., 2013).

The conventional wastewater parameters such as biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) always show a dominance of COD over BOD_5. The biodegradability of greywater is determined by the BOD_5/COD ratios. The ratio determines the ease with which bacteria can decompose the organic matter in the greywater. Mostly, all types of greywater show good biodegradability in terms of the BOD_5/COD ratios (Li, Wichmann, & Otterpohl, 2009). The average BOD_5/COD ratios in greywater have ranged between 0.31-0.71 which is an indication that almost half of the organic matter in greywater is biodegradable (Halalsheh et al., 2008). However, other studies have recorded ratios as high as 4:1 (Boyjoo et al., 2013). The dominance of COD to BOD_5 has largely been due to the presence of XOC's that increases COD. XOC's are synthetic organic compounds that are present in household chemicals and pharmaceuticals such as bleaches, surfactants, softeners and builders and beauty products. XOC's can also be formed by partial modification of chemicals in chemical or biological treatment of greywater (Fatta-Kassinos et al., 2011). XOC's are recalcitrant to conventional treatment protocols and can easily accumulate in plants and animals and subsequently pose risks to the natural environment (Fatta-Kassinos et al., 2011). It has been reported that about 900 potential

XOC's have been identified in greywater solely based on the ingredients of different cosmetics and detergents in Denmark (Eriksson et al., 2002). A study identified the presence of antibiotics in greywater which may lead to proliferation of resistant bacteria strains (Le-Minh, Khan, Drewes, & Stuetz, 2010). Another study (Revitt, Eriksson, & Donner, 2011) also identified the presence of benzene and 4-nitrophenol in greywater in appreciable concentrations. Other hazardous substances such as brominated flame retardants, polycyclic aromatic hydrocarbons, monocyclic aromatics and triclosans, phthalates have been identified in greywater (Palmquist & Hanaeus, 2005). Table 2.2 presents some selected physicochemical parameters of greywater with their concentrations in some selected high and low-income countries.

Table 2. 2 Physicochemical characteristic of Greywater s in low and high-income countries

Parameter	Low income countries				High income countries			
	India[a]	Pakistan[b]	Niger[c]	Yemen[d]	USA[e]	UK[f]	Spain[g]	Germany[h]
pH	7.3-8.1	6.2	6.9	6	6.4	6.6-7.6	7.6	7.6
Turbidity NTU	-	-	85	619	31.1	26.5-164	20	29
EC µS/m	-	-	-	-	23	32.7	-	64.5
TSS mg/L	100-283	155	-	511	17	37-153	32	-
TDS mg/L	573	102	-	-	171	-	-	-
BOD_5 mg/L	100-188	56	106	518	86	39-155	-	59
COD mg/L	250-375	146	-	2000	-	96-587	151-177	109
Cl mg/L	53	-	-	-	-	-	-	-
Oil & Grease mg/L	7	-	-	-	-	-	-	-
Nitrate mg/L	0.67	-	-	98	-	3.9	-	-
T. Nitrate mg/L	-	-	-	-	13.5	4.6-10.4	10-11	15.2
T. Phosp mg/L	0.012	-	-	-	4	0.4-0.9	-	1.6
FC (CFU)	-	-	-	1.9	-	-	-	$1.4x10^5$
E. Coli (CFU)	-	-	-	-	$5.4x10^5$	$10\text{-}3.9x10^5$	-	-
Ca mg/L	0.13	-	-	-	-	-	-	-
Mg mg/L	0.11	-	-	-	-	-	-	-
Na mg/L	32-50	-	-	-	-	-	-	-

[a](Parjane & Sane, 2011)
[b](Pathan, Mahar, & Ansari, 2011)
[c](Hu et al., 2011)
[d](Al-Mughalles, Rahman, F.B., Mahmud, & Jahil, 2012)
[e](Jokerst, Sharvelle, Hollowed, & Roesner, 2011)
[f](Birks & Hills, 2007; Pidou et al., 2008)
[g](March & Gual, 2007; March, Gual, & Simonet, 2004)
[h](Merz, Scheumann, El Hamouri, & Kraume, 2007)

Biological Characteristics

Greywater contains microorganisms such as bacteria, protozoa and helminths which are introduced into it by body contact. Inappropriate food handling in the kitchen and direct handling of contaminated food have been identified as sources of enteric pathogenic bacteria such as Salmonella and Campylobacter into greywater (Maimon, Friedler, & Gross, 2014; Ottoson & Stenstrom, 2003). Fecal contamination is also common in greywater and is largely associated with poor personal hygiene and disposal of greywater which contains washed nappies. Pathogenic E. coli and enteric viruses have been detected in greywater with majority of the water originating from laundry sources during a microbial monitoring programme in Melbourne Australia (O'Toole et al., 2012). In this study, 18% of samples contained enteric viruses, 7%

enterovirus and 11% of E. coli. The most common indicators used to assess fecal contamination are coliform bacteria and E. coli. Studies conducted by (Eriksson et al., 2002; Ottoson & Stenstrom, 2003) revealed a large collection of excreta-related pathogens associated with greywater**.** Other studies have further identified a number of pathogens in greywater and these are *Pseudomonas* (Benami, Gillor, & Gross, 2015a; Khalaphallah & Andres, 2012), *Legionella* (Birks, Colbourne, Hills, & Hobson, 2004), *Giardia* (Birks et al., 2004; Birks & Hills, 2007), *Cryptosporidium* (Birks et al., 2004), and *Staphylococcus Aureus* (Benami et al., 2015a; Kim et al., 2009; Maimon et al., 2014; Shoults & Ashbolt, 2017) in greywater. Table 2.3 presents some selected biological parameters with their concentrations as reported in other studies.

Table 2. 3 Biological characteristic of Greywater s in low and high-income countries

Name of microbe	Concentration	Source
Total coliforms Counts/100mL	$1.2x10^3 – 8.2x10^8$	(Alsulaili, Hamoda, Al-Jarallah, & Alrukaibi, 2017; Dwumfour-Asare, Adantey, Nyarko, & Appiah-Effah, 2017; Mandal et al., 2011; Masi et al., 2010; M. Oteng-Peprah et al., 2018)
E. coli	Up to $6.5x10^6$	(Atanasova et al., 2017; Friedler, Kovalio, & Ben-Zvi, 2006; Khalaphallah & Andres, 2012; Kim et al., 2009; M. Oteng-Peprah et al., 2018; Paulo, Begosso, Pansonato, Shrestha, & Boncz, 2009)
Fecal coliforms	Up to $1x10^6$	(Halalsheh et al., 2008; Mandal et al., 2011; Masi et al., 2010)
Pseudomonas aeruginosa	$1.4x10^4$	(Benami et al., 2015a; Khalaphallah & Andres, 2012)
Staphylococcus aureus	$1.2x10^2$- $1.8x10^3$	(Benami, Gillor, & Gross, 2015b; Kim et al., 2009; Maimon et al., 2014; Shoults & Ashbolt, 2017)
Salmonella typhi	$5.4x10^3$	(Kim et al., 2009)
Salmonella spp	$3.1x10^3$	(M. Oteng-Peprah et al., 2018)

Treatment systems

Management of greywater graduates from simple to extremely complex when the necessary strategies and technology is not in place or not properly implemented. Many developed countries have however implemented from simple to advanced methods of handling, managing and treating greywater with some countries recycling the greywater for both potable and non-potable uses. Treatment systems have been used to reduce the level of contamination in greywater before reuse or final disposal. They are contaminant-specific and each is applied along the conventional wastewater treatment sequence (pre-treatment, primary, secondary and tertiary treatment). Each of these systems adopt either a physicochemical or biological means of treatment. Physicochemical methods adopt physical and/or chemical methods of treatment including filtration, adsorption, reverse osmosis, among others. Biological treatment methods adopt a combination of microbes, sunlight and oxygen manipulation; examples of such systems include activated sludge systems, trickling filters, waste stabilization ponds, rotating biological contactors and many others. The widely used systems have mostly been filtration, rotating biological contactors, membrane bioreactors, constructed wetlands and upflow anaerobic sludge blankets (UASB). These systems have found their application in addressing the emerging greywater pollution experienced in most developing countries. This review therefore discusses the performance of these systems.

Filtration

Filtration involves removal of particulate matter which is not removed by preceding processes. In filtration systems, both physical and biological processes remove solids, however, this review considers only physical

removal of solids because that is the method adopted in most greywater treatment schemes. Filtration media could be in the form of sand, gravel, fine mesh and many others. Gross, Shmueli, Ronen, and Raveh (2007) studied the performance of a filtration system in greywater treatment using pebbles of 2cm thick placed over drain holes and followed by a 12cm middle layer consisting of 12cm of plastic filter media and finally topped by 4cm thick layer of peat. Dalahmeh et al. (2012) also studied the performance of a filtration system using pine bark, activated charcoal, polyurethane foam and sand as filter media in treating greywater. The performance of a coarse filtration system followed by slow sand filtration with a hydraulic retention time of 8hr and 24hrs respectively was studied by Finley, Barrington, and Lyew (2009). Parjane and Sane (2011) used coconut shell, coarse saw dust, charcoal, bricks and sand as filter materials to assess the performance of greywater treatment. A four-barrel filtration unit has been used to investigate greywater treatment by Al-Hamaiedeh and Bino (2010). These barrels were arranged in series and the first three were loaded with gravels of 2-3cm diameter. The final barrel was used to collect the treated effluent for irrigation. Gross (2008) adopted a hybrid filtration system utilizing a 130µm net filtration, a tuff filter, a sand filter and followed by electrolysis in Israel. Zuma, R, Whittington-Jones, and Burgess (2009) used a mulch tower system to treat greywater in south Africa. This was constructed by using mulch, coarse sand, fine and coarse gravel. This was contained in a 650mm high plastic column of 150mm diameter with a stainless-steel sieve mesh placed on top to remove big particles. From the reviewed filtration systems, only bark filters were able to meet the pH criteria for reuse. More so, only the bark and charcoal filters could meet the BOD_5 regulatory standard for reuse. Removal rates of total phosphorous was high in bark, charcoal and sand filters. The performance of filtration systems discussed is presented in table 2.4.

Constructed wetland

Constructed wetland (CW) is an artificial wetland constructed utilizing ecological technology to mimic conditions that occur in a natural wetland. The technology adopts special flora and fauna, soil and microorganisms to remove pollutants of interest. They are normally classified under three main types namely subsurface flow, surface flow and floating treatment wetland. The subsurface flow systems have been the most widely used constructed wetlands and they come in two main technologies, vertical flow constructed wetland (RVFCW) and horizontal flow constructed wetland (HFCW). Each removes contaminants by a combination of physical, chemical and biological processes and the treatment efficiency depends on factors such as loading rate and the availability of electron acceptors (Halalsheh et al., 2008). They have high potential of removing BOD_5, suspended solids, and some heavy metals such as Pb, Zn, Fe among others. The performance of a RVFCW was studied and it was observed that removal of ammonia nitrate was very low as compared to other systems (Gross et al., 2007; Travis, Wiel-Shafran, Weisbrod, Adar, & Gross, 2010). Gross (2008) also investigated the performance of HFCW in greywater treatment and observed that the quality of effluent improved if there was a pretreatment of the greywater**.** In this study, the average retention time was about 30hrs and it was realized that electrical conductivity increased from 170 to 190mS/m, T-N was reduced from 31 to 23mg/L and T-P was also reduced from 48 to 46mg/L representing 25.8 and 4.2% respectively. One major advantage of CW is its ability to run on its own without the attention of an operator. However, its removal rates for Na, Ca and Mg are relatively low and it also leads to increases in electrical conductivity (EC) which might be due to the dissolution of organic matter in the treated water leading to increase in the Total dissolved solids (TDS) and subsequently affecting the EC. They are also unable to remove some microbiological agents such as *E. coli* and helminth eggs and as such will require further treatment if the objective of the treatment is reuse. However, CW can produce effluents with BOD_5 and TSS meeting the regulatory limits. The removal efficiencies of these discussed CW are presented in table 2.4.

Rotating Biological Contactors

Rotating biological contactors (RBCs) are fixed bed reactors consisting of rotating disks and mounted on a horizontal shaft. They are partially submerged and rotated as wastewater flows through. The microbes that do the treatment are alternatively exposed to the atmosphere allowing both aeration and assimilation of dissolved organic pollutants and nutrients for degradation. Pathan et al. (2011) studied the performance of a single-stage RBC on greywater in Pakistan. The RBC was made of plastic sheets and the disks from textured plastic. The greywater was kept in the system for a specified period of time while the rotating discs were submerged up to 40% in the greywater**.** Friedler, Yardeni, Gilboa, and Alfiya (2011) studied the potential of RBC to remove indicator bacteria (Faecal Coliforms, Heterotrophic bacteria) and specific pathogens (*Pseudomonas aeruginosa sp*., *Staphylococcus aureus sp*.). The study concluded that RBC removed 88.5-99.9% of all four bacteria groups. Gilboa and Friedler (2008) studied the performance of RBC on removal of faecal coliforms (FC), *Staphylococcus Aureus sp*., *Pseudomonas aeruginosa sp*. and *Clostridium perfringes sp* in greywater using RBC followed by sedimentation. The study concluded that the system removed up to 99% of all these microorganisms which were in the greywater. RBC systems perform well with respect to pH, BOD_5, COD, reduced microbial loads and produced effluents that meet discharge guidelines. Performance of the system is presented in table 2.4.

Sequencing Batch Reactor

A sequencing batch reactor (SBR) is a type of activated sludge process used for wastewater treatment. All the treatment process takes place in batches in the reactor tank. The batch is sequenced through a series of treatment stages and performs equalization, biological treatment and secondary clarification in a single tank using a time-controlled sequence. Lamine, Bousselmi, and Ghrabi (2007) conducted a study on greywater treatment using SBR in a student house. This study assessed the performance of treatment by varying the hydraulic retention times (HRTs) and it revealed an effect on nitrification with the varying HRT**.** A similar study by (Scheumann & Kraume, 2009) also used a pilot scale SBR by varying the retention time and observed the removal of COD, NH_4-N, and TN was sufficient to meet discharge reuse guidelines, however, there was nitrification in this study as also reported by (Lamine et al., 2007). In this study, feed stock concentration of COD 250mg/L, NH4-N 11.9mg/L and TN = 17.1 were reduced to 18.9mg/L, 4.1mg/L and 0.37mg/L respectively all being below the mandatory values for reuse applications. Krishnan, Ahmad, and Jeru (2008) investigated the performance of greywater treatment from residential houses in Malaysia on a square bottom SBR at fixed HRT. An SBR has also been used in a demonstration project in the Netherlands to treat greywater from 32 houses (Hernandez Leal et al., 2010). SBRs have removal efficiencies of up to 98% for BOD_5 and COD, up to 80% TN and up to 99% for NH_4-N**.** The HRT has been found to be a limiting factor in the performance of SBRs since difference HRTs result in different effluent qualities as is shown in the different studies (Lamine et al., 2007; Scheumann & Kraume, 2009). The performance of this system has been presented in table 2.4.

Membrane Bioreactor

A membrane bioreactor (MBR) is a perm-selective process integrated with a biological process for treating greywater. It works on a combination of biological, microfiltration and ultrafiltration systems to achieve treatment. It is an appropriate solution that can be used for greywater treatment and reuse in densely urbanized areas where space has high value, due to its compact size. Atanasova et al. (2017) studied the performance of an MBR on greywater treatment in a hotel in Spain. The removal efficiency for COD ranged from 80 to 95%, where COD concentration in the effluent was below the quantification limit 30 mg/L based on the Spanish legislation for water reuse. Ammonia and TN removal were on average at high level 80.5% and 85.1% respectively. The treatment performance of an MBR made up of an ultrafitration membrane was also studied by Merz et al. (2007) on greywater from a sports complex in Morocco. Huelgas and Funamizu (2010) studied the treatment of greywater using a laboratory scale MBR under varying pressure. Jong et al.

(2010) also used anaerobic-anoxic-oxic MBR to treat greywater in Korea with micro filter of pore size 0.45µm. These systems could achieve very good effluent which meets regulatory standards for reuse. A nominal pore size of 0.1µm has been found to remove fecal coliforms. Performance of this system is presented in table 2.4.

Upflow Anaerobic Sludge Blanket

The Upflow anaerobic sludge blanket (UASB) has remained one of the most widely used wastewater treatment system for various types of wastewater streams. It works on an anaerobic process and retains a high concentration of active suspended biomass and produces better settleable sludge than other treatment systems. Greywater from 32 houses in the Netherlands were treated using this system (Hernandez Leal et al., 2010). Elmitwalli, Shalabi, Wendland, and Otterpohl (2007) also used this system to study the treatment of greywater in Lubeck Germany by varying the retention time. Abdel-Shafy, Al-Sulaiman, and Mansour (2015) investigated the efficiency of UASB in greywater treatment for unrestricted use in Egypt. The raw greywater characteristics with average concentrations of 95, 392, 298, 10.45, 0.4, 118.5 and 28mg/L for TSS, COD, BOD_5, TP, Nitrates, oil and grease, and TKN respectively was treated in a UASB. After treatment, the effluents concentration was 76.65, 165.4 96.85 and 19.31mg/L for TSS, COD, BOD_5 and oil and grease respectively. This represents removal efficiencies of 19.3% for TSS, 57.8% for COD, 67.5% for BOD_5 and 83% for oil and grease. UASB's perform better when they are integrated with other systems. The performance of the system is presented in table 2.4.

Table 2. 4 Treatment efficiencies of some selected greywater treatment systems

Parameter	Filtration[a]	Wetlands[b]	SBR[c]	RBC[d]	MBR[e]	UASB[f]
Turbidity NTU	-	-	-	-	98-99%	-
EC uS/m	-	-	-	-	-	-
TSS mg/L	53-93%	90-98%	-	9-12%	Up to 100%	-
TDS mg/L	-	-	-	-	-	-
BOD_5 mg/L	89-98%	up to 99%	90-98%	27-53%	93-97%	Up to 67%
COD mg/L	37-94%	81-82%	90-98%	21-61%	86-99%	38-79%
Cl mg/L	-	92-94%	-	-	-	-
Oil & Grease mg/L	Up to 97%	Up to 95.45	-	-	-	83.7%
Nitrate mg/L	17-73%	-	-	-	6-72%	-
T. Nitrate mg/L	5-98%	26-82	80%	-	52-63%	24 to 58%
T. Phosp mg/L	Up to 100%	Up to 71%	-	-	Up to 19%	10 to 39%
FC (CFU)	-	-		88.5-99.9%	Up to 99%	-
E. Coli (CFU)	Up to 100%	-		88.5-99.9%	-	-
Ca mg/L	Up to 100%	-	-	-	-	-
Mg mg/L	Up to 100%	-	-	-	-	-
Na mg/L	47%	-	-	-	-	-

[a] (Al-Hamaiedeh & Bino, 2010; Dalahmeh et al., 2012; Finley et al., 2009; Gross, 2008; Parjane & Sane, 2011; Zuma et al., 2009)

[b] (Gross, 2008; Gross et al., 2007; Travis et al., 2010)

[c] (Hernandez Leal et al., 2010; Krishnan et al., 2008; Lamine et al., 2007; Scheumann & Kraume, 2009)

[d] (Friedler et al., 2011; Gilboa & Friedler, 2008; Pathan et al., 2011)

[e] (Atanasova et al., 2017; Huelgas & Funamizu, 2010; Jong et al., 2010; Merz et al., 2007)

[f] (Abdel-Shafy et al., 2015; Elmitwalli et al., 2007; Hernandez Leal et al., 2010)

Naturally occurring greywater treatment media

These are naturally occurring materials that have been applied as either standalone media or used as a complementary medium in some of the available conventional greywater treatment systems. Many researchers have studied the effect of treatment offered by these media and their performance is listed in table 2.5. Unlike other conventional treatment systems, these media are used for removing targeted contaminants and their mode of treatment is either by adsorption, filtration or coagulation.

Table 2. 5 Naturally occurring materials for greywater treatment

Type of material	Target pollutant removal	Percentage removal	Mode of removal	Source
Activated carbon	BOD_5	97%	Adsorption	(Sahar et al., 2012)
	COD	94%		
	TN	98%		
	TP	91%		
Activated Charcoal	EC	12%	Adsorption	(Dalahmeh et al., 2012)
	BOD_5	97%		
Peat Moss and Lime pebbles	COD	90%	Filtration	
	BOD_5	95%		
	E.Coli	100%		
Pine Bark	BOD_5	98%	Adsorption	(Sahar et al., 2012)
	COD	74%		
	TN	19%		
	TP	97%		
Moringa oliefera	COD	64%	Coagulation	(Bhuptawat, Folkard, & Chaudhari, 2007)
	Turbidity	98%		(Hendrawati et al., 2016)
	Conductivity	11%		
	BOD_5	12%		
	Turbidity	96%		(Effendi, Sari, & Hasibuan, 2015)
	TSS	88%		
Saw dust	TSS	83%	Filtration	(Parjane & Sane, 2011)
	TDS	70%		
	O&G	97%		
	COD	82%		

Reuse strategies

A number of greywater treatment and reuse schemes have been implemented across the globe using both conventional and hybrid systems. Most of these systems have been developed as an environmental intervention measure and have since been operational while some have had their own challenges from both the technical and public point of view. Table 6 presents some examples of successful application of greywater treatment and reuse schemes in some countries.

Table 2. 6 Greywater reuse strategies in some developing countries

Location	System Used	Application	Performance	Source
Auroville, India	Reed beds and irrigation beds using banana	Treats greywater from a student dormitory.		(Chuck, 2004)
Koulikoro, Mali	Vertical flow filter and greywater garden	Treats greywater generated by a community and the treated greywater is used in subsurface irrigation of fruits and vegetables		(GTZ, 2005)
Mexico	Bioreactor and mulch bed	Treats greywater for a rehabilitation center for children		
Djenne, Mali	Infiltration trench	Was intended to stop the unregulated discharge of greywater into the streets. Unsightly conditions ceased within the community because greywater was discharged into trenches		(M. C. Alderlieste & J. G. Langeveld, 2005)
Gauteng, South Africa	Tower garden	Was intended to promote gardening due to proximity to water for irrigation and further empower the unemployed aged financially. Leafy vegetables are planted into the silts and its embraced by many people		(Adendorff & Stimie, 2005)
Monteverde, Costa Rica	Constructed wetlands, Submerged flow reedbeds	Was intended to be used to treat greywater from single households to prevent discharge of greywater into the environment. Treated greywater was used to irrigate reeds which was an economic plant.		(Dallas, Sceffe, & Ho, 2004)
Kuching, Malaysia	Anaerobic filter, horizontal flow planted filter	An intervention to stop discharge of septic tank effluent directly into stormwater drains and subsequently into receiving water.	Oil and grease: 99% TSS: 96% BOD_5: 99% COD: 95% NH_4-N: 94% T-P: 88% T-N: 76%	(Chong, 2005)
Billen, Palestine	Anaerobic upflow filters, aerobic filter	Intended to reduce frequency of desludging in a city which is water stressed	TSS: 93-96% BOD_5: 78-95% PO_4-N: 39-74% NO_3-N: 39-74%	(Mahmoud, Amarneh, Al-Sa'ed, Gijzen, & Lettinga, 2003)

Sri Lanka	Anaerobic filter, vertical-flow planted filter	Greywater treatment systems in some selected hotels and schools		(Harindra, 2001)
Kathmandu, Nepal	Vertical flow planted filter	A local responsive approach to solve problems of water scarcity in Nepal. The greywater treated is reused for other non-potable purposes while the impact of this system leads to significant savings in water expenditure.	TSS: 97% BOD_5: 98% COD: 93% PO_4-P: 33% NH_4-N: 96%	(Shrestha, Haberl, & Laber, 2001)
Monteverde, Costa Rica	Horizontal-flow planted filter	An intervention to stop haphazard discharge of greywater onto the streets and into streams. This caused unsightly conditions. After construction of this system, conditions improved.	BOD_5: 99% NH_4-N: 95% PO_4-P: 84%	(Dallas & Ho, 2005)
Tufileh, Jordan	Automated greywater system	Optimization and validation of a system for reusing greywater in home gardens in Jordan		(Al-Jayousi, 2003)

Greywater reuse perceptions

Public perception which is a social phenomenon can be seen as the difference between an absolute truth based on facts and virtual truth shaped by popular opinion (Conjucture, 2017). In implementation of any project public perception has been recognized as an integral factor in determining the success of the project. Many technically sound and environmentally friendly programs have failed because it was not accepted by the intended beneficiaries. Several studies have been conducted to assess public perception towards greywater reuse in different parts of the world using different strategies. These strategies include interviews, questionnaires, focus group discussions, informal discussions and other equally good social surveys. Most of these surveys identified clear support for the concept of greywater reuse as an environmentally sustainable method of protecting freshwater resources and pollution prevention. It has been reported by (Dolnicar & Schafer, 2006; Friedler, Lahav, Jizhaki, & Lahav, 2006; Hurliman & McKay, 2007; Kantanonleon, Zampetakis, & Manios, 2007; Marks, 2004) that the highest acceptability of greywater reuse schemes are for non-potable uses. S Dolnicar and Schafer (2006) identified reduced levels of acceptance as the recycled water got closer to human contact. A similar study by Jeffery (2001) in the United Kingdom identified that people were more willing to use 'own' recycled greywater than to use recycled water from an unknown source. Alhumoud and Madzikanda (2010) identified that public support was greater for areas which are water stressed and areas with unreliable water supply. The results of a study by Adewumi, Olanrewaju, Ilemobade, and van Zyl (2010) conducted in three universities in South Africa among students and staff concluded that the level of education and level of awareness contributes to the success of greywater reuse. Religious and cultural practices have been identified as factors that influence reuse programs. This is supported by another study by (DeSena, 2006; Parkinson, 2008) who identified misinformation, lack of knowledge or instinctive repugnance as accounting for objections in reuse programs.

Potable reuse perceptions

The interruption and complete obstruction of many potable water reuse projects by stiff public opposition have been reported by (DeSena, 2006; Hurliman & Dolnicar, 2013; Meehan, Ormerod, & Moore, 2013). This stiff opposition to potable reuse has been attributed to the close association of greywater with sewage which creates a phenomenon known as wisdom of repugnance. This phenomenon assumes that recycled water is associated with human waste therefore it renders it unpalatable from the public's point of view. A study by Marks (2004) in three developed countries (Australia, United States and United Kingdom) identified low public support and acceptance for greywater reuse for potable purposes. The main barrier encountered in these studies were the associated perceived health risk of reusing recycled water in activities that involve direct contact with the user. Other studies identified language of the names given to recycled water as one of the obstacles affecting reuse schemes (Dolnicar & Saunders, 2006). A study by (Friedler, Lahav, et al., 2006; Omerod & Scott, 2013; Russell, Lux, & Hampton, 2009) identified public trust arising out of a combination of technical and non-technical issues. The study identified strong public opposition to reuse projects where there is little trust in the implementing body even in the face of the most advanced technology applicable. Currently most of the research in this area is targeting determinants that increases acceptance of reuse programs.

Conclusions

This study reviewed greywater characteristics, treatment systems, reuse strategies and perception of greywater reuse among users. It shows that there is a wide variation in greywater characteristics and volume generation rates which is largely dependent on the water use, lifestyle patterns and type of

settlement. From the list of reviewed conventional treatment systems, filtration methods seem feasible and has the potential of integration with other systems to achieve target specific treatment. The study described different reuse strategies, most using discharged greywater for food production and landscaping while others have been used for poverty alleviation in irrigation farming.

The available technologies have been developed to treat or remove specific pollutants and not offer a full treatment of the greywater. Moreover, quality criteria differ for each type of reuse application and greywater composition and generation rates vary greatly from one point to the other. It will therefore be prudent if systems are designed to target a specific reuse option taking into consideration the regional variability and complexities such that effluent from a treatment system will meet the required effluent guidelines. All the treatment systems reviewed were applicable on large scale and cannot be applied at the household level. This in our view discourages local level participation in greywater reuse schemes. From the review the potential of some natural materials to be used as media in greywater treatment systems also emerged. These natural materials are widely available in most developing countries and their total integration into the conventional treatment systems should be explored. They can be used to design simple household level greywater treatment systems that target a certain reuse option and thereby increase local level participation.

Perception of greywater reuse has been closely related to the choice of reuse as most users will want to reuse greywater for activities that do not involve personal contact. In general, public perceptions are important to consider when implementing a certain method for a specified use. On the basis of this review we conclude that to achieve effective greywater treatment and reuse, extensive contributions from technical and non-technical experts in many disciplines are called for. It also requires a comprehensive assessment of the greywater characteristics in order to choose an appropriate method or system of treatment. That notwithstanding, greywater treatment and reuse if embraced and enforced can lead to substantial decline in over-reliance on freshwater resources for non-potable uses.

three

Chapter three

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Abstract

The quantity and quality of combined greywater from houses with in-house water supply and houses that rely on external sources of a peri-urban area in a developing country were determined. Data for quantity of greywater was collected from 36 households while 180 samples of greywater were collected from 60 households between December 2016 and February 2017. The results indicate that, average water consumption from households with in-house access was 82.51 ± 12.21 $Lc^{-1}d^{-1}$ while households which rely on external sources was 36.64 ± 4.31 $Lc^{-1}d^{-1}$ with return factors of 74.16% and 88.57% respectively. Quality analysis also showed significant differences between greywater from the two sources with most of the quality parameters exceeding the regulatory limit. The ratio between biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) ranged between 0.22–0.59 for greywater from in-house sources and 0.23-0.62 for external sources indicating low biodegradability of the greywater. The nutrients recorded exceeded the trigger levels for eutrophication while significant levels of microorganisms such as *E.Coli* and *Salmonella spp.* were also detected in both streams. Direct reuse of greywater for irrigation was found to be unsuitable based on the salinity and sodium hazard analysis. Principal component analysis of the data indicated that the characteristics of the combined greywater in the study area is influenced by cooking and cleaning practices, personal hygiene, biodegradability, frequency of water use before disposal and sanitary practices in the bathroom. The greywater discharged is detrimental to the environment and poses a health risk to humans and livestock. There is therefore the need for authorities involved to prioritize greywater management and treatment in peri-urban areas of developing countries.

Keywords:

Peri-urban, Greywater, in-house, outside source, Ghana

Introduction

The united nations define a peri-urban area as an area between consolidated urban and rural region (UNICEF, 2012). In developing countries, it is where poverty and social displacement are more common, a frontline between the problems of the city and the rural areas. The growth of these peri-urban areas in developing countries are associated with sanitation challenges such as solid waste, excreta collection and management and wastewater management for the relevant institutions. Due to the disparities in economic and social status associated with peri-urban areas in developing countries, certain basic amenities like water supply within a house is not automatic for every house. Houses without piped water in their dwelling will have to resort to other sources of water such as from water vendors, springs, streams among others. Many of these peri-urban areas in developing countries are saddled with wastewater management largely due to the non-existence of sewer network. The primary focus on peri-urban areas by authorities has remained solid waste and excreta management which is aimed at improving the sanitary conditions and improving public health. However, this is in sharp contrast to greywater management which accounts for the high volumetric flux of wastewater generated in non-sewered areas. There is a clear lack of planning in addressing greywater management in peri-urban areas in developing countries mostly arising from lack of commitment or by the overwhelming rapid growth associated with these areas. Lack of proper management of greywater in peri-urban areas of developing countries has led to indiscriminate discharge of greywater, which has contributed to public health issues arising out of uncontrolled and unmonitored discharges. These discharges result in both short term and long-term effects on both environment and human (Gross et al., 2005; Scott & Jones, 2000). It also affects water resources and soils due to the presence of surfactants, (Mohamed, Kassim, Anda, & Dallas, 2013), heavy metals (Aonghusa & Gray, 2002; Eriksson et al., 2010) in high quantities. Nutrient buildup in water bodies as a result of greywater discharge may lead to eutrophication which is detrimental to aquatic environment. (Kohler, 2006) in his research identified sodium polyphosphate which is a major ingredient in soaps to be a major contributor of nutrients in eutrophication. Studies conducted by (Escher & Fenner, 2011; Taghipour & Mosaferi, 2013) identified a distortion in the ecological balance due to toxicity of food chain caused by accumulation of heavy metals and micro-pollutants in the environment which negatively affects both plants and animals alike after long exposure times. Long periods of exposure to pathogens and microorganisms in greywater has been reported to cause diseases that results in either mortality or morbidity (Birks & Hills, 2007; Ottoson & Stenstrom, 2003). Many studies have all analyzed greywater without cognizance to the source of water and the lifestyle patterns. Research on greywater characterization and quantity generations has largely focused on sources such as kitchen, bathroom, hand wash basin (Abedin & Rakib, 2013; Katukiza et al., 2014), water use fixtures such as washing machines, dishwashers (Abedin & Rakib, 2013; O'Toole et al., 2012) and location or type of settlement such as peri-urban and slums, (Antonopoulou, Kirkou, & Stasinakis, 2013; do Couto et al., 2013; Katukiza et al., 2014; Ramona, Green, Semiat, & Dosoretz, 2004).

However, the differences in quality and quantity between greywater from houses fitted with household taps and those that rely on other external sources of water in a peri-urban area in a developing country remains uninvestigated. According to the UNDP (2017), about 663 million people lack access to improved water and a majority of this fraction are in developing countries. This is an indication that greywater discharges from peri-urban areas in developing countries should not be treated as all coming from one source as has always been the case in many studies that have characterized greywater quality and quantities.

The objective of this study therefore is to characterize greywater and quantify its pollutant loads for these two categories in a typical peri-urban area of a developing country within sub-Saharan Africa and provide the relevant data necessary to policy makers to inform decision and influence policy.

Materials and methods

Study area

This study was conducted in the Komenda Edina Eguafo Abirem (KEEA) municipality of the Central region of Ghana during the periods of December 2016-February 2017. KEEA is located in the central region of Ghana between longitude 1^0 20' West and 1^0 40' West and latitude 5^0 05' North and 15^0 North and covers an area of 452.5km^2 with a population of 144,705 (GSS, 2014). It is located within the coastal belt of the country along the Atlantic Ocean and it is drained by the Benya lagoon. Potable water supply to the area is exclusively by Ghana Water Company Limited (GWCL) which has a network coverage of less than 40% within the municipality while other areas which are not connected to the GWCL lines resort to alternative water supply systems such as groundwater, streams and springs, rainwater and water vendors. Greywater is discharged through open gutters and undeveloped plots. Other methods of disposal also include direct irrigation of certain plant species such as *Musa Balbisiana*, *Carica Papaya* among others and open discharge onto compounds in areas where there are no gutter or undeveloped plots. Majority of residents use on-site sanitation systems such as septic tanks and household latrines while others rely on public sanitation facilities. These practices are mostly common in peri-urban areas in developing countries within the sub-Sahara Africa, Latin America, and Asia. There is no wastewater management system in place and wastewater is discharged without any regulation. This survey was done in different towns/villages within the study area in order to have a cross-sectional variation in water use and greywater generation rates and also simulate similar conditions in other developing countries.

Selection of households: Characterization

Greywater samples were collected from all six zonal councils within the study area. A total of one hundred and eighty (180) samples were collected from the study area. Sixty households were selected to participate in the study within the six zonal councils after consultation with local leaders within the community. The criteria for selecting these households were willingness to participate in the study, households with in-house access, households that rely on outside sources, households with children under age 3, households that have greywater from kitchen, hand wash basin and bathrooms going through one discharge point. Volunteers were asked to discharge water used for laundry into this drain during the periods of data collection.

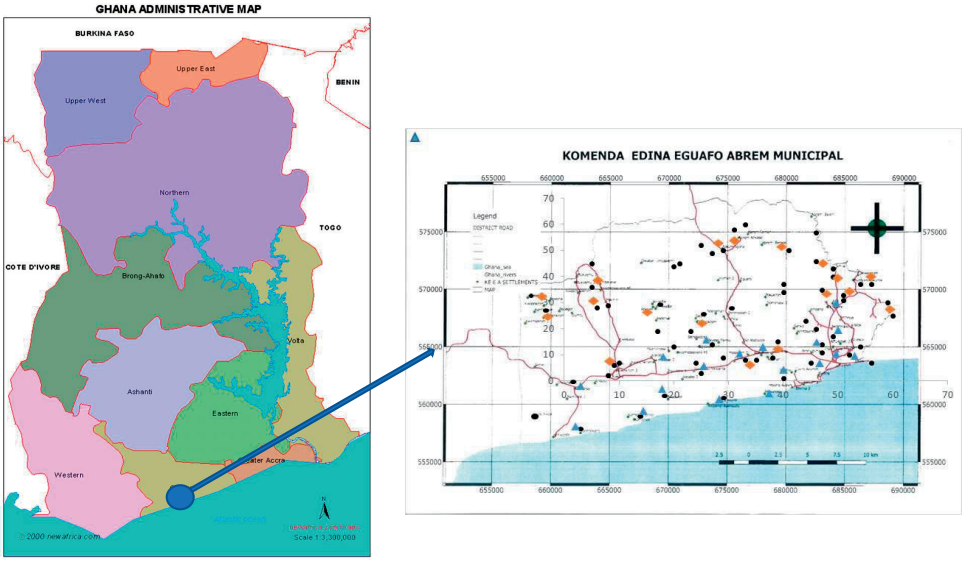


Figure 3. 1 Map of study area with sampling points

Selection of households: Volume estimation

Volume estimation was done by recruiting two sets of volunteers – those with in-house access and those who rely on an outside source. Criteria for selection of volunteers with in-house access was willingness to participate in the study. With respect to those who rely on outside sources, the criteria for selecting such volunteers were willingness to participate, willingness to use special 20L buckets provided for the study to collect both potable and greywater after use.

Collection of greywater samples: Quality estimation

Greywater samples (n=180) were collected and stored in sterilized 0.5L sample bottles and 0.2L sterilized glass bottle for oil and grease analysis. The sampling points indicated with round dots are shown in figure 3.1. These samples were stored in laboratory ice chest with ice packs and transported to the laboratory for analyses within 24hours.

Collection of greywater samples: Volume estimation

A total of 18 households with in-house access were provided with a special digital flow meter – white-line smart flowmeter. The discharge spouts of their wastewater discharge lines were retrofitted in order to install this flowmeter. This flowmeter is not disturbed by solids and has a very low sensitivity (0.5 $Lmin^{-1}$). However, the drawback of this flowmeter is its inability to read more than 1000L. Volunteers were alerted of this and were given a tally card to record the number of times it resets itself after recording 1000L. The volume recorded on the water meter supplied by GWCL is taken before the study was initiated in order to estimate the volume of water that will be used by the household. Sampling points represented by triangle are presented in figure 3.1. Participants were also asked to note any day when there was no water supply.

A total of 18 households that relied on outside sources were selected in this study. These households were given special 20L buckets for use during the study period to help estimate the quantity of water used. To help estimate the volume of greywater discharged, they were asked to pour greywater generated into

these 20L buckets before final disposal. A tally card indicating the number of times the bucket got full and was emptied and the number of times they fetched water with the bucket was given to each household. Sampling points represented by diamond is presented on figure 3.1.

Laboratory analysis

The following parameters: pH, Dissolved Oxygen (DO), Electrical Conductivity (EC) and Total Dissolved solids (TDS) were measured on site using a Horiba U-50 multi parameter water quality meter. The concentrations of Nitrate-nitrogen (NO_3-N), Ammonium-nitrogen (NH_4-N), Total Suspended Solids (TSS), Chloride (Cl^-) and Potassium (K) were measured using a HACH DR6000 spectrophotometer according to HACH methods 8171, 8006, 8113 and 8049, respectively. The five-day Biochemical Oxygen Demand (BOD_5) concentration was determined using the Lovibond BD 606 BOD system. The concentration of Chemical Oxygen Demand (COD) was determined using the closed reflux colorimetric method as stated in (APHA) 5220C. The concentration of Sodium (Na^+) was determined with flame photometer while total phosphorous (T-P) was determined using the persulfate method as stated in (APHA) 4500-P. Oil and grease concentrations were determined using the partition gravimetric method as stated in the (APHA) 5520-B. Concentrations of Magnesium (Mg^{2+}) and Calcium (Ca^{2+}) were determined with atomic absorption spectrometric method using a Varian AA 50 spectrometer. The bacteriological parameters (Total coliforms, *E.coli* and *Salmonella spp.*) were determined with *chromocult* coliform agar media using spread plate method as outlined in the (APHA) 9215C.

Statistical analysis

Independent t-tests were used to determine the statistical significance in the parameters measured between greywater from In-house and outside sources. Principal component analysis (PCA) was used to reduce the dimensionality of the data from 17 to 5 using Oblique rotation (direct oblimin). An oblique rotation is recommended if there is a good reason to suppose that the underlying factors could be related in theoretical terms (Field, 2014). This method of rotation was adopted because there is theoretical evidence that suggests some of the factors may be related. PCA is used to reduce a data set to a more manageable size while retaining as much of the original information as possible. All statistical analyses were carried out using IBM SPSS statistics 21 and Microsoft Excel.

Results and Discussion

Water consumption and greywater volume generation

Independent sample t-tests were conducted to compare water consumption, greywater generation and return factors between in-house access and outside access. Summary results are presented in Table 3.1.

Table 3. 1 T-test Results of water consumption and greywater generation rates

	Outside Source	In-house Access	t-test for equality of means		
	N=18	*N=18*	p	t	df
Water Consumption ($Lc^{-1}d^{-1}$)	36.64 (±4.3)$_a$	82.51 (±12.21)$_b$	0.00	15.02	34
Greywater generation ($Lc^{-1}d^{-1}$)	32.44 (±3.83)$_a$	73.41 (±11.01)$_b$	0.00	14.91	34
Return factor %	88.57 (±3.4)$_a$	74.16 (±2.56)$_b$	0.00	14.32	34

Values in the same row not sharing the same subscript are significantly different at p< .05 in the two-sided test of equality for in-house and outside source greywater.

The average water consumption of and 36.64 $Lc^{-1}d^{-1}$ for outside access and 82.51 $Lc^{-1}d^{-1}$ for in-house source were above the minimum recommended value of 30 $Lc^{-1}d^{-1}$ (UNICEF, 2016) but below the national average

of 100 $Lc^{-1}d^{-1}$ (GWCL). These differences can be attributed largely to lifestyle and sanitation facilities and practices adopted by these two groups. The water consumption recorded for in-house access falls within the range of a similar study in South Africa by (CSIR, 2001; Schalkwyk, 1996), which recorded water consumption within 30-100 $Lc^{-1}d^{-1}$ for in-house access. The return factors of 88.57% and 74.16% recorded for this study were within the range reported by other studies (Alderlieste & Langeveld, 2005; Busser et al., 2006; Faraqui & Al-Jayyousi, 2002; Shresta, 1999). These results suggest that access to in-house connection is likely to lead to increase in water consumption and its associated greywater generation. The high return factor recorded for greywater from outside access can be attributed to sanitation and hygiene practices. Most people under this category use dry sanitation systems such as pits or patronize public sanitation facilities. It could also be attributed to other factors such as distance, reliability of source and many other latent factors. It has been reported that households with dry latrines can record as high as 100% return factors (SANDEC, 2006). Studies of greywater generation rates from different sources is presented in Table 3.2.

Table 3. 2 Rates of greywater generation from in-house and outside water sources reported in similar studies

Location	Generation ($Lc^{-1}d^{-1}$)	Water source	Reference
South-Africa	20	Outside source	(Adendorff & Stimie, 2005)
Mali	30	Outside source	(Alderlieste & Langeveld, 2005)
Nepal	72	In-house source	(Shresta, 1999)
Vietnam	80-110	In-house source	(Busser et al., 2006)
Jordan	50	In-house source	(Faraqui & Al-Jayyousi, 2002)
Ghana	32	Outside source	This study
Ghana	73	In-house source	This study

Greywater characteristics

Summary results of independent t-tests on greywater quality parameters comparing in-house and outside source is presented in Table 3.3. Most of the physical parameters measured exceeded the permissible limits set by the regulating agency which is the Environmental Protection Agency of Ghana (EPA). The pH recorded was within a range of 5 – 8 but the average pH of 7 was within the acceptable range of 6 – 9. The extreme pH of 5 recorded in some of the samples could be attributed to organic acids produced by edible organic compounds while the high pH of 8 could be partly attributed to the use of sodium hydroxide-based soaps. However, there is no significant difference between the pH recorded in both groups (p=.62). This indicates that having in-house source or relying on outside source has no influence on the pH of the greywater generated. The average values of (DO) recorded within the study area were within the acceptable limits. However, the range recorded showed some samples which were below the acceptable limits set by the EPA. Although no significant differences were observed between these two groups the low DO recorded could be attributed to water storage practices which is very common within the study area. Low dissolved oxygen impairs aquatic organisms and also creates septic conditions for water. The average electrical conductivity (EC) of 2,044 μScm^{-1} for outside sources and 1617 μScm^{-1} for

in-house sources recorded were above the regulatory limit of 750 μScm^{-1} for both groups. There is a significant difference (p=.00) between the two groups, which implies EC of greywater from outside sources is higher than in-house sources. This could be due to extensive use of water in the form of internal recycling practices such as reusing laundry water for scrubbing or rinsing cooking pots and pans in the same bowl of water, which are mostly practiced by houses that rely on outside source. This internal recycling leads to massive buildup of dissolved ions in the water, which increases the electrical conductivity. It could also be from the sources of water, which might largely be groundwater sources. Since the study area is close to the sea, groundwater supplies could have very high EC. This phenomenon is also confirmed in the results from the Total Dissolved Solids. The average TDS of 1,288 mgL^{-1} recorded for greywater from outside sources is higher than concentration of 1,010 mgL^{-1} recorded for greywater from in-house sources, which is statistically significant at p=.00. The TDS concentrations for both groups also exceed the regulatory guideline limits of 50mgL^{-1}. TDS is largely due to the presence of salts and other dissolved fractions in greywater. A linear trend with positive slope shows a significant correlation between these two parameters, which is also established in other studies (Tchobanoglous, Burton, & Stensel, 2003) that TDS is a factor of EC.

The concentration of Total Suspended Solids (TSS) for both groups were below the regulatory limits. The TSS measured also indicate that greywater from in-house sources had lower TSS concentration of 269 mgL^{-1} than that of 538 mgL^{-1} from outside sources, the difference of which is statistically significant (p=.00). These differences in concentrations can be attributed to the quantity of water used. High total suspended solids in greywater can lead to cloudiness in the receiving water body, impair visibility and cause reduction in dissolved oxygen in the receiving water body. It can also lead to buildup of sediments in the receiving water body or drain and create suitable conditions for flooding. The high concentration recorded for greywater from outside sources could be due to the repeated use of water for different activities before it is finally disposed.

The average concentration of BOD_5 for in-house access was 204 mgL^{-1} and outside access was 253 mgL^{-1} while the COD concentrations were 644 mgL^{-1} for in-house and 744 mgL^{-1} for outside access. This difference is statistically significant at p=.05 and p=.00 for BOD_5 and COD respectively. Comparing the concentration range of greywater from outside sources to greywater from in-house sources, which is BOD_5 of 61.5 mgL^{-1} – 301 mgL^{-1} and COD of 207 mgL^{-1} – 1,299 mgL^{-1}, it can be seen that all the concentrations are above the permissible limits set by the regulatory agency. This indicates that greywater from outside sources had higher BOD_5 and COD than those from in-house source. This could be due to some form of internal recycling within the house before the greywater is finally discharged, hence, accounting for the higher concentration of biodegradable and non-biodegradable materials within the greywater. It could also be attributed to excessive disposal of biodegradable and non-biodegradable materials into greywater. Nevertheless, BOD_5 and COD values recorded for both areas were within the range for greywater (Tchobanoglous et al., 2003). The relatively low values recorded for in-house source may, however, be attributed to dilution. Therefore, discharging greywater with high BOD_5 and COD concentrations into drains and surface water can result in oxygen depletion and impair aquatic life. A similar study have reported BOD_5 ranges of 102-215 mgL^{-1} and COD of 425-1583 mgL^{-1} for greywater (Hernandez, Leal, Zeeman, Temmink, & Buisman, 2007).

The concentration of Sodium (Na^+) in greywater samples from outside sources, which is 140 mgL^{-1} was significantly higher than that of in-house source of 119 mgL^{-1} at p=.00. The concentration of both groups exceeded the regulatory limit. The differences observed can be attributed to the type of soaps used by both groups. The source of Na^+ could be from cooking salt and detergents. Dilution or the source of water can also play a role in the marked differences recorded between these two groups. The presence of Na^+

in greywater can lead to Na^+ buildup within the environment, which is detrimental to plant growth (Tavakkoli, Fatehi, Coventry, Rengasamy, & McDonald, 2011). It also increases the electrical conductivity of water as well as its Total Dissolved Solids. The results obtained in this study is within the range reported in a similar study by Leal, Zeeman, and Buisman (2011), which reported Na^+ concentrations of 123-144 mgL^{-1}. The average concentrations of chloride (Cl^-), potassium (K), calcium (Ca^{2+}) and magnesium (Mg^{2+}) from outside source were slightly higher than in-house sources. The observed differences are statistically significant at p=.00 for Ca^{2+}, p=.00 for Magnesium and p=.00 for Cl^- and p=.01 for potassium. The presence of Cl^- can be attributed to the use of table salt for cooking. Cl^- has also been reported as being a component of urine (Tchobanoglous et al., 2003) suggesting the practice of urination during showering also contributes chlorine into greywater. The difference in the Cl^- concentrations between these groups can be due to dilution and cooking practices. The presence of excessive concentration of Cl^- in the environment may impact freshwater organisms and plants by increasing species mortality and changing reproduction rates (WHO, 1996). Cl^- ions can also percolate down into the water table and affect groundwater quality. There were significant differences between concentration of K for outside source and in-house source. Greywater from outside sources recorded an average concentration of 10.9 mgL^{-1} while in-house sources recorded an average of 9.0 mgL^{-1}. The presence of K could also be from use of certain potassium-based soaps. K may contribute nutrients to a receiving water body or environment and promote eutrophication in ponds and streams. The results obtained for K in this study falls within a similar study by (Christova-Boal, Eden, & McFarlane, 1996; Hernandez et al., 2007) which reported concentrations of K within 8.13-15.2 mgL^{-1}.

Oil and grease

Although the concentrations of oils and grease from greywater from outside sources of 67 $mgL^{-1}$was slightly higher than that from in-house source of 66 mgL^{-1}, this difference is not significant (p=.86). From the 180 samples taken, 81% recorded positive results for oil and grease. This is to be expected since mixed greywater samples include greywater from the kitchen, where oil and grease are mostly used. Christova-Boal et al. (1996) also recorded oils and grease in greywater within a concentration range of 37-78 mgL^{-1}. Oil and grease in greywater is a major concern because of the translucent film it forms on the surface of water blocking the water-oxygen interface, which is detrimental to aquatic life. In an area where there are limited major drains, current practices of open disposal of greywater may impair soil porosity and ultimately affect infiltration, which can lead to flooding in the extreme circumstances.

Nutrients

The average concentration of NH_4-N for greywater from outside and in-house sources were both 14.8 and 14.4 mgL^{-1} respectively. However, this observed difference was not statistically significant (p=.35). The average values recorded for NH_4-N in both groups seems to deviate from what has been widely reported in literature. However, Katukiza et al. (2014) has also reported NH_4-N values for greywater within the range of 22-33 mgL^{-1}. This indicates that the levels of NH_4-N recorded in this study and other studies are all above the regulatory limit. The average concentration of NO_3-N for greywater samples from outside sources and in-house source had the same average values of 2.5 mgL^{-1}. These results were, however, not statistically significant (p=.87). Katukiza et al. (2014) also recorded NO_3-N in greywater samples within the range of 1.9-3.1 mgL^{-1}. Since NH_4-N is not used in production of soap, the most probable source of NH_4-N and NO_3-N in greywater might be from urine, which can be explained by the habit of some users probably urinating during showers and also from mineralization of organic materials from kitchen.

The Total Phosphorous (TP) concentrations for greywater from outside sources and in-house were both 2.3 mgL^{-1}, but these average concentrations were not statistically significant (p=.72). (Elmitwalli & Otterpohl, 2007) in a study on greywater also recorded NO_3-N concentrations within the range of 5.2 – 6.3 mgL^{-1}, which were slightly higher than what is recorded in this study. The main sources of phosphorous

are soaps and cleaning materials. The concentration of these nutrients recorded in this study exceed the trigger values of 0.1 mgL^{-1} for TP, 0.1 mgL^{-1} for NO_3-N and 0.01 mgL^{-1} for fresh water which is stated by ANZECC (2000). This implies their continued buildup within the environment can lead to excessive eutrophication in streams and water bodies. The presence of nutrients suggests that the nutrients content can also be exploited for beneficial use.

Salinity hazard

One of the most important characteristics of determining the suitability of water for direct irrigation is the relative proportion of sodium to other principal cations which is termed the salinity hazard. A better measure of sodium hazard for irrigation is known as sodium adsorption ratio SAR which is used to express reactions with the soil. This parameter is computed using equation 1. All the samples are found to be less than 10 for both groups and are classified as excellent for irrigation. Figure. 3.2 presents a graphical representation of SAR. This is generated by plotting the specific conductance and SAR values on the US salinity diagram (USSL). When the specific conductance and SAR are known, the classification of irrigation water can be graphically determined by plotting these values on the US salinity diagram. From the results obtained, only 3 samples from In-house sources and 26 samples from outside source were found to be unsuitable for irrigation. However, the remaining samples were all within the doubtful class. Low sodium water can be used for irrigation on most soils with little danger of developing harmful levels of exchangeable sodium while medium sodium is not suitable for fine textured soils but can be safely applied to coarse soils. High and very high sodium water are not suitable for irrigation since they may produce harmful levels of exchangeable sodium and this will lead to soil sodicity which is highly undesirable in irrigation. From the chart, it can be observed that all the samples fall within the sodium hazard class C3S1, C4S1 and C4S2 which is an indication of high to very high salinity. This therefore suggests that greywater within the study area cannot be safely used for irrigation based on the salinity hazard. The (SAR) values obtained in this study (4 – 11.7) are within than what is reported in a similar study by Katukiza et al. (2014) in Uganda which recorded (4 – 15). The high SAR values could probably be due to the use of more sodium-based detergents.

$$SAR = \frac{[Na^+]}{\sqrt{\frac{([Ca^{2+}] + [Mg^{2+}])}{2}}} \qquad (1)$$

Where $[Na^+]$, $[Ca^{2+}]$ and $[Mg^{2+}]$ are in $mmolL^{-1}$

Table 3. 3 Summary of physicochemical, microbiological and recommended discharge standards of greywater quality parameters for in-house and outside waters sources N=180

Parameter	Outside Source			In-house Source			Discharge	t-test for equality of means		
	Mean	Max	Min	Mean	Max.	Min	Standard	p	t	df
pH	7.0 (±.9)$_a$	8	5	6.89(±.9)$_a$	8	5	6.0-9.0*	.62	.498	178
DO (mgL^{-1})	6.1(±1.7)$_a$	9.0	2.2	6.0(±1.7)$_a$	9.0	2.3	5.0*	.76	.30	178
EC (µS/cm)	2,044.2(±314.4)$_a$	2,530	1,208	1,617.4(±320.2)$_b$	2,434	1,204	750*	.00	9.02	178
TDS (mgL^{-1})	1,288.7(±210.6)$_a$	1,584	720	1,010.3(±221.9)$_b$	1,584	700	50*	.00	8.63	178
TSS (mgL^{-1})	537.5(±120.07)$_a$	744	333	296.8(±65.12)$_b$	414	192	1,000*	.00	16.72	178
Oil and Grease (mgL^{-1})	67.2(±56.19)$_a$	170	0	65.8(±54.36)$_a$	170	0	30**	.86	.175	178
BOD_5 (mgL^{-1})	252.6(±81)$_a$	394	114	204.1(±61.5)$_b$	301	87	50.0*	.00	4.53	178
COD (mgL^{-1})	757.7(±325.4)$_a$	1595	270	643.8(±249.9)$_b$	1299	207	250.0*	.00	2.63	178
Cl^- (mgL^{-1})	36.3(±7.6)$_a$	50	18	31.9(±7.3)$_b$	49	18	140*	.00	3.91	178
Ca^{2+}(mgL^{-1})	27.2(±7.9)$_a$	43	10	23.2(±8.2)$_b$	43	9	NS	.00	3.32	178
Mg^{2+} (mgL^{-1})	9.8(±2.5)$_a$	14	3	8.4(±2.7)$_b$	15	3	NS	.00	3.60	178
Na^+ (mgL^{-1})	140.0(±30.79)$_a$	203.84	72.94	118.6(±29.65)$_b$	190	52	100**	.00	4.75	178
K^+ (mgL^{-1})	10.9(±5.0)$_a$	22	2	9.0(±4.6)$_b$	18	0	NS	.01	2.71	178
Tot-P (mgL^{-1})	2.3(±0.7)$_a$	3	1	2.3(±.6)$_a$	3	1	20.0**	.72	.35	178
NO^-_3 (mgL^{-1})	2.5(±1.3)$_a$	5	0	2.5(±1.3)$_a$	5	0	11.5*	.87	.168	178
NH_4—N (mgL^{-1})	14.8(±4.1)$_a$	22.0	7.0	14.2(±4.3)$_a$	22.0	7.0	1.5*	.35	.94	178
Total Coliforms (CFU/100mL)x10^6	3.8(±.8)$_a$	4.9	2.5	3.7(±.8)$_a$	4.9	2.5	400*	.34	.95	178
E.coli (CFU/100mL) x10^4	2.4(±2.5)$_a$	6.7	.0	1.8(±2.4)$_a$	6.9	.0	10*	.10	1.67	178
Salmonella spp. (CFU/100mL) x10^3	3.1(±3.0)$_a$	7.9	.0	2.4(±2.9)$_a$	7.9	.0	10*	.09	1.70	178

Values in the same row not sharing the same subscript are significantly different at p< .05 in the two-sided test of equality for in-house sources and external sources means.

*standards as stated by (Ghana., 2000) ** Standards as stated by (WHO, 2006a) NS = No Standard

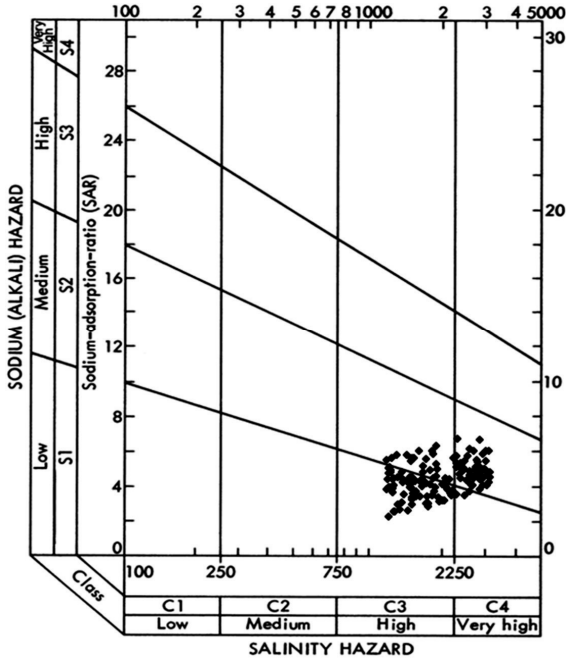


Figure 3. 2 USSL classification of greywater for Irrigation within the study area

Biodegradability potential of greywater

The potential of biodegradability of greywater is largely based on the BOD_5/COD ratio. According to Tchobanoglous et al. (2003), a BOD_5 to COD ratio close to or above 0.5 is an indication of good biodegradability of the greywater and as such any treatment schemes can rely on microbiological processes. In this study, a BOD_5 to COD ratio for greywater from outside sources ranged between 0.23 – 0.62 while greywater from in-house sources ranged between 0.22 – 0.59. This shows a very wide variability within which to justify the biodegradability of the greywater. About 78% of the BOD_5 to COD ratios recorded for greywater from outside sources fell below the recommended ratio of 0.5 while about 83% recorded from in-house sources also fell below the 0.5 ratio. This is an indication that, the greywater analyzed from both sources have low potential for biodegradability. It also supports the assertion that mixed greywater is not easily biodegradable. The results obtained in this study however fall within the range of typical BOD_5 to COD ratios reported by Tchobanoglous et al. (2003) of 0.3 - 0.8.

Microbiology

There were significant number of microorganisms in the samples taken from the sampling sites. Total Coliforms, *E.coli* and *Salmonella spp.* were detected in 100%, 52% and 48% respectively out of 180 samples tested. The presence of *E.coli* is a strong indication of fecal contamination, which is registered in both groups. This could be due to washing of baby's nappies or from ablution. The presence of *Salmonella spp.* is also a strong indication of fecal contamination. It can also be attributed to washing of meats and other household items which already carry the bacteria. There were no significant differences between

microorganism loads recorded between outside and in-house sources. This could be an indication of probably equal sanitation lifestyles practiced by both groups. These high concentrations of *E.coli* and *Salmonella spp.* in greywater from households pose a health risk to residents. Similar studies conducted by (Alsulaili & Hamoda, 2015; Birks & Hills, 2007; Dalahmeh, Lalander, Pell, Vinneras, & Jonsson, 2016; Sievers, Watzel, Londong, & Kraft, 2016) also identified these microorganisms in greywater samples. A study by Westrell, Schonning, Stenstrom, and J. (2004) states about 8% of *E.coli* and *Salmonella spp.* are pathogenic hence the occurrence of fecal coliform and *Salmonella spp.* in greywater indicates a risk of human illness or infection through contact with water. Therefore 10^2-10^6 cfu(100 mL^{-1}) is a clear indication that the greywater is not fit for direct reuse or human contact.

Constituent loading

In estimating constituent loading, the parameter of interest are the parameters analyzed and the volume of greywater discharged into the environment. It was calculated using equation 2.

$$P_{av.c} = C_n Q_{av.c} \qquad (2)$$

P_{avc} = the specific pollutant load generated per capita per day
C_n = is the average concentration of parameter n in greywater
Q_{av} = is the average greywater generated per capita per day.

The specific pollutant loads calculated for all the parameters indicates that houses with in-house source generate higher loads than outside source. This can be due to the volume of water consumption, which is about twice that of outside source. Some of these values obtained in this study compared with other studies is presented in Table 3.4. However, some studies also showed completely wide variations from this study as also reported in the table below. It was impossible to calculate the overall pollutant load per day due to unavailability of data on numbers who have in-house connection and those without. A relative pollution contribution of in-house and outside sources is shown in figure. 3.3.

Table 3. 4 Pollutant loading from different studies

Parameters	Outside Source	In-house source	(Friedler, 2004)	(SANDEC, 2006)	(Busser et al., 2006)	(Sievers et al., 2016)
TSS ($gc^{-1}d^{-1}$)	17.2	22.0	29	10-30	-	-
Oil and Grease ($gc^{-1}d^{-1}$)	2.15	4.9	19	-	-	-
BOD_5 ($gc^{-1}d^{-1}$)	8.06	15.1	23	20-50	-	-
COD ($gc^{-1}d^{-1}$)	24.24	47.6	46	-	18-37	45
NH_4 ($gc^{-1}d^{-1}$)	14.8	1.1	0.15	-	-	-
TP ($gc^{-1}d^{-1}$)	0.1	0.2	-	0.2-6	0.4-0.6	0.4
Salmonella spp. ($CFUc^{-1}d^{-1}$) $x10^5$	9.9	17.8	-	-	-	-
E.coli ($CFUc^{-1}d^{-1}$) $x10^6$	7.7	13.3	-	-	-	-
Total Coliforms ($CFUc^{-1}d^{-1}$) $x10^9$	1.2	2.7	-	-	-	-

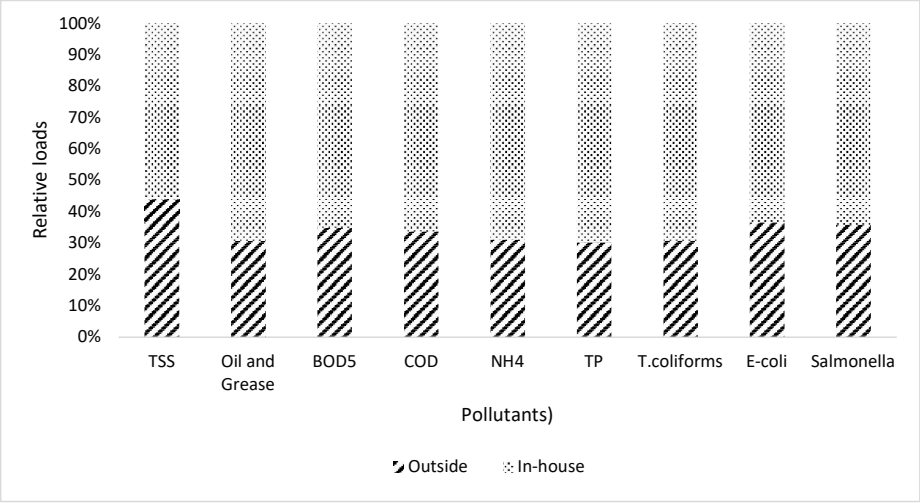


Figure 3. 3 Relative distribution of load between in-house and outside sources

Evaluation of factors influencing greywater quality (Principal Component Analysis)

A principal component analysis was conducted on 17 out of 19 parameters because two (2) parameters pH, and oil and grease failed the Kaiser-Meyer-Olkin (KMO) test. An oblique rotation (direct oblimin) was used and the KMO measure verified the sampling adequacy for the analysis, KMO = .757 which is adequate based on the classification of adequacy of KMO by Hutcheson and Sofroniou (1999). All the KMO values for the individual items were greater than 0.5 which is above the acceptable limit as described by Field (2014). An initial analysis was run to obtain eigenvalues for each factor in the data. Five (5) factors had eigenvalues over the Kaiser's criterion of 1 and in combination explained 61.45% of the variance. The scree plot was unambiguous and showed inflexion that would justify retaining 5 factors. Table 3.5 presents the principal components after rotation.

Table 3. 5 Coefficients for each variable in the first five principal components

Variables	PC1	PC2	PC3	PC4	PC5
DO (mgL^{-1})	.127	-.028	-.039	-.004	-.243
EC (μScm^{-1})	**.769**	.127	-.015	.394	.025
TSS (mgL^{-1})	.309	.083	.273	**.438**	-.029
TDS (mgL^{-1})	**.770**	.122	-.022	.381	.038
BOD_5 (mgL^{-1})	-.013	.075	**.905**	.078	-.044
COD (mgL^{-1})	.016	-.022	**.899**	-.074	-.024
Cl^- (mgL^{-1})	**.851**	-.056	.069	-.161	.021
Ca^{2+}(mgL^{-1})	**.725**	-.213	-.028	-.221	-.032
Mg^{2+} (mgL^{-1})	**.773**	.023	.090	-.163	.063
Na^+ (mgL^{-1})	**.833**	.016	.015	-.050	.086
K^+ (mgL^{-1})	**.529**	.057	.024	.090	-.238
TP (mgL^{-1})	-.035	.117	.085	.127	**-.575**
NO_3-N (mgL^{-1})	-.179	-.178	-.057	**.735**	.007
NH_4-N (mgL^{-1})	.125	.157	-.157	.194	**.666**
Total Coliforms	.081	-.131	.337	-.049	**.505**
E.coli	-.064	**.929**	.095	-.092	.013
Salmonella spp.	.015	**.928**	-.060	-.129	-.009
Eigen Values	4.58	1.90	1.67	1.16	1.14
% Variance explained	26.93	11.20	9.82	6.80	6.70
% cumulative	26.93	38.13	47.95	54.75	61.45

Principal component 1 explained 26.93% of the total variance and the variables which most positively contributed to it were EC, Cl^-, Ca^{2+}, Mg^{2+}, K, and TDS. This component shows the importance of certain migratory ions in solution and their impact on greywater quality. The main sources of these variables are cleaning materials and salt. It is possible to state that PC1 represents cooking and cleaning activities. Principal component 2 explained 11.20% of the total variance and presents a strong contribution by the variables *E.coli* and *Salmonella spp.* The main sources of these variables are associated with fecal contamination therefore it is possible that Principal component 2 represents personal hygiene. Principal component 3 explained 9.82% of the total variance and the variables which most positively contributed to it were BOD_5 and COD. The main sources of these variables can be associated with biodegradable and non-biodegradable materials in the greywater. It is therefore justified to state that PC3 represents biodegradability of the greywater. Principal component 4 explained 6.80% of the total variance and the variables associated with it are Total Suspended Solids and NO_3-N. These could be associated with the frequency of water use before final disposal. It is therefore possible to state that PC4 represent internal recycling activities. Principal component 5 explained 6.70% of the total variance and the variables associated with this are NH_4-N, TP and Total Coliforms. NH_4-N is a component of urine and TP is a component of detergents. It is possible that this component is associated with sanitary practices in the bathroom. do Couto et al. (2013) also performed PCA on greywater samples and observed three components that explained 72.63% of the total variability in the samples. These components were source

of water, biodegradability and faecal contamination which have also been confirmed as being contributing factors in this study.
Long term disposal of untreated greywater can result in increases in soil chemical parameters and may further result in negative soil and human health impacts (Siggins, Burton, Ross, Lowe, & Horswell, 2016).

Conclusions

The study concludes that there are significant differences in quantity and quality of greywater between in-house sources and outside sources and this is largely influenced by lifestyle and water use. This is an indication that there is the need for a critical look at the impact of greywater management in peri-urban areas in developing countries. Due to the level of contamination coupled with the practice of irrigation with water from open drains as practiced in most developing countries, public health could be at a great risk. The contaminated greywater can also serve as drinking water for some livestock which stray out of their pens to graze in the open fields and the implications of these cannot be over emphasized. This situation should therefore inform the policy makers in formulating appropriate policies that aim at addressing the impact of untreated greywater discharge into the environment without recourse to treatment. It should also bring to bear the need to start thinking about domestic greywater treatment systems in such areas before the greywater is finally discharged into the environment.

four

Chapter four

Submitted as

Oteng-Peprah, M., Acheampong, M. A., Agyei-Tuffour, B., Yankson, E. & de Vries, N. Adsorptive removal of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) from greywater using activated carbon prepared from tropical almond and palm kernel shells

Abstract

This study was carried out to assess the reduction of 5-day biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) of household greywater using palm kernel activated carbon (PKAC) and tropical almond activated carbon (TAAC) produced from locally available materials in a kiln at 800oC and activated using steam at a flowrate of 120ml/hr. This study was done in a batch mode to determine the best performing material and further determine the optimum parameters. Brunauer-Emmet-Teller (BET) surface area determination revealed that PKAC had a larger surface area than TAAC. Scanning electron microscope (SEM) imagery of the carbons also revealed amorphous and large internal shapes for TAAC while crystalline and closed packed shapes for PKAC. X-ray diffraction (XRD) analysis indicated that the major component present in the PKAC and TAAC was carbon and other allotropes of carbon. Batch results showed that reduction of BOD_5 and COD was affected by particle size. The maximum percentage reduction of BOD_5 and COD by PKAC was 76% and 65% respectively while reduction by TAAC was 62% and 52% respectively. The adsorption process was well described by the Freundlich adsorption isotherm. The kinetics of the reaction followed a pseudo-second order kinetics model. The studies showed that PKAC is a better adsorbent for reducing BOD_5 and COD from domestic greywater as compared with TAAC. The PKAC is a potential low-cost adsorbent for BOD_5 and COD removal from domestic greywater.

Keywords

Palm kernel, tropical almond, activated carbon, biochemical oxygen demand, chemical oxygen demand, adsorption

Introduction

Rapid urbanization in most developing countries has led to a rise in water demand in most towns and villages. Associated with this rise in demand is an increase in volumes of wastewater generated. Most developing countries lack the technical and non-technical competences to manage the wastewater generated and this leads to indiscriminate discharge of wastewater into the environment. Many studies (Adendorff & Stimie, 2005; Alderlieste & Langeveld, 2005; Boyjoo et al., 2013; Busser et al., 2006; Faraqui & Al-Jayyousi, 2002; Oteng-Peprah et al., 2018) have revealed wastewater generation rates of between 20-80l/p/d in some developing countries. Greywater which accounts for a large percentage of the domestic wastewater generated is often contaminated with different hazardous materials both as organic and inorganic compounds (Boyjoo et al., 2013; Katukiza et al., 2014; Oteng-Peprah, Acheampong, & deVries, 2018). These organic and inorganic wastes originate from many sources such as human waste, food waste, washing and personal hygiene product (Edwin et al., 2014; Eriksson et al., 2003). A study by (Oteng-Peprah et al., 2018) further revealed that greywater composition is affected by the hygienic practices, cooking methods, type of use and quality of the raw water. During decomposition of organic matter in the greywater, the oxygen content is depleted due to the high organic loads and this finds its way to other receiving water bodies; further increasing the organic loads and depriving other aquatic organisms of oxygen for survival. In order to reduce the impact of organic loads caused by high BOD_5 and COD, it is imperative for greywater to be treated before final discharge into natural waters. Conventional processes of treating greywater before reuse or final disposal are limited or non-existent in most developing countries. These conventional systems are expensive to install and mostly require an extensive network of piping coupled with its associated management protocols. The non-availability of these treatment systems exposes the environment to contaminants associated with greywater and this has a chain effect on plants and animals. Advocacy for household greywater treatment before discharge has been very limited or non-existent in most developing countries. This may be due to both technical and non-technical challenges associated with managing treatment systems at the household level. In order to encourage greywater treatment at the household level, there is the need to provide an alternative low-cost solution for greywater treatment and reuse.

Adsorption process which is a physico-chemical process has remained one of the most widely used techniques for treating water and wastewater and has proven to be very useful in many studies (Ali, Asim, & Khan, 2012; Bansode, Losso, Marshall, Rao, & Portier, 2004; Hararah et al., 2010; Zhang et al., 2014). It has remained one of the most efficient and important methods thus if the adsorbent used is cheap and locally available and does not require further pretreatment steps. In order to promote household greywater treatment and reuse, there is the need to provide an alternative low cost and sustainable solution. Activated carbon has proven to be an effective adsorbent in wastewater treatment due to its high surface area, high adsorptive capacity and its large microporous structure (Mohammad-Khah & Ansari, 2009). It can be prepared from a large number of low-cost sources and agricultural wastes such as rice husk, apricot, bamboo, date pal, residue, avocado (Nayl et al., 2017). Tropical almond and palm kernel shell are a considerable part of the abundant agricultural waste materials within the study area. Many researchers have investigated the performance of palm kernel activated carbon on removal of certain wastewater parameters (Abdulrazak, Hussaini, & Sani, 2017; Birgani et al., 2016; Hidayu & Muda, 2016; Mook, Aroua, & Szlachta, 2016; Pamidimukkala & Soni, 2018) but studies of its effect on removal of BOD and COD have remained scanty or non-existent. Tropical almond, a fruit with a mesocarp, has not been explored in its application for use as activated carbon. This agricultural product, which is very common in most tropical countries, is discarded as waste or burnt in the open. In recent times, there has been

awareness on the environmental impact created by organic loads which is represented by BOD_5 and COD on freshwater resources. The present study explores the potential of tropical almond activated carbon (TAAC) and palm kernel activated carbon (PKAC) in the removal of BOD_5 and COD from domestic greywater.

Methodology

Material processing

The palm kernel shell was obtained from a local palm oil mill and the tropical almond fruits were obtained from the campus of University of Cape Coast all in Cape Coast Ghana. The almond fruits were crushed to remove the fleshy mesocarp from the hard endocarp. The hard endocarp is further crushed to reveal the edible kernel. The hard endocarp is the material of interest in this study. These two materials (almond shell and palm kernel shell) were cleaned several times with distilled water to eliminate any dirt and water-soluble impurities. The cleaned shells were then airdried in a laboratory drier for 8hours and then further oven dried at 110^oC in a Heratherm gravity convection laboratory oven for 24hours in order to remove any surface moisture. The dried samples were then size reduced to desired sizes (2-6mm) using a laboratory crusher and sieves. The activated carbons were prepared by physical activation with steam at 800^oC and steam flowrate at 120mL/hr. After the activation process, the samples were taken out and washed with distilled water to remove any residual ash that might be on the carbons. Greywater was collected from different households within the central region of Ghana and a composite is formed for the sorption experiment.

Analytical methods

The pH, was measured on site using a Horiba U-50 multi parameter water quality meter. The five-day biochemical oxygen demand (BOD_5) concentration was determined using the Lovibond BD 606 BOD system. The concentration of chemical oxygen demand (COD) was determined using the closed reflux colorimetric method as stated in (APHA) 5220C. The initial pH of the greywater was 7.4.

Sorption experiment

All experiments were carried out at ambient temperature (25^oC) in batch mode and in triplicates. The batch experiments were conducted in Erlenmeyer flasks of 1000ml capacity using an orbital shaker at a speed of 400rev/min as recommended by Nayl et al. (2017).

Greywater pre-treatment

The greywater collected were first filtered through a laboratory sand filter to reduce the total suspended solids (TSS) content. The BOD_5 and COD of the greywater is determined for the basis of establishing the initial BOD_5 and COD concentrations of the sample. The initial BOD_5 and COD concentration of the greywater samples were 252mg/l and 421mg/l respectively.

Effect of particle size.

The optimum dosage of the two materials were weighed and added to two sets of 3 different 1000ml Erlenmeyer flasks. The first, second and third contain 2mm, 4mm and 6mm average particle sizes respectively of the material. These flasks were agitated at 400rev/min for 180mins at room temperature and a pH of 7.4. 500ml from each flask is sampled and filtered and the filtrate analyzed for BOD_5 and COD.

Dosage determination

Batch sorption experiment were carried out using specified weights of both materials 1g/L to 10g/L with increases of 1g for each experiment and mixed with 1000ml of greywater in 1000ml Erlenmeyer flasks. The setup consisted of 10 Erlenmeyer flasks for each of the materials. The mixtures were agitated continuously using an orbital shaker at the following conditions: 400rev/min, temperature of 25°C, pH = 7.4, time of agitation = 180mins, particle size = 2mm. 500ml of the solution was collected after the sorption period of 180mins and filtered with a Whatman filter paper and the BOD_5 and COD concentrations measured. The optimum dosage is the sample with the lowest BOD and COD values recorded.

Effect of contact time

The optimum dosage and optimum particle size of the two materials were weighed and added to two sets of 7 different 1000ml Erlenmeyer flasks containing 1000ml of the greywater each. The first, second, third, fourth, fifth, sixth and seventh flasks was agitated for 10, 30, 60, 90, 120, 150, 180mins respectively. 500ml of each flask is filtered for analysis of BOD_5 and COD.

Characterization of the materials

The density of the materials was determined by using an ultra-pycnometer 1000 after it had been dried at 105°C in an oven for 24hours. The surface area S_{BET} was determined using a Micromeritics tristar 3000 system. The scanning electron microscopy (SEM) and x-ray microanalysis was done using a Hitachi TM – 1000 microscope and quantax energy dispersive x-ray spectrometry system respectively. The XRD was determined by using a Bruker D2 phaser x-ray diffractometer.

Calculations

The percentage of removal, thus uptake per gram and equilibrium concentrations of sorbent was calculated using equations 1 2 and 3

$$R\% = \frac{C_o - C_t}{C_o} \times 100 \quad (1)$$

$$q_t = (C_o - C_t)\frac{V}{m} \quad (2)$$

$$q_e = (C_o - C_e)\frac{V}{m} \quad (3)$$

where q_t shows the amount of COD and BOD_5 adsorbed by the sorbents at time *t*. C_o, C_t and C_e represents the COD and BOD_5 concentrations in the solution (mg/L) at initial time, instantaneous time t, and equilibrium respectively. V represents the volume of solution (L) and m is the mass of the sorbent (g).

Mathematical equations and models of adsorption isotherms

These are expressions or relationship curves that describes the conditions under which sorption equilibrium is reached at a constant temperature. These isotherms can be used to compare the adsorptive

properties of different adsorbents under varying conditions. They further provide insight into the mechanisms involved in the sorption process.

Linear isotherm

$$q_e = \frac{x}{m} = k_p C_e \quad (4)$$

where x/m represents the amount adsorbed by unit mass (mg/g)

The Freundlich isotherm model

It is represented by the following equation:

$$q_e = K_F C_e^{1/n} \quad (5)$$

In its linear form, it assumes the following state:

$$log q_e = log K_F + \frac{1}{n} log C_e \quad (6)$$

where q_e is equal to the uptake (mg/g) at equilibrium, K_F is a measure of the sorption capacity, *1/n* is the sorption intensity, and C_e is the final BOD_5 or COD concentration in solution (mg/L). The Freundlich isotherm constants K_F and *1/n* are evaluated from the intercept and the slope respectively, of the linear plot log q_e against log C_e

Langmuir isotherm model

It is represented by the following set of equations

$$q_e = \frac{q_e K_L C_e}{1 + K_L C_e} \quad (7)$$

where q_e is the amount adsorbed per specific amount of adsorbent (mg/g), C_e is the equilibrium concentration of the solution (mg/L) and q_m is the maximum amount required to form a monolayer (mg/g). The Langmuir equation can be rearranged to a linear form for the convenience of plotting and determination of the Langmuir constant (K_L) as below. The values of q_m and K_L can be determined from the linear plot of C_e/q_e versus C_e.

$$\frac{C_e}{q_e} = \frac{1}{K_L q_e} + \frac{1}{q_m} C_e \quad (8)$$

The essential characteristics of the Langmuir isotherm parameters can be used to predict the affinity between the sorbate and the sorbent using the separation factor or dimensionless equilibrium parameter R_L expressed as in the following equation

$$R_L = \frac{1}{1 + K_L C_o} \quad (9)$$

where K_L is the Langmuir constant and C_o is the initial concentration. The value of the separation factor R_L provides important information about the nature of adsorption. The value of R_L is between 0 and 1 for favourable adsorption, while R_L*>1* represents unfavourable adsorption and R_L*=1* represents linear adsorption.

Dubinin-Radishkevich isotherm (D-R) model
This is represented in the linear form by the equation

$$\ln q_e = \ln Q_D - 2B_D RT \ln(1 + \frac{1}{C_e}) \quad (10)$$

where Q_D is the theoretical maximum capacity (mol/g), B_D is the D-R model constant (kJ/mol/K), T is the absolute temperature (K) and R is the gas constant (kJ/mol). The value of Q_D and B_D can be obtained from the intercept and slope of the plot of ln (q_e) versus ln (1+1/C_e). The mean energy of sorption, E (kJ/mol) is calculated from the relation

$$E = 1\sqrt{2B_D} \quad (11)$$

Temkin
This is represented in the linear form as:

$$q_e = \frac{RT}{b_T} \ln K_T + \frac{RT}{b_T} \ln C_e \quad (12)$$

where K_T (L/g) is the Temkin isotherm constant, b_T (J/mol) is a constant related to the heat of sorption and R (8.314 J/mol/K) is the gas constant. A plot of q_e versus ln (C_e) gives a straight line from which K_T and b_T can be evaluated from the slope and intercept.

Sorption kinetic models

These are mainly used for determination of substances or physical and chemical reactions in the process of adsorption rate control steps. Knowledge about the kinetics of the sorption process facilitates the understanding of the mechanisms involved in the sorption process. The classical models commonly used to study the mechanism of reactions are the pseudo-first-order and pseudo-second-order models.

Pseudo-first order kinetic model
It is represented by the following equations

$$\frac{dq_t}{dt} = k_1(q_e - q_t) \quad (13)$$

Integrating of the above equation with boundary conditions of *t=0, q_t=0* and *t=t, q_t=q_t* gives the following equation

$$\log(q_e - q_t) = log q_e - \left(\frac{k_1}{2.303}\right) t \quad (14)$$

where q_e and q_t are the amounts of COD or BOD_5 adsorbed at equilibrium and at time *t* (mg/g), respectively, *t* is the contact time (min) and K_1 is the pseudo-first-order rate constant (/min). The straight-line plot of log (q_e-q_t) against *t* gives log (q_e) as slope and intercept equal to $k_1/2.303$. Hence the amount of solute sorbed per gram of sorbent at equilibrium (q_e) and the first order rate constant (k_1) can be evaluated from the slope and intercept.

Pseudo-second-order kinetic model
This is represented by the following equations

$$\frac{dq_t}{dt} = k_2(q_e - q_t)^2 \quad (15)$$

Integrating of the above equation with boundary conditions of $t=0,\ q_t=0$ and $t=t,\ q_t=q_t$ gives the following equation

$$\left(\frac{t}{q_t}\right) = \frac{1}{k_2 q_e^2} + \frac{1}{q_e}t \quad (16)$$

where k_2 represents the rate constant, q_t is the uptake capacity at any time t

Results and Discussion

Physical characteristics of the materials

The physical characteristics of the activated carbons are presented in Table 4.1. The apparent density of palm kernel activated carbon (PKAC) is higher than tropical almond activated carbon (TAAC). The recommended range of densities for activated carbon is within 0.4-0.5g/cm^3 (TIGG, 2019) which implies that PKAC falls within the recommended densities for commercial activated carbon. The TAAC, however, could not meet the density requirement. This could be attributed to its very high fibrous nature, which is an indication that it cannot be used for commercial purposes. The BET surface area obtained showed that the PKAC had a higher surface area 620m^2/g as compared to TAAC of 407m^2/g. The surface area of TAAC does not fall within the recommended range of surface area of commercial activated carbon (500-1500 m^2/g). A similar study by Hidayu and Muda (2016) on characterization of activated carbon using palm kernel shell obtained surface area of 584m^2/g. The slight variations in the surface area recorded for this study may be due to the activation method that was used. A higher BET generally suggests higher adsorption capacity because the carbon has wider surface to allow for adsorption under different conditions.

Table 4. 1 Physical characteristics of the materials

	Apparent Density g/cm^3	BET Surface Area m^2/g
TAAC	0.35	407
PKAC	0.46	620

SEM images of the activated sorbents

Figure 4.1 and Figure 4.2 show the SEM images of TAAC and PKAC respectively (6,000 times magnification). Using the scale of 5µm, it is seen that majority of the particles in the PKAC (Figure 4.2) are less than 5µm. It can also be said that the particles are crystalline because they have distinct shapes. However, the TAAC (Figure 4.1) shows no distinct shape or particle size hence it has an amorphous structure. The pores of the TAAC are large and few and the particles have bulky shape when comparing to PKAC. Using the scale, it can be seen that most particles fall below the 5µm compared to the TAAC where most of the particles fall above the 5µm.

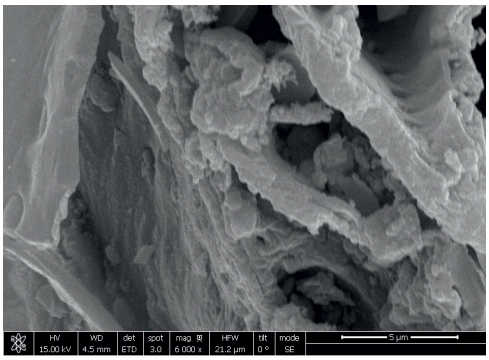


Figure 4. 1 Activated almond shell

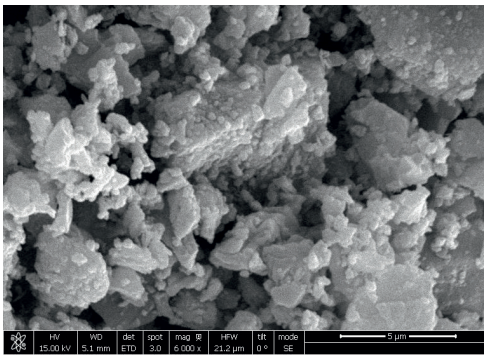


Figure 4. 2 Activated palm shell

X-Ray Diffraction

The powder diffraction spectrum was compared with standard crystallographic data retrieved from the International Centre for Diffraction Data (ICDD) database using the PDF-4+ 2019 program. Because of the amorphous nature of the sample, several phases were observed. The highly probable match for most of the peaks was carbon (C) with reference number 00-026-1077 with 2θ values of 26.76, 42.94, 44.04, 45.76, 62.82, 66.96 and 77.72° (ICDD, 2018) as shown in figure 4.3 and figure 4.4. Other phases corresponding to C_{60} (00-044-0558), C_{70} (00-048-1206) and graphite (00-056-0159) were also observed. These are different allotropes of carbon.

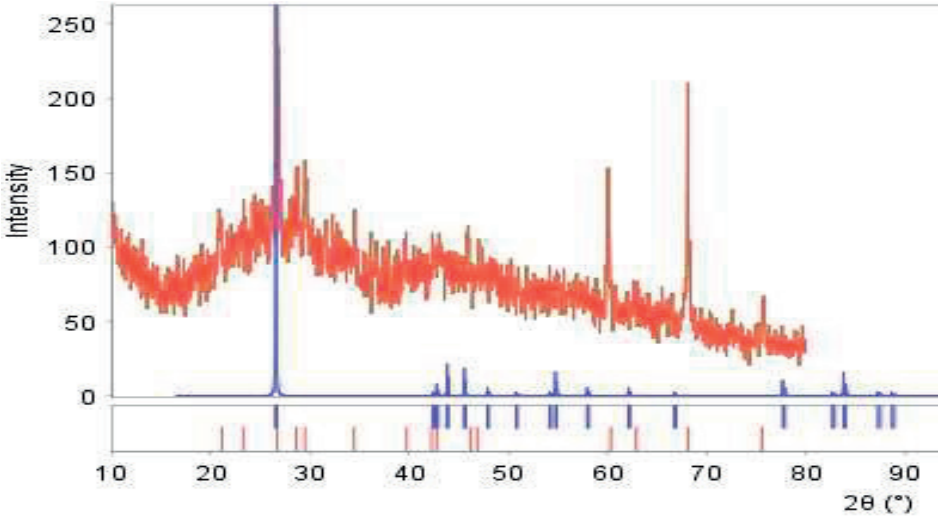


Figure 4. 3 XRD for tropical almond activated carbon

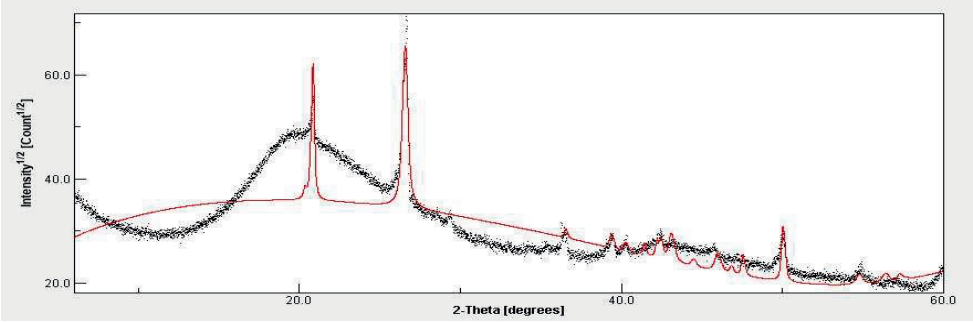


Figure 4. 4 XRD of Palm kernel shell activated carbon

Equilibrium concentrations

The equilibrium concentrations of the study are presented in Figure 4.2. From this table, it can be seen that PKAC had the highest sorption capacity of 34mg/g in removing COD and 22.88mg/g in removing BOD_5 as compared with TAAC of 27mg/g and 19.5mg/g COD and BOD_5 respectively. These results indicate that PKAC has a higher potential at removing BOD5 and COD as compared to TAAC. Studies by Nayl et al. (2017) obtained equilibrium concentration of 41.3mg/l for COD and 20.2 BOD_5 using activated carbon prepared from date palm.

Table 4. 2 Equilibrium concentrations (qe)

	PKAC	TAAC
BOD (mg/g)	22.88	19.50
COD (mg/g)	34.00	27.00

Effect of particle size

Particle size plays a key role in adsorption studies and this study adopted three different particle sizes in the study. This study was conducted at a pH of 7.4, temperature of 25°C, agitation rate of 400rpm and dosage of 10g/L. Figure 4.5 shows the percentage removal of BOD_5 and COD for the different particle sizes studied. From the figure it can be seen that generally the percent removal increased with decreased particle sizes as also observed by Devi, Singh, and Kumar (2008); (Mangaleshwaran, Thirulogachandar, Rajasekar, Muthukumaran, & Rasappan, 2015) obtained similar results of increased performance of activated carbon in removing BOD and COD when particle sizes were reduced. This may be attributed to increase in effective specific surface area of the sorbent hence more active sites for adsorption to take place (Devi et al., 2008) . As seen from the figure 4.5, PKAC shows dominance over TAAC in both BOD_5 and COD removal percentages. This shows that removal of BOD_5 and COD from greywater is considerably affected by changes in particle size as was also reported by Devi et al. (2008).

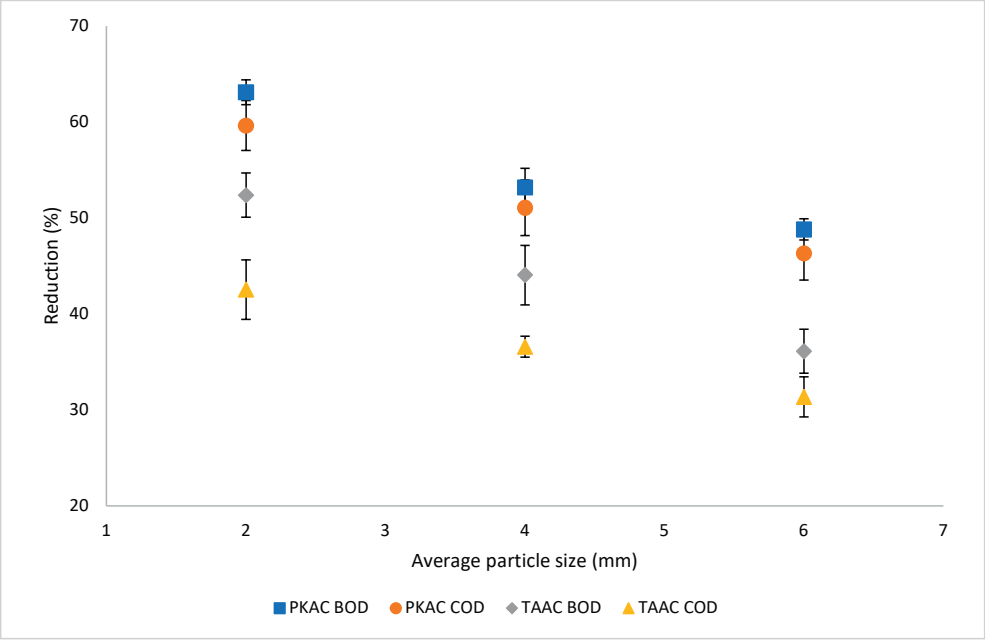


Figure 4. 5 Effect of particle size on BOD and COD reduction

Effect of adsorbent dose

The effect of carbon dosage on percentage removal of BOD_5 and COD from greywater was conducted at a particle size of 2mm, pH of 7.4, temperature of 25°C, contact time of 210mins and agitation rate of 400rpm. Figure 4.6 shows the effect of dosage on BOD_5 and COD removal. It can be seen from the figure that generally, the percentage removal of BOD_5 and COD for both TAAC and PKAC increased with increasing dosage of carbon until equilibrium is reached. Equilibrium was reached at about 8g/L of carbon dose for both PKAC and TAAC. This increase in percent removal with dosage may be due to more active sites available for BOD_5 and COD adsorption on the activated carbon which may be attributed to increase in the functional groups and increased surface area as a result of increased dosage (Devi et al., 2008; Nayl et al., 2017). With respect to percentage reduction of BOD_5 between the TAAC and PKAC, it can be seen that PKAC is able to remove a higher percentage (72%) of BOD_5 as compared with 65% for TAAC. COD removal also displays a similar behaviour as shown in figure 4.6. COD reduction with PKAC shows dominance (66%) over TAAC (58%). This dominance is supported by the SEM images which shows that the PKAC has more porous features than TAAC and hence it has large internal surface area as further supported by the BET results.

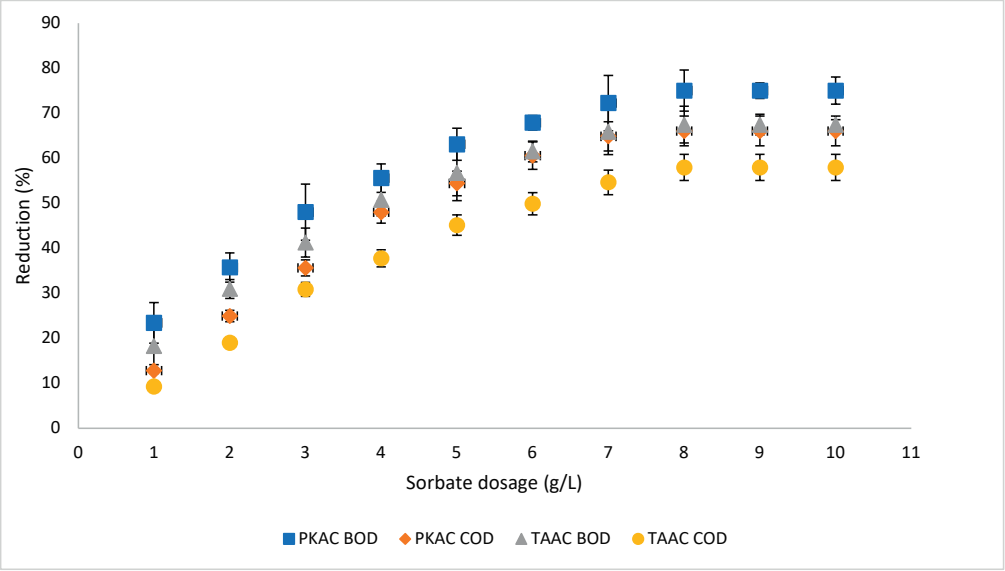


Figure 4. 6 Percentage reduction of BOD and COD against dosage

Effect of Contact time

The effect of contact time on removal of BOD_5 and COD from greywater was studied at a pH of 7.4, agitation rate of 400rpm, temperature of 25°C and the optimum dosage of 8g/L and in time periods of 15mins to 210mins (figure 4.7). The first 120mins of the reaction showed very rapid reduction of BOD and COD to about 73% and 65% of BOD_5 and COD for PKAC and 62% and 52% of BOD_5 and COD for TAAC. Equilibrium was reached at about 150mins for both PKAC and TAAC. The rapid reduction of BOD and COD by the materials may be as a result of large unoccupied active sites available for adsorption at the initial contact time periods. The smooth nature of the curve may be attributable to the formation of monolayer of BOD_5 and COD over the outer surface of the activated carbon as suggested by Aluyor, Oboh, and Obahiagbon (2009). The PKAC is able to remove more BOD_5 and COD than the TAAC under the different time conditions in the study. This might be due to the high surface of the PKAC as shown in the SEM images and also supported by the BET results.

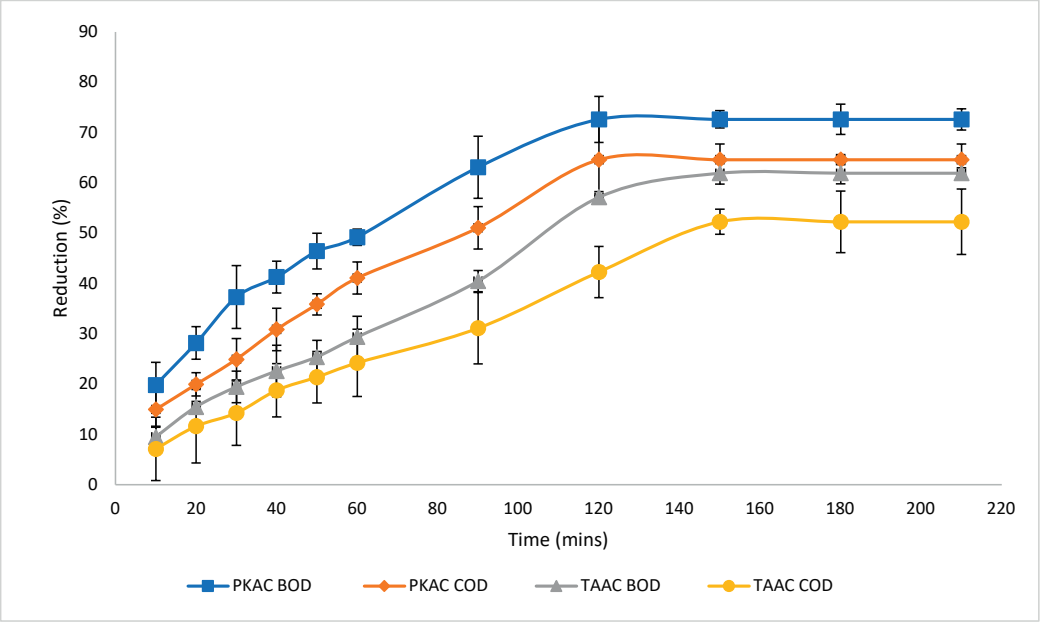


Figure 4. 7 Percentage reduction of BOD and COD against time

Final concentrations of treated greywater

The initial and final concentrations of the greywater treated under batch conditions using optimum conditions of 8g/l dosage, 150mins of adsorption time and 2mm particle size is presented in Table 4.3. It is clear the BOD_5 concentration of the treated greywater for both materials were above the EPA standards for discharge of wastewater into the environment. However, the COD concentrations were all below the EPA standards for discharge of wastewater into the environment. This suggests that within the studied concentrations, there might be the need for further treatment of the greywater to be able to bring the BOD_5 level to the acceptable limits which has been set up by the EPA.

Table 4. 3 Initial and final concentrations of greywater after batch treatment

	Initial concentrations		Final concentrations		EPA (Ghana., 2000)	
	BOD_5 (mg/l)	COD (mg/l)	BOD_5 (mg/l)	COD (mg/l)	BOD_5 (mg/l)	COD (mg/l)
PKAC	252	421	69	149	50	250
TAAC	252	421	96	201	50	250

Adsorption isotherms

The experimental data were fitted with the Langmuir, Freundlich, Dubinin-Radushkevich, and Temkin isotherm models and the results obtained is presented in Table 4.4. By using the correlation coefficient, BOD_5 removal using PKAC and TAAC fits well the Freundlich isotherm model (R^2=0.9820 and 0.9863

respectively) whereas COD removal using PKAC and TAAC fitted the Langmuir isotherm model (R^2=0.9854 and 0.9054). Similar studies have all reported a good fit of the Freundlich model for BOD_5 removal (Devi et al., 2008; Nayl et al., 2017). The fits with Dubinin-Radushkevich and Temkin models were comparatively less good. The best model describing the fit were the Freundlich and Langmuir models. The adsorption intensity of the Freundlich model 1/n was less than 1 for both materials studied which indicates favourable adsorption (Belhachemi & Addoun, 2012; Yan, Du, Li, Yu, & Tang, 2015). This is also supported by the separation factor in the Langmuir model which is between 0 and 1 indicating favourable adsorption. The Q_D value obtained for the materials indicated that PKAC had a higher sorption capacity for BOD_5 removal as compared to TAAC. The low values of the mean sorption energy show that the forces of attraction are Van der Waal and not chemical bonding which further suggests that the process investigated is a physisorption (Acheampong, Pereira, Meulepas, & Lens, 2011).

Table 4. 4 Adsorption isotherm parameters

Isotherm parameters	**PKAC**		**TAAC**	
	BOD_5	**COD**	**BOD_5**	**COD**
Freundlich				
1/n	0.7549	0.3407	0.7722	0.4061
K_F	1.0299	5.6364	0.7461	5.1511
R^2	0.9820	0.6504	0.9863	0.8446
Langmuir				
q_m	161.2903	75.7576	140.8541	52.3560
K_L	0.0067	0.0039	0.0039	0.0029
R_L	0.3710	0.3808	0.5029	0.4504
R^2	0.7569	0.9584	0.8835	0.9054
Dubinin-Radushkevich (D-R)				
Q_D	4.329	4.27	4.2392	3.9909
B_D	0.0157	0.0186	0.0194	0.0186
E (kJ)	0.1770	0.1927	0.1971	0.1931
R^2	0.9393	0.9094	0.9840	0.7406
Temkin				
$b_T(J)$	99.6169	135.9734	100.5753	202.0364
K_T	0.0345	0.0584	0.0293	0.0831
R^2	0.9529	0.8783	0.9846	0.6380

Kinetic adsorption modelling

Different kinetic models have been used to test the experimental data in this study. This is done to understand the mechanism of the adsorption process. Two kinetic models thus Lagrengen pseudo-first-order and pseudo-second-order models were used to fit the experimental data in order to determine the model that best fitted the experimental data. The calculated model parameters are presented in Table 4.5. The BOD_5 and COD removal by PKAC increased rapidly within the first 150minutes of the experiment and then became gradually steady during the last 60minutes of contact time. A maximum removal of 74% and 63% were achieved for BOD_5 and COD respectively. Removal of BOD_5 and COD by TAAC exhibited similar characteristic with rapid removal of BOD_5 and COD within the first 150minutes and gradually steady during the last 60mins of the study. A maximum removal of 56% and 50% was achieved for BOD_5 and COD respectively. This study therefore shows that the equilibrium time for BOD_5 and COD removal from greywater is with PKAC is 150mins, and removal of BOD_5 and COD from greywater with TAAC is 150mins as it can be seen in figure 4.7. This clearly shows that to achieve a greater removal efficiency, PKAC is suitable as compared with TAAC because it achieves a higher removal percentage at the same equilibrium time. It can be seen from Table 4.5 that the values of the correlation coefficient (R^2) for the pseudo first order model are slightly lower than for the pseudo second order model. The pseudo second order model predicts the sorption behaviour over the whole period of the sorption process. Based on the correlation coefficient values obtained from the pseudo-first-order and pseudo-second-order models, it can be said that the reaction follows a pseudo-second-order kinetic model. A pseudo-second order model for BOD_5 and COD removal from waste water was also obtained in a similar study which used activated carbon prepared from date palm (Nayl et al., 2017).

Table 4. 5 Parameters of pseudo first and second order models

		Pseudo-first-order parameters			**Pseudo-second-order parameters**			
		k_1 (min^{-1}) x 10^{-3}	q_e calc (mg/g)	R^2	k_2 (g/mg min) x10^{-5}	q_e, calc (mg/g)	h (mg g^{-1} min^{-1})	R^2
PKAC	BOD	20.96	22.05	0.9795	84.20	28.33	0.67	0.9904
	COD	16.58	33.35	0.9924	32.40	46.73	0.70	0.9738
TAAC	BOD	11.05	18.97	0.9862	21.10	33.22	0.25	0.9089
	COD	9.90	26.58	0.9958	12.80	50.01	0.32	0.9142

Conclusion

This study explored the adsorption capacity of PKAC and TAAC activated by steam to remove BOD_5 and COD from greywater. The physical characteristics of the materials revealed that activated carbon prepared from PKAC had larger surface area as compared with TAAC. The densities of the materials further revealed that TAAC was very light and may float if used in adsorption process without any aid while the density of PKAC was within the recommended densities for activated carbons. The XRD results also showed that both materials had no specific functional groups and they were mostly dominated by carbon. The SEM images identified large fan-like structure of the particles of the TAAC while PKAC showed closely packed

small particles confirming the high adsorptive capacity of PKAC over TAAC. The experimental results obtained showed that PKAC performed slightly better as compared with TAAC. The PKAC is able to remove 73% BOD_5 and 65% COD while TAAC removed 62% of BOD_5 and 52% COD under the same conditions. The optimum dose of carbon that was obtained from the study was 8g/L of adsorbent dose and an optimum time of 150mins. The optimum particle was identified to be 2mm for both materials. However, PKAC performs better over TAAC within the same particle size range. It was also established that the adsorption data fitted the Freundlich model well than the other models considered in this study. The adsorption kinetics followed the pseudo-second-order model well more than the pseudo-first-order model. This study indicates that PKAC and TAAC can be used as an adsorbent to remove BOD_5 and COD. The PKAC, however, performs better under the study conditions. This study used a batch system to arrive at this conclusion. It must be said that for this material to be fully adopted for use into a system for greywater treatment, additional work on the performance of this material in a continuous process using laboratory columns and other models is required.

Wi-Fi

Chapter five

Submitted as

Oteng-Peprah, M., Acheampong, M. A., Osei-Marfo, M., Agyei-Tuffour, B. & de Vries, N. Fixed-bed column studies on adsorption of biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) in domestic greywater using palm kernel activated carbon.

Abstract

This study explored a continuous sorption study in a fixed bed column using activated carbon prepared from palm kernel shell in removing biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) from domestic greywater. The study explored the effects of flowrate (5 – 15ml/min) and variations in bed-depth (10, 15 and 20cm) at a constant inlet concentration of 251mg/l BOD_5 and 421mg/l COD. The experimental data were fitted with different models such as the Thomas, Yoon-Nelson, Adam-Bohart and the Bed Depth Service Time (BDST) models. Though the experimental data fitted well with the Thomas, Yoon-Nelson and BDST models, the Yoon-Nelson model was found to show a good agreement with the experimental data as compared with the other models explored. The adsorbents were found to have a good sorption capacity potential of 34mg/g for BOD_5 and 56mg/g for COD.

Introduction

There has been growing concerns about the effect of untreated greywater entering the environment and this has called for more stringent environmental regulations for both industrial and domestic effluents. Greywater is known to vary both in quantity and quality based on many factors. It has been stated that The composition of greywater depends on factors such as cooking and cleaning practices, personal hygiene, biodegradability frequency of water use before disposal and sanitary practices (Oteng-Peprah et al., 2018). Of particular interest is the concentration of BOD_5 and COD greywater discharged into the environment. The environmental protection agency (Ghana., 2000) has set the limit for the discharge of BOD_5 and COD at 50mg/l and 150mg/l respectively, however, wastewater discharged into the environment are mostly above this regulatory limit. To meet the discharge guidelines greywater from households and industrial settings will require an appreciable level of treatment. One of the most efficient and simple methods for removal of BOD_5 and COD from greywater is adsorption which is much preferred due to its ease of use and wide-scale application. This technique is quite popular due to its simplicity as well as the availability of a wide range of adsorbents. Activated carbon remains one of the most widely used range of adsorbents. It remains one of the most effective and widely used adsorbents because of its excellent adsorption ability (Mohammad-Khah & Ansari, 2009). It has been prepared from many substrates over the years, however, commercial grade activated carbon comes with a higher price tag as compared to the those prepared with low-cost materials (Bulut, Gozubenli, & Aydin, 2007; Errais et al., 2011; Nayl et al., 2017; Sartape, Mandhare, Salvi, Pawar, & Kolekar, 2013). Batch adsorption experiment is the most commonly utilized tests by many researchers in assessing the suitability of potential adsorbents because of its simplicity and low cost (Crini et al., 2008). The data obtained from a batch study are usually used to construct isotherms which are considered a critical step in the design and optimization of the adsorption process (Behnamfard & Salarirad, 2009; Hamdaoui & Naffrechoux, 2007). Many studies have reported removal of BOD_5 and COD in batch systems using various adsorbents (Bansode et al., 2004; Devi et al., 2008; Nayl et al., 2017; Oteng-Peprah, De Vries, & Acheampong, 2019) but little has been known on the removal of BOD_5 and COD in a fixed bed column application. Of particular interest is the batch study by Oteng-Peprah et al. (2019) which reported BOD_5 and COD removal from domestic greywater using activated carbon prepared from palm kernel shell. It has been reported that the data obtained under batch conditions are generally not applicable in most systems or do not mimic what happens in the real world (Patel & Vashi, 2012). Therefore, in order to validate the data obtained in this batch study (Oteng-Peprah et al., 2019), there is the need to perform column studies to provide data for direct application to large scale use. The aim of this study is to investigate the adsorption capacity of the palm kernel activated carbon (PKAC) in a fixed bed column with regards to BOD_5 and COD removal. The PKAC investigated in this study has previously been shown to be effective in removing BOD_5 and COD from greywater in a previous study under batch conditions (Oteng-Peprah et al., 2019). The breakthrough curves are analyzed using Adams-Bohart, Thomas, Yoon-Nelson and the BDST models to determine the characteristic parameters of the column useful for process design.

Column adsorption model

To design a column adsorption process, it is important to predict the breakthrough curve or concentration-like profile and adsorption capacity of the adsorbent for the selected adsorbate under a given set of operating conditions. It is also necessary to determine the maximum sorption column capacity which is a significant parameter for any sorption system. For analysis of the experimental breakthrough curves under different conditions, these common models were used thus the Thomas, Yoon-Nelson, Adams-Bohart models and the bed-depth service time (BDST) model.

The Thomas model

The Thomas model (Thomas, 1944) is one of the most general and widely used models in column performance theory. It is based on the assumption that the process follows Langmuir kinetics with no axial dispersion and the rate driving force follows second order reversible kinetics (Futalan, Kan, Dalida, Pascua, & Wan, 2011). It is represented by equation 1 as shown:

$$\ln\left(\frac{C_o}{C_i}-1\right)=\frac{k_{Th}q_o w}{Q}-k_{Th}C_o t \qquad (1)$$

where k_{th} is the Thomas rate constant (ml/min/mg) q_o is the maximum solid-phase concentration of solute (mg/g); w is the mass of the PKAC in the column (g); Q is the flow rate (ml/min); C_i is effluent concentration (mg/L) and C_o is the influent concentration (mg/L).
A plot of $ln(C_o/C_t - 1)$ against t gives a straight line from which the values of k_{Th} and q_o are determined from the intercept and the slope respectively.

Adams-Bohart

This model assumes that the adsorption rate is proportional to both the residual capacity of the adsorbent and the concentration of the adsorbing species. The model is mostly used for the description of the initial part of the breakthrough curve (Han et al., 2008). It is expressed by equation 2 as shown:

$$\ln\left(\frac{C_o}{C_t}-1\right)=k_{AB}N_o\frac{z}{u}-k_{AB}C_t t \qquad (2)$$

Where C_i is the effluent concentration (mg/l), C_o is the influent concentration (mg/l), K_{AB} is the kinetic constant (L/mg/min), N_o is the sorption capacity (mg/l), Z is the bed-depth (cm), u the linear velocity (mm/h) and t is the time (h).

A plot of $ln(C/C_o - 1)$ against t gives a straight line from which the model constants K_{BA} and N_o can be determined from the slope and intercept.

Yoon Nelson

This model is based on the assumption that the rate of decrease in the probability of adsorption for each adsorbate molecule was proportional to the probability of adsorbate adsorption and the probability of adsorbate breakthrough on the adsorbent (Han et al., 2008). This model is less complicated and requires no detailed data concerning the characteristics of sorbate, the type of adsorbent and the physical properties of the sorption bed (Yoon & Nelson, 1984). It is expressed by equation 3 as shown:

$$\ln\left(\frac{C_t}{C_o-C_t}\right)=K_{YN}t-\tau K_{YN} \qquad (3)$$

Where C_t is the effluent concentration (mg/l), C_o is the influent concentration (mg/l), K_{YN} is the rate constant (/min), τ the time required for 50% sorbate breakthrough and t is the time (min).

A linear plot of $ln(C_t/C_o-C_t)$ against time t gives a straight line where K_{YN} and τ are determined from the intercept and slope.

Bed depth service time (BDST)

This is a simple semiempirical model used in fixed bed analysis to predict the performance of adsorbent. It is based on the assumption that the rate of adsorption is controlled by surface reaction between adsorbate and the unused capacity of the adsorbent (Han et al., 2008; Singha & Sarkar, 2015). It is expressed by equations 4 and 5 as:

$$t = \frac{N_o}{C_o F} Z - \frac{1}{K_o C_o} \ln\left(\frac{C_o}{C_i} - 1\right) \qquad (4)$$

A plot of t versus bed-depth Z gives a straight line from where N_o and K_a can be evaluated from the slope and intercept respectively

$$Z_o = \frac{F}{K_a N_o} \ln\left(\frac{C_o}{C_i} - 1\right) \qquad (5)$$

Where C_t is the effluent concentration (mg/l), C_o is the influent concentration (mg/l), Z_o is the critical bed-depth, k_a is the rate constant, Z is the bed-depth (cm), F is the vertical velocity (cm/min)

Methodology

Greywater samples

Greywater for this experiment was obtained from domestic sources within the study area. The greywater was filtered to remove large and floating objects and their initial concentrations determined. The pH was determined using a Horiba U-50 multiparameter water quality meter, the BOD_5 was measured using the Lovibond BD 606 system, and the COD was determined using the close reflux method.

Fixed-bed Column experiments

The fixed bed column experiments were carried out to assess the performance of palm kernel activated carbon in removing BOD_5 and COD from greywater. This was conducted in a 25mm inner diameter and 37cm length Perspex glass column. Palm kernel activated carbon of average particle size of 2mm was loaded into the Perspex glass column. Glass beads were placed at the bottom of the column to provide support for the adsorbents and placed at the top to prevent the adsorbents from being pulled with the overflow. All experiments were conducted at room temperature with a pH of 7.3 and the direction of flow was from top to bottom using a peristaltic pump. The effluents were collected at regular intervals and the BOD_5 and COD concentrations determined. Flowrate and bed-depth were varied in these experiments. Flowrates of 5, 10 and 15ml/min were used to analyze the effect flowrate variations while bed-depth of 10, 15 and 20cm were used to analyze the effect of different bed-depth on the column performance. Before the column experiment, deionized water was passed through the column in order to wet the entire adsorbate and remove any dirt residue on the surface of the carbon. All experiments were done in triplicates.

Results and discussions

Effect of flow rate on BOD_5 and COD removal

The effect of BOD_5 and COD removal in a fixed bed column by using three different flowrates is studied. The breakthrough curves obtained at different flowrates (5, 10, 15ml/min), constant inlet concentration (BOD_5=252mg/l, COD=421mg/l) and bed-depth of 20cm are presented in figure 5.1 and figure 5.2

respectively. As can be seen from the figures, the breakthrough time, as well as the exhaustion time, increased with decreasing flowrate for both BOD_5 and COD removal. The slope of these plots shows a decrease in duration from breakthrough time to exhaustion time as the flowrate is increased from 5 to 15ml/min. This is supported by the increase in the steepness of the breakthrough curves as the flowrate decreases. The reason for the high breakthrough time associated with low flowrates can be due to increased contact time of the greywater with the activated carbon which results in higher removal of BOD_5 and COD. At high flowrates, the mass transfer rate increases which lead to fast saturation and this is characterized by a reduction in the slope of the curve which is an indication of a high volume of unsaturated zone due to insufficient contact time (Lopez-Cervantes, Sanchez-Machado, Sanchez-Duarte, & Correa-Murrieta, 2018). At lower flowrate, adsorbate has more time to contact with adsorbent and this results in high removal of adsorbate in the column (Sheng, Zhang, Tang, & Liu, 2018). Generally, breakthrough points occur faster with higher flowrate for both BOD_5 and COD removal. The breakthrough and exhaustion time for BOD_5 occurred faster than COD for all the flowrates studied. Results obtained in this study are in agreement with similar studies that used activated carbon from different biomasses (Ademiluyi, Amadi, Amakama, & Nimisingha, 2009; Amale, Kulkarni, & Kulkarni, 2014; Nekoo & Shohreh, 2013) and agricultural waste (Ghaed, Marandi, & Mazhar, 2015) to reduce BOD_5 and COD concentrations in fixed bed studies.

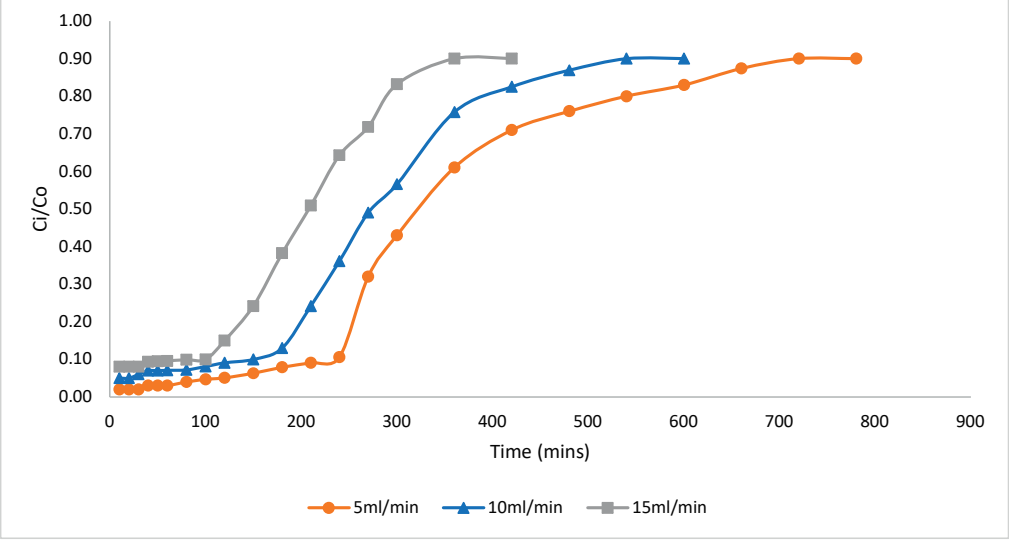


Figure 5. 1 Breakthrough curves of BOD_5 removal by PKAC (pH = 7.3, bed-depth = 20cm, temperature = 25°C, inlet concentration = 252mg/l)

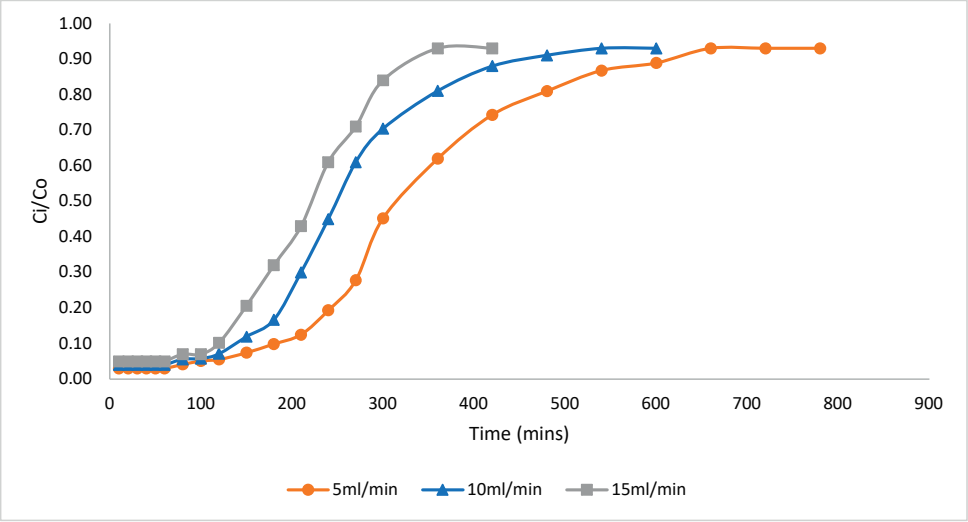


Figure 5. 2 Breakthrough curve COD removal by PKAC (pH = 7.3, bed-depth = 20cm, temperature = 25°C, inlet concentration = 421mg/l)

Effect of bed-depth on BOD_5 and COD removal

The effect of bed-depth on the breakthrough curve is studied by using three different bed-depth (10, 15, 20cm). These were achieved by charging 15, 20 and 26g representing 10, 15 and 20cm respectively of the activated carbon into the column. Greywater with initial BOD_5 and COD concentrations of 252mg/l and 421mg/l respectively was used as feed to the fixed bed column at a constant flowrate of 5ml/min. The breakthrough curve for BOD_5 and COD are presented in figure 5.3 and figure 5.4 respectively. As it can be seen from the shapes and slopes of each curve, there are slight variations for the different bed-depth. Generally, the breakthrough time increases at higher bed-depth of the adsorbent. As the bed-depth increases from 10cm to 20cm, there is a corresponding decrease in the slope of the breakthrough curve that is observed. The breakthrough time for BOD_5 and COD also increased when the bed-depth was increased from 10 to 20cm. This, therefore, implies that breakthrough and exhaustion times are longer with increasing bed-depth. An increase in bed-depth implies an increase in the surface area and the number of binding sites available for adsorption. This then leads to higher contact time needed for adsorption to take place as suggested by Teutscherova et al. (2018). The exhaustion time which is the time taken for the adsorbent to be totally used up also increased with the change in height for both BOD_5 and COD. There was however a remarkably high exhaustion time for the 20cm bed-depth for both BOD_5 and COD. This could be attributed to increased utilization of the bed. Generally, breakthrough time for BOD_5 is shorter than for COD for all the bed-depth studied. From the figures, it can be said that a higher bed-depth indicates a higher BOD_5 and COD can be adsorbed due to increase in the surface area of the adsorbent, hence providing more vacant sites for adsorption to take place (Ahmad & Hameed, 2010; Futalan et al., 2011). Other researchers have reported similar changes in breakthrough curve with changes in bed-depth using activated neem leaf powder (Patel & Vashi, 2015), activated carbon from different biomasses (Ademiluyi et al., 2009; Amale et al., 2014; Nekoo & Shohreh, 2013) and agriculture waste (Ghaed et al., 2015) to reduce BOD and COD in similar studies.

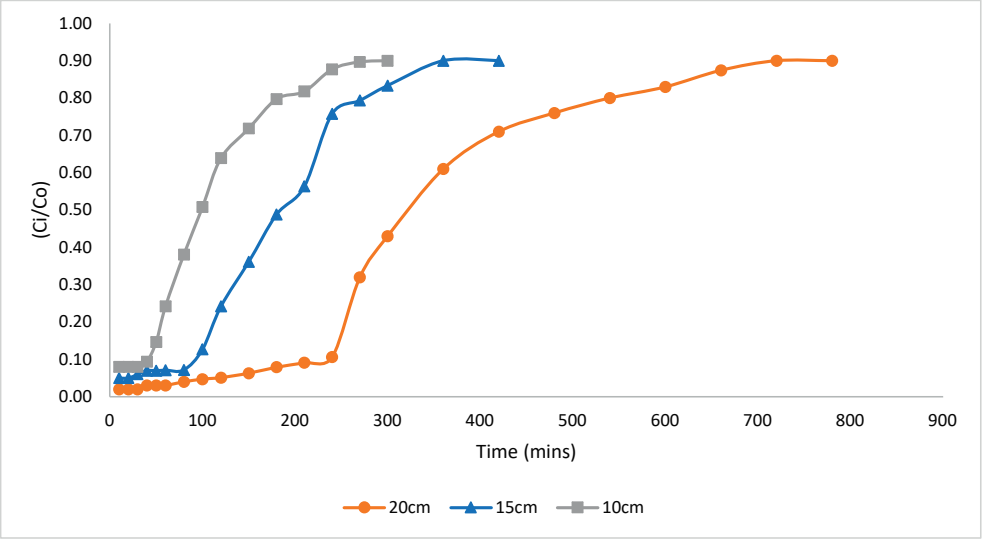


Figure 5. 3 Breakthrough curve BOD_5 removal by PKAC (pH = 7.3, flowrate = 5ml/min, temperature = 25°C, inlet concentration = 252mg/l)

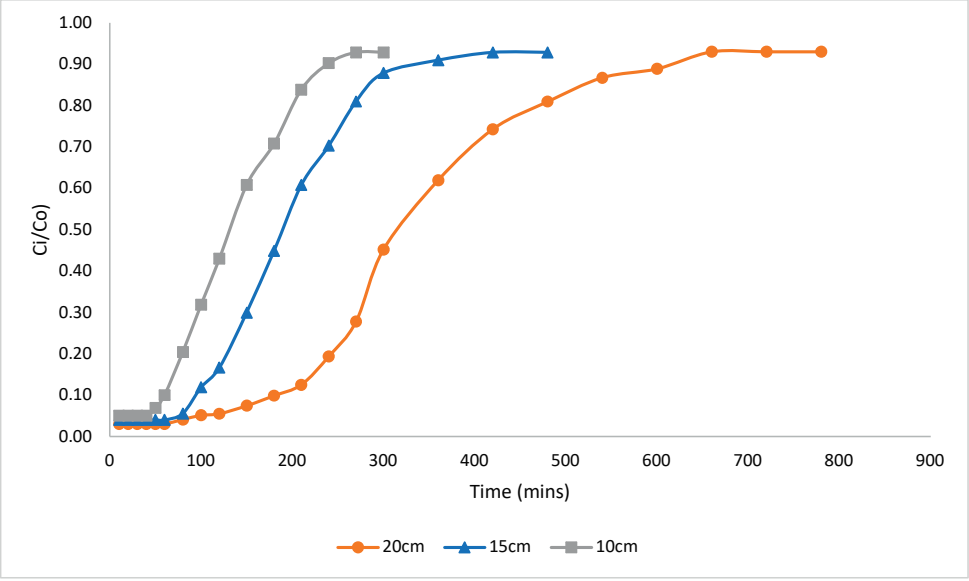


Figure 5. 4 Breakthrough chart for COD removal by PKAC (pH = 7.3, flowrate = 5ml/min, temperature = 25°C, inlet concentration = 421mg/l)

Dynamic models

The Thomas models

The model was applied to the experimental data under conditions of constant influent concentration, different bed-depth and different flowrates. The linearized form of the model was used to determine the Thomas rate constant (k_{TH}) and the bed capacity (q_o) of the Thomas equation for both BOD_5 and COD. The model parameters which were determined have been presented in table 5.1. From this table, it can be seen that k_{Th} for BOD_5 and COD increased with increasing flowrate, but it decreased with increasing bed-depth. Similarly, q_o for BOD_5 and COD decreased with increase in flowrate whereas an increase in bed-depth saw a corresponding increase in q_o over the entire adsorption period. Other studies have reported similar findings in fixed bed column (Chowdhury, Zain, Rashid, Rafique, & Khalid, 2013; Lin et al., 2013; Nguyen et al., 2015). The maximum bed capacity of 34.4mg/g and 56.93mg/g were obtained for BOD_5 and COD respectively at flowrate of 5ml/min and a bed-depth of 20cm. This maximum bed capacity was obtained at the lowest flowrate and a highest bed-depth. The maximum bed capacity occurring at this point can be due to the fact that at lower flowrates and maximum height, the adsorption capacity is high due to sufficient residence time which allows for effective utilization of the vacant sites before equilibrium is reached as suggested by Tan, Ahmad, and Hameed (2008). A good fit (R^2>0.98) was obtained for both BOD_5 and COD as shown in table 5.1. Comparing the k_{TH} between BOD_5 and COD, it can be seen that BOD_5 has a higher k_{TH} which is an indication of good column adsorption for BOD_5 as compared with COD. Comparing the q_o, it can also be seen that the q_o for COD is higher than BOD_5 indicating a higher uptake capacity of the Palm kernel activated carbon to reduce higher proportions of COD than BOD_5.

Table 5. 1 . Thomas model parameters at different conditions

Parameter	Initial Concentration (mg/L)	Flowrate (mL/min)	Bed height (cm)	k_{TH} (mL/min-mg) x 10^{-5}	q_o (mg/g)	R^2
BOD_5	252	5	10	7.18	11.13	.92
	252	5	15	5.99	13.19	.96
	252	5	20	3.61	34.40	.95
	252	10	20	4.05	31.50	.96
	252	15	20	4.92	21.26	.95
COD	421	5	10	4.04	23.53	.89
	421	5	15	2.92	26.41	.88
	421	5	20	2.30	56.93	.96
	421	10	20	2.85	49.73	.96
	421	15	20	3.82	32.82	.97

The Yoon-Nelson model

The experimental data were fitted to the Yoon-Nelson model under constant influent concentration, varying flowrate and varying bed-depth. The linear form of the Yoon-Nelson model was used to determine the mass transfer coefficient (K_{YN}) and the time for 50% breakthrough (τ) and is presented in table 5.2. Generally, as the flowrate increases, it can be seen that there is a corresponding increase in K_{YN} for BOD_5 and COD. Greater mass transfer coefficient (K_{YN}) implies narrower mas transfer zone, greater transfer coefficient between the phases and therefore lower mass transfer resistance and hence adsorption of BOD_5 and COD is easier with higher values of K_{YN}. There is also a corresponding decrease in the time taken to reach 50% breakthrough as flowrate is increased. Brion-Roby, Gagnon, Deschenes, and Chabot (2018) have reported similar changes in the Yoon-Nelson model parameters in a similar study. The changes observed can be attributed to reduced residence time associated with high flowrates. An increase in bed-depth leads to a corresponding reduction in the mass transfer coefficient but an increase in the time taken for 50% breakthrough to be achieved. This could be due to more vacant sites for adsorption to take place and hence a longer time to reach 50% of the breakthrough period. A comparatively good fit (R^2>0.89) was obtained for both BOD_5 and COD as shown in table 5.2 which suggests that the Yoon-Nelson model fitted the experimental model for BOD_5 and COD in the sorption experiment.

Table 5. 2 Yoon-Nelson parameters at different conditions

Parameter	Initial Concentration (mg/L)	Flowrate (mL/min)	Bed height (cm)	K_{YN} (mL/min-mg)	τ (mins)	R^2
BOD_5	252	5	10	0.0181	426.66	.92
	252	5	15	0.0151	209.38	.96
	252	5	20	0.0091	421.90	.95
	252	10	20	0.0102	312.57	.96
	252	15	20	0.0124	227.48	.98
COD	421	5	10	0.0170	2.8502	.89
	421	5	15	0.0171	3.6589	.96
	421	5	20	0.0095	389.83	.96
	421	10	20	0.0120	295.31	.96
	421	15	20	0.0161	225.36	.98

The Adams-Bohart model

The linear form of the Adams-Bohart model was applied to the experimental data by plotting C_i/C_o against *t* for both BOD_5 and COD. This model is based on surface reaction theory and assumes that equilibrium is not instantaneous therefore the adsorption rate is proportional to both the residual capacity of the adsorbent and the adsorbate concentration (Lopez-Cervantes et al., 2018). The values of maximum adsorption capacity (N_o) and the kinetic constant (K_{AB}) of the model have been calculated and presented

in table 5.3. Comparatively, the values for BOD_5 are higher than COD for all the studied conditions. The values of K_{AB} and N_o increase with an increase in flowrate for both BOD_5 and COD. Additionally, as the bed-depth is increased, the value of K_{AB} decreases while N_o increases. Similar findings have been obtained in a fixed bed column study by (Brion-Roby et al., 2018; Mondal, Mehta, Saharan, & George, 2018; Xavier et al., 2018). The values of the $R^2 > 0.78$ recorded are lower as compared to the other models studied and thus suggests that the Adam-Bohart model cannot be used to predict the experimental data in the range of conditions used. This may be due to the fact that the Adams-Bohart model is applied in regions of low concentration and large discrepancies can be found between the experimental and predicted curve if applied outside the concentration range (Karimi, Shojaei, Nematollahzadeh, & Abdekhodaie, 2012).

Table 5. 3 Adams-Bohart Model parameters at different conditions

Parameter	Initial Concentration (mg/L)	Flowrate (mL/min)	Bed height (cm)	k_{AB}(mL/min-mg) x 10^{-5}	N_o (mg/g) x10^4	R^2
BOD_5	252	5	10	3.69	.9683	.78
	252	5	15	3.45	.8872	.87
	252	5	20	2.26	1.26	.87
	252	10	20	2.34	1.97	.91
	252	15	20	2.62	2.34	.88
COD	421	5	10	2.85	1.64	.86
	421	5	15	2.40	1.46	.87
	421	5	20	1.31	2.05	.88
	421	10	20	1.62	3.16	.87
	421	15	20	2.21	3.49	.92

The BDST Model

The experimental results obtained from the column sorption experiment is fitted with the BDST model to determine the sorption capacities and kinetic constants for BOD_5 and COD. This is mostly used to predict the relationship between bed-depth (Z) of a fixed bed column with service time. The service time corresponding to bed-depth 10, 15 and 20cm at a constant flowrate of 5ml/l at constant inlet concentration of 252mg/l BOD_5 and 421mg/l COD were recorded. A plot of the service time versus bed-depths at the different bed-depth is presented in 5.5. From the slope and intercept of figure 5.5, the BDST parameters viz sorption rate constant (k), sorption capacity (N_o) and critical bed-depth (Z_o) were calculated and presented in table 5.4. The high values of R^2 imply a probable linear relationship for the systems and show that the BDST model can be applied to the continuous column studies.

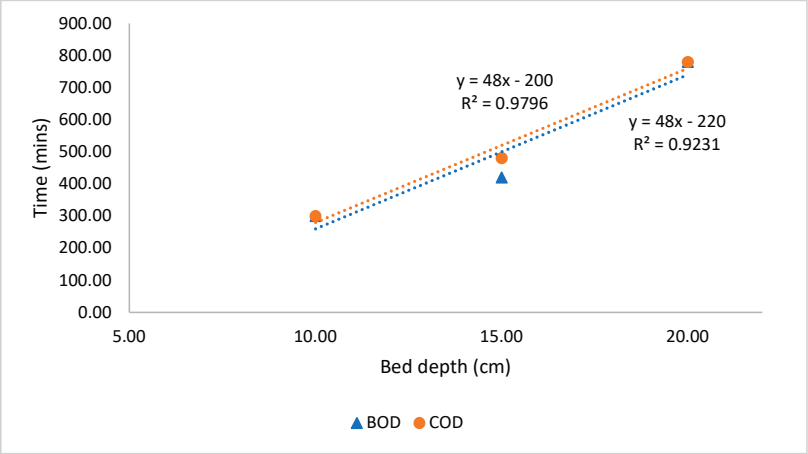


Figure 5. 5 Bed Depth Service Time for BOD5 and COD

Table 5. 4 BDST model parameters for BOD5 and COD

	N_o	K_a	Z_o	R^2
BOD_5	19,353.60	3.96x10-5	4.58	.92
COD	24,249.60	2.61x10-5	5.56	.98

Conclusion

The removal of BOD_5 and COD from domestic greywater by sorption using PKAC was investigated in a fixed bed column under conditions of fixed inlet concentration, different inlet flowrate and different bed-depths. Based on the experimental results, PKAC has shown to be a very efficient adsorbent in the removal of BOD_5 and COD under the studied conditions. The sorption of BOD_5 and COD was strongly dependent on flowrate and bed-depth. An increase in bed-depth resulted in increased uptake capacity while an increase in flowrate resulted in a reduced uptake capacity for both BOD_5 and COD. A maximum uptake capacity of 35mg/g and 54mg/g was achieved for BOD_5 and COD respectively. The experimental data fitted well the Thomas, Yoon Nelson and BDST models. The Yoon-Nelson provided a better description of the experimental kinetic data in comparison to the Thomas model. This study has established the potential of using a free, locally and abundantly available waste material for the preparation of activated carbon in reducing the BOD_5 and COD in domestic greywater.


XIS

Chapter six

Published as

Oteng-Peprah, M., Acheampong, M. A., & DeVries, N. K. (2019). Predicting greywater reuse for potable and non-potable purposes in a developing country - a theory of planned behaviour approach. *Desalination and Water Treatment, 142*, 56-64. doi:10.5004/dwt.2019.23414

Abstract

This study was aimed at predicting greywater reuse in a municipality of a developing country using the theory of planned behaviour. It sought to identify the beliefs that influence people's intentions to reuse greywater for potable and non-potable purposes. Residents within the municipality completed a questionnaire designed with the TPB constructs and other demographic data. Results revealed an excellent fit for potable reuse intention and a mediocre fit for non-potable reuse intentions. Attitudes and behavioural control were the constructs that significantly influenced intentions to reuse greywater for both potable and non-potable purposes. Location of the source of water to the respondents and level of education were introduced as background factors. Location of the source of water had no significant direct or indirect influence on intentions to reuse greywater for potable or non-potable purposes. Level of education had a non-significant indirect and direct effect on intentions to reuse greywater for potable but is mediated through attitudes and perceived behavioural control for non-potable reuse intentions. Strategies aimed at promoting greywater reuse should be targeted at a specific reuse option and not a wholesale intervention that is expected to address all reuse interventions.

Keyword

Greywater, Reuse, Theory of planned behaviour, Potable, Non-potability

Introduction

Water use and demand around the globe have increased rapidly, even at a higher rate than population growth (WHO, 2006b). Due to industrialization and urbanization, most developing countries are using more water than they previously used in order to sustain both standard of living and economic growth. However, these developing countries have to deal with limited access to clean and potable water. Water resource professionals believe reclaiming water after use is an important and underutilized element of sustainable water resources management. Lack of access to clean water has been shown to be directly linked to poor sanitation and hygiene and a decline in economic growth (UNICEF, 2016). Wastewater generated from human activities is not regarded as a byproduct that can be reused but should be discarded. However, greywater which forms part of wastewater can be easily treated for reuse. Greywater is characterized as a high-volume low strength stream that constitutes about 50% – 80% of domestic wastewater (DHWA, 2002; Jamrah, Al-Futaisi, Prathapar, Ahmed, & Al-Harrasi, 2008; Oteng-Peprah et al., 2018). It is considered a very useful resource, which can address the emerging water crisis that the world is expected to face and further reduce the overreliance in treating freshwater for non-potable uses. Water reuse can help improve water conditions in areas with a lot of strain on their water resources. Many states in the United States support the general concept of greywater reuse for non-potable purposes (EPA, 2012). Direct potable reuse (DPR) has also been used in some arid and semi-arid countries. DPR involves the introduction of treated wastewater into the raw water supply system of a drinking water treatment facility or direct injection of this treated water into a potable water supply distribution system (WRF, 2015). There are many technologies that exist today which can treat greywater into drinking water quality standards. However, despite the proof and certainty that the water meets the required standards for consumption, it has seen more resistance and less interest in the population. Currently, the only city that has adopted DPR on a large scale is Windhoek, the capital city of Namibia where highly treated waste water is recycled into a drinking water system that serves close to 250,000 people (Gale, 2017; WRF, 2015). Other agencies and municipalities in the United States have also begun looking at DPR as a viable option.

In the implementation of any project, public perception has been recognized as one of the integral factors in determining the success of the project. Several studies have been conducted to assess public perception towards greywater reuse in different parts of the world using different strategies. These strategies include interviews, questionnaires, focus group discussions, informal discussions and other equally good social surveys (Alhumoud & Madzikanda, 2010; Bruvold, 1998; Dolnicar & Schafer, 2009; Dolnieara & Saunders, 2006; Higgins, Warnken , Sherman, & Teasdale, 2002; Jeffery, 2001; Marks, 2006). It is however clear that most of these surveys identified clear support for the concept of greywater reuse as an environmentally sustainable method of protecting freshwater resources and pollution prevention. However, Gifford and Nilsson (2014) identified that simply transmitting knowledge is not enough to change lifestyles and behaviour patterns. It is obvious that communities support the concept of water reuse as a means of responsible water resources management to mitigate scarcity and abate pollution. However, internationally, many technically sound schemes have failed because communities have rejected them. Ajzen, Joyce, Sheikh, and Cote (2011) have suggested that there is the need to identify the beliefs people hold towards an issue and how these beliefs affect their intentions and behaviour rather than making sure people have accurate information. Although some researchers have studied the behaviours of recycled water reuse (Hurlimann, Hemphill, McKay, & Geursen, 2008; Nancarrow, Leviston, Po, Porter, & Tucker, 2008), little has been known of how people in developing countries make their decisions to accept or reject greywater reuse schemes.

This research is therefore aimed at providing a deeper understanding of the factors that will influence the perception of individuals in developing country to accept greywater as an alternative source of water by using a social cognitive model known as the Theory of Planned Behaviour (TPB). This study holistically investigates the reasons why people will want to reuse greywater from the cultural, religious, location of current water supply, regulatory and environmental points of view. Developing this kind of knowledge is crucial for creating interventions that aim to promote greywater reuse and further develop a theoretical decision model for policymakers in developing countries.

Analysis of the framework

According to the theory, human behaviour is guided by three kinds of considerations: beliefs about the likely consequences of the behaviour (behavioural beliefs), beliefs about the normative expectations of others (normative beliefs) and beliefs about the presence of factors that may facilitate or impede performance of the behaviour (control beliefs) (Ajzen, 1991; Fishebein & Ajzen, 2015). In their respective aggregates, behavioural beliefs produce a favourable or unfavourable attitude towards the behaviour; normative beliefs result in perceived social pressure or subjective norms and control beliefs give rise to perceived behavioural control. In combination, attitude toward the behaviour, subjective norm and perception of behavioural control lead to the formation of a behavioural intention which may then be converted into action. The direct path between perceived behavioural control and behaviour models the actual behavioural control. This refers to the extent to which a person has the skills, resources and other prerequisites needed to perform a given behaviour. Therefore, the successful performance of the behaviour depends not only on favourable intention but also on a sufficient level of behavioural control (Ajzen, 1991). According to the model, people's attitudes toward behaviour are determined by their accessible beliefs about the behaviour, where a belief is defined as the subjective probability that the behaviour will produce a certain outcome. The outcome probability is weighed with the subjective evaluation of the outcome (Ajzen & Fishebein, 1975). In the theory of planned behaviour, the expectancy values of attitude, subjective norm and perceived behavioural control are obtained by the product of behavioural belief and outcome evaluations, normative belief and motivation to comply and, control belief and perceived power to control respectively. The conceptual framework supporting this theory is presented in figure 6.1.

The defining behaviour of interest in the design of the questionnaire is the individual perception towards greywater reuse thus the flexibility within which an individual is willing to accept greywater as an alternative source of water. Following the definition of the three main determinants, as described in the theory of planned behaviour, the individual determinants of greywater reuse consider the various reuse options that are available for greywater reuse and these are non-potable and potable uses. An individual's societal norms refer to the pressure or level of acceptance for the option of greywater reuse and these include family, neighbours and the regulatory body. The individual's perceived behavioural control refers to the ability of an individual to reuse greywater.

The predictive strength of these factors is analyzed using structural equation modelling (SEM) to examine the relationship between factors and individual perceptions of greywater as an alternative source of water. Fundamentally, SEM is a term for a large set of techniques based on general linear models. It is often used to access hidden factors that contribute significantly to a phenomenon or condition. SEM multivariate technique combines aspects of multiple regression and factor analysis to assess a series of

dependent relationships simultaneously which is not possible using other multivariate techniques (Hair, Anderson, Tatham, & Black, 2014).

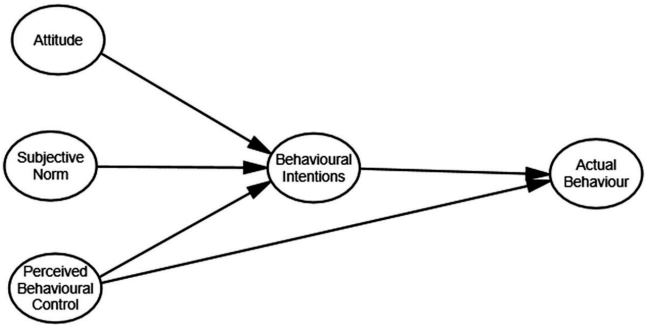


Figure 6. 1

Methodology

This was a cross-sectional study carried out among local residents of a peri-urban municipality within the central region of Ghana. The central region of Ghana is chosen for this study because it has a blend of rural, peri-urban and urban settlements. It also has people from different cultures and ethnicities. The study adopted a random sampling approach to collect data. The study used the TPB to assess the predictive power of the Theory's constructs on the intention to reuse greywater for potable and non-potable reuse options.

Pilot study

Fishebein and Ajzen (2015) suggest elicitation of accessible beliefs from a sample of respondents prior to designing the TPB questionnaire. A pilot study was conducted among 50 local residents within the study area. An open-ended questionnaire was administered to them to determine their readily accessible beliefs about greywater reuse. They were asked to write their opinion about greywater reuse with specific emphasis on the advantages and disadvantages of reusing greywater for domestic potable and other non-potable uses such as irrigation, toilet flushing, car washing etc. They were also to state the persons or groups of people who would approve or disapprove of their actions in greywater reuse and finally factors that could either facilitate or prevent them from reusing greywater for the above-listed functions. A content analysis of the responses was conducted to determine frequencies of each of these responses and the most frequent responses were included in the model set.

Prior to conducting the main study, 60 local residents were selected for a pretest of the questionnaire. This was conducted to test the coherence, understandability, clarity and psychometric properties of the questionnaire. Modifications were then made to questions that were not clearly worded or sounded ambiguous. Because the study is interested in identifying the determinants of greywater reuse for two specific reuse options, the questionnaire was a two-in-one type that had constructs of the TPB model with each section capturing specific reuse option. An overall Cronbach alpha for potability and non-potability reuse were 0.670 and 0.839 respectively indicating that the scales were all adequate.

Main study

Residents within the study area were approached by the investigator and after declaring their willingness to participate in the study, they were asked to sign a consent form and received information regarding the aim of the study. The questionnaire was in two parts; one part included items on demographics while the second part included the TPB constructs. All the items on the TPB section were scored using a 7-point Likert scale. Three research assistants were present to support respondents who had difficulty in responding to the questionnaires.

Questionnaires

Attitude

The attitude was measured using behavioural beliefs and their outcome evaluation. The questionnaire had a total of 4 questions that were used to assess the participants' beliefs and 4 outcome evaluations about the consequences of reusing greywater for various reuse options. The questionnaire assessed the individual's advantages and disadvantages of reusing greywater. From the elicitation, the relevant beliefs that were identified are water conservation, environmental protection, reduction in water bills and health concerns.

Subjective norms

Subjective norm was measured using normative beliefs and motivation to comply. The questionnaire had a total of 3 questions that were related to normative beliefs and 3 questions on accompanying motivation to comply. Participants were asked to rate how specific important people either agreed or disagreed to them reusing greywater and whether this has any influence on their decision to either reuse or not reuse greywater for the various reuse options.

Perceived behavioural control

Perceived behavioural control was measured using control beliefs and power of control factors. The questionnaire had a total of 5 questions that were related to control beliefs and 5 questions that were related to the matching perceived power to control factor. The questionnaire assessed the ability of the individual to reuse greywater without any hinderances.

Behavioural Intentions

A total of 3 questions were used to assess the intentions of greywater reuse.

Demographics

The questionnaire assessed demographic information about the respondents. In total, 5 demographic items were assessed in the questionnaire.

Statistical analyses

A total of 853 respondents were approached and responses were received from 526 indicating a response rate of 61%. The researchers cancelled questionnaires that had any item vacant. In all, 462 respondents

completed all items from the survey. The model constructs are analyzed using factor analysis with structural equation modelling using SPSS Amos 23 with Maximum likelihood estimation. The analyses were performed in two steps. First**,** the original TPB model was tested for both reuse options. Secondly, in order to better understand the role of education and proximity to the source of water played in intentions, these distal variables (proximity to source and level of education) were introduced into the model.

Descriptive analysis of variables

The research framework consists of three exogenous and one endogenous variable for each of the reuse options. Each construct shows an acceptable Cronbach alpha value of above 0.60 as recommended by Field (2014). A composite variable of each belief was derived by multiplying each belief statement by its corresponding belief evaluation. The model is assessed by using sample size independent fit indices such as root mean square error of approximation (RMSEA), normed fit index (NFI), Tucker-Lewis index (TLI) and comparative fit index (CFI). According to Cangur (2015), the acceptable values of TLI and CFI are 0.90 while values above 0.95 are classified as excellent, and RMSEA values smaller than 0.08 classified as acceptable while values less than 0.06 classified as excellent. The NFI ranges from 0-1 with 1 being a perfect fit.

Results

Demographic profile of respondents

The demographics and other distal factors are presented in table 6.1. The mean age of the respondents was 40 (12.8) years. From the descriptive statistics of the profile of respondents, it can be observed that a majority of the respondents had tertiary education implying their comprehension of the questionnaire administered to them. The majority of these respondents were Christians which also reflects the religious dynamics within the study area. With reference to the source of water, the majority of the respondents relied on potable pipe borne water supplied by the water company with just a minority still relying on unsafe drinking water sources such as streams. Though a majority indicated they relied on a piped network, not all of them have the resource in their house. As can be seen in table 6.1, about 31.6% will have to walk or move out of their dwelling to have access to water. A majority of respondents are Akans which is the largest tribe in Ghana.

Table 6. 1

Demographics	**Frequency**	**Percentage**
Sex		
Female	229	50.7
Male	223	49.3
Educational Level		
No formal education	44	9.7
Basic	75	16.6
Secondary	123	27.2
Vocational	32	7.1
Tertiary	178	39.4
Religion		
Christianity	331	73.2
Islam	101	22.3
Traditional	10	2.2
Hinduism	10	2.2
Source of Water		
Pipeborne	387	86.6
Stream	6	1.3
Well	59	13.1
Location of source of water		
In-house	309	68.4
Outside	143	31.6
Tribe		
Akan	297	65.7
Ewe	56	12.4
Ga	45	10.0
Northerner	54	11.9

Descriptive statistics

Participants reported weak intentions (M=2.04, SD=0.10), negative attitude (M=-4.26, SD=13.04), low social pressure (M=2.32, SD=1.28) and negative controllability (M=-3.81, SD=0.73) to reuse greywater for potable purposes. However, for non-potable uses, participants reported strong intentions (M=5.15, SD=0.24), positive attitude (M=9.37, SD=5.81), moderately high social pressure (M=4.54, SD=3.59) and high controllability (M=12.43, SD=0.64). The correlation matrix presented in table 6.2 indicates that almost all the variables in the TPB are significantly associated with behavioural intentions. The results showed that the significant predictors of greywater reuse intentions were attitudes and perceived behavioural control while social pressure has no significant influence on intentions to reuse greywater.

Table 6. 2 Correlation, Cronbach Alpha, Grand Means and factor means table for model. Lower triangular matrix represents non-potability and upper triangular matrix represent potability reuses

Latent	Cronbach Alpha		Mean (SD)			Mean		Correlation Matrix															
	Pot	N.Pot	Pot	N. Pot		Pot	N.Pot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Attitude	0.60	0.70	-4.26[b] (13.04)	9.37[b] (5.81)	1 Water conservation	-10.73[b]	11.73[b]	1	.636**	.694**	-.316**	-.165**	-.035	-.107*	.031	.021	.048	.127**	-.096*	.158**	.038	.059	.098*	.033
					2 Environmental protection	-10.74[b]	12.28[b]	.744**	1	.619**	-.292**	-.137**	-.042	-.118*	.082	.017	.075	.108*	-.067	.237**	.140**	.152**	.174**	-.013
					3 Reduction in water bill	-10.88[b]	12.78[b]	.754**	.772**	1	-.365**	-.190**	-.063	-.126**	.060	.028	.056	.127**	-.033	.121**	.039	.035	.222**	-.036
					4 Health concerns	15.32[b]	0.68[b]	.001	-.030	-.044	1	.080	-.015	.085	-.018	.085	-.017	-.047	-.990*	-.114*	-.109*	-.006	-.093*	.025
Subjective norms	0.611	0.60	2.32[b] (1.28)	4.54[b] (3.59)	5 Family	2.64[b]	1.41[b]	.343**	.310**	.353**	-.068	1	.240**	.330**	-.010	.010	.030	-.026	.009	-.002	.040	.024	-.068	-.081
					6 Neighbours	0.91[b]	3.77[b]	-.013	-.057	-.019	-.109*	.226**	1	.466**	-.014	.019	.007	-.045	.056	-.043	-.051	-.011	-.075	.008
					7 Authority	3.42[b]	11.50[b]	.054	.051	.128**	-.134**	.298**	.508**	1	.004	.011	.042	-.031	.016	-.019	-.011	.002	-.088	.040
Perceived Behavioural control	0.791	0.92	-3.81[b] (0.73)	12.43[b] (0.64)	8 Technology	-3.42[b]	12.70[b]	.664**	.596**	.599**	.038	.334**	.002	.076	1	.449**	.520**	.467**	.544**	.259**	.201**	.206**	-.042	-.010
					9 Water scarcity	-3.76[b]	12.39[b]	.578**	.576**	.565**	-.050	.252**	-.036	.056	.690**	1	.403**	.382**	.442**	.198**	.209**	.190**	-.043	-.039
					10 Religion	-3.30[b]	13.27[b]	.570**	.540**	.573**	-.014	.262**	-.013	.094*	.610**	.746**	1	.480**	.316**	.275**	.192**	.215**	-.105*	-.006
					11 Incentives	-3.49[b]	12.29[b]	.416**	.426**	.432**	-.017	.188**	-.038	.008	.514**	.604**	.718**	1	.352**	.387**	.277**	.286**	-.001	.076
					12 Culture	-5.08[b]	16.51[b]	.573**	.565**	.572**	-.023	.258**	-.035	.078	.641**	.807**	.959**	.710**	1	.182**	.110*	.142**	-.078	-.024
Intentions	0.878	0.95	2.04[a] (0.10)	5.15[a] (0.24)	13 Make and effort	1.91[a]	5.36[a]	.349**	.395**	.340**	-.118*	.220**	.084	.099*	.356**	.316**	.326**	.246**	.349**	1	.687**	.689**	.047	.013
					14 Have plans	2.10[a]	5.21[a]	.323**	.356**	.307**	-.122**	.200**	.081	.094*	.330**	.290**	.312**	.204**	.337**	.920**	1	.748**	.027	-.020
					15 Will reuse	2.09[a]	4.89[a]	.273**	.294**	.272**	-.045	.203**	.050	.077	.305**	.241**	.278**	.171**	.291**	.807**	.849**	1	.021	.013
Background factors	-	-	-	-	16 Education	-	-	-.095*	-.181**	-.157**	-.085	-.148**	.007	-.089	-.140**	-.105**	-.145**	-.096*	-.142**	.006	.027	.001	1	-.205**
	-	-	-	-	17 Proximity	-	-	-.078	-.048	-.026	.002	-.064	.023	.068	-.073	-.038	.022	-.012	.003	-.122*	.101*	.104*	.205**	1

*=p<0.05, **=p<0.01 level [a] Theoretical range = 1 – 7 [b] Theoretical range = -21 – 21

Testing the TPB model

The structural models representing potable reuses and non-potable reuses are presented in figure 6.2 and 6.3 respectively. The test indicates that this model accounted for 16% and 18 % of the total variance in respondent's intentions to reuse greywater for potable and non-potable purposes respectively. Based on the Cohen (2013) classification it can be seen that Attitude (β=0.11, SE=0.008, p=0.039) had a small but significant effect on intentions for potable reuse whereas there was a moderate and significant effect of Attitude (β=0.28, SE=0.017, p<0.01) on intentions towards non-potable reuse. Both subjective norms had small size effect and were insignificant on intentions for potable reuses (β=0.00, SE=0.014, p=0.996) and non-potable reuses (β=0.10, SE=0.019, p=0.056). Perceived behavioural control (β=0.37, SE=0.027, p<0.01) had a moderate but significant effect on intentions towards potable reuses whereas the effect was weak but significant (β=0.37, SE=009, p<0.001) towards non-potable reuses.

The direct links between composite beliefs and the TPB latent variables were all between (β=0.40 - 0.98, p<0.01) indicating very high effects on the individual latent variables on both potable and non-potable uses. However, there is an insignificant small effect between attitude and health concerns belief composite (β=0.03, p=0.281). Effects between latent variables indicate significant paths for both categories with the strongest effect being between perceived behavioural control and attitude in non-potable reuse (β=0.68, SE=0.062, p<0.001) and between attitude and subjective norm (β=-0.19, SE=0.011, p<0.001) for potable reuse. The remaining paths show small and insignificant effects (β=0.02 – 0.17, p>0.05).

The fit indices indicate that the standard TPB model provided an excellent fit to the data on potable reuses (CFI=0.963, NFI=0.929, TLI=0.954, RMSEA=0.047) and a mediocre fit for non-potable reuses (CFI=0.939, NFI=0.925, TLI=0.924, RMSEA=0.092).

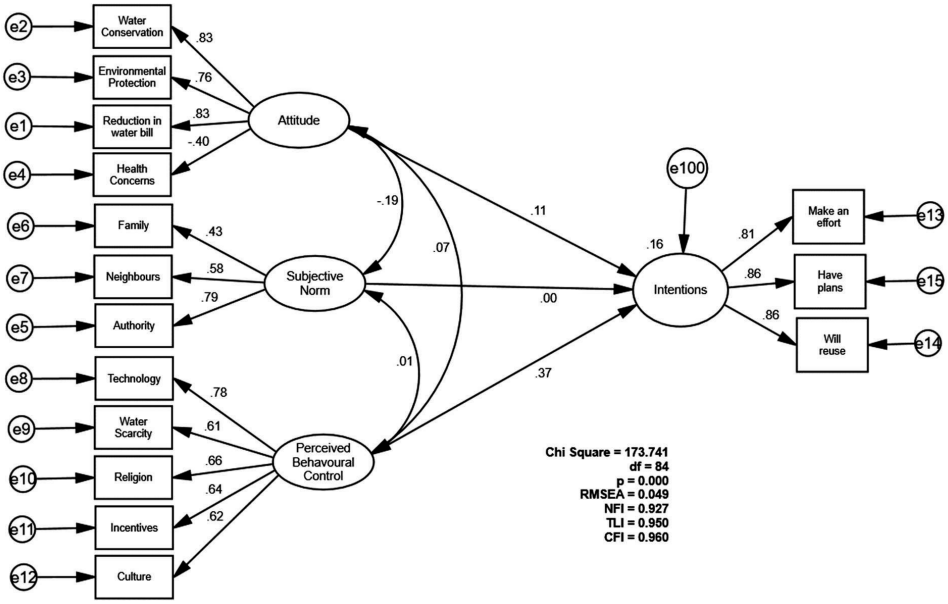


Figure 6. 2 Potability

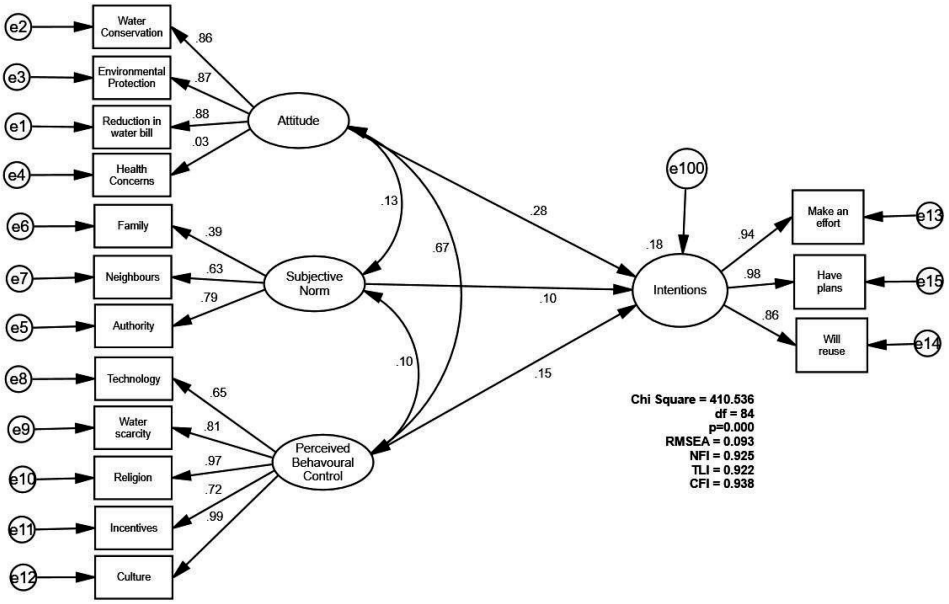


Figure 6. 3 Non-potability

Effects of beliefs

The four behavioural beliefs explained 80.4% of the variance in attitude towards greywater reuse towards both potable and non-potable purposes. These beliefs were '*reusing greywater for potable/non-potable purposes will help me save water at home', 'reusing greywater for potable/non-potable purposes will help me protect the environment', 'reusing treated greywater at home for potable/non-potable purposes will help me reduce my water bills' and 'reusing treated greywater at home for potable/non-potable purposes will be dangerous to my health'*. The effect of these beliefs on potable reuses is water conservation (β=0.83, p<0.001), environmental protection (β=0.76, p<0.001), reduction in water bill (β=0.83, p<0.001) and health concerns (β=0.40, p<0.001). Whereas the effects on non-potable reuses are: water conservation (β=0.86, p<0.001), environmental protection (β=0.87, p<0.001), reduction in water bill (β=0.88, p<0.001) and health concerns (β=0.03, p=0.281).

Five composite control beliefs explained 79.7% of the variance in perceived behavioural control towards potable reuse and 92% towards non-potable reuses. These beliefs were*: 'an appropriate technology for treating greywater will encourage me to reuse it for potable/non-potable purposes', 'water scarcity will force me to reuse treated greywater for potable/non-potable purposes', 'my religious practices does not prevent me from reusing treated greywater for potable/non-potable purposes', 'incentives for reusing treated greywater potable/non-potable purposes will encourage me to adopt it', 'my cultural practices does not prevent me from reusing treated greywater for potable/non-potable purposes'*. The effect of these beliefs on potable reuses are: technology (β=0.78, p<0.001), water scarcity (β=0.61, p<0.001), religion (β=0.66, p<0.001), incentives (β=0.64, p<0.001) and cultural practices (β=0.62, p<0.001). Whereas the effects on non-potable reuses are: technology (β=0.62, p=0.001), water scarcity (β=0.81, p<0.001), religion (β=0.97, p<0.001), incentives (β=0.72, p<0.001) and cultural practices (β=0.99, p<0.001). Subjective norm was not significant in the model hence the effects of individual beliefs on this latent variable were not examined.

Effects of level of education and proximity to the water source

Level of education and proximity to a source of water were introduced as distal factors into the TPB model as shown in figure 6.4. To avoid overloading the figure, only significant paths have been displayed in the figure. The model provided an excellent fit for potable reuses (RMSEA=0.050, NFI=0.922, TLI=0.933, CFI=0.956) and a mediocre fit for non-potable reuses (RMSEA=0.091, NFI=0.923, TLI=0.904, CFI=0.937). Level of education and proximity to a source of water had neither direct nor indirect significant effects on intentions to reuse greywater for potable purposes. For non-potable purposes, there was no significant direct effect of level of education and proximity to source on intentions, however level of education had a significant direct effect on all five factors of perceived behavioural control: technology (β=-.158, SE=0.244, p<0.01) water scarcity (β=-0.125, SE=0.219, p<0.01), Religion (β=-0.154, SE=0.231, p<0.01), Incentives (β=-0.106, SE=0.213, p=0.026) and Culture (β=-0.155, SE=0.228, p<0.01) and all four factors of attitude: water conservation (β=-0.118, SE=0.261, p=0.012), environmental protection (β=-0.203, SE=0.247, p<0.001), reduction in water bill (β=-0.165, SE=0.255, p<0.001), health concerns (β=0.095, SE=0.258, p=0.047).

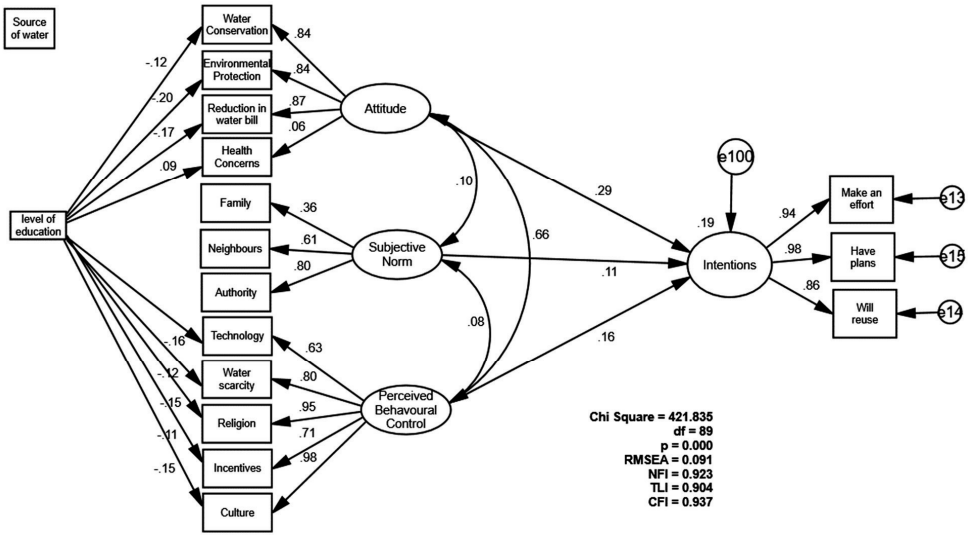


Figure 6. 4 Effect of education on non-potable uses

Discussion

The results of this study confirm to a large extent that the TPB as a framework can be used to understand greywater reuse in developing countries. Attitudes and behavioural controls accounted for the proportion of variance in intentions to reuse greywater for both potable and non-potable purposes. The use of structural equation modelling revealed an excellent fit for potable reuses and a mediocre fit for non-potable reuses between the standard TPB model and the data. A scrutiny of the specific behavioural and control beliefs that impacted the overall reuse options among the respondents revealed four behavioural beliefs (Water conservation, environmental protection, reduction in water bill and health concerns) and five control beliefs (technology, water scarcity, religion, incentives and culture).

With reference to the behavioural beliefs, it was realized that water conservation, environmental protection, reduction in water bill and health concerns were all significantly impacting on intentions to reuse greywater and this is also supported in another study (Hurlimann et al., 2008). However, health concerns were not significantly related to the intention to non-potable reuses. With respect to potable reuses, it was realized that participants had a very negative attitude towards this reuse application and this is also supported in a similar study (Marks, 2004). The application of potable water is mostly for consumptive purposes, therefore, use of recycled water can be seen as a health risk and this is supported by the study which identified a very high positive evaluation of good health thus, substituting piped water for recycled water may be seen as a potential health risk. Even though substituting piped water with recycled water can lead to some water reduction, the perceived health risk associated with reusing treated greywater for potable purposes far outweighs its environmental, economic and water conservation benefits. On the other hand, participants had a very positive attitude towards non-potable applications and this could also be due to the volume and uses of water for non-potable applications. Large volumes of water are needed for non-potable applications such as watering of lawns, scrubbing among many others. Since most of these water uses are not for consumptive purposes, there is a clear

support for accepting a substitute as seen in this study. The study also showed only a very weak perceived health risk associated with this type of use. This suggests that interventions aimed at promoting greywater reuse should consider different approaches since a single approach might not yield positive outcomes for both reuse options. Interventions emphasizing the positive outcomes of greywater reuse are less likely to be effective in potable reuse applications but may rather be effective in non-potable reuse applications. However, interventions that emphasize the perceived health risk are more likely to be effective in potable reuse applications.
The study found out that subjective norm did not significantly influence greywater reuse intentions. This suggests that the judgement of significant others do not matter much in this domain.
For control beliefs, it was realized that all five factors; Appropriate technology, water scarcity, religious practices, Incentives, and cultural practices had a significant effect on intentions to reuse greywater for both potable and non-portable purposes. The study further revealed that participants showed a strong positive ability towards non-potable reuses but moderately negative control over potable reuses. This suggests that providing the necessary skills or technology may only facilitate non-potable uses but will not influence potable reuses.

Our findings have some limitations that should be mentioned. This is a cross-sectional study and this type of study prevents us from making causal inferences. The second limitation is its reliance on self-reports of greywater reuse intentions. It is possible participants may have misreported, be elusive or biased with some of the questionnaire items in their responses. Finally, the representativeness of participants may be limited given the sampling strategy employed which may have introduced selection bias.

Conclusions

The study sought to find the determinants of greywater reuse in a developing country by considering the two major reuse applications: potable and non-potable reuses. The study identified attitude and behavioural control as the two main constructs that affect intentions to reuse greywater for both reuse applications. However, one intervention method for both reuse options is not likely to lead to effective outcomes. Interventions are supposed to target a specific reuse option by using the factors outlined in the study. It further concludes that level of education does not have a direct effect on intentions to reuse greywater for non-potable purposes but effects are rather mediated through attitude and behavioural control, also supporting the need for a diverse approach to shaping public opinion. From the discussions above, it is evident that non-potable reuse approaches might be easier to implement and monitor as compared to potable reuses. To achieve potable reuse behaviour, it is imperative to approach it from the perceived health risk point of view and further enhance trust in the ability of the individual. It will also be prudent to assess the determinants of willingness to adopt a technology for greywater treatment at the household levels to achieve household level participation of greywater reuse schemes.

seven

Chapter seven

Published as

Oteng-Peprah, M., de Vries, N., & Acheampong, M. A. (2020). Households' willingness to adopt greywater treatment technologies in a developing country - Exploring a modified theory of planned behaviour (TPB) model including personal norm. *J Environ Manage, 254*, 109807. doi:10.1016/j.jenvman.2019.109807

Abstract

This study explored willingness of households to adopt a greywater treatment and reuse system using the theory of planned behaviour in its original form and an extended model including personal norms. The study was conducted among 478 household heads in the central region of Ghana. The results indicate the original theory of planned behaviour (TPB) model explained about 44% of the variance in respondents' intentions to adopt this system and the extended model which includes personal norms explained 58% of the intentions. The extended model turned out to be the better model to predict willingness to adopt this household greywater and treatment system. The findings of this study shed more light on the role of personal norms in households' willingness to adopt a greywater treatment and reuse system and may inform interventions aimed at promoting such systems.

Keywords

Households' willingness, greywater, personal norms, theory of planned behaviour,

Introduction

Most developing countries are facing huge challenges with pollution in freshwater bodies caused by domestic greywater discharges. This has been attributed to lack of treatment of the greywater before discharge, lack of sewer networks and non-enforced or non-existent greywater discharge guidelines. It has been estimated that in some developing countries as much as 89% of domestic water demand is converted into greywater (Hernandez Leal et al., 2010; Oteng-Peprah et al., 2018) which is further discharged into either open drains or haphazardly without treatment. However, lightly polluted greywater can be easily treated and reused. Many studies have been conducted on greywater reuse strategies and all these studies point to the fact that this practice is not only worthwhile, it is also a sustainable way of managing water pollution and its effects on the environment (Alderlieste & Langeveld, 2005; Chong, 2005; Dallas et al., 2004). However, issues of perceived health risks associated with greywater reuse remains a barrier to this practice. Greywater reuse can be best achieved if there is a central collection system for treatment (Hophmayer-Tokich, 2010); however, this collection system is non-existent in most developing countries which has hitherto aggravated the already complicated situation of greywater management.

Another approach to achieve greywater reuse and further reduce the burden on water resources is to tackle it from the households' point of view. Applicable systems such as membrane bioreactor, sequencing batch reactor, rotating biological contactors exist, however, these are mostly applied on large scale greywater reuse systems (Oteng-Peprah et al., 2018). Household greywater treatment and reuse systems are largely non-existent in many developing countries largely be due to the poor dissemination of greywater reuse practices or lack of household treatment system. Encouraging household treatment and reuse schemes in individual households can improve the sanitation situation of participating households and further reduce contaminants that get discharged into the environment.

The key objective for wastewater reuse is to achieve the appropriate quality for its intended use and its subsequent protection of public health and the environment. This intended use can be directly tied to the end application which prescribes the type of treatment required and this can include aesthetics or user specific requirements. Therefore, water reuse technologies are mostly tailored to a specific purpose so that the treatment objectives can be appropriately set for application purpose, public health and environmental protection while being cost effective (Li et al., 2009; March et al., 2004).

Public health concerns remain one of the key barriers to implementing greywater reuse practices. Many states in the United States, however, support the general idea of greywater reuse for non-potable purposes and this has led to implementation of numerous greywater reuse projects. These projects have demonstrated that use of properly treated reclaimed water is safe for human health and the environment as it has been reported that 'to date, epidemiological analyses of adverse health effects likely to be associated with use of reclaimed water have not identified any patterns from water reuse projects in the United States'(NAS, 2012). Another report which investigated the health impact of reclaimed water on landscape irrigation conclusively states that 'there have not been any confirmed cases of infectious disease that have been documented in the United States as having been caused by contact, ingestion or inhalation of pathogenic microorganisms at any landscape irrigation site subject to reclaimed water criteria"(USEPA, 2012). The city of Windhoek in Namibia uses recycled water to augment water supplies for potable purposes and has also not reported any public health problems (Haarhoff & VanderMerwe, 1996; Menge, 2010; Onyango, Leslie, & Wood, 2014). All these points to the fact that once the necessary technology is put in place, reusing wastewater can be considered a safe and sustainable method of managing our water resources and also reduce the burden on water treatment plants. However, if

household greywater treatment is to be implemented, there is the need to assess the willingness of households to practice and adopt such a treatment system.

This study adopts a social cognitive model known as the theory of planned behaviour (TPB) in identifying beliefs of heads of households that lead to adoption of a greywater treatment and reuse system. It extends the original TPB model to include personal norms. Personal norms have been demonstrated to be closely related with attitudes and subjective norms by Conner and Armitage (1998). Figures 7.1 and 7.2, shows the default and extended TPB models respectively. Studies by Klockner (2013) have further revealed that personal norms not only contribute to a better explanation of intentions and behaviour, but also improves the predictability of attitudes. Various authors have further argued that especially people's environmental attitude seems to be determined by personal norms (Arvola et al., 2008; Kaiser, 2006). The TPB model has been successfully applied to analyze different pro-environmental behaviors in both its original state and extended forms (Botetzagias, Dima, & Malesios, 2015; De Leeuw, Valois, Ajzen, & Schmidt, 2015; Fielding, McDonald, & Louis, 2008; Ford, Williams, Bishop, & Webb, 2009; Harland, Staats, & Wilke, 1999; Peters, Gutscher, & Scholz, 2011; Quintal, Lee, & Soutar, 2010; Tonglet, Phillips, & Bates, 2004; Wauters, Bielders, Poesen, Govers, & Mathijs, 2010).

The inclusion of additional variables into the TPB model has been theoretically supported by many authors due to the improved explanatory power it derives after the inclusion (Botetzagias et al., 2015; Christian, Armitage, & Abrams, 2007; Thogersen & Olander, 2006). However, application of this model to pro-environmental behaviour in developing countries is very limited. Considering the hazard caused by discharging of untreated greywater into the environment in some developing countries such as Ghana, Uganda, Nepal, Mali and lack of treatment facilities as reported by (Alderlieste & Langeveld, 2005; Katukiza et al., 2014; Oteng-Peprah et al., 2018; Shresta, 1999) it is prudent to explore greywater treatment and reuse at the household levels. Therefore, the purpose of this study is to investigate household's willingness to adopt a greywater treatment and reuse system by first using the theory of planned behaviour in its original state and then extend this model to include personal norms. Knowledge of this will be a stepping stone on which interventions targeted at promoting greywater treatment and reuse at the household level in developing countries can be developed.

Analysis of the framework

The theory of planned behaviour

This theory has shown that people's behaviour in most situations can be explained and predicted by intentions, attitudes, subjective norms and behavioural control. Intention is defined by the theory as a cognitive representation of a person's readiness to perform a given behaviour, and it is considered to be the immediate antecedent of behaviour (Ajzen, 1991). Attitude according to the theory is defined as an individual's positive or negative feeling associated with performing a specific behaviour. It further states that an individual will hold a favorable attitude toward a given behaviour if he/she believes that performing the behaviour will lead to mostly positive outcomes. Therefore, attitude toward a behaviour is a positive or negative evaluation of performing that behaviour. Subjective norm is defined by the theory as the perceived social pressure to engage or not to engage in a behaviour. It is the outcome of how important referent others approve or disapprove a behaviour or intention. Finally, perceived behavioural control refers to people's perception of their ability to perform a given behaviour.

Following the definition of the three main determinants of human planned behaviour (attitude, social pressure, perceived behavioural control), the attitude of the household can be defined as the degree to

which the household head expects good or bad outcomes from adopting a household greywater treatment and reuse system. The household's social pressure refers to the expectation of others to adopt or develop a greywater reuse and treatment system from important referent people. The household's perceived control focuses on beliefs about how easy or difficulty it will be to adopt or develop a greywater treatment and reuse scheme. Personal norms is defined by Schwartz and Tessler (1972) as expectations that people hold for themselves. This translates into how the household head may perceive the personal norms on the household to contribute to making a change in the environment.

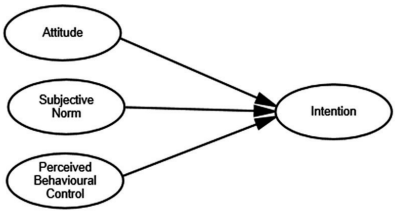


Figure 7. 1 Default TPB model

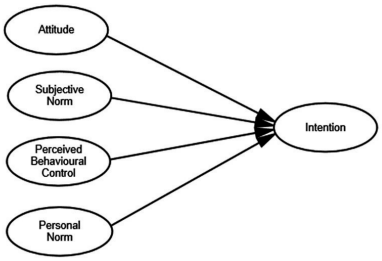


Figure 7. 2 Modified TPB model with personal norm

Questionnaire

The questionnaire used for this study consisted of two parts; one part included items from the TPB constructs while the other part included demographics. The measurement items were developed from an elicitation study among 25 selected household heads. All the TPB constructs were measured with a 7-point Likert scale. The intention to adopt/develop greywater treatment systems was measured with 2 items, attitude measured with 3 items, subjective norms measured with 3 items, perceived behavioural control measured with 4 items and personal norms measured with 3 items. With the exception of intentions and personal norms, belief measurements had corresponding outcome evaluations.

Methodology

The target group was restricted to the head of the household since they are responsible for making decisions on behalf of the family. About 810 households were surveyed within the central region of Ghana using random sampling method and 521 household heads completed a self-report questionnaire representing a 64% response rate. Each respondent was introduced to the concept of greywater treatment and the treatment systems. This was done by defining greywater, and pointing to their sources, average per capita generation rates, physical and chemical characteristics and their mode of discharge into the environment. Since greywater is generated by each household, respondent easily identified with these descriptions. The researcher recruited research assistants who received training on how to assist individuals who may not be able to complete the questionnaire. The research cancelled questionnaires which had any items vacant and finally arrived at 478 responses which were used for the analysis. Statistical package for social scientists (SPSS) version 23 and Amos Version 23 were used for analysis. Structural equation modelling (SEM) was utilized to fit the data to the TPB model. SEM is a multivariate technique that combines aspects of regression and factor analysis to assess a series of dependent relationships simultaneously which is not possible using other multivariate techniques (Hair et al., 2014).

Descriptive analysis of variables

The model is assessed by using sample size independent fit indices such as root mean square error of approximation (RMSEA), normed fit index (NFI), Tucker-Lewis index (TLI) and comparative fit index (CFI). The acceptable values of TLI and CFI have been pegged at 0.90 while a value of 0.95 and above indicates an excellent fit; RMSEA values between 0.06 – 0.08 are classified as acceptable while values less than 0.06 can be classified as excellent fit and finally, the NFI ranges between 0 – 1 with 1 being a perfect fit (Cangur, 2015).

Results and discussion

Descriptive statistics

Most of the respondents were male (63.2%) and had an average age of 45(±8.2) years. This is representative of the household heads in Africa and most of the developing countries. In these countries, the eldest adult male culturally is the head of the household and he makes decisions for the household. In terms of level of education, majority of the respondents (43.10%) had acquired some level of tertiary education hence an indication of comprehension of the questionnaire items. Participants reported moderate intentions (M=3.78, SD=1.31), a moderate positive attitude (M=8.13, SD=0.90), moderate social pressure (M=9.19, SD=10.44), low controllability (M=5.74, SD=3.39) and a slightly high personal norms (M=4.99, SD=0.93). The correlation matrix of the latent variables presented in table 7.1 indicates that almost all the variables in the models are significantly associated with intentions.

Testing the default model

The structural model representing willingness of households to adopt a greywater treatment and reuse system is presented in figure 7.3. The model was able to explain 44% of the variance of intentions of households to adopt a greywater treatment system. From the structural model, it can be seen that attitude (β=.31, SE=.014, p=000), subjective norms, (β=.24, SE=.021, p=0.019) and perceived behavioural control (β=.36, SE=.016, p=0.000) all had moderate intentions by household heads to adopt a greywater treatment and reuse system which were all statistically significant. All items loaded above 0.60 on their assigned factors with the exception of water conservation (λ=0.53) and were significantly associated with their specified constructs. The strongest effect on intentions is perceived behavioural control (β=.36), followed by attitude (β=0.31) and subjective norms (β=.24). The fit indices indicate that the standard TPB model provides an excellent fit to the data for the default model (χ^2=110.82, df=48, p<0.000, NFI = 0.935, TLI = 0.942, CFI = 0.962, RMSEA = 0.044).

Testing the modified model

The modified structural model with personal norms is presented in figure 7.4. This shows an improvement in prediction over the default model and explained 58% of the variance in the model. In the modified model, the strongest effect on intentions is personal norms (β=.50) followed by perceived behavioural control (β=.30), subjective norm (β=.11) and attitude (β=.10). The modified model also shows an improvement in the fit indices over the default model (χ^2=184.18, df=80, p<0.001, NFI = 0.949, TLI = 0.951, CFI = 0.970, RMSEA = 0.041) which is an excellent fit for the data.

Table 6.1 presents the average scores on the determinants of willingness. The willingness is assumed to be based on the rational expectations of the household head, therefore data in table 6.1 represent the household head's expectations on adoption of a greywater treatment and reuse system at the household level.

Effect of beliefs

Comparing the three-path coefficient of the default model (figure 7.3), results showed that the impact of beliefs from attitude thus, environmental hazard, pollution prevention and water conservation were the most important factors that affect the intentions of households to adopt a greywater reuse and treatment system. Again, comparing the four-path coefficient of the modified model (figure 7.4), it can be seen that the impact of beliefs from personal norm thus, moral obligation, feeling of guilt and better feeling had the greatest impact on household's willingness to adopt a greywater treatment and reuse system.

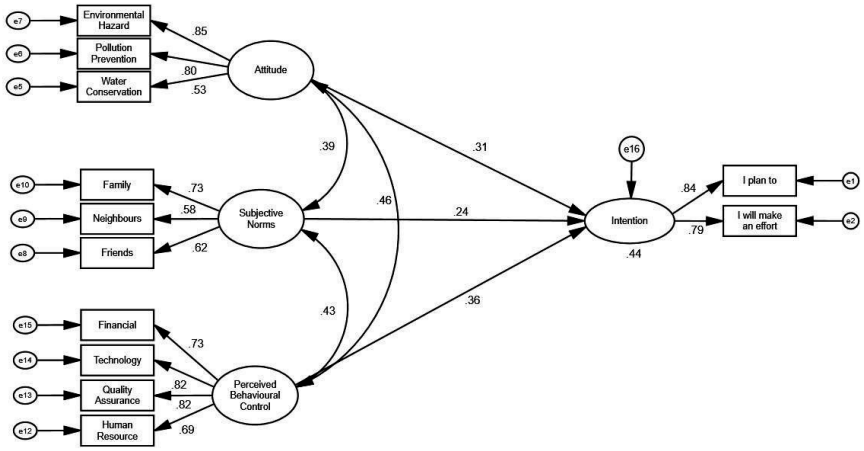


Figure 7. 3 Default model

Table 7. 1

		Cronbach Alpha	Mean	S.D.	1	2	3	4	5
1.	Attitude[1]	0.77	8.13	0.90	1				
2.	Subjective norm[1]	0.61	9.19	10.44	0.44**	1			
3.	Perceived behavioural control[1]	0.65	5.74	3.39	0.24	0.23	1		
4.	Intentions[2]	0.84	3.78	1.31	0.50**	0.46**	0.49**	1	
5.	Personal Norm[2]	0.75	4.99	0.93	0.59**	0.50**	0.29**	0.69**	1

Theoretical range (-21 to 21)[1] (1 to 7)[2] **p<.01

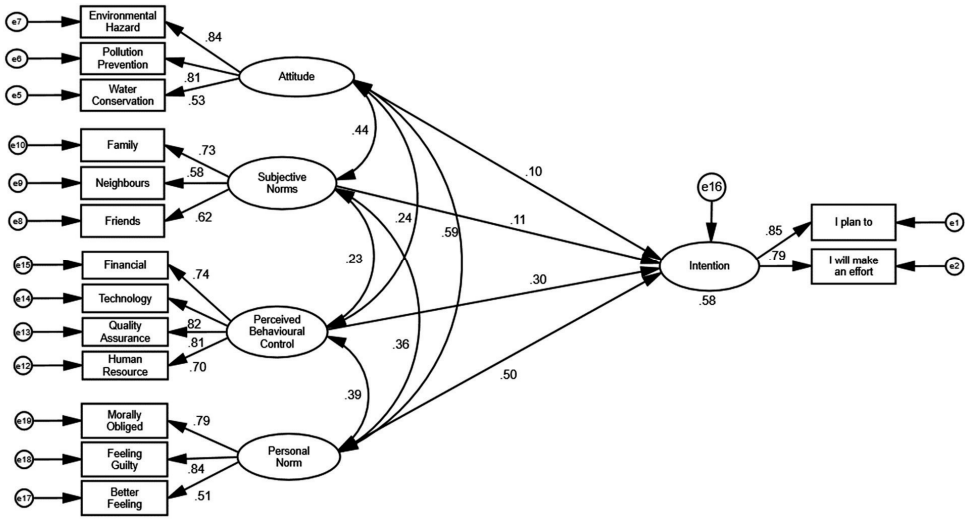


Figure 7. 4 Modified model

Discussion

To better understand households' intentions to adopt a greywater treatment and reuse system at the household level, two models were tested. The first was the original TPB model and the second an extended TPB model with personal norms. These personal norms are not part of the original TPB model. Greywater treatment and reuse systems are not common in the study area as it is the situation in many developing countries so in this hypothetical case, household heads cannot refer to their past habits and behaviour. Danner, Aarts, and de Vries (2008) suggested that when there is no past behaviour or habits, the future behaviour is guided by intentions. The inclusion of personal norms has been reported to improve the predictive ability of the model especially for pro-environmental behaviours (Arvola et al., 2008; Kaiser, 2006; Klockner, 2013) . The results of the study support the main premise of the original TPB model which says that people who have positive attitude towards the behaviour, receive the support of people who are important to them and think they are able to participate in the behaviour in question will be more likely to carry out that behaviour (Ajzen, 1991). From figure 7.3 it can be seen that attitude, subjective norm and perceived behavioural control are all positively associated with behavioural intentions. The original TPB model explained 44% of the variance in household's willingness to adopt the greywater treatment and reuse system. When the original model was extended to include personal norm, this increased to 58% of the variance being explained. The obtained results confirm similar research on pro-environmental behaviour where there was also an increase in the percentage variance explained when the TPB model was extended with personal norms (Harland et al., 1999). The improvement in the model can be associated with better linkage of environmental attitudes with personal norms as suggested by Arvola et al. (2008). The household head's attitude is considered to be a determining factor in adopting this system. The findings of this research further support that the households head perceived attitude has positive impact on the adoption of a treatment system as can be seen in figure 7.3. Generally, for a household to adopt this system it is perceived that it can reduce environmental hazard, prevent environmental pollution and provide economic relief in terms of bills paid for use of water. Social pressure

has positive and significant impact on households' intentions to adopt this treatment and reuse system. For example, increase in pressure from family members, friends and neighbors that the adoption of this system will reduce environmental hazard, reduce pollution and provide some financial relief will lead to a positive intention towards adopting this system. All four control beliefs: financial incentives, technology, quality assurance and human resource had significant effect on intentions to adopt the treatment and reuse system. For households to adopt this system, they must be able to overcome these factors such as financial commitment into obtaining this system, understand the appropriate technology, have the relevant human resource or expertise available and be assured of the quality assurance of the treated water.

Limitations

This study used the responses of the household heads and as such it might be possible the responses from the household head may not be the general consensus from members within the household. Again, actual behaviour could not be measured because household greywater treatment and reuse systems are not commonly available in most developing countries, therefore the association between consumers' intention and actual behaviour could not be assessed. Also, most likely, most household heads do not exactly know what a greywater treatment and reuse system might look like – even with the explanation offered in this study and this might also affect the responses to the questionnaire items. The research has only been conducted in the central region of Ghana which makes generalization of the results risky though the social dynamics in the central region can be compared to what prevails in most developing countries. Finally, this is a self-reported questionnaire and hence it might not reflect the true state of the issues as expounded in this questionnaire items.

Conclusions

The results of this study can be applied by stakeholders and agencies that intend to promote greywater treatment and reuse at the household level in developing countries. In order to convince household heads to adopt household greywater treatment and reuse systems, specific drivers of intentions must be addressed in the campaign. Attitude, personal norms, subjective norm, and perceived behavioural control seemed to all contribute to intentions; however, attitude and personal norms seem to be the strongest determinants. From the viewpoint of attitudes, campaign messages on attitudes could focus on some environmental benefits of greywater treatment and reuse. For example, greywater treatment and reuse systems could prevent environmental hazards and pollution associated with untreated greywater releases and further contribute to conservation of water by adopting a treatment and reuse system. Including these messages in a campaign or intervention message could contribute to attitude change which could then result in actual behaviour. With respect to personal norms, household greywater treatment and reuse systems could be promoted by making it known to households that they could contribute to making a change and that adopting this system could be seen as a moral obligation. This can be done by appealing to households about the hazard associated with release of untreated greywater into the environment without treatment and how this could lead to pollution of freshwater resources and subsequently affect aquatic life and the fact that their adoption of this system can reduce or bring about a change in this environmental hazard. With respect to perceived behavioural control, the treatment system should have a certification of quality and it also should not also affect the finances of the households. In fact, a free system will be easily adopted since it provides no financial burden on households while reducing the volume of treated water that will be paid for. For social norm, household treatment and reuse schemes can be promoted when important others such as family, friends and neighbours have all embraced the concept and fully support this concept.

eight

Chapter eight

8

General discussions

Introduction

Greywater reuse has been a practice in existence for many years, however, this practice is largely limited to developed countries equipped with the necessary technology and infrastructure. The adoption of this practice into developing countries has been largely non-existent due to numerous reasons. This thesis explores greywater reuse in a developing country by adopting a two-pronged approach. It explores the option of greywater reuse from the technical and social perspective. The technical perspective explores the technicalities viz greywater quality and pollution levels and identifies suitable media for treatment. The thesis used socio-cognitive models to identify factors that are associated with the selection of a particular reuse option. It further explores the willingness of household heads to support the concept of household greywater treatment and reuse schemes. The diversity in the approach used in this dissertation is the key strength in this research. This chapter presents the major findings and discussion points from the entire thesis.

Greywater characteristics

In order to streamline the research, a comprehensive literature review on greywater reuse, user perception and treatment systems was undertaken. From this comprehensive review (chapter 2), it emerged that there is a wide variation in greywater characteristics and volume generation rates which are mostly associated with lifestyle and type of settlement. It further emerged that most greywater treatment and reuse systems are not applicable at the household levels and this discourages individuals from practicing greywater reuse at the household level especially in developing countries. The review further established the importance of assessing public or user perception in implementing any greywater treatment and reuse schemes. Finally, it was established that in order to develop any greywater treatment and reuse scheme, there is a need to assess the greywater characteristics because this will form the basis on which any treatment or reuse plans will be based upon.

The characteristics of the greywater were studied (chapter 3) and the quantity of water used, the return factor and contaminants present were identified. The results of this research conducted with greywater from two main categories (in-house water access and outside source) revealed significant differences in quantity generated and levels of contaminants present. Greywater originating from houses that do not have in-house water connection were much polluted than those originating from houses with in-house water connections. Most of the parameters studied were above the regulatory guideline levels (Ghana., 2000). The study further established that there were huge bacterial loads that were being discharged into the environment. Direct reusage of the greywater for irrigation was identified to be unsuitable to the crop, livestock and soil because it can lead to public health issues and affect soil quality. The study identified hygienic practices, frequency of water use before discharge, detergents used for laundry, and cooking practices, the biodegradability of the greywater as being the main factors that determine the quality of greywater studied within the study area. Though most of the greywater quality parameters were above the regulatory limits, of particular interest in this study were the biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) contents because they are mostly the yardstick used to assess the suitability of wastewater before being discharged into the environment (Tchobanoglous et al., 2003). The greywater generated in this study area, therefore, cannot be discharged into the environment without prior treatment. Therefore, regulatory agencies will have to find methods of addressing this issue through both technical and non-technical means.

Adsorption techniques for BOD and COD removal

In order to reduce the levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) in the greywater using adsorption techniques, activated carbon was prepared from two different locally available agricultural wastes (tropical almond and palm kernel shell). Although there were many agricultural waste materials available for this research, the study used these two materials because of their availability in most tropical regions and because these materials have been regarded as waste materials without any economic value. Again, literature on activated carbon from tropical almond is non-existent as at the time of this research.

The assessment of the suitability of these materials for their adsorptive capacities constituted an important step in this process. A characterization study was conducted on these two materials for internal surface area (BET), x-ray diffraction (XRD) and scanning electron microscope (SEM). The internal surface area (BET) analysis revealed that palm kernel activated carbon (PKAC) has a higher internal surface area than tropical almond activated carbon (TAAC) suggesting that PKAC has a higher potential to adsorb organic contaminants than TAAC. X-ray diffraction further revealed the entire materials were dominated by carbon and other allotropes of carbon (chapter 4). SEM imagery showed crystalline and distinct shape for the particles of PKAC and large, loose and amorphously shaped particles for TAAC.

It was shown that the effect of particle size was very crucial in the removal efficiency and an optimum average particle size of 2mm was obtained for this experiment. Furthermore, the effect of dosage played a key role in the adsorption process and optimum dosage of 6g/l was obtained in the batch experiment.

In order to gain a better understanding of the BOD and COD removal, a batch adsorption experiment was conducted using two common adsorption models; Freundlich and Langmuir adsorption isotherms (chapter 4). To further understand the kinetics involved in this study, the pseudo-first and second-order kinetic models were used. The adsorption data fitted well the Langmuir isotherm being suggestive that the process is more favourable towards adsorption (Belhachemi & Addoun, 2012; Yan et al., 2015). The kinetic data fitted the pseudo-second order model well with a very high correlation value for both BOD and COD removal from greywater under batch conditions. The value of the adsorption intensity suggests that the adsorption process is very favourable under the conditions studied. From the batch results, it is evident that for maximum removal of BOD and COD from domestic greywater, PKAC performs better than TAAC. The best performing material, PKAC, was used in a fixed bed column studies (chapter 5) in order to determine the optimum operating conditions because results obtained in a batch system have mostly been found not to be applicable to what exists in the field (Patel & Vashi, 2012). The fixed bed system was found to perform better than the batch system achieving as high as 90% and 86% removal rates for BOD and COD respectively as compared to the removal efficiency in the batch system.

The fixed bed system was found to perform better at lower feed flowrate and high bed height. At low feed flowrate, the residence time of the greywater in the column is increased allowing for effective adsorption to take place (Sheng et al., 2018). At higher bed depths, there is an increase in the surface area, therefore more available sites for adsorption to take place (Teutscherova et al., 2018). The fixed bed experimental data were fitted to various fixed bed column models and the best performing model identified was the Yoon-nelson (Yoon & Nelson, 1984) and the BDST models.

Socio-cognitive models

From the extensive literature review, it was clear that communities support the concept of water reuse as a means of responsible water resources management to mitigate scarcity and abate pollution. This chapter (6) used the theory of planned behaviour (TPB) (Ajzen, 1991) in its default state to gain a deeper understanding of the factors that will influence an individual in a developing country to accept greywater as an alternative source of water taking into consideration cultural, religious, regulatory and gender perspectives. The results from this study confirmed to a large extent that the TPB framework can be applied in understanding greywater reuse in developing countries.

The study identified a very strong negative intention towards the reuse of greywater for potable purposes but rather showed a good acceptance for reuse for non-potable purposes. Attitudes and behavioural control accounted for a higher proportion of the variance in explaining intentions to reuse greywater. The study revealed that participants showed a strong positive ability towards non-potable reuses but moderately negative control over potable uses which suggests that providing the necessary technology may only facilitate non-potable uses but will not influence potable reuses. Therefore, stakeholders who might want to promote the concept potable greywater reuse must rather channel their efforts at non-potable reuses. For transfer to potable uses, it was realized that participants had a very negative attitude towards this reuse application as also established in another research (Marks, 2004).

This is closely associated with the perceived health risk associated with using recycled water for consumptive purposes. Although, substituting piped water with recycled water can lead to economic benefits, the perceived health risk associated with this far outweighs this economic benefit and this affects the use of recycled water for potable purposes. The adoption of greywater treatment and reuse system at the household level was explored using the household heads as the focal point (chapter 7). This study used an extended version of the theory of planned behaviour with the inclusion of personal norm (Conner & Armitage, 1998; Harland et al., 1999). Personal norms was adopted into this study because of the improved explanatory power in pro-environmental behaviour studies and studies that explore willingness (Botetzagias et al., 2015; De Leeuw et al., 2015; Fielding et al., 2008; Klockner, 2013). Although, attitude, personal norms, subjective norms and perceived behavioural control seemed to all contribute to intentions, however, attitude and personal norms seem to be the strongest determinants. This implies that to achieve comprehensive coverage of promoting household greywater and treatment systems, the emphasis should be on factors associated with personal norms and attitudes. For example, campaign messages can be based on the impact caused by discharging untreated greywater into the environment and how recycling and reusing this greywater can contribute to making a change therefore adopting this system could be seen as a moral obligation.

Methodological considerations

This section describes the methodological approaches used in this dissertation. The study approach, design, strength and limitations are briefly discussed. The approach used in this research may have implications for future research. The study adopted a two-pronged approach to data collection viz laboratory data collection and field instruments. Data for chapters 3, 4 and 5 were obtained through laboratory analysis while data for chapters 6 and 7 were obtained with a scientifically designed research instrument. The diversity in the design of the study is a major strength of this study. The studies were very broad and allowed for the possibilities of many findings on the concept of greywater reuse. This study is

also based on existing and scientifically proven methodological approaches. For example, greywater sample collection and analysis used protocols from the standard methods for examination of water and wastewater as stated in APHA (2005) (chapters 3, 4 and 5). Chapter 6 used the theory of planned behaviour (Ajzen, 1991) and chapter 7 used an extended form of the theory of planned behaviour which included personal norm (Harland et al., 1999). A very extensive and broad literature review (chapter 2) formed the basis which shaped and supported the theoretical approach used in this study.

Laboratory data

The data obtained in chapter 3 were from the sampling of different sources using protocols outlined in the APHA (2005). Since the approach used to collect data on water use and wastewater generation for houses that had no water on their compound was a self-report tally card, it could be possible some aspect of the data captured might not reflect what actually exists. The water quality parameters examined in this chapter focused on physicochemical and bacteriological water quality indicators and these parameters were chosen after extensive literature review (chapter 2). The data obtained from laboratory analysis was adequate for a detailed characterization of the greywater. Data for chapter 4 and 5 were also obtained from households. In this study real wastewater was used in order to assess the potential of the adsorbent taking into consideration the natural state of the greywater. Due to this, it was not possible to explore the effect of changing the initial concentration of greywater since the same source of greywater was used throughout the experiments. Though there exist many wastewater quality parameters and many of them have been examined in this study, the researchers opted to study the BOD and COD parameters because they represented the organic and inorganic fractions in the greywater.

Field instrument

In chapters 6 and 7, the data was obtained using a cross-sectional study approach for data collection. The instrument used for data collection was based on the Theory of Planned Behaviour by Ajzen (1991). This explains the intentions of respondents to adopt or reuse greywater. The attitudinal beliefs, referent persons and control beliefs examined in the chapter were obtained through elicitation and from the comprehensive literature review (chapter 2). Chapter 6 collected data from willing respondents while chapter 7 used a targeted approach at collecting data from household heads. Household heads were targeted because they are responsible for decision making within the study area and culturally their decision is binding on the entire household. The study analyzed the data using structural equation modelling (SEM). Due to the cross-sectional nature of these studies, causality could not be explicitly established and thus caution should be exercised when interpreting these findings. Although the researchers made very good efforts at explaining the concept of greywater reuse and treatment to respondents before they participated in the research, however, because the concept of greywater reuse and systems were not available and easily known by respondents, it is possible they may not be able to associate it properly with what the intended purpose of the study is and might lead to misrepresentation in some of the collected data.

Conclusions

The findings of this research provide insight into fundamental reasons which affect greywater reuse in a developing country and factors that can be used to initiate it. This is important to inform future

interventions aimed at promoting this practice in developing countries. This practice if embraced will lead to improved sanitation practices and ultimately reduce the environmental pollution associated with the discharge of untreated greywater into the environment. First, the research reveals that the greywater quality indicators are mostly all above the regulatory limits for discharge of water into the environment and ultimately affect freshwater resources. Secondly, it identifies an agricultural waste that has the potential of reducing the organic loads that contribute to BOD and COD to appreciable levels on a batch treatment basis. Thirdly, the research explored the application of this material on a continuous basis using a column and obtained an increase in performance of the continuous removal of BOD and COD. The study further established, through the use of social cognitive models, that advocates for greywater reuse should rather target uses for non-potable applications since there was a very strong negative attitude towards the use of greywater for potable purposes even under very trusted treatment systems. Finally, it established a favourable willingness of households to adopt and begin practicing greywater reuse. It concludes that for advocacy or interventions aimed at initiating greywater treatment and reuse schemes in developing countries, the message should be more centered on personal norms and attitudes; thus the message of such an event should be more tailored at how adopting this practice can help salvage the environment rather than the personal gains they will make from adopting such a system.

Implication for application

This study has provided a tool for policymakers in developing countries that are faced with water supply issues to rely on for advocacy and planning in trying to address this impact by promoting an alternative source of water supply; greywater reuse. The suitability of the material for reducing organic and inorganic loads in greywater is an indication of its suitability in treating large volumes of greywater into a quality that is reusable for non-potable purposes. This would help improve sanitation practices within water-stressed areas and further improve their economic activities because the time that was previously used to fetch water for non-potable purposes, can be channeled into other productive ventures. It must be emphasized that in implementing this concept, there should not be any financial burdens on the participants since this might lead to the rejection of this concept. There must be available resources that will facilitate this practice and this can be sustained for a while until beneficiaries have accepted this practice and are willing to take it up by themselves. For a comprehensive greywater treatment and reuse scheme to be adopted in Ghana, there is the need for a policy on this concept. This policy document should include building code and plumbing standards for houses that may be interested in adopting this system. It should also contain quality assurance of the treatment system for treating the greywater for reuse. Houses or institutions that adopt this system should also be incentivized as a reward for environmental protection. The lessons learnt in this study can be applicable to other developing countries which share common characteristics and traits with the community studied in this study. It must however be emphasized that, this has been a cross-sectional study and generalizability may not always lead to the same expected outcome.

Further research

This research has established the suitability of using a locally made adsorbent in reducing the organic and inorganic composition of greywater by adsorption methods. There is the need to design a fully functional domestic greywater treatment and reuse system applying the media as an adsorptive agent and piloted on a small-scale level. There is also the need to explore the regenerative and disposal methods of the

material after it has been completely used up in order not to also contribute to environmental pollution. It will also be interesting to explore the administrative aspects of this study by studying exploring the economic benefits that will be derived from implementing this concept from the environmental point of view and the personal point of view. Designing of a building code that will address quality issues, monitoring and installing of greywater treatment and reuse schemes will also be an aspect that will require further research.

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Summary

The findings in this study examine sustainable wastewater management in Ghana by exploring the option of greywater reuse at the household level. Urbanization in developing countries has brought about an increase in demand for potable water. Associated with this increase in demand is the generation of greywater resulting from the myriad of water use activities. The greywater discharged are mostly left untreated and mostly end up in rivers and other aquatic ecosystems that are sources of livelihood for humans and livestock which can lead to health risks. the main aim of this study is to explore the possibilities of reusing greywater to achieve sustainability as stated in the sustainable development goal 6 which is to ensure sustainable management of water and sanitation for all.

Chapter 2

Chapter two reviews relevant literature on greywater characteristics, treatment systems, reuse strategies and user perception. The chapter places special emphasis on greywater systems in developing countries. It emerged from this review that there is a wide variation in greywater characteristics and generation rates and this is influenced by lifestyle, fixtures used and climatic conditions. There are many technologies for treating greywater, however, available technologies have mostly been designed for a targeted pollutant. The study further established that most of the treatment systems were applicable on a large scale and this discourages household greywater treatment and reuse intentions. Considering the variations in characteristics and quality, it is, therefore, necessary to establish the quality of greywater before implementing any treatment or possible reuse scheme. The study further identified the impact of public perception as a key element in implementing greywater reuse. The study concludes that greywater treatment and reuse if embraced can lead to substantial decline in over-reliance on freshwater resources for potable and non-potable purposes.

Chapter 3

An assessment of greywater quality is necessary to decide on which contaminant to remove. This chapter presents the quality assessment and generation rates of greywater within the study area. This assessment involved grouping of households into households that had water on their premises and households that had to move out of their premises to access water. There were significant differences between the two groups of households with water consumption of houses with access at home being 82.51l/c/d and 36.65l/c/d for those who relied on external sources and return factors of 74.16% and 88.75% respectively. The study showed the majority of the pollutants in the greywater within the study area exceeded the Ghana EPA discharge guidelines and therefore not suitable for discharge without prior treatment. The discharged greywater was also identified not to be suitable for direct irrigation based on the salinity and sodium hazard analysis. Principal component analysis conducted on the data indicated that the characteristics of the greywater were influenced by cooking and cleaning practices, personal hygiene, biodegradability, frequency of water use before disposal and sanitary practices in the bathroom. The study concluded that the practice of discharging greywater into the environment is detrimental to the environment and a health risk to both humans and livestock. It is, therefore, necessary to start exploring household greywater treatment in such areas before final disposal or possible reuse.

Chapter 4

This chapter explores the application of two different locally available agricultural waste materials as sorbent material in reducing the BOD_5 and COD of the greywater. These two parameters were chosen

because they have been the parameters that are used to assess the level of pollution of wastewater before it is finally discharged. The two agricultural waste materials (tropical almond shell and palm kernel shells) which are common in the study area were used for the preparation of activated carbon. A batch adsorption study was conducted on greywater sample from the study area and reduction of as high as 76% BOD_5 and 65% COD were obtained. From the study, it emerged that the palm kernel shell had larger internal surface and was able to perform better as compared to tropical almond shells. The equilibrium concentration for BOD_5 (q_e = 22.88mg/g) and COD (q_e = 34.00mg/g) was achieved by palm shell activated carbon. The adsorption data were fitted to the adsorption isotherms and the best model that fitted this process was the Freundlich isotherm. The Freundlich isotherm model described BOD_5 (R^2 = 0.98) removal and COD (R^2=0.65) removal with palm kernel shell as the adsorbent. The reduction of BOD (R^2=0.99) and COD (R^2=0.97) followed pseudo-second order kinetics. The study identified palm kernel activated carbon to be a better material for removal of BOD_5 and COD.

Chapter 5

The performance of a fixed-bed column packed with palm kernel activated carbon for the reduction of BOD_5 and COD in greywater was evaluated using column breakthrough data at different flow rates and bed depths. The Yoon-Nelson, Thomas, Adams Bohart and Bed Depth Service Time (BDST) models were used to evaluate the design parameters of the column. A maximum uptake capacity of 35mg/g and 54mg/g was achieved for BOD_5 and COD respectively. The Yoon-Nelson model provided a superior description of the kinetic data as compared to the Thomas model. The study concluded that the activated carbon prepared from palm kernel shell which is an agricultural waste material can be used to reduce the BOD_5 and COD concentrations in greywater. the design of a fixed-bed column for BOD_5 and COD removal from greywater can be based on these models.

Chapter 6

This chapter explored the determinants that influenced people's intentions to reuse greywater for either potable or non-potable purposes. This study adopted a socio-cognitive model known as the theory of planned behaviour (TPB) in identifying the construct that influences one's choice of reuse application thus potable or non-potable applications. The study was conducted taking into consideration the role of cultural practices, educational background, source of water and religious beliefs. It emerged that participants generally had a positive intention towards greywater reuse; however, potable reuse had a very strong negative intention indicating the unwillingness to reuse greywater for potable purposes. The study identified attitude and behavioural control as the two main constructs that affect intentions to reuse greywater for both reuse applications. It further emerged from the study that to promote greywater reuse, one intervention method that targets the two reuse applications is not likely to lead to effective outcomes. Interventions are to be targeted at the specific reuse application with its associated factors. From the study, it emerged that non-potable reuse approaches might be easier to implement as compared to potable reuses largely due to the perceived health risk associated with potable reuses. To promote potable reuses, the best mode of approach will be to address it from the perceived health risk and further enhance trust in the ability of the individual. The study concludes with a recommendation for assessing the willingness of households to adopt greywater treatment and reuse systems to promote household treatment.

Chapter 7

This chapter explored the willingness of households to adopt a greywater and reuse system. The study adopted the theory of planned behaviour (TPB) in its original form and an extended model including personal norms. The personal norm was selected because it has been argued to improve the predictive ability in determining willingness for pro-environmental behaviours. Data was collected from 478 household heads within the study area. The results from analyzing the data using structural equation modelling indicated that the extended model with personal norms gave an improved fit and explained a higher percentage of the variance in the data as compared with the original TPB model. Although, all the four factors thus attitude, personal norms, subjective norms and perceived behavioural control seemed to all contribute to the intentions, however, attitudes and personal norms seem to be the dominant determinants. This indicates that to promote household participation in greywater treatment and reuse, it is imperative to tailor intervention methods around personal norms and attitudes. The results of this study can be applied by stakeholders who intend to promote greywater reuse in developing countries.

Chapter 8

This chapter summarizes the main findings from the different studies, the different methodologies adopted in data collection and analysis and the recommendations. From the main findings of this study, it can be concluded that greywater is discharged into the environment without treatment. Some of the pollutants analyzed in the greywater were above the regulatory limit of discharge without treatment and this is detrimental to both human and livestock. It also identified a locally available waste material which has a high potential of being used to reduce the BOD_5 and COD levels in greywater. It further emerged from the study that, attitude and perceived behavioural control were the two main factors that influenced one's choice of either reusing greywater for potable or non-potable purposes. The willingness of households to adopt a treatment system at home was assessed. It emerged that attitude and personal norms were the two main factors that could be used in promoting household participation of greywater and reuse schemes. The study recommends the design a fully functional domestic greywater treatment and reuse system using the media studied in this research as the adsorptive media on a pilot scale. It further recommends a study that will explore the regenerative method of the media once it loses its treatment capacity and the proper disposal methods. It further recommends an institutional approach to greywater treatment and reuse which will address issues such as policy, economics, treatment quality guidelines and installation and design codes for buildings that will be interested in adopting this concept.

Valorization

Access to adequate potable water has remained a problem in many developing countries. While this situation has received significant attention in some countries, many other countries continue to experience limited access to this resource. Lack of access can be associated with many conditions such as limited resource, polluted resource, limited technology among others. However, greywater which is less polluted is mostly discharged untreated into the environment in areas which do not have proper sewer networks. These unregulated discharges can then lead to environmental pollution of both soil and freshwater resources leading to environmental hazards. The high volumes of greywater discharged and the low level of contamination makes greywater a good resource that can be harnessed to augment water supplies in areas of limited access. The limited supply of water has a huge effect on sanitation practices and this can lead to bad sanitation practices which in the long run affect the environment and the individual. The research presented in this thesis provides an overview of greywater reuse in Ghana and forms the foundation for future studies in the area of greywater treatment and reuse in sub-Saharan Africa. This study, therefore, provides a stronger theoretical basis for future studies into greywater treatment and reuse schemes within the sub-region from both the socio-cognitive and technical points of view. It may also serve as an introduction to students, scholars, institutions and interested parties into greywater treatment and reuse.

It further underscores the importance of reusing greywater to supplement water use activities at the household level. Greywater treatment and reuse is a strategy that can reduce the pollution loads to the environment and further augment water supplies for other non-consumptive purposes. Adopting this greywater and treatment system can also lead to reduced water demand from freshwater resources and improved sanitation practices in water-stressed areas.

The economic consequence of lack of water or environmental pollution can translate into many deleterious effects such as the reduction in labour and productivity. The environmental challenges also caused by agricultural waste remain a concern to many in developing countries. The results reported in the thesis emphasize the increasing environmental pollution resulting from the discharge of untreated greywater into the environment. This study identified an agricultural waste that can be converted into suitable material for treating greywater. The application of this local material can promote local acceptability of the concept of greywater treatment and reuse and further create business opportunities for individuals and groups to exploit this material for economic benefits.

The study identified non-potable reuses as the preferred method of reuse application. Concerning beliefs, attitudes and behavioural control that influence the choice of reuse application, the study identified perceived behavioural control and attitude as the dominant significant antecedent of behavioural intentions toward reusing greywater for non-potable purposes. The inclusion of background factors also identified educational level as a distal factor that contributed to the behavioural intentions to reuse water for non-potable purposes. The study further established the willingness of households to begin implementing greywater treatment and reuse practices by adopting treatment systems. The outcome of this study led to the conclusion that personal norms played a major role in the willingness of household heads to begin greywater reuse. Therefore, interventions aimed at promoting greywater reuse should target personal norms rather than other factors. Such campaigns should use messages that appeal to the personal norms of the individual.

This study contains valuable information surrounding the approach, strategy, potential pitfalls, appropriate treatment media and media performance in greywater treatment and reuse in developing countries. It is the first of its kind in Ghana documented in peer-reviewed publications and addresses the lack of data in the area of greywater reuse as a method of wastewater management practice in Ghana and the sub-region. Additional studies further investigating the real implementation of this concept and the environmental auditing of the impact of unregulated greywater discharge are needed to inform stakeholders on the way forward. Such a study should involve policymakers, environmental experts, development agencies and water quality experts.

Previous studies in some developed countries have used a singular approach in exploring greywater reuse and little has been known about how individuals make their decision to use or not to use greywater. Little has also been known about what informs the choice of the reuse application for greywater in these developed countries. To the best of our knowledge, no previous study has directly assessed these factors using socio-cognitive models in developing countries. In sum, a lot of the innovation lies in the statistical techniques used in this study which was a two-prong approach of socio-cognitive models and laboratory analysis. The lessons learned in this study such as the role of personal norms, level of education and gender has reinforced our understanding of the approach to adopt in implementing greywater and reuse strategies.

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Author's resume

Michael Oteng-Peprah was born in Takoradi in the Western Region of Ghana on 5th of September 1979. He received his bachelor's degree in metallurgical engineering specializing in mineral processing from the Kwame Nkrumah University of Science and Technology, Ghana in 2004. After his undergraduate studies, he worked with the Golden star resources mining company as a trainee metallurgist on one of its gold treatment plants situated in Akyempim. It was during his time with the mines that he developed the passion for water and wastewater management. This led him to enrol for a master's programme at the Civil Engineering department of the Kwame Nkrumah University of Science and Technology in 2006. He completed the studies in 2008 obtaining an MSc in Water Supply and Environmental Sanitation. Just after his master's program at the Kwame Nkrumah University of Science and Technology in 2008, he received an Erasmus Mundus scholarship to study in Europe. He studied in four universities in Europe including University of Exeter in the United Kingdom, Wroclaw University of Technology in Poland, RWTH Aachen in Germany and Aalto University in Finland. He obtained a double degree in 2010; MSc Minerals and Environmental Engineering specializing in Process systems engineering and MEng Minerals and Geology specializing in mineral upgrading. His professional career started with the University of Cape Coast where he was first engaged as a part-time lecturer in the Department of Chemistry in 2011 and his appointment was regularized in 2013. Though he is officially in the Department of Water and Sanitation and due to his versatility, he sometimes lectures in the Industrial Chemistry unit. In 2016 he received a scholarship as part of the capacity-building project of the Netherlands Organization for International Cooperation in Higher Education (NUFFIC) to pursue his PhD at the University of Maastricht, Netherlands. His research interest includes water and wastewater management, hydraulic structures, process control and optimization and sanitation-related behaviour studies.

Publications

Included in thesis

Oteng-Peprah, M., de Vries, N., & Acheampong, M. A. (2020). Households' willingness to adopt greywater treatment technologies in a developing country - Exploring a modified theory of planned behaviour (TPB) model including personal norm. *J Environ Manage, 254*, 109807. doi:10.1016/j.jenvman.2019.109807

Oteng-Peprah, M., Acheampong, M. A., & DeVries, N. K. (2019). Predicting greywater reuse for potable and nonpotable purposes in a developing country - a theory of planned behaviour approach. *Desalination and Water Treatment, 142*, 56-64. doi:10.5004/dwt.2019.23414

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