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Physical, Chemical and Biological Greywater Treatment Technologies for Effective Reuse: Critical and Comparative Analyses

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ABSTRACT

The aim of this study was to review and compare the physical, chemical and biological treatment options for greywater for recycling in order to achieve pollution reduction and water conservation. The Performance, advantages and disadvantages of twenty treatments were investigated which included granular filtration, microfiltration, ultrafiltration, nanofiltration, reverse osmosis, chemical coagulation-flocculation, electrocoagulation, electrooxidation, photooxidation, adsorption, wetlands, aerated lagoons, rotating biological contactors, sequencing batch reactors, expanded bed up-flow bioreactors, vertical flow bioreactor, membrane bioreactors, trickling biofilter, anaerobic up-flow biofilter and up-floe anaerobic sludge blanket. Each treatment method was evaluated and compared with others using a standard set of criteria with the objective of selecting the most applicable and economically and environmentally feasible treatment system (or systems) that results clean water for recycling. Eight criteria (cost, maintenance and control, efficiency, suitability, value added product, environmental and health impact and size and land requirement) were selected for evaluation and each criterion was assigned a figure based on its relative important. A comparative analysis was performed on the 20 treatment methods using the eight criteria. The granular filter scored the highest (89) among the physical treatments, the electrochemical coagulation scored the highest (80) among the chemical treatments group and the rotary biological contactors scored the highest (89) among the biological treatments group. The top 3 treatments were granular filter (89), rotary biological contactors (89) and sequencing batch bioreactor (88), A through review of the literature indicated that non of the 20 treatment options can be used alone safely to treat greywater for reuse onsite for toilet flushing, landscape, crop irrigation and other non-potable uses. It is, therefore, recommended that a combination of granular filter and rotating biological contactors be used to treat greywater from a large group of houses, apartment complex, large commercial establishment or recreational facility and a combination of granular filter and sequencing bed bioreactor be used to treat greywater from a single house, a school or small business such as a sport center or shopping mall. The utilization of treated greywater reduces the demand for fresh clean water and provide substantial benefits for the municipal wastewater system by reducing the amount of wastewater to be treated.

Keywords: Water Shortage, Greywater, Chemical Treatments, Physical treatments, Adsorption, Biological Treatment, Selection Criteria, Comparative Analyses.

I. INTRODUCTION

Greywater is a wastewater discharge originating from kitchen sinks, showers, baths, washing machines and dishwashers [1-6]. Kitchen greywater contains food residues, high amounts of oil and fat, high salt concentrations, bacteria and dishwashing detergents and is, therefore, high in nutrients, suspended solids, biological oxygen demand (BOD), turbidity, and alkalinity. Bathroom greywater is the least contaminated greywater and contains soaps, shampoos, toothpaste, shaving waste, skin, hair, body-fats, lint and traces of urine and feces and is, therefore, has odor, turbidity, and BOD. Laundry greywater contains high concentrations of chemicals from soap powders (sodium, phosphorous, surfactants, nitrogen), suspended solids, solvents and nonbiodegradable fibers from clothing, amounts of pathogens from washing nappies and is, therefore, has high pH, salinity, and turbidity [3].

Greywater is generally safer to handle and easier to treat and reuse onsite for toilet flushing, landscape, crop irrigation and other non-potable uses [7-13]. The utilization of greywater provides solution for the water shortage by reducing the demand for fresh clean water, and substantial benefits for the wastewater system by reducing the amount of wastewater to be treated [14,15]. In an average residence, greywater is about 50-80% of the total wastewater produced. The percentage depends on the number of occupants, demographic, and personal habits [16,17]. Also, greywater generation rates vary significantly worldwide from 20 to 225 L/d per person depending on the level of development and availability of water among nations [1,6,18-28].

Greywater can be treated using physical, chemical, and biological treatment technologies. However, the physical, chemical, and biological characteristics (pH, temperature, electrical conductivity, surfactants, SS, COD, BOD, nutrients) of greywater vary significantly and must be taken into consideration when selecting the proper treatment [29-35]. Greywater temperature varies within the range of 18–30 ^oC [3,36,37]. The pH levels of greywater fluctuate (6.3-8.3) depending on the source of greywater and is affected by the level of oil and grease [3,19,28]. The electrical conductivity of greywater is in the range of 300-1500 µS/cm. Oil and grease concentrations in the ranges of 37-78 mg/L and 8–35 mg/L have been observed in bathroom and laundry greywater sources, respectively [28,37]. The concentration of surfactants in greywater is in the range of 17-60 mg/L and is dependent on the type and amount of detergent used [10,19,37]. Suspended solids concentrations are in the range of 1389-1396 mg/L [28,36]. The biodegradable proportion of greywater (BOD:COD) vary between 0.25 and 0.44 [3,21,36] and the microbial nutrient in greywater (ratios COD:NH_4-N:PO_4-P) is 100:5:1 [19]. Typical values of nitrogen in mixed household greywater are within a range of 5–50 mg/L [36] while the average phosphorous concentrations are within the range of 4–14 mg/L [3]. The small traces of faces that enter the grey water stream via effluent from the shower, sink, or washing machine do not pose practical hazards under normal conditions [10,16].

The aim of this study was to examine greywater treatment technologies and to determine the most effective and economically and environmentally feasible treatment method through comparative analyses. The specific objectives were to: (a) evaluate available physical, chemical and biological treatments, (b) develop evaluation criteria (c) perform quantitative analyses on various treatment methods using the developed criteria and (d) select the best system, or combination of systems, for the safe treatment of greywater for effective reuse.

II. PYSICAL TREATMENTS

Physical treatment of greywater refers to the separation of contaminants from the water by physical means such as sedimentation and filtration. In sedimentation, suspended particles are allowed to settle out of liquid under the effect of gravity forming a sludge [37]. However, sedimentation will not be considered in this study because greywater contains very low concentration of suspended solids. In filtration, particulate matter is removed from water by forcing the wastewater through a porous media that can be natural (sand, gravel and clay) or synthetic (membranes made of cellulose acetate, cellulose nitrate, polyamide, polycarbonate, polypropylene, and polytetrafluoroethylene) [38]. Membrane filtration is used for removal of microorganisms, particulate matter and organic materials which can impart color, taste and odor and react with disinfectants to form disinfection by-products. The size of materials that can be removed from the water depends upon the size of the membrane pores and, therefore, the membrane filtration processes are divided into four classes: microfiltration, ultrafiltration, nanofiltration and reverse osmosis as shown in Figure 1 [39].

2.1 Granular Filtration

In granular filtration, water or wastewater flows through granular material where suspended solids (sand, clay, organic particles and iron and aluminum flocs) and pathogenic microorganisms (bacteria, algae and protozoa) are removed. The granular media are made of sand, gravels, pebbles, synthetic polymers**,** diatomaceous earth, coal, charcoal, and cotton [40.41].

Typical sand filter (Figure 2) consists of a column of sand and course materials. Influent is introduced to the top of the column, passes through the medium and is collected at the bottom of the column [40]. Sand filters are typically classified in terms of their feed operation as semi continuous or continuous. Semi continuous filters can be taken offline periodically for cleaning, while continuous filter can be backwashed [42]. To backwash the sand filter, freshwater is pumped in the opposite direction of the flow until the filter bed is fully fluidization and the water is clear. Then, the backwash is discontinued, and the filter must go through a ripening period during which the filer media is allowed to settle and reform [37]. The ripening period is influenced by porosity of filter media, depth of filter and wastewater contaminants [44]. The filter can effectively retreat water or wastewater if the turbidity of effluent is below 0.2 NTU and backwashing commences once the turbidity of the effluent reaches 0.2 NTU [45].

Removal efficiencies of granular filters are within the range of 90-99%. Pathogen reductions are typically >99% with pre-treatment (chemical coagulation). However, 90-99% reductions of larger pathogens (helminth ova and protozoans) and <90% reductions of viruses and free bacteria can be achieved with no pretreatment [46]. Droste [45] reported that typical sand filters can remove particles as small as 0.5 μm and harmful pathogens such as Cryptosporidium and Giardia Cysts. Guala et al [46] reported that greywater can be reused for flushing hotel toilets after treatment in sand filter and the

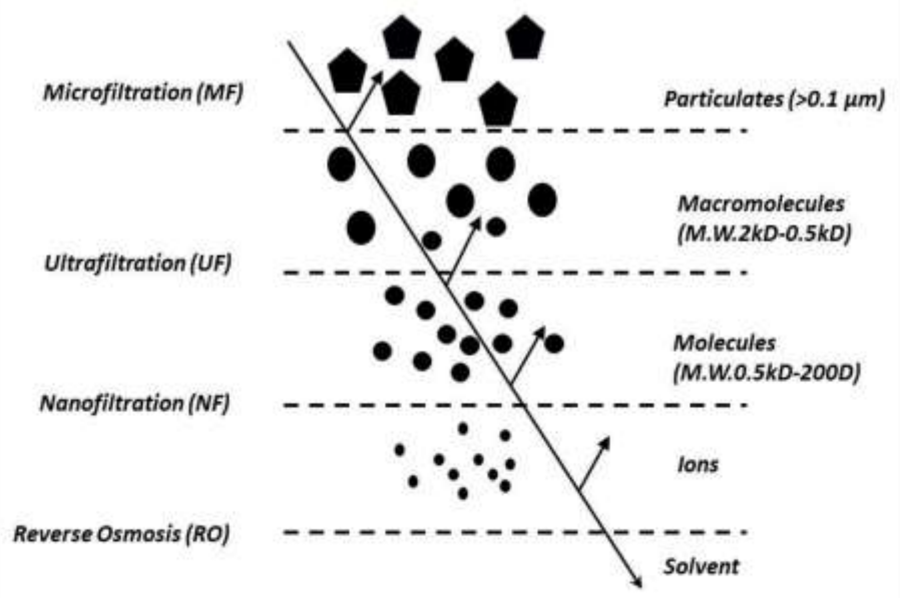


Figure 1. Membrane filtration behavior in wastewater [39].

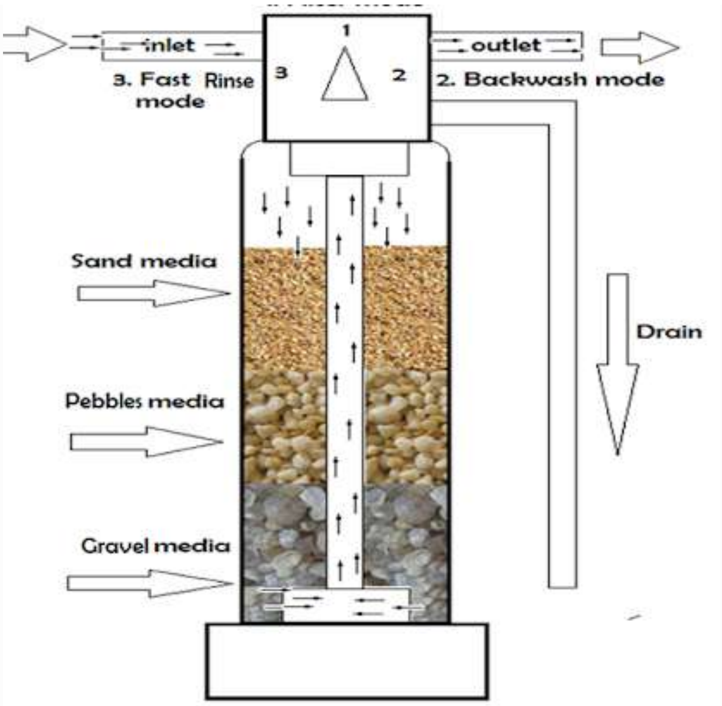


Figure 2. Granular filter made up of fine sand, fine and coarse gravels [40].

filter can remove greywater constituents that contribute to turbidity, COD and total suspended solids. Spychala et al. [47] reported greywater volatile solids and COD removal efficiencies of a sand filter of up to 60% and 26.8%, respectively. Albalawneh et al. [48] evaluated the efficiency of a granular filtration system for greywater treatment and reported BOD, COD and TSS removal efficiencies of 73%, 65%, and 85% when using gravel media and 49%, 51%, and 76% when using volcanic tuff media, respectively. Abdel-Shafy et al. [49] evaluated different designs of sand filter as a secondary treatment of the greywater and reported residual concentrations of COD, BOD_5, and TSS of 43, 16, and 7.5 mg/L, respectively. The quality of the final effluent complied with the National Regulatory Standards for treated greywater effluent reuse in irrigation.

2.2 Microfiltration

Microfiltration is a low pressure (100-400 kPa) physical separation process in which a contaminated fluid is passed through a membrane with a porosity of 0.1-10 µm (Figure 3) to separate microorganisms (Giardia lamblia and Crypotosporidium cysts, algae, and some bacterial species) and suspended particles from the liquid stream. It does not, however, remove virus and dissolved contaminants. Microfiltration filters are made from organic materials (polymers) and inorganic materials (ceramic or stainless steel). Microfiltration has been used in water and wastewater treatments and its use limits the concentrations and number of chemicals applied during the treatment [50,51].

de Oliveiraa et al. [52] used the microfiltration process for greywater treatment and found it to tolerate variations concentration of pollutants in greywater and to have high removal efficiencies of apparent color, turbidity, and suspended particles. Bhattacharya et al. [53] used a microfiltration ceramic membrane for treatment of graywater with high concentration of organics and noticed that about 73–90% COD reduction was achieved after 30 min with an operating pressure of 2 bar. Kim et al. [54] treated graywater using a microfiltration membrane and reported removal efficiencies of 98% for color, 99% for turbidity, 99% for COD, 99% for suspended solids and 30% for E. coli, total coliform, Salmonella and Staphylococcus.

Manoucheri and Kargari [55] treated laundry wastewater using a mixed cellulose ester microfiltration membrane with

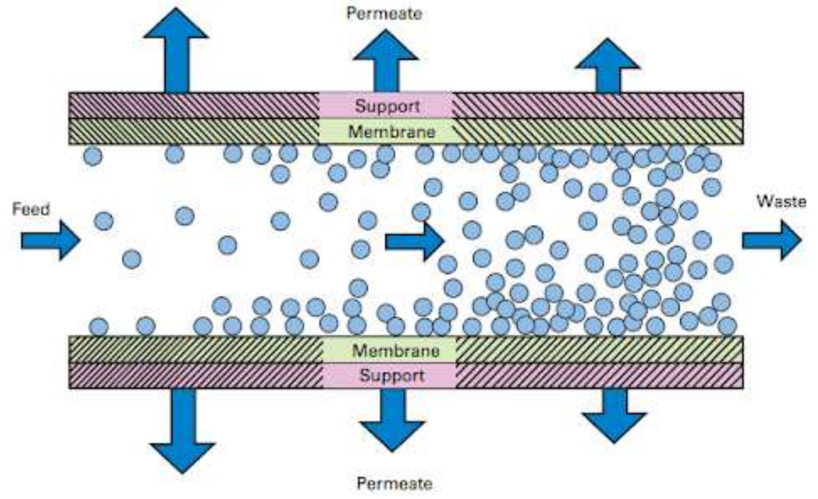


Figure 3. Tubular microfiltration [50].

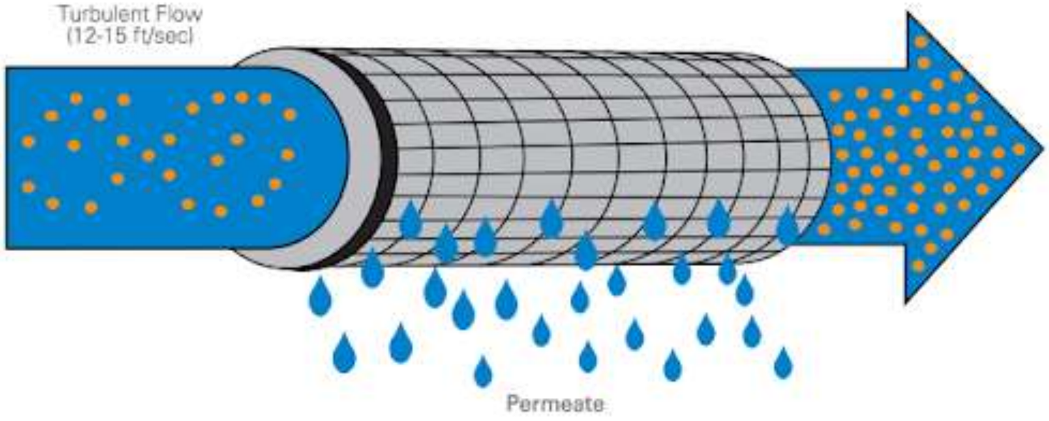


Figure 4. Cross flow tubular ultrafiltration [59].

0.22 µm pore size and noticed that changes in trans-membrane pressure and feed flow rate affected the permeate flux and membrane rejection performance. The highest removal efficiencies (93.9, 90.8 and 98.7% for BOD, COD, TSS and turbidity, respectively) were obtained at a trans-membrane pressure of 1 bar and feed flow rate of 44 L/h.

2.3 Ultrafiltration

Ultrafiltration is a pressure-driven physical separation process in which a hydrostatic pressure forces a liquid against a semi permeable membrane with a pore size of 0.01-0.02 µm to remove large particles, most microorganisms (bacteria, protozoa, algae and virus) and some natural minerals (divalent ions). It cannot, however, remove dissolved substances. Most ultrafiltration membranes use polymeric materials (polysulfone, polypropylene, polyvinylidene fluoride, polyacrylonitrile, cellulose acetate, polylactic acid), but ceramic membranes are used for high temperature applications [56,57]. Ultrafiltration is used to pre-treat surface water and various types of seawaters because of many advantages including: no need for chemicals (coagulants, flocculants, disinfectants, pH adjustment), constant quality of the treated water, removal of particles and microbes, compactness of process and simplicity of automation [58-61]. However, fouling can cause difficulties in using ultrafiltration membrane technology for water and wastewater treatment [61].

Bhattacharya et al [53] evaluated the efficiency of an ultrafiltration process and reported COD reduction of 73–90% after 30 min with operating pressure of 2 bar. Li et al [62] evaluated a decentralized greywater treatment system that used a submerged spiral-wound ultrafiltration membrane. The system was able to maintain a permeate flux between 6 and 10 L/m^2/h and reduce the TOC from 161 to 28.6 mg/L (83.4% removal efficiency). The permeate had total nitrogen of 16.7 mg/L, total phosphorus of 6.7 mg/L and a turbidity below 1 NTU and was free of suspended solids. Kaminska and Marszalek [63] treated greywater by a crossflow ultrafiltration system and obtained high-quality effluent with very low COD (5.8–18.1 mg/L), TOC (0.47–2.19 mg/L), nitrate (0.18–0.56 mg/L), phosphate (0.9–2.1 mg/L), ammonium (0.03–0.11 mg/L), and total nitrogen (3.3–4.7 mg/L) with lack of E. coli and enterococci. Schafer et al. [64] investigated the performance of an ultrafiltration system treating greywater and observed bisphenol removal efficiency of 30–45%. Nghiema et al. [65] stated that most research on the utilization of membrane filtration for treatment of various wastewaters have shown the UF treatment to be the preferred method and noticed that the biggest contributors to membrane fouling of greywater were the organic matter and calcium. Sumish et al. [66] investigated the treatment of laundry greywater using hydrophilic polyvinyl pyrollidone (PVP) modified polyethersulfone (PES) ultrafiltration membranes and found the PES membrane with 10% of PVP had higher permeate flux, faster flux recovery, less fouling and higher COD (88%) and TDS (82%) removals when compared with other membranes.

2,4 Nanofiltration

Ultrafiltration is a high pressure physical separation process that can remove most organic molecules, viruses, cysts, bacteria and a wide range of salts as shown in Figure 5 [67]. Pushing liquid through smaller membrane pores (0.001 µm) requires higher operation pressure of 600-1000 kPa [68]. Nanofiltration is used to treat surface and ground water [69,70] and various wastewaters [67]. It provides high rejection of multivalent ions such as calcium and low rejection of monovalent ions such as chloride. It rejects various salts in proportion to their molecular size in this order $Na_2SO_4 > CaCl_2 > NaCl$ [68-70]. The advantages of nanofiltration includes lower discharge volumes, lower retentate concentrations for low salt concentrations, reduction of salt and dissolved matter contents in water, and reductions of heavy metals, nitrates, sulphates, color, tannins and turbidity. The disadvantages are high energy consumption (0.3 to 1 kWh/m³), the needed for prefiltration of heavily polluted waters, limited retention for salts and univalent ions and high cost of membranes [67].

Hourlier et al. [71] used three nanofiltration membranes (AFC30, AFC40 and AFC80) to treat greywater for reuse at 25°C and transmembrane pressures of 20 and 35 bars. The best results were obtained with AFC80 membrane at 35 bars and a flux of 50 L/m²h. COD and anionic surfactants retentions of 95% were observed and no Enterococcus was detected in the permeate. Ramona et al. [72] used the nanofiltration membrane 200 Da MWCO for treating sports center shower graywater for onsite reuse.

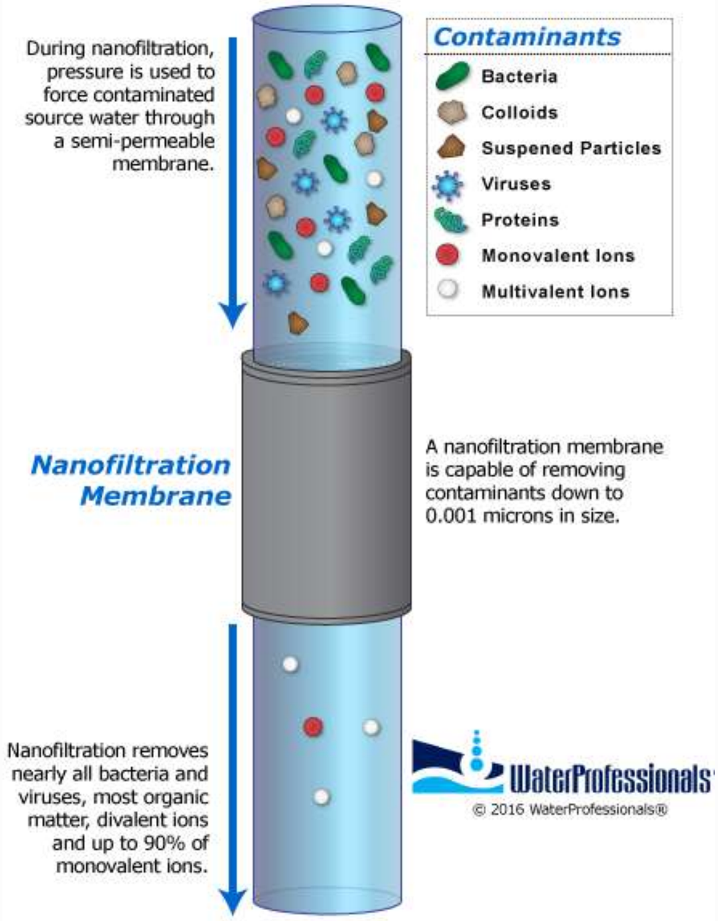


Figure 5. Contaminants removed by nanofiltration [67].

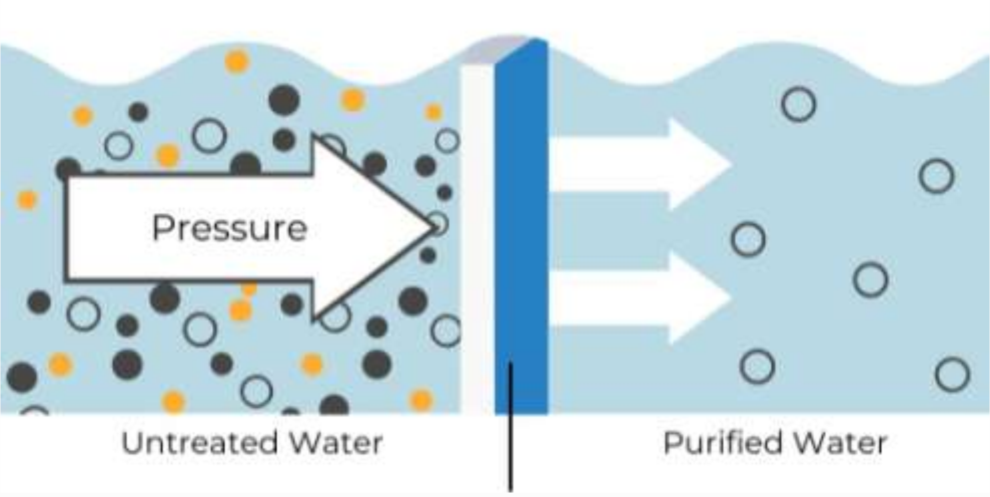


Figure 6. Reverse osmosis [77].

The permeate produced was of high quality with high rejection of soluble organic matter (>90%) and ionic species (50%). Guilbaud et al. [73] implemented a nanofiltration process to treat laundry greywater on board a ship and recycle 80% of treated water for washing of machines. Using a tubular PCI-AFC80 membrane, at a pressure of 35 bars, a temperature of 25 °C, and a volume-reduction-factor of 5, produced a permeate free of microorganisms and SS and with only

48 mg/L COD and 7 mg/L TOC. Guilbaud et al. [74] reported that nanofiltration of greywater by AFC80 membrane at a pH of 7, a pressure of 35 bars and a temperature of 25 °C achieved high COD rejection rate (93%). van der Bruggen et al. [75] reported that the flux of nanofiltration declined as a function of the concentration of the organic compound and was related to adsorption on the membrane material.

2.5 Reverse Osmosis

Reverse osmosis is the tightest membrane separation process in which water is separated from dissolved salts by filtering through a semipermeable membrane having a pore size of 0.0001 µm at a pressure greater than osmotic pressure (Figure 6) [76]. Reverse osmosis membrane removes all organic molecules, pesticides, cysts, bacteria, viruses, and all minerals including monovalent ions. It allows removal of dissolved individual ions (sodium, chlorine, calcium, and magnesium), metal ions, minerals, and organics. It, thus, produces water that meets most demanding specifications [77]. The advantages of reverse osmosis are: (a) removal of nearly all contaminant ions and most dissolved non-ions, (b) insensitive to flow and dissolved solids concentration, (c) suitable for small systems with a high degree of seasonal fluctuation in water demand, (d) operates immediately without break-in period, (e) low effluent concentration of dissolved solids, (f) removes bacteria and viruses, and (g) simplicity of operational and automation, (h) requires minimum operator attention and (i) suitable for small system applications. The limitations of reverse osmosis are: (a) high capital and operating costs, (b) managing the brine solution is a potential problem, (c) high level of pretreatment is required in some cases, (d) membrane fouling and (e) clean water produced for use is only 25-50 % of the feed [78,79].

Singh et al. [80] treated greywater containing detergent and a salinity of 2,000

ppm by reverse osmosis and obtained reusable water with <300 ppm inorganic solutes and trace amounts of detergent. Senthilmurugan and Venkatesh [81] reported on a treatment system for washing machine greywater for surfactant recovery and water reuse. The greywater was processed first through a polymeric ultrafiltration membrane to remove the turbidity and then through reverse osmosis membrane for surfactant recovery. The surfactant recovery was affected by feed detergent concentration, backwash pressure, backwash temperature and back-flush flow rate and the maximum surfactant recovery was 82 %. Boddu et al. [82] treated graywater using reverse osmosis after microfiltration treatment. The results showed that microfiltration in combination with reverse osmosis can achieve adequate reduction of COD but at the cost of progressively decreasing water flux through the reverse osmosis membrane. Reang and Nath [83] used a combination of spiral wound ultrafiltration and spiral wound reverse-osmosis membranes to treat greywater from washing machine for surfactant recovery. The dirt and dust particles were separated from the greywater by the ultrafiltration membrane and the surfactant solution and water were separated from the mixture using the reverse osmosis membrane. Engin et al. [84] used a compact reverse osmosis unit to treat greywater for reuse and obtained COD and BOD removal rates around 80%. The permeate obtained was free of suspended solids and had an excellent physical appearance. DiPaolo [85] stated that reverse osmosis systems use a pump to increase the pressure on the feed side of the equipment and forces the water across and through a semipermeable membrane, a process that results in approximately 96-99 % total dissolved solids removal.

III. CEMICAL TREATMENTS

There are several chemical treatment systems that have been used for treatment of greywaters for pollution load reduction and water reuse. These are chemical coagulation-flocculation, electrochemical coagulation, electrooxidation and photooxidation.

3.1 Chemical Coagulation-Flocculation

Coagulation and flocculation processes are used for treatment of a variety of wastewaters containing colloids and metal ions. In coagulation, particles aggregate with themselves by a change in pH while in flocculation, particles aggregate using polymers to bind them together [86,87]. Particles in water are electrically charged as shown in Figure 7 [88]. The area nearest the particle has two layers: (a) the first layer is the closest to the electrically charged particle and in which counter-ions gather to create the stern layer and (b) the next layer is composed of both counter-ions and co-ions, but with a surplus of counter-ions. The surrounding water has an equal distribution of counter-ions and co-ions [89-90]. In coagulation, the two layers around the particle cause it to be stable in the water but when changes in pH or conductivity occur, the number of ions in the layers change, thereby affecting the stability of the particles and force them to settle as shown in Figure 8_{top} [91]. In flocculation, by using a polymer with the opposite charge to that of the particles, the polymer bounds to the particles making larger particles that cannot stay suspended as shown in Figure 8_{bottom} [91]. When particles are precipitated from the solution (Figure 9), further filtration treatment is necessary to obtain the desired water quality [92]. Figure 10 shows a system having the processes of coagulation, flocculation, and sedimentation [93].

Polymers are a large range of natural and synthetic water soluble macromolecular compounds that can enhance flocculation of the water constituents. Natural polymers have long been used as flocculants because they are free of toxins, biodegradable and often locally available. The advantage of synthetic polymers are: they are more effective, easier to control and available in various forms including solutions, powders, beads, oils and water-based emulsions. The problem with synthetic polymers relates to potential toxicity issues arising from unreacted monomer residual [87,89]. The commonly used metal coagulants fall into two categories: those based on aluminum (Al) and those based on iron (Fe). The Al coagulants are aluminum sulfate, aluminum chloride, and sodium aluminate. Pre-hydrolyzed aluminum forms include aluminum chlorohydrate, poly-aluminum chloride, polyaluminum sulfate chloride, polyaluminum silicate chloride and forms of polyaluminum chloride with organic polymers. The Fe coagulants include ferric sulfate, ferrous sulfate, ferric chloride, and ferric chloride sulfate. Pre-hydrolyzed iron forms include polyferric sulfate and ferric salts with polymers and also polymerized aluminum-iron blends [88-94].

Bolto et al. [92] reported that organic polymeric flocculants are used in water

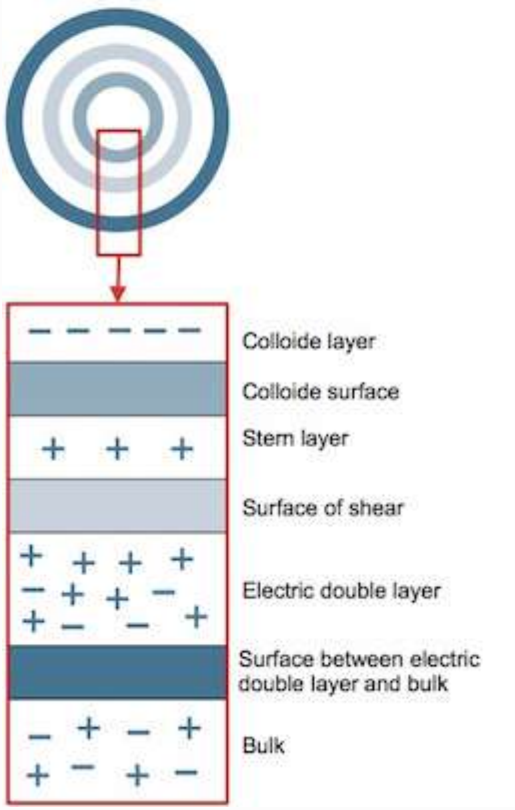


Figure 7. Electrically charged particle in water [88].

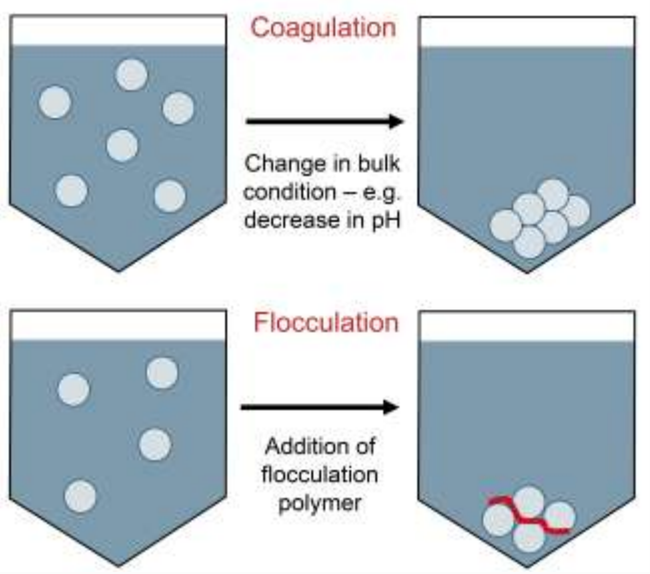


Figure 8. Coagulation and flocculation [91].

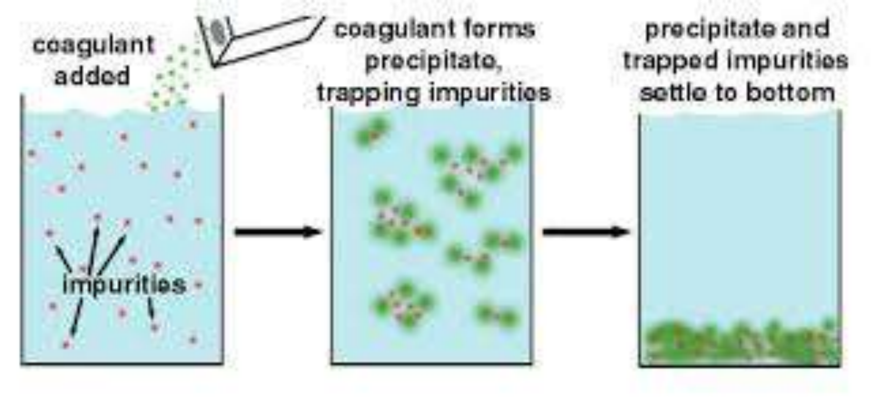


Figure 9. Coagulation of wastewater impurities [92].

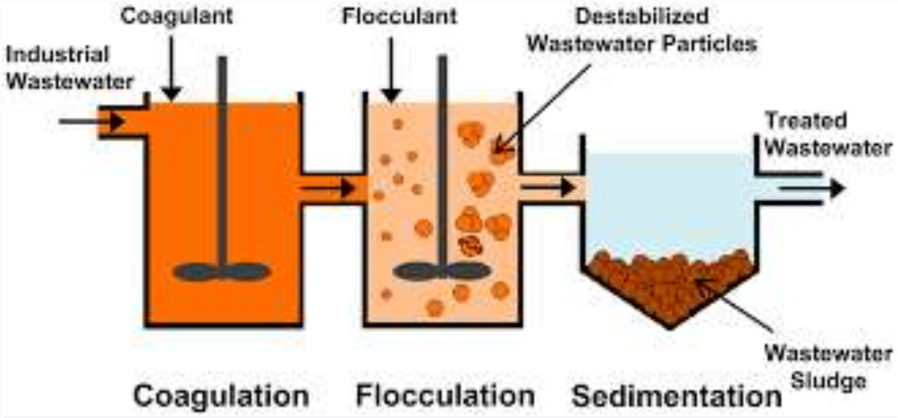


Figure 10. Coagulation and flocculation treatments followed by sedimentation [93].

purification as floc builders to replace inorganic coagulants like alum, iron salts and lime. Odegaard [93] showed that coagulation with metal salts was very efficient but can lead to excessive sludge production. Jahel and Heinzmann [95] stated that coagulation and flocculation can be used for removal of dissolved solids and suspended particles including pathogens (Giardia and Cryptosporidium, a parasite that cases diarrhea), virus, arsenic, phosphorus, and fluoride. De Feo et al. [96] reported that most inorganic salts used as coagulants have high removal rates (up to 80%) of natural organic molecules. Vinitha et al [97] treated greywater by chemical coagulation using polyaluminium chloride and reported removal efficiencies of turbidity, COD and TSS of 91, 73 and 83% compared to 93, 74 and 89% when using alum, respectively. Bielski and Giermek [98] treated greywater using polyaluminum chloride and found that coagulant doses within the range of 25-100 g Al^{3+}/m^3 produced the best removal of turbidity, COD and TOC. Ghaitidak and Yadav [99] investigated the effect of coagulation treatment using alum on greywater characteristics and reported turbidity, BOD and Escherichia coli removals of 88%, 77% and 99%, respectively. Alharbi et al. [100] used alum coagulation (alum dose of 20 mg/L) to treat greywater produced at a mosques from cleaning certain parts of the body before performing prayers and reported removal efficiencies of 95.8% for turbidity, 31.6% for COD and 50.0% for BOD. Chitra and Muruganandam [101] evaluated the coagulating efficiencies of powdered coagulants obtained from tamarind seeds, moringa oleifera, banana peels and fly ash for greywater treatment and reported turbidity removal efficiencies of 49, 61.33%, 85.75%, 90.42% and 94.27% for tamarind seeds, moringa oleifera, banana peels and fly ash, respectively. Pidou et al. [94] stated that the effectiveness of coagulants was greatly dependent upon contact time, pH, temperature, coagulant dose, and mixing speed. Jahel and Heinzmann [95] showed that the efficiency of the coagulation-flocculation process was dependent on the type of coagulant, coagulant dosage, coagulant feed concentration, type and dosage of chemical additives, sequence of chemical addition, pH, time lag between dosing points, intensity and duration of mixing, velocity gradients applied during flocculation stage, flocculator retention time, type of stirring device and flocculator geometry.

3.2 Electrocoagulation

Electrocoagulation (EC) is an electrochemical process that simultaneously removes heavy metals, suspended solids, emulsified organics and many other contaminants from water and wastewater using electricity instead of chemicals. The EC device (Figure 11) operates continuously and performs automated coagulation, flocculation, flotation, separation, and removal of contaminants in a single enclosed reactor [102]. The advantages of EC are: (a) it removes any size of suspended solids, (b) it requires no filters, no daily maintenance and no additives, (c) it removes oil, grease and heavy metals, (d) it requires simple equipment and is easy to operate (e) it results in clear and colorless water with low dissolved solids, (f) the formed sludge tends to be settable and easy to de-water, (g) the formed flocs tend to be much larger, contain less bound water, acid- resistant, more stable, and can be separated faster by filtration, (h) it has little impact on sodium and potassium ions in solution and (i) the gas bubbles produced during electrolysis can carry the pollutants to the top of the solution where it can be more easily concentrated, collected, and removed by skimmer [103,104]. EC technology has been increasingly used for treatment of various wastewaters [102-116].

Ansari and Shrikhande [104] reviewed the recent electrocoagulation studies on greywater treatment, examined electrode arrangement, cell design, treatment facilities and economic concern and suggested recommendations to boost the technology to maximize resource conservation. Sahu et al. [105] reviewed the mechanism, affecting factors and applications of the electrocoagulation process and found the process to be widely accepted over other physicochemical processes due to its ability to treat large volume at low cost. An et al. [102] used the electrocoagulation process for the removal of oil from wastewater and found the treatment to be effective in destabilizing oil-in-water emulsions by neutralizing charges and bonding oil to generated flocs and hydrogen bubbles. Barzegar et al. [106] used the electrocoagulation process for the treatment of greywater and found that 85% of COD and 70% of TOC were removed during 60 min electrolysis time at a pH of 7.0 and a current density of 15 mA/cm^2. Nghiema, L.d Turkay [107] investigated the treatment of greywater by an electrocoagulation process using eight different electrode combinations and stated that the highest COD removal was obtained with the Al–Fe–Fe–Al hybrid combination and a current density of 1 mA/cm^2.

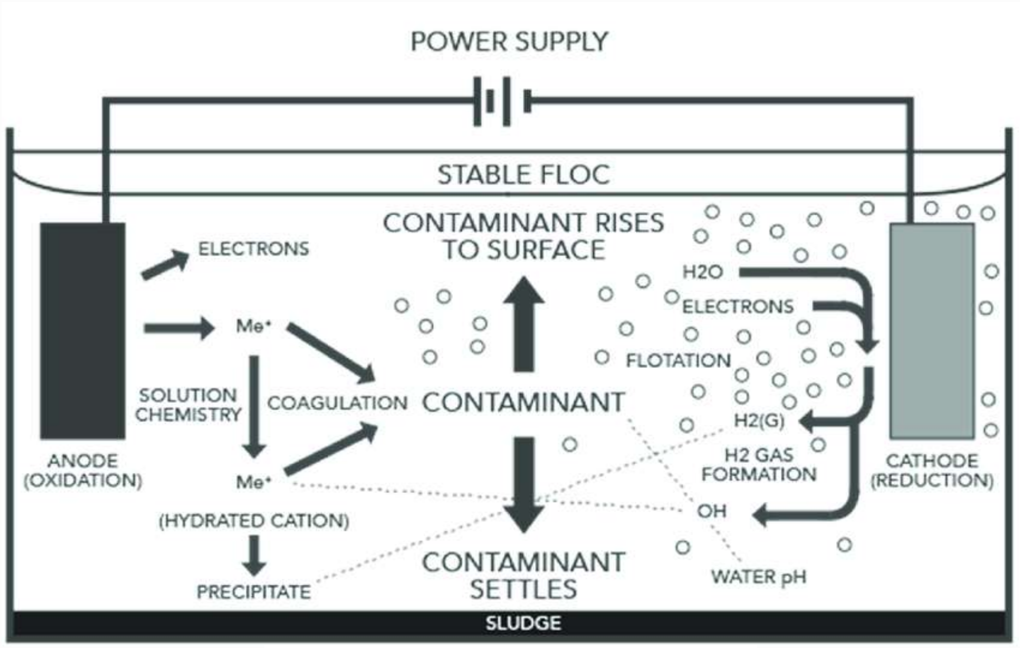


Figure 14. Electrochemical coagulation [102].

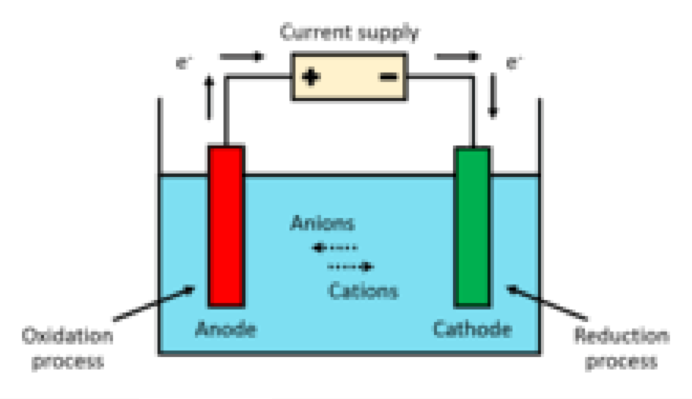


Figure 12. Electrooxidation unit [110].

Karichappan et al [108] used an electrocoagulation process to treat greywater and observed optimal operating conditions at al pH of 7, a current density of 20 mA/cm^2, an electrode distance of 5 cm and an electrolysis time of 20 min.

3.3 Electrooxidation

Oxidation is the loss of electrons whereas reduction is the acquisition of electrons. The species being oxidized is known as the reducing agent or reductant, and the species being reduced is called the oxidizing agent or oxidant. Electrooxidation (EO) is an advanced oxidation process used for wastewater treatment [109]. The process comprises two electrodes (anode and cathode) connected to a power source as shown in Figure 12 [110]. When an energy input and sufficient supporting electrolyte are provided to the system, strong oxidizing species are formed and interact with the contaminants to degrade them into water and CO_2 by complete mineralization [110-115]. EC has been used to treat different types of wastewaters because it is easy to set-up, is effective in treating harmful and recalcitrant organic pollutants which are difficult to degrade with conventional wastewater remediation processes and does not require external addition of chemicals because the required reactive species are generated at the anode surface [114-119]. However, due to its relatively high operating costs, it is often combined with other technologies such as biological remediation [113].

Ghanbari and Martinez-Huitle [120] treated washing machine greywater by electrochemical advanced oxidation processes using photo-electro-Fenton (PEF) combined with peroxy-mono-sulfate (PMS) and reported removals of 99.5% of COD and 97.1% of total organic carbon at a pH of 5.0, current density of 30 mA/cm^2, and reaction time of 180 min. Patidar and Srivastava. **[121]** performed critical analysis of reported studies from 1996 to 2020 on the treatment of wastewaters using the sonolysis and electrooxidation process for the degradation of the persistent organic pollutants and found that coupling these two techniques (sonolysis and electrooxidation) increased the mineralization rate by increasing the mass transport rate and the chemical reaction rate and reduces the electrode passivation. Zhang et al. [122] studied photocatalytic (PC) of ammonia/ammonium pollutants in wastewater and found the oxidation of ammonia based on active chlorine species is efficient and exhibits some advantages compared to the
chemical chlorination approach.

3.4 **Photooxidation**

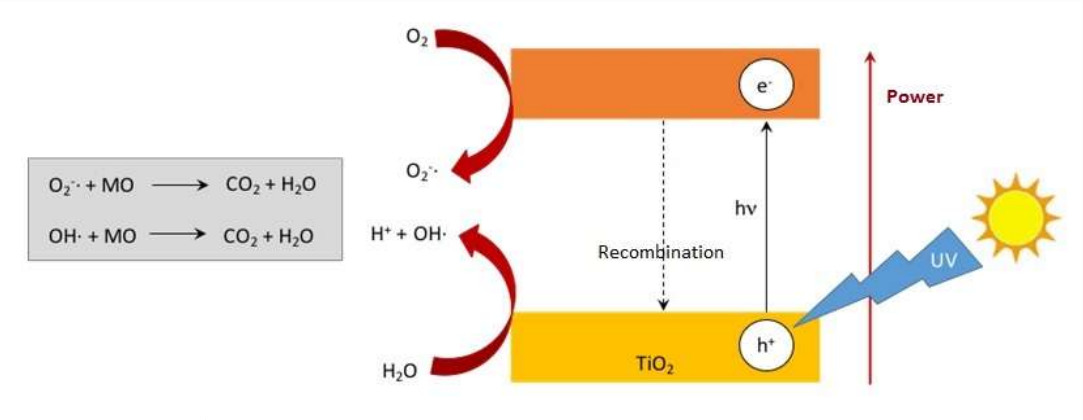
Photooxidation is an advanced oxidation processes used for effective treatment of recalcitrant organic products in wastewaters. In this process, the highly reactive hydroxyl radical (OH•) is formed and triggers a series of chemical reactions that end up in the complete mineralization of organic compounds to CO_2 and water. Photooxidation has several advantages including: high reactivity with most organic compounds, complete oxidation of both organic and inorganic compounds and emission of harmless compounds since all oxidants are destroyed in the process [123-125]. There are two types of photooxidation: photolysis and photocatalytic.

Photolysis is based on irradiating the effluent with ultraviolet light (170-230 nm) which causes oxidation reactions by forming free radicals in the presence of oxidizing species (ozone and hydrogen peroxide). The lower the radiation wavelength, the more energy is absorbed by the chemical compounds and the greater the efficiency of destroying contaminants. The combination of ultraviolet radiation with ozone or hydrogen peroxide is very effective in providing free radicals for non-selective oxidation of most organic molecules. These compounds are environmentally sustainable as they break down into oxygen and water [126].

Photocatalytic oxidation destroys contaminants using ultraviolet radiation with catalysts (salts of iron such as chlorides, fluorides and bromides, or semiconducting oxides such as TiO_2, Al_2O_3 or ZnO) to increase the formation of hydroxyl radicals which oxidize the contaminants. Titanium dioxide is particularly efficient as it has another free radical production mechanism for the OH• radical. In the presence of ultraviolet radiation, the electrons in one valence band of TiO_2 migrate to a conduction band, leaving a corresponding hole in the valence band, thereby producing electron-hole pairs (h+- e-). The energy required to excite TiO_2 is 3.2V, corresponding to the absorption of ultraviolet light ($\lambda < 385$nm). The electron-hole pairs can recombine and cancel each other out or move to the catalyst surface. To prevent the electron-hole pairs (h+- e-) from recombining, an oxidant (O_2) acting as an electron acceptor is required, which forms the superoxide ion (O_2•). An organic molecule adsorbed in the holes can also be oxidized by electron transfer as shown in Figure 13 [127,128].

Photooxidation treatment is used for treating several wastewaters to remove cyanide, Zn, Ni, antibiotics, hormones, organochlorides, organic polyphosphates, hetero-cycloaliphatic compounds, nitrogenous and aromatic organics and heteroaromatic compounds [123-125]. The destruction of contaminants by photooxidation has several advantages including: (a) toxic pollutants are destroyed and converted into harmless substances (water, CO_2 and mineral salts), (b) the process is non-selective and can decompose virtually any organic molecules, (c), additional pre-treatment or post-treatment processes are not required, (d) energy consumption is very low as the process takes place at moderate temperatures (30-80 °C), (e) the radiation source could be solar energy, and (f) the chemicals used are relatively low cost and available.

Chong et al. [128] stated that semiconductor photocatalytic process is a low-cost, environmentally friendly and sustainable treatment technology for the water and wastewater industries and can remove persistent organic compounds and microorganisms. Reviro et al. [129] used photooxidation for treating recalcitrant organic compounds in greywater and reported that the process oxidized organic reactants at the catalyst surface in the presence of ultraviolet light into carbon dioxide and water. Lopez et al. [130] reported that treating greywater using photooxidation over TiO_2 films resulted in catalytic reaction and indicated that photoactivation was caused in part by contact of the films with water and degradation products were produced during the initial cycle of photooxidation. Alrousan et al. [131] investigated the mineralization of total organic carbon (TOC) in greywater using a combinations of H_2O_2, O_3, and immobilized TiO_2 under dark and UVA irradiation conditions which included TiO_2/dark, O_3/dark (ozonation), H_2O_2/dark (peroxidation), TiO_2/UVA (photocatalysis), O_3/UVA (Ozone photolysis), H_2O_2/UVA (photo-peroxidation), O_3/TiO_2/dark (catalytic ozonation), O_3/TiO_2/UVA (photocatalytic ozonation), H_2O_2/TiO_2/dark, H_2O_2/TiO_2/UVA, H_2O_2/O_3/dark (peroxonation), H_2O_2/O_3/UVA (photo-peroxonation), $H_2O_2/O_3/TiO_2$/dark (catalytic peroxonation), and $H_2O_2/O_3/TiO_2$/UVA (photocatalytic peroxonation). Combining different treatment methods with UVA irradiation dramatically enhanced the organic mineralization efficiency. The optimum TiO_2 loading was 0.96 mg/cm^2 and the highest TOC removal (54%) was achieved using photocatalytic peroxonation with 25 mg O_3/min, and 0.7 H_2O_2/O_3 molar ratio. Boyjoo et al. [132] performed a pilot scale study of photocatalytic degradation (with TiO_2) of impurities in shower greywater. Up to 57% of TOC elimination was obtained after 6 hours of treatment at a pH of 3, catalyst concentration of 0.07 mg/cm^2, air flow rate of 1.8 L/min, and slurry recirculation rate of 4.4 L/min). Dubowski et al. [133] investigated the removal of triclosan and oxybenzone micropollutants in greywater using combined UVC/VUV radiation in a continuous-flow reactor. The treatment removed both micropollutants at lower efficiency. as particles and dissolved organics acted as radical scavengers. Filtration prior to irradiation improved the process efficiency and reduced energy requirements. Grcic et al. [134] treated bathroom greywater using solar photocatalysis in a reactor with constant recirculation over photocatalytic layer exposed to direct sunlight. The photocatalytic layer consisted of TiO_2-coated textile fibers prepared by applying TiO_2–chitosan pasteous dispersion on polyester/wool blend textile (75% polyester, 25% wool). The results showed significant decrease in organic content, COD, toxicity, emulsifying compounds and surfactants and complete degradation of dye molecules and certain aromatic compounds over a period of 4 h. Agullo-Barcelo et al. [135] assessed the disinfection of a secondary effluent from a municipal wastewater treatment plant using H_2O_2 (20-50 mg/ L), TiO_2 (100 mg/ L) and photo-Fenton under natural solar radiation in compound parabolic collector photo-reactors. The best treatments efficiency for Escherichia coli was photo-Fenton at a pH of 3 followed by H_2O_2 (20 mg/L)/solar, TiO_2/solar and solar photo-inactivation. On the other hand, for Somatic coliphages and F-specific RNA bacteriophages the ranking was: photo-Fenton at pH 3 > TiO_2/solar > H_2O_2 (20 mg/L)/solar > solar photo-inactivation. Spores of sulfite-reducing clostridia was the most resistant microorganism in all the evaluated processes.



$TiO_2 + h\nu \rightarrow TiO_2\,(e^{-}+h^{+})$
$OH^- + h^+ \rightarrow \bullet OH$
$H_2O + h^+ \rightarrow \bullet OH + H^+$
$\bullet OH$ + organic compounds $\rightarrow CO_2 + H_2O$

Figure 13. Photooxidation [127].

IV. ADSORPTION TREATMENT

Adsorption is the adhesion of atoms, ions or molecules from a gas or liquid to a surface, creating a film of the adsorbate on the surface of the adsorbent. Common examples of adsorbents are clay, charcoal, silica gel, colloids and metals. There are two types of adsorptions: physical adsorption (physisorption) and chemical adsorption (chemisorption) as shown in (Figure 14). Adsorption may, also, occur due to electrostatic attraction [147,148]. Adsorption differs from absorption in which a fluid (the absorbate) is dissolved by a liquid or solid (the absorbent). Thus, adsorption is a surface phenomenon, while absorption involves the whole volume of the material. Adsorption occurs at uniform rate throughout the material and the process is endothermic and unaffected by temperature. On the other hand, the rate of absorption increases initially then decreases, the process is exothermic and is affected by temperature, and concentration on the surface of adsorbent is different from that in the bulk. Sorption encompasses both the adsorption and absorption processes. The process of removal of adsorbent from the surface of adsorbate is known as desorption [149-151]. Figure 15 shows the processes of adsorption, absorption and desorption [1147].

Siyal et al. [152] stated that treating wastewater containing surfactants by adsorption is effective and activated carbon is the most suitable adsorbent for removing surfactants. Thompson et al. [153] compared biochar to activated carbon for removing dissolved organic carbon from graywater. A wood-based biochar was effective for graywater treatment, but activated carbon removed more dissolved organic carbon. Sales et al. [154] prepared activated charcoal of coco-da-baia mesocarp and tested it as adsorbent material for treating wastewater in a column with a continuous flow. Reductions of 50% in hardness, 87.5% in chloride and 66.6% in acidity were achieved and the effluent was qualified for use in agricultural irrigation. Patel et al. [155] reported on batch and continuous adsorption studies for the treatment of greywater using activated carbon prepared from sawdust. The optimum conditions in batch mode for the removal of contaminants were a pH of 7, a contact time of 240 min. and an adsorbent dose of 8 g/L with initial greywater COD of 554 mg/L and BOD of 120 mg/L. Topkava et al. [156] treated greywater from laundry washing by adsorption using adsorbents synthesized from rice husk. The removal efficiencies were 98%, 70% and 96% for color, turbidity and detergent, respectively. Guo et al. [157] studied the adsorption mechanisms of mercury ion (Hg^{2+}) in contaminated water by different fractions of corn straw biochar (inorganic carbon (IC), organic carbon (OC), hydroxyl-blocked carbon (BHC), and carboxyl-blocked carbon (BCC)). The reaction mechanisms of biochar for Hg^{2+} removal included

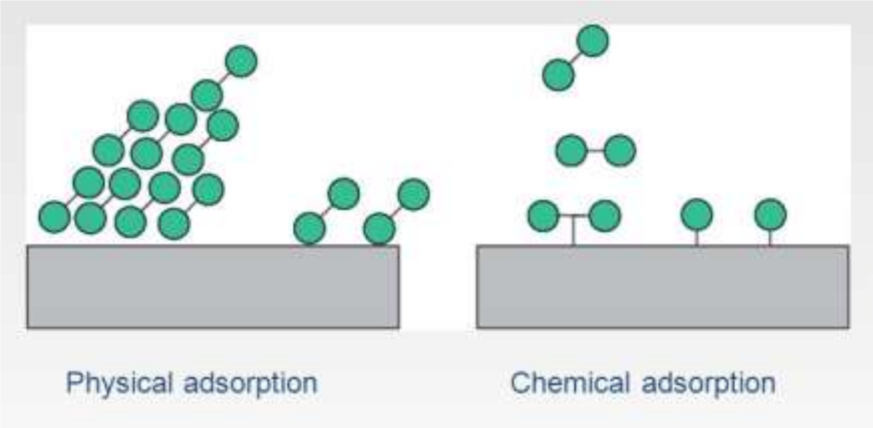
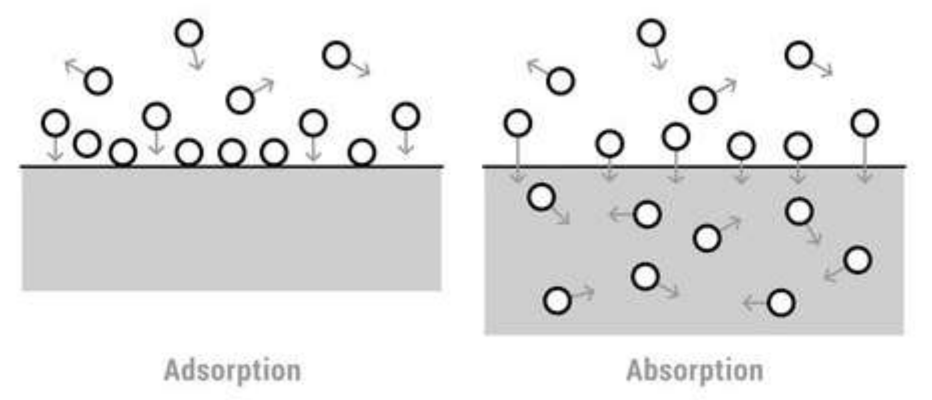
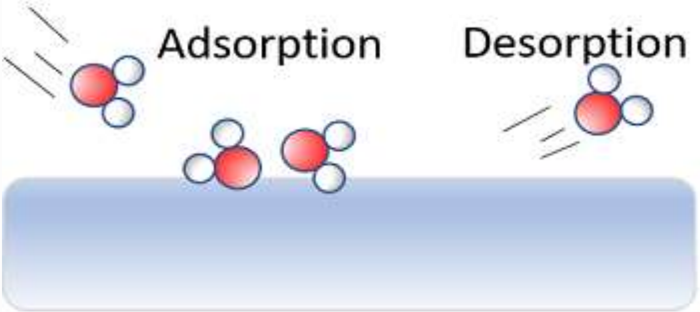


Figure 14. Types of adsorptions [[147].



(a) Adsorption and absorption.



(b) Adsorption and desorption.

Figure 15. Adsorption, absorption and desorption [151].

electrostatic adsorption, ion exchange, reduction, precipitation, and complexation. The equilibrium adsorption capacity of biochar for Hg^{2+} was 75.56 mg/g, and the adsorption contribution rates of IC and OC were 22.4% and 77.6%, respectively. IC adsorption was attributed to all the mechanisms with ion exchange being the main reaction mechanism. The main adsorption mechanism of OC was the complexation of carboxyl and hydroxyl groups with Hg^{2+}. BHC and BCC adsorbed mercury mainly via the reduction–adsorption mechanism.

V. BIOLOGICAL TREATMENTS

Degradation and transformation of greywater constituents are carried out by biochemical reactions occurring in the liquid medium by the microbial population in the biological treatment. The oxidation of organic compounds in greywater reduces BOD and nutrients (ammonia and phosphate). However, some constituents in greywater may only be partially degraded or not affected at all by biological processes because: (a) the compounds are non-biodegradable, (b) the absence of specific organisms required for the degradation process and (c) the presence of inhibitors in the medium. The existing biological treatment systems for greywater include: (a) constructed wetlands, (b) aerated lagoons, (c) rotating biological contractors, (d) sequencing batch bioreactor, (e) vertical flow bioreactor, (f) expanded bed up-floe reactor, (g) membrane bioreactor, (h)) trickling filters, (i) anaerobic up-flow biofilter, and (j) up-flow anaerobic sludge blanket,

5.1 Constructed Wetlands

Wetlands are considered a low-cost treatment for various wastewaters and have shown high removal rates of suspended solids, BOD, fecal coliform and pathogen. The wetland final effluent quality is safe for non-potable water reuses [158,1159]. The advantages of wetlands include: (a) they can provide removal rates in the range of 60-95% for many pollutants, (b) they are less costly to build and operate, (c) they provide important functions as habitat enhancement, and (d) they are a less intrusive and (e) they provide more environmentally sensitive approach to pollution abatement [160-163]. Some of the disadvantages of wetlands are: (a) they generally require larger land areas, (b) bioremediation and phytoremediation processes require longer time, (c) monitoring is difficult, and (d) the reliability is less consistent because of weather [164].

When designed properly, constructed wetlands are capable of effectively purifying greywater by the processes carried out by vegetation, soils, and their associated microbial assemblages [158,165]. The specific treatment mechanisms include gravitational settling of suspended matter, chemical transformations, bioremediation and phytoremediation [163,166]. There are two types of constructed wetlands: (a) free water surface (FWS) wetlands and (b) sub-surface flow (SSF) wetlands [167].

In FWS wetlands, the surface water flowing through is exposed to the atmosphere and the wetland consists of several cells with water surface being 0.15-2.00 m above the bottom. The near-surface water layer is aerobic while the deeper water is anaerobic [168]. FWS wetlands can be further sub- classified according to their dominant type of vegetation into emergent macrophyte wetlands, free-floating macrophyte wetlands, and submerged macrophyte wetlands. The emergent macrophyte based wetlands (Figure 16) has a considerable sediment layer above the impervious liner in which emergent macrophytes such as cattails (Typha spp.), rushes (Juncus spp.) and bulrushes (Scirpus spp.), are planted. Suspended solids, nutrients and pollutants are removed by gravitational settling and are then exposed to aerobic rhizome areas created by the macrophytes [163]. Free floating macrophyte based wetlands (Figure 17) use floating plants such as duckweed (Lemna spp.) and water hyacinth (Eichhornia crassipes) to remove nutrients and other pollutants in wastewater. A floating barrier grid is used to support the growth of floating macrophytes and to reduce wind effects. The densely packed floating plants may block out sunlight, thereby preventing photosynthesis and inhibiting algae growth [162,163]. In submerged macrophyte based wetlands (Figure 18), submerged macrophytes such as pondweed (Potamogeton spp.) remove nutrients and other pollutants from wastewaters [162,169].

The advantages of FWS wetlands include: (a) simple construction and lower operating costs, (b) no requirements for mechanical equipment, energy, and skilled operator, and (c) high removals of BOD, COD, TSS, and fecal coliforms. The main disadvantages of FWS wetlands are: (a) they require a larger land area, (b) the wastewaters are accessible to humans and animals, (c) pollutants such as phosphorus,

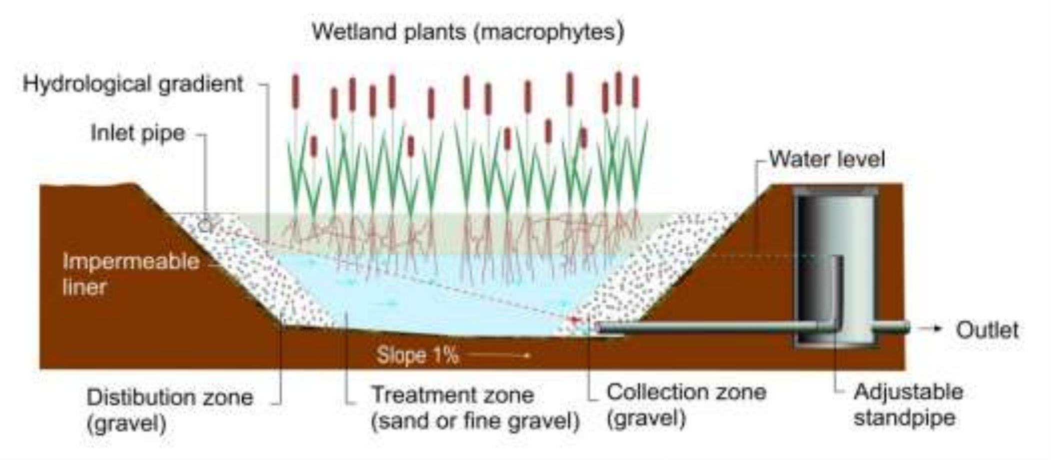


Figure 16. Surface water flow emergent macrophyte constructed wetland [162}.

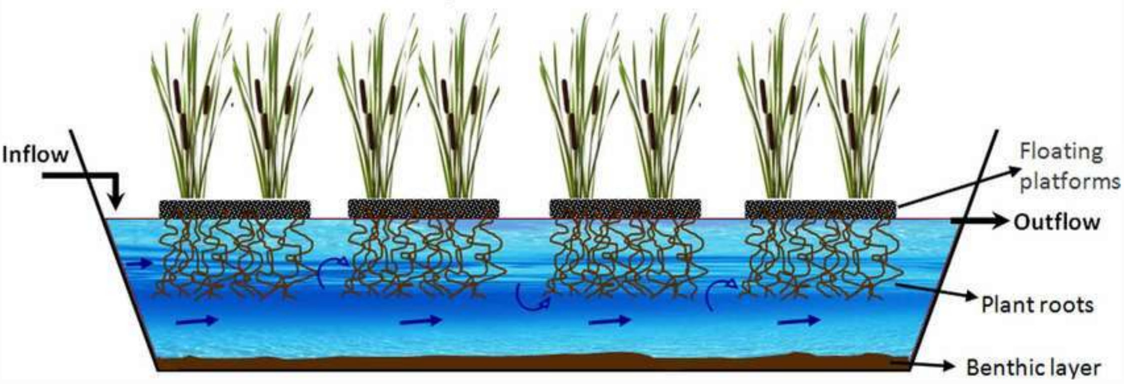


Figure 17. Free water surface floating macrophyte wetland [163].

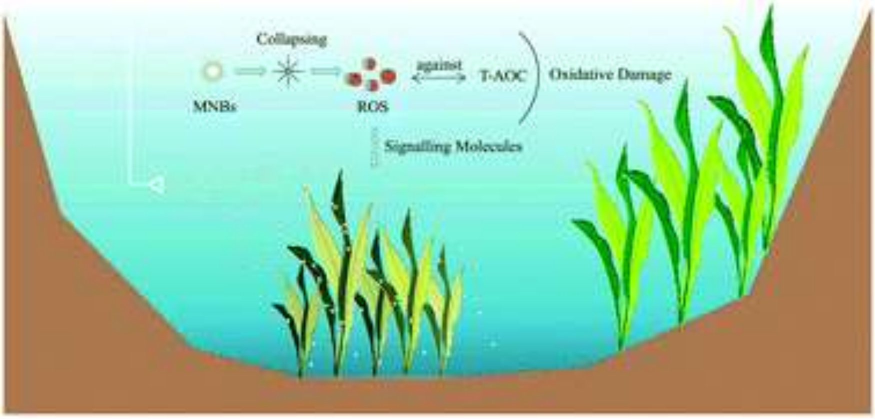


Figure 18. Free water surface submerged macrophyte wetland [169].

metals, and some persistent organics can become bound in wetland sediments and accumulate over time, (d) the open water environments can attract unwanted mosquitoes and (e) routine harvest vegetation is necessary [163,167,168].

A SSF wetland consists of a sealed basin with a porous substrate of rock, gravel or coarse sand with a depth of 0.3-0.9 m and planted with emergent macrophytes such as reeds (Phragmites spp.), Eurasian watermilfoil (Myriophyllum spicatum), and duckweeds (Lemna spp.). The water level remains below the substrate allowing the same mechanisms to remove contaminants. SSF wetlands are used to treat wastewaters from small-scale sources such as individual homes, schools, apartment complexes, commercial establishments, and recreational facilities [167]. There are two classes of SSF wetlands: (a) horizontal flow SSF wetlands (Figure 19) in which there is a continuous horizontal flow of wastewaters through the medium and oxygen is transferred into the system via atmospheric diffusion through the emergent aquatic plants and (b) vertical flow SSF wetlands (Figure 20) in which wastewater is added at timed intervals and drains between dosing and oxygen diffuses easily from the atmosphere into the drained, porous substrates [162].

The major advantages of SSF wetlands are: (a) the rocky substrates provide greater surface area for microbial reactions and therefore SSF wetlands can be smaller in size yet treat large flow volumes, (b) they are better suited where the available land area is limited, (c) they are more suitable to public areas as contaminated wastewaters are not exposed, and (d) the nature of their substrates and flow regimes allow for better thermal protection and, thus, are considered to be more effective in colder climates [170]. The disadvantages of SSF wetlands are (a): they are more expensive to construct, maintain and repair, (b) they have problems with clogging, (c) plants can reach their points of saturation in terms of pollutants absorption, rendering them no longer effective, thus requiring costly and time consuming harvesting, (d) they tend to be anoxic which limits the biological removal of ammonia nitrogen via nitrification, (e) phosphorus removal rates are inferior and (f) they can have problems associated with the accumulation of pollutants in sediments over time [162,163,171].

Vymazal [172] reported that the constructed wetlands are a reliable wastewater treatment technology for various types of wastewaters as they require very low energy input, low cost of operation and low maintenance compared to conventional treatment systems. Rodriguez-Dominguez et al. [173] reviewed 169 documents on wetlands from 20 countries and found that horizontal subsurface flow wetlands were the most reported constructed wetlands (62%), followed by free water surface constructed wetland (17%), vertical flow wetland (9%), intensified constructed wetlands (8%), and finally French wetlands (4%). About 114 plant species were used in these wetlands and the COD, total nitrogen, and total phosphorous removal efficiencies were in the ranges of 65-83%, 55-72%, and 30-84%, respectively. Scheumann et al. [174] reported on the treatment of graywater from a small camping site in a horizontal fellow wetland at a flow of 9.5 m³/d for recycling in toilet flushing. The treated greywater had TSS of 10 mg/L, COD of 100 mg/L, BOD of 20 mg/L, NH_4-N of 2 mg/L, TN of 15 mg/L, TP of 2 mg/L and E. coli of 50 cfu/100 mL The treated water quality complied with the Country Regional Environmental Protection Agency. Zidan et al. [175] reported on a horizontal subsurface flow constructed wetlands for

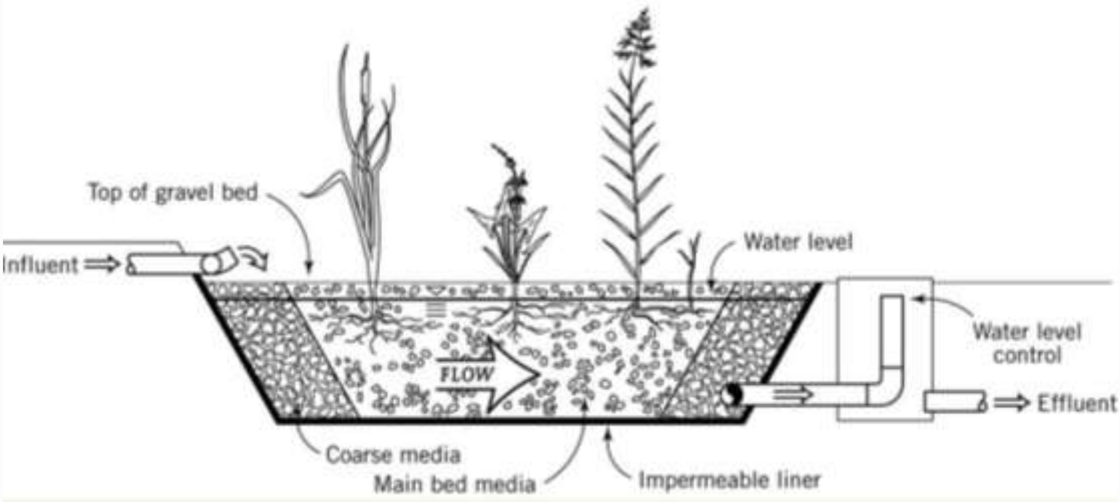


Figure 19. Horizontal subsurface flow constructed wetland [162].

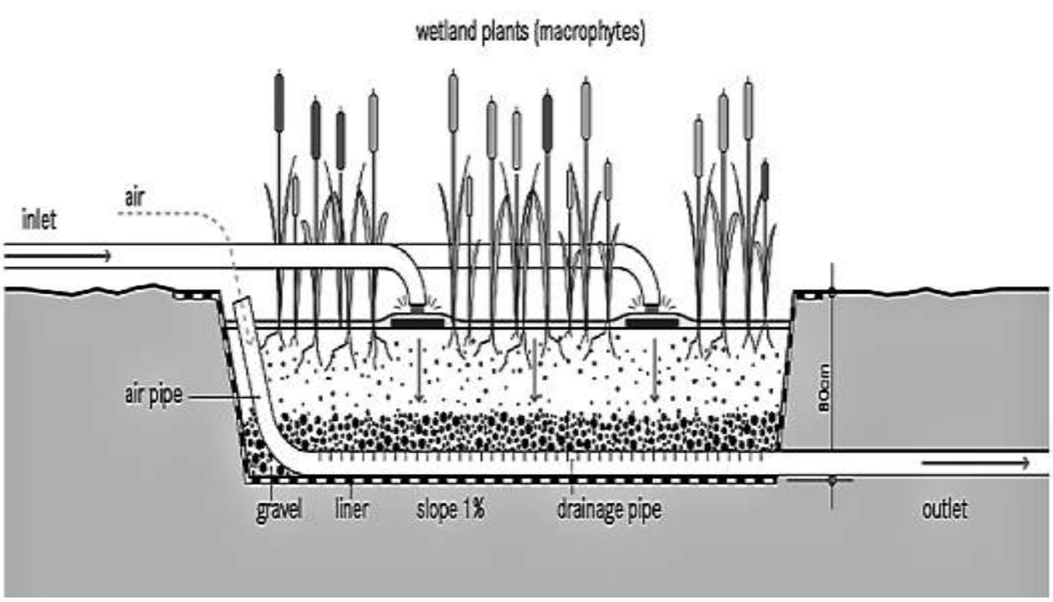
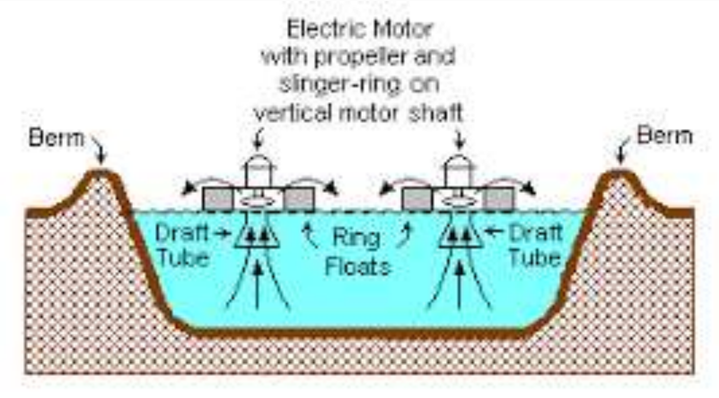


Figure 20. Vertical subsurface flow constructed wetland [162].

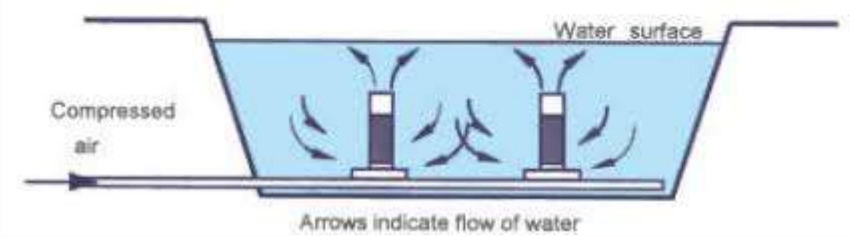
wastewater treatment having three different treatment media (gravel, pieces of plastic pipes, and shredded tire rubber chips). The pollutants reduction efficiency of plastic medium bed was better than gravel and rubber media and the gravel medium was better than the rubber medium. Reductions in TSS, BOD and COD were 39–61%, 20–49% and 19–49%, respectively.

5.2 Aerated Lagoons

The aerated lagoon system consists of a large earthen basin equipped with mechanical aerators to maintain an aerobic environment and to prevent settling of the suspend biomass. It has an inlet at one end and an outlet at the other end to enable the wastewater to flow through and to be retained for a specified detention time. The microbial population in aerated lagoons is much lower than that in the anaerobic sludge blanket because there is no sludge recycle and thus a longer residence time is required. Also, the biological oxidation processes are sensitive to temperature and the reaction rates increase with increases in temperature within the range of 4-32 °C [176]. Aerated lagoons can be aerated from the surface using floating aerators or from subsurface using submerged aerators as shown in Figure 21 [177]. In a surface-aerated system, the aerators provide two functions: (a) the transfer of the air into the liquid required by the biological oxidation reactions, and (b) the mixing required for dispersing the air and contacting the reactants (oxygen, wastewater, and microbes). Aerated lagoons using floating surface aerators may range in depth from 1.5 to 5.0 m and achieve 80-90% removal of BOD with retention times of 1-10 days [178,179]. The submerged aerator is essentially a form of a diffuser grid inside the lagoon and this system utilize medium bubble diffusers to provide aeration and mixing to the wastewater. The diffusers can be suspended slightly above the lagoon floor or rest on the bottom. A flexible airline supplies air to the diffuser unit [178-181].



(a) Surface aerated lagoon.



(b) Subsurface aerated lagoon

Figure 21. Aerated lagoon [177].

There are two types of aerated lagoons based on how the microbial solid in the system is handled: (a) suspended growth aerated lagoon and (b) facultative aerated lagoons. Suspended growth aerated lagoons are relatively shallow earthen basins varying in depth from 2 to 5 m and are provided with mechanical aerators to provide oxygen for the microorganisms, keep the biological solids in suspension and maintain fully aerobic conditions from top to bottom. No settlement occurs in such lagoons and under equilibrium conditions, the new microbial solids produced in the system equal to the microbial solids leaving the system. Because the aerated lagoon is a complete mix reactor without recycle, the SRT is equal to HRT and vary from 3 to 6 days. In facultative aerated lagoon, the aeration power is sufficient for oxygenation but not for keeping solids in suspension and as a result, some solids leave with the effluent while some settle down in the lagoon. Therefore, the lower part of facultative lagoons may be anaerobic while the upper layers are aerobic. Facultative aerated lagoons have been more commonly used because of their simplicity in operation and minimum need of machinery. They can provide 70–80% BOD removal from readily degradable wastes such as domestic and grey wastewaters [182-186].

Lagoons typically have 50-200 mg/L dry weight biomass compared to activated sludge systems which typically have 1000-5000 mg/L dry weight biomass and, thus, function 10-20 times slower than activated sludge systems. The microorganisms responsible for the biological treatment in lagoons are interrelated. Bacteria decompose the organic material and convert it into new bacterial cells and carbon dioxide. The carbon dioxide produced by this process (and atmospheric carbon dioxide) is used by algae to generate new alga cells and produce oxygen during the sunlight period. Herbivores graze on the algae and bacteria and carnivores graze on the herbivores. Most of the microorganisms in aerated systems convert food to energy in the presence of free dissolved oxygen. Anaerobes obtain oxygen from chemically bound oxygen compounds such as nitrate and sulfate. Facultative organisms use either free dissolved oxygen or chemically bound oxygen [181-182]. The advantages of aerated lagoons are**:** (a) they are simple and rugged in operation, the only moving piece of equipment is the aerator, (b) the removal efficiencies and the power input are comparable to the other aerobic treatment methods, and (c) construction mainly entails earthwork and land requirement is not excessive [176,182-184].

Rich [186] modified the procedure for the design of a dual-power multicellular aerated lagoon systems using a steady-state model for the hydrolysis of the fraction of influent biodegradable materials and a steady-state algal growth model. The results showed that the modifications improve performance with respect to effluent quality. Fonade et al. [187] developed a methodology to achieve the best fit between the biological reactions and the ideal hydrodynamic behaviour of a lagoon treating wastewater, based on the real kinetics of the degradation process This methodology led to a minimum volume and good behaviour of the lagoon that resulted in the degree of conversion required to meet the discharge regulations. Andiloro et al. [188] investigated the effects of the aeration rates, concentration of polyphenols (PP) and nitrogen shortage on depuration performance of aerated lagoon treating olive oil mill wastewater. Compared to the non-aerated lagoon, aeration increased the removal rates for COD from 61% to 90% and for PP from 52% to 64%. A shortage in nitrogen availability (COD: N higher than 400: 5) reduced COD removal by about 20% and PP removal by 25%. The pH was less influenced by the variations in aeration rates, PP concentration and COD:N ratio.

5.3 Rotating Biological Contactors

A rotating biological contactor (RBC) is a biological fixed-film secondary treatment process used to treat wastewater following primary treatment that involves removal of grit, sand and coarse suspended material through a screening process, followed by settling of suspended solids. The RBC allows the wastewater to be in contact with a biological film to remove pollutants from wastewater before discharge to water courses. It consists of a series of closely spaced, parallel discs mounted on a rotating shaft which is supported just above the surface of the wastewater (Figure 22). Microorganisms grow on the surface of the discs where biological degradation of pollutants takes place. The microbes are alternatively exposed to the atmosphere allowing both aeration and assimilation of dissolved organic pollutants and nutrients for degradation [189-194].

Pathan et al. [195] studied the performance of a single-stage laboratory scale RBC treating greywater. The RBC tank was made of plastic sheets and the disks were made from textured plastic. An electric motor equipped with gear box to control the rotations of the disks was mounted on the tank and the system was run at of 1.7 rpm. The disc area was immersed about 40% in the greywater. The removal of BOD_5 and COD were 53% and 60%, respectively. Friedler et al. [196] used an RBC system for the treatment of greywater to remove bacteria (faecal coliforms, heterotrophic bacteria) and specific pathogens (Pseudomonas aeruginosa sp., Staphylococcus aureus sp.) and reported removal of 88.5–99.9% of all four bacterial groups. Gilboa and Friedler [197 evaluated the effectiveness of RBC for removal of faecal coliforms, Staphylococcus aureus, Pseudomonas aeruginosa and Clostridium perfringens in greywater and reported reductions in the BOD_5, COD and microbial loads of up to 99% and the produced effluent meet discharge guidelines. Hassard et al. [198] used the RBC system to remove organic matter from wastewater with loading rates of up to 120 g/m^3 d and found the optimum loading rate to be around 15 g/m^3 d (combined BOD and ammonia). Full nitrification was achievable with oxidation rates of 6-14 g/m^3 d. Total phosphorus removal of 70% and reduction of 99% of faecal coliforms and most other pathogens were achieved. Tawfik et al. [199] evaluated the RBC treatment process of domestic wastewater at temperatures of 12–24°C using a two- stage system connected in series and operated at different organic loading rates (OLR) and hydraulic retention times (HRT). The overall removal efficiencies for COD_{total}, $COD_{suspended}$ and $COD_{colloidal}$ significantly decreased when decreasing the HRT from 10 to 2.5 h and increasing the OLR from 11 to 47 g COD/m^3d.. At HRTs of 10, 5 and 2.5 h, the Escherichia coli concentration was reduced by 1.6, 1.5 and 0.8 $\log_{10}$, respectively.

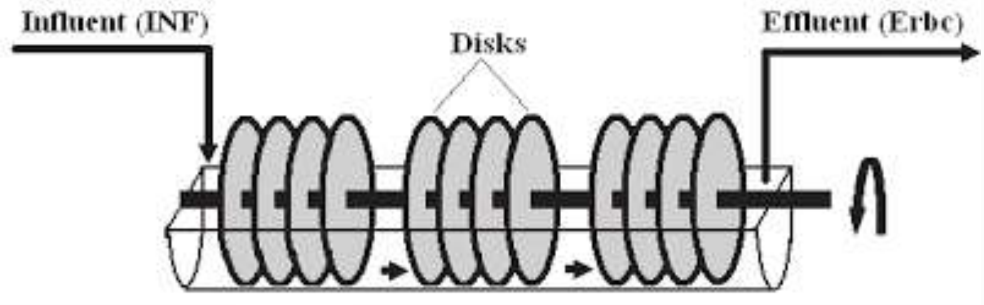


Figure 22. Rotating biological contactors [192].

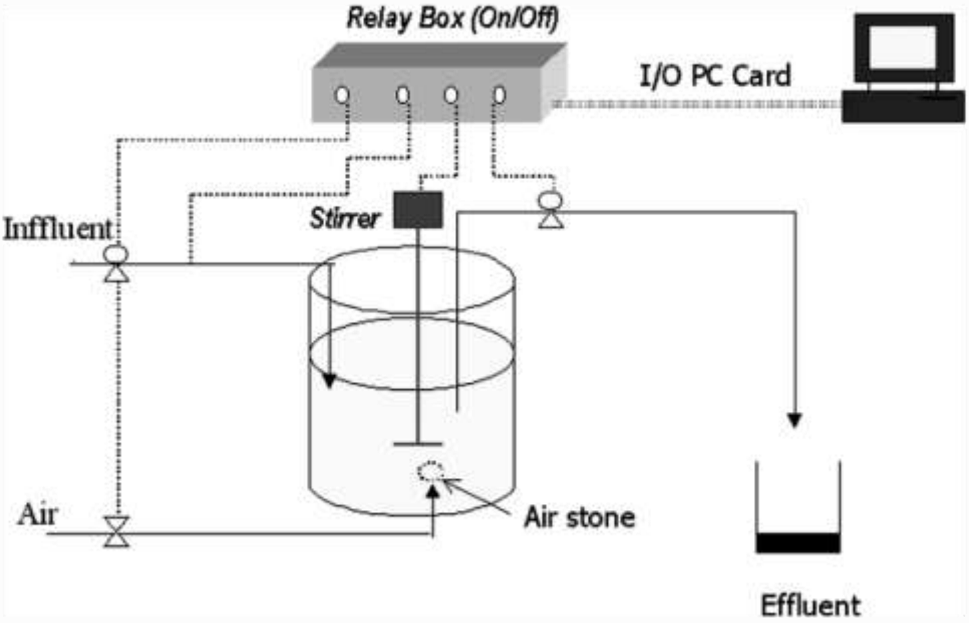


Figure 23. Sequencing batch bioreactors [200].

5.4 Sequencing Batch Bioreactor

Sequencing batch bioreactors (SBBRs) are used for treatment of greywater for small scale operation due to their compact treatment, low cost, simple operation, and the ability to offer great operational flexibility, effective nutrient removal, and easy-to-use interface [200]. The SBBR (Figure 23) is a cyclic “fill and draw” system that performs equalization, biological treatment, and secondary clarification in a single tank using a time control sequence [201]. The biological treatment is achieved by the microorganisms in the activated sludge. When wastewater is mixed with a suspension of microbes, they assimilate pollutants by degrading the biological portion whereas the nonbiodegradable materials settle and can be separated from the effluent [202]. There are three types of living media in SBBRs: (a) anaerobic, where organic matter is mineralized into biogas (methane and carbon dioxide) in the absence of oxygen, (b) anoxic, where nitrates are used as the oxidation reagents to produce free nitrogen and other compounds through denitrification and (c) aerobic, where dissolved oxygen is used for oxidation of the carbonaceous material and nitrification [203]. The performance of the SBBR is influenced by the amount and quality of inoculum, reaction time, retention time, rate of mixing and flow rate [200-203].

Lamine et al. [200] treated greywater from a student house using an SBBR system utilizing both anoxic and aerobic media and operating at various hydraulic retention times and reported BOD and COD removal rates greater than 90%. Jamrah et al. [204] used an SBBR system to treat greywater collected from various households and reported a fill and react time of 2-3 h and the COD removal over 90 %. Scheumann and Kraume [205] used a pilot scale SBBR to treat greywater at varying retention times. The COD was reduced from 250 to 18.9 mg/L, the NH4-N was reduced from 11.9 to 4.1 mg/L and the TN was reduced from 17.1 to 0.37 mg/L, all being below the mandatory values for discharge reuse guidelines. Krishnan et al. [206] used an aerobic SBBR at a hydraulic retention time of 36 h to treat nutrient-deficit greywater (COD: N: P ratio of 100:2.5:0.5) and nutrient-spiked dark greywater (COD: N: P ratio of 100:5:1) for agricultural reuse. The preferred ratio for biological oxidation is 100:5:1. The aerobic oxidation of nutrient-deficit and nutrient-spiked dark greywater resulted in outlet COD values of 12 and 64 mg/ L, with a corresponding BOD value of 8 and 37 mg/ L, respectively. Hernandez Leal et al. [207] compared an aerobic SBBR with an up-flow anaerobic sludge blanket reactor and a combined up-flow anaerobic sludge blanket reactor + sequencing batch reactor in treating greywater at hydraulic retention times of 12–13 hours. The aerobic conditions of SBR resulted in a COD removal of 90%, which was significantly higher than the 51% removal by anaerobic treatment.

5.5 Vertical Flow Bioreactor

Vertical flow bioreactors (VFBRs) use similar concepts to horizontal flow constructed wetlands as the wastewater enters through an inlet and is subjected to treatment in the system. A typical system uses two basins stacked vertically (Figure 24), one acts as the working mechanism while the other operates as a retention basin. The first container is comprised of various layers of organic soils, plastic media, and limestone pebbles. Water passes through these various layers and the contaminants are filtered out. Holes are evenly spaced along the bottom of the container and allow water to drain into a drainage basin and then sent to the distribution system. The VFBR systems vary in size depending on the flow rate [208-211].

Gross et al. [208] reported on a VFBR system treating greywater from several households. The system comprised of a three-layer bed: (a) the first layer consisting of 15 cm planted organic soil, (b) the second layer consisting of 30 cm of plastic media and (c) the third layer consisting of 5 cm of limestone pebbles. The greywater entered through the root structure of the system and then passed through the medium of evenly spaced holes to the reservoir below. The wastewater was recycled from the reservoir to the VFBR for retreatment. The system produced high removal rates of COD, TSS, surfactants, total-P and nitrite-N of 86, 93, 98, 73 and 97 % mg/L, respectively. Kanawade [209] used a VFBR for the removal of contaminants from synthetic greywater, enriched with wastes from a dining hall. The greywater was recirculated for 3 days, after which time half of the greywater was removed from the system and replaced with fresh greywater. The VFBR system reduced the effluent concentrations of NO_3-N, NH_4-N, NO_2-N, TSS, boron, and anionic surfactants to below the levels considered acceptable for either recreation or irrigation. Al-Zubi et al. [210] treated ablution greywater in a VFBR

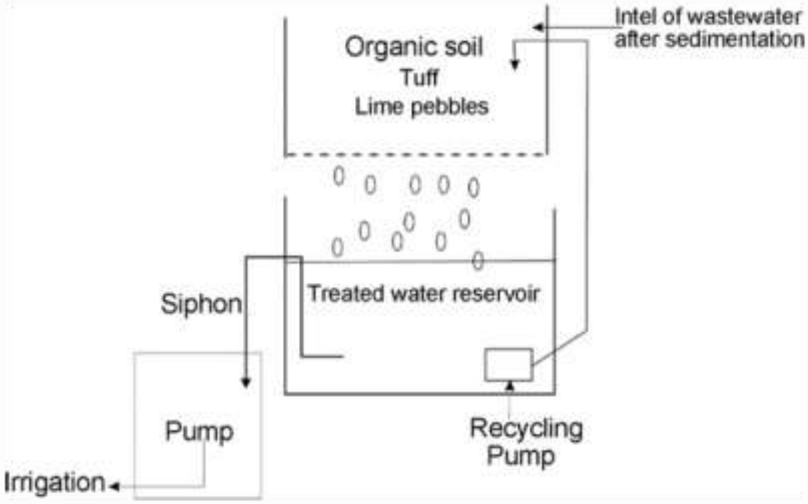


Figure 24. Vertical flow bioreactors [208].

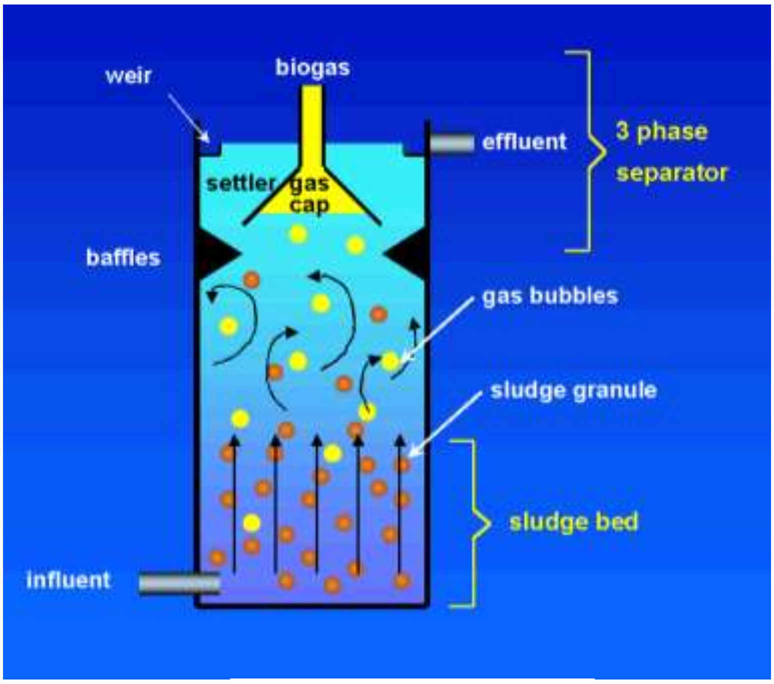


Figure 25. Expanded bed up-flow bioreactor [214].

for use in landscape irrigation. The treatment system adequately removed 94, 88, 90, 48, and 33% of the BOD_5, COD, TSS, chloride, and Na, respectively. The treated greywater was suitable for irrigation of ornamentals, fruit trees, and fodder crops. Ammari et al. [211] evaluated a VFBR for greywater treatment and reported BOD_5, COD, PO_4, TSS, NO_3, Cl, and SO_4 removal efficiencies of 97%, 94%, 100%, 90%, 45%, and 55%, respectively. Total coliform and Escherichia coli were reduced by 2.5 and 2.3 log, respectively. The treated greywater was suitable for irrigation of ornamentals, fruit trees and fodder crops.

5.6. Expanded Bed Up-flow Bioreactor

The expanded bed up-flow bioreactor (EBUBR) is a variant of the up-flow anaerobic sludge blanket digestion concept for anaerobic wastewater treatment. The distinguishing feature is that a faster rate of upward-flow velocity is designed for the wastewater passing through the sludge bed. The increased flux permits partial expansion (fluidization) of the granular sludge bed, improving wastewater-sludge contact and enhancing segregation of small inactive suspended particle from the sludge bed. The EBUBR (Figure 25) relies on the development of biomass on the surfaces of a media. The primary concept of the process consists of passing wastewater up through a bed of inert sand sized particles at sufficient velocities to fluidize and partially expand the bed. The system design is appropriate for low strength soluble wastewaters (less than 1-2 g soluble COD/L) or for wastewaters that contain poorly biodegradable suspended particles which should not be allowed to accumulate in the sludge bed [212-214].

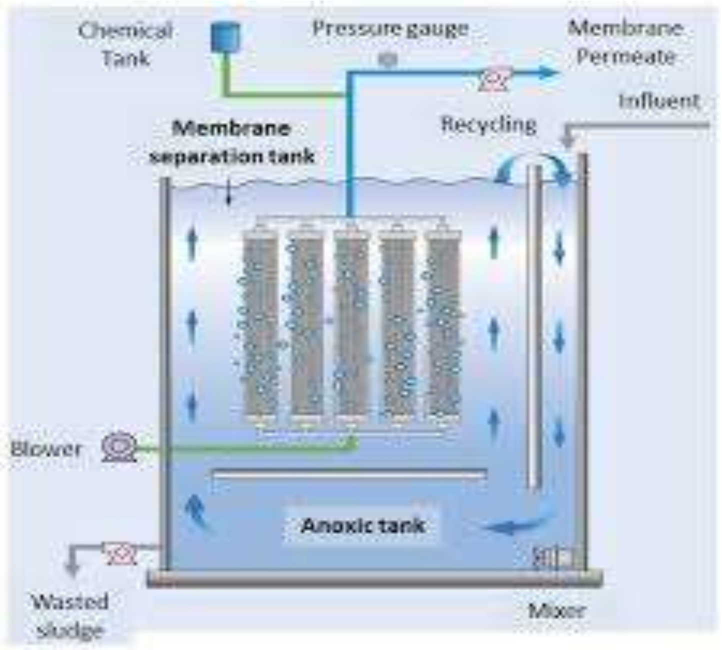
Moharram et al. [215] studied the performance of an anaerobic up flow fluidized bed reactor as a primary treatment unit in domestic wastewater treatment at different temperatures (14–25 °C), organic loading rates (OLR) and HRT (6, 4, 2.5 h). The best methane yield rate (0.285 l/g COD total) and COD removal rate (70.82%) were achieved at a temperature of 19 °C, OLR of 7.76 kg COD/m^3/day and HRT of 6 h. Switzenbaum and Jewell [216] found the anaerobic attached film expanded bed reactor to be effective for the treatment of low strength soluble organic wastes at reduced temperatures, short retention times, and high organic loading rates. The system permitted the maintenance of high solids retention times with low hydraulic retention times. Yoochatchaval et al. [217]

operated a laboratory scale expanded granular sludge bed reactor at 20°C with low strength wastewater (0.6-0.8 g/L COD). The reactor was inoculated with mesophilic granular sludge and the up-flow velocity was 5 m/h. The COD loading was increased up to 12 kg COD/m^3/d until the day 76, resulting in hydraulic retention time of 1.5 h. The growth yield (Y_g) of retained sludge (0.13 g VSS/g COD) was about two times higher than mesophilic and thermophilic granular sludge processes while the endogenous decay constant (K_d) was very low (0.0001/day). Jaafari et al. [218] studied the effect of up-flow velocity on performance and biofilm characteristics of an anaerobic fluidized bed reactor treating wastewater at various loading rates. At organic loading rates of 9.4-24.2 kg COD/m^3 at steady state, the reactor performances (COD reductio) with up-flow velocities of 0.5, 0.75 and 1 m/min were 63.4-89.3, 79.6-96.9 and 73.4-95 %, respectively. The total biomass in the reactor increased with increases in the organic loading rate. The biofilm thickness increased from the bottom to the top of the reactor representing a stratification of the media while the bed porosity increased from the bottom to the top of the reactor.

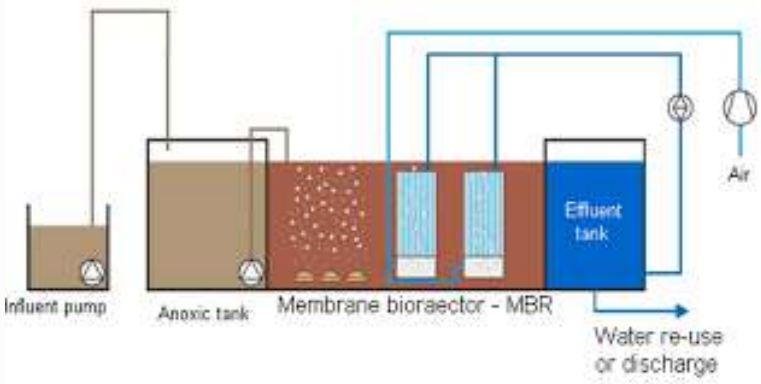
3.7 Membrane Bioreactor

A membrane bioreactor (MBR) is a combination of biological, microfiltration and ultrafiltration systems. It is an appropriate solution for greywater treatment in densely urbanized areas where space has high value due to its compact size. The MBR can be operated under aerobic or anaerobic conditions as shown in Figure 26 [219].

Atanasova et al. [220] treated hotel greywater using MBR and reported COD, ammonium, and TN removal efficiencies of 80-95%, 80.5 and 85.1%, respectively. The effluent quality complied with the legislation quantification limit for wastewater reuse. Chae et al. [221] investigated the characteristics of membrane fouling in a laboratory scale anoxic/oxic (A/O) MBR treating synthetic wastewater. The high concentrations of extracellular polymeric substances, high viscosity, high sludge volume index and low hydraulic retention time corresponded to high membrane resistance, indicating severe membrane fouling in the MBR. Merz et al. [222] evaluated the performance A 3L-laborastory scale MBR treating shower greywater from a sports club and reported a permeate of excellent aesthetic quality and free from odour. Huelgas and Funamizu



(a) Anaerobic membrane bioreactor [221].



(b) Aerobic membrane bioreactor [219].

Figure 26. Membrane bioreactors.

[223] treated a mixture of washing machine and kitchen sink greywater using a laboratory scale MBR under varying pressure at a constant flux of 0.22 m^3/m^2 d and an HRT of 13.6 h and reported COD and alkylbenzene sulfonate removals of 96% and 99%, respectively. Jong et al. [224] used a laboratory scale anaerobic-anoxic-oxic MBR to treat greywater and produced a very good effluent that meets regulatory standards for reuse. However, pathogenic microorganisms Escherichia coli, Coliform, Staphylococcus aureus and Salmonella were detected in the effluent.

5.8 Trickling Biofilters

A trickling biofilter (TBF) is a wastewater treatment system consisting of a fixed bed of rocks, coke, gravel, slag, foam, sphagnum peat moss, ceramic, or plastic media over which wastewater flows downward and causes a layer of microbial slime (biofilm) to grow and cover the bed media. Aerobic conditions are maintained by splashing, diffusion, and either by forced air flowing through the bed or natural convection of air if the filter medium is porous. Wastewater enters at a high level and flows through the primary settlement tank and the supernatant from the tank flows into a dosing device, often a tipping bucket which delivers flow to the arms of the filter. The flush of water flows through the arms and exits through a series of holes pointing at an angle downwards. The liquid is distributed evenly over the surface of the filter media as shown in Figure 27. The removal of pollutants from the wastewater stream involves absorption and adsorption of organic and inorganic (nitrate and nitrite) compounds by the microbial biofilm. Passage of the wastewater over the media provides the dissolved oxygen required for the biochemical degradation of the organic compounds and the release of carbon dioxide gas, water, and other end products. As the biofilm layer thickens, it eventually sloughs off into the liquid flow and subsequently forms part of the secondary sludge that can be removed by a clarifier or sedimentation. The biofilm contains many species of bacteria, ciliates, protozoa, annelids, roundworms, and insect larvae. Within the thickness of the biofilm, both aerobic and anaerobic zones can exist supporting both oxidative and reductive biological processes [225].

The major components of trickling biofilter are: (a) rotary distributors with speed

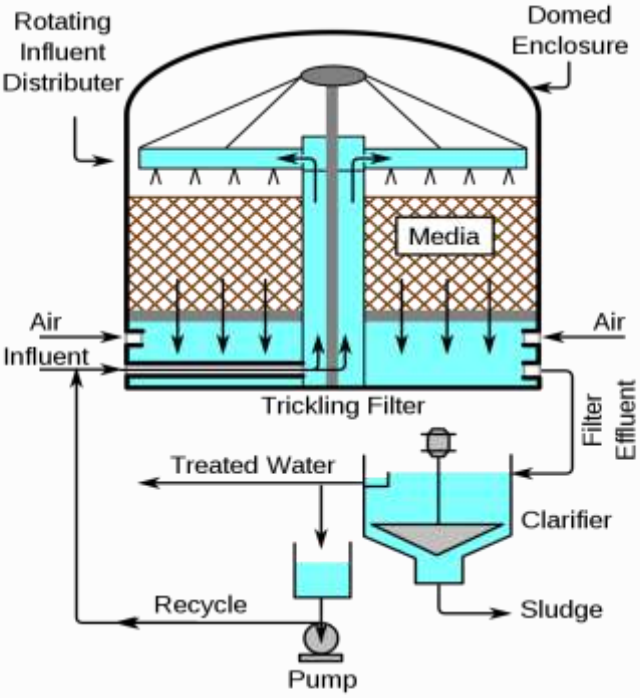


Figure 27. A trickling biofilter [212].

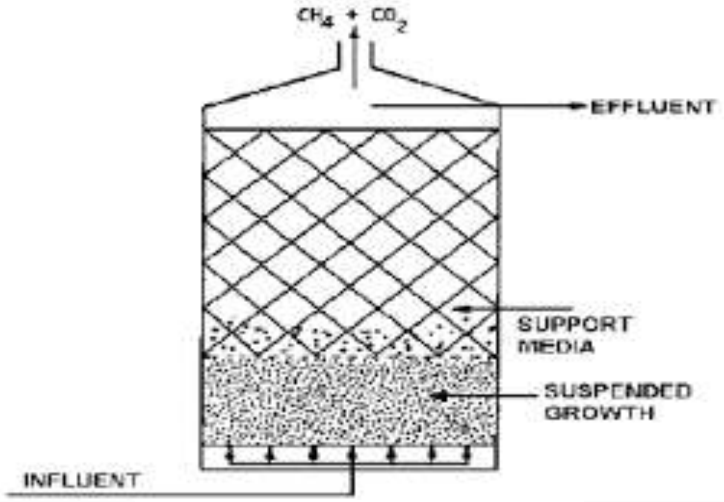


Figure 28. Anaerobic up-flow filter [234].

control, (b) modular plastic media (c) a mechanical aeration system that consists of air distribution piping and low-pressure fans, (d) recirculation pump and (e) covers that aid in the uniform distribution of air and foul air containment and may be equipped with sprinklers that can spray water to cool the media during emergency shut down periods [226].

Vianna et al. [227] treated domestic sewage in laboratory trickling biofilters in which peeled dehydrated fruits of Luffa cyllindrica were used as a support medium for microbiological growth. The capacity of the system to remove $BOD_{5,20}$ and COD as well as suspended and settleable solids compared to similar system using stones as supporting medium, showed that peeled dehydrated fruits of Luffa cyllindrica support medium can be used as a substitute to the traditional stones support media. Naz et al [228] assessed selected packing media (rubber, polystyrene, plastic and stone) for trickling biofilters (BTFs) at two temperature ranges (5–15°C and 25–35°C). The average removals of COD and BOD were higher than 80 and 90% at the temperature ranges of 5–15 and 25–35°C, respectively. The geometric mean of faecal coliforms at the low temperature range of 5–15°C was reduced by 4.3, 4.0, 5.8 and 5.4 $\log_{10}$ when using polystyrene, plastic, rubber and stone filter media, respectively. At the higher temperature range of 25–35°C, the faecal coliform count was reduced by 3.97, 5.34, 5.36 and 4.37 $\log_{10}$ by the polystyrene, plastic, rubber and stone media, respectively. Zylka et al [229] used a trickling biofilter for the treatment of dairy wastewater and reported removal efficiencies of 87.3%, 78.3% without circulation and 27.9% and 95.2%, 85.5% and 42.0% with 100% recirculation for BOD, COD, total phosphorus, respectively. Dhokpande et al. 230] reviewed research on application of trickling biofilters for removal of various pollutants from several wastewaters and concluded that the trickling biofilter processes are very efficient in handling many types of polluted waters with COD removal up to 90 %, nitrogen removal up to 99 % and heavy metals (copper, lead and nickel) removal around 90 %.

5.9 Anaerobic Up-flow Biofilters

The anaerobic up-flow biofilter (AUBF) has a bed of media on which microorganisms attach and grow to form a biological layer called biofilm. The biofilm is formed by a community of different microorganisms (bacteria, fungi and protozoa) and extracellular polymeric substances. The wastewater to be treated can be applied intermittently or continuously over the media [231]. The anaerobic up-flow biofilter (Figure 28) represents a significant advance in anaerobic waste treatment since the filter can trap and maintain a high concentration of biological solids which allows for long SRT's at large wastewater flows necessary to anaerobically treat low strength wastes at low temperatures economically. This system has been successfully used for the treatment of different types of wastewaters including domestic wastewater, aquaculture wastewater, greywater and carwash wastewater [232-234].

The main factors influencing the efficiency of trickling biofilter are the wastewater composition, the biofilter hydraulic loading, the type of media, the feeding strategy (percolation or submerged media), the age of the biofilm and temperature. Biological filters internal hydrodynamics and the microbial biology and ecology confer robustness to the process and give it the capacity to maintain its performance or rapidly return to initial levels following periods of no flow, intense use, toxic shocks or media backwash [235]. The structure of the biofilm protects microorganisms from difficult environmental conditions and retains the biomass inside the process, even when conditions are not optimal for their growth. Other advantages include: the development of microorganisms with relatively low specific growth rates because microorganisms are retained within the biofilm, the biofilters are less subject to variable or intermittent loading and hydraulic shock, operational costs are low, final treatment results are less influenced by biomass separation since the biomass concentration in the effluent is much lower than that in suspended biomass and attached biomass are specialized. However, because filtration and growth of biomass leads to an accumulation of matter in the filtering media, this process is subject to bio-clogging and flow channeling. But, bio-clogging can be controlled using backwash by air and/or water to disrupt the bio-mat and recover flow or using oxidizing chemicals (Peroxide and ozone) or biocide agents [236].

Young and Yang [237] stated that anaerobic biofilters represent a treatment technology suitable for treatment of wastewaters containing soluble biodegradable organic materials and the most critical design factors affecting performance are hydraulic retention time, media type, and flow direction. However, the treatment performance is not affected by

influent wastewater having COD values above about 3,000 mg/L and the reactor height has no significant effect on performance. Kavittha [238] reported that anaerobic biofilters have been successfully used world-wide for treating high-strength industrial and domestic wastewaters and the system efficiency has been improved. Pak and Chang [239] tested a two-biofilter system operated under alternating anaerobic/aerobic conditions to remove nutrient and organics from low organic wastewater generated from car washing facility and found the factors affecting phosphorus removal to be influent COD, nitrogen and the COD/TP, BOD/COD and SS/TP ratios.

3.10 Up-flow Anaerobic Sludge Blanket

The up-flow anaerobic sludge blanket (UASB) is widely used for the treatment of various types of wastewaters. The UASB (Figure 29) retains a high concentration of active suspended biomass, has superior flocculation and settling characteristics of solids which allows for a high solid retention time (SRT) at high HRT and produces better settleable sludge than other treatment systems [240]. The UASB degradation process is a combination of physical (separation of solids and gases from the liquid) and biological (degradation of decomposable organic matter under anaerobic conditions) processes. No separate settler with sludge-return pump is required as is the case in activated sludge bioreactor, and no loss of reactor volume through filter or carrier material as the case with the anaerobic filter and fixed film reactor types. Also, there is no need for high-rate effluent recirculation and concomitant pumping energy as in the case with fluidized bed reactor. Mechanical mixing is omitted in the system because of the good settling properties of anaerobic sludge and the biogas production guarantees sufficient contact between substrate and biomass and as a result the UASB reactor approaches the completely mixed reactor [241].

Hemandez et al. [242] treated greywater from 32 houses using UASB system and compared it to an aerobic sequencing batch reactor (ASBR) at a hydraulic retention time of 12–13 h. The ASBR resulted in a COD removal of 90%, which was significantly higher than 51% removal by the UASB. Elmitwalli et al. [243] used a UASB system for the treatment of greywater at varying retention times (8, 12 and 20 h) and ambient temperatures (14-24 ^{o}C). COD, total nitrogen and total phosphorus removals of 31-41%, 24-36% and 10-24% were achieved. Abdel-Shafy et al. [244] evaluated the efficiency of a UASB treating greywater with average concentrations of 95, 392, 298, 10.45, 0.4, 118.5 and 28 mg/L for TSS, COD, BOD_5, TP, nitrates, oil and grease and TKN, respectively. Removal efficiencies of 19.3% for TSS, 57.8% for COD, 67.5% for BOD_5 and 83% for oil and grease were achieved. The characteristics of the treated effluent complied with the guidelines for unrestricted water reuse. Isik and Sponza [245] treated a simulated wastewater containing sizing agents, azo dyes, salts and other additives using a lab-scale UASB at different hydraulic retention times and noticed the COD removal efficiency was decreased from 80 to 29.5% when the HRT was decreased from 100 to 6 h. Bressani, et al. [246] stated that since the high-rate anaerobic treatment of sewage using UASB

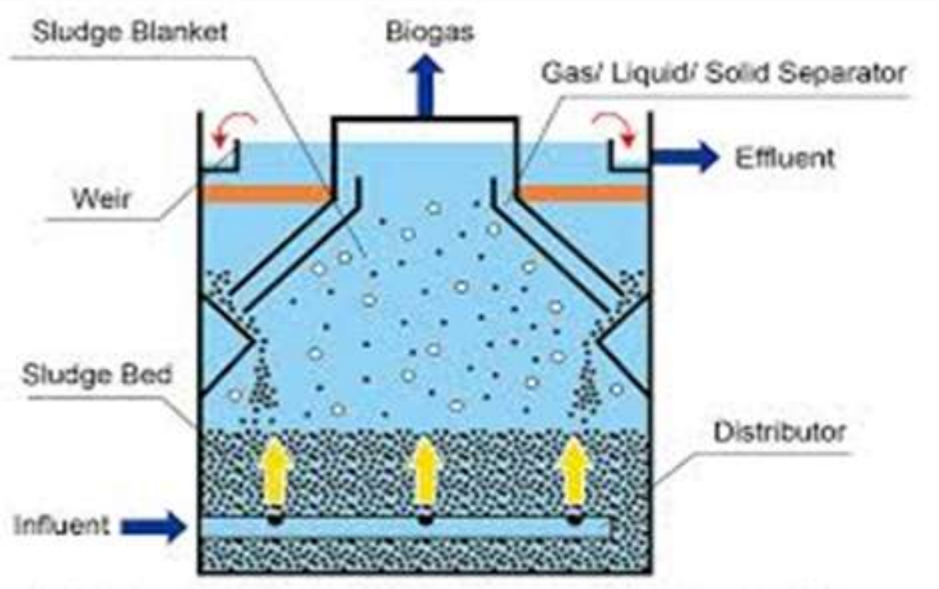


Figure 29. An up-flow anaerobic sludge blanket [240].

reactor only removes organic carbon, a cost-effective post-treatment such as trickling filters (TF) is required to remove nitrogen.

VI. COMPARITIVE ANALYSIS

A comprehensive review and indepth discussion of the various greywater treatment methods have been reported in the previous sections. The advantages and disadvantages of each treatment method are summarized in Tables 1-20 and were used as a guide to select the most important set of criteria for the comparative analysis. These criteria were developed with the objective of selecting the most applicable and economically and environmentally feasible treatment system (or systems) that meet the operating requirement of obtaining clean water for recycling. Each treatment method was evaluated with the standard set of criteria and the results tabulated to determine the optimum treatment method for use.

6.1 Selection of Criteria

Eight criteria were selected for evaluation: cost, maintenance and control, efficiency, suitability, value added product, environmental and health impact and size and land requirement. Each criterion was assigned a score based on its relative important as sown in Table 21. The following are the descriptions of these criteria.

Table 1. Advantage and disadvantages of granular ofilters.

Advantages	Disadvantages
Effective (reductions of 100% in COD, 100% in turbidity, and 80% in total nitrogen) Easy to set up from locally avilable cheap materials (sand, gravels, pebbles, diatomaceous earth, coal, charcoal, cotton and ceramics) Economical Good residence time (8-12 h) Removes sand, clay, organic particles and iron and aluminum flocs With pre-treatment can remove more than 99% of pathogenic bacteria, protozoa and fungi Has no environmental hazard	Must be combined with other technologies (sedimentation, coagulation, ultrafiltration and revers osmosis) Low reduction of virus bacteria and protozoa without pre-treatment Has health hazard and require disinfection process Efficiency depends on concentration of SS and type of filter materials Does not remove DS (organic or inorganic)

Table 2. Advantage and disadvantages of microfiltration.

Advantages	Disadvantages
Effective (reductions of 82-99% in COD, 96% in SS, 99% in organic carbon, 99% in inorganic carbon, , 92-100% in oil and grease, 88-100% in turbidity, and 50% in amonium) Easy to set up Good residence time (1-6 h) Trouble fee operation Removes suspended solids, bacteria and algae Does not require external addition of chemicals which reduces fouling Provide 80% water recovery Economically attractive and compact Has no environmental and health hazard	Does not remove virus High operating cost Does not remove DS Require a disinfection step (UV treatment) Must be combined with other technologies such as settling and biological remediation (biological reactor) Efficiency depends on concentration of pollutants, type of membrane, pressure, feed flow rate and temperature

Table 3. Advantage and disadvantages of ultrafiltration.

Advantages	Disadvantages
Effective (reductions of 97% in COD, 92% in turbidity, 95% in TOC and 35% in salinity) Removes all organic molecules, salt, all viruses, cysts, bacteria Removes DS Provide high rejection of multivalent ions (Ca $^{++}$) and low rejection of monovalent ions (Cl$^-$) Easy to set up Energy efficient process Rejects various salts in proportion to their molecular sizes (Na_2SO_4 > $CaCl_2$ > NaCl) Has no environmental and health hazard	High presure High operating cost Fouling is a major problem Removes alkalinity and adding alkalinity is needed to reduce corrosivity Must be combined with other technologies such as biological remediation Efficiency depends on concentration of organic compounds, membrane adsorption, membrane surface charge, membrane hydrophobicity, concentration of pollutants, polarity of the components in the solution, size of molecules, physical-chemical properties of molecules

Table 4. Advantage and disadvantages of nanofiltration.

Advantages	Disadvantages
Effective (reductions of 99% in COD, 100% in SS, 98 in oil and grease, 100% in turbidity, 98% in total organic carbon and 42% in amonuim) Easy to set up Short residence time (20-120 min) Simple automation Removes large particles, divalent ions, bacteria, algae and protozoa Provides high rejection of multivalent ions (Ca $^{++}$) and low rejection of monovalent ions (Cl$^-$) Does not require external addition of chemicals for pH adjustment No need for disinfection step Has no environmental and health hazard	High presure Does not remove DS High operating cost Fouling is a major problem Must be combined with other technologies such as coagulation adsorption, biological remediation or ozonation Efficiency depends on concentration of pollutants and membrane properties

Table 5. Advantage and disadvantages of reverse osmosis.

Advantages	Disadvantages
Effective (reductions of 96% in COD, 100% in SS, 83-93% in DS, 90% in oil and grease, 100% in turbidity) Easy to set up and operate without break-in-periods Easy to control Short residence time (30-12- min) Removes all organic molecules, cysts, bacteria, algae, protozoa and virus Removes all DS (Na, Cl, Ca and Mg)	High pressure Energy intensive High capital and operating costs High level of pre-treatment is required Managing/disposal brine solution is a major problem Membrane fouling Require pre-heating treatment to reduce fouling (1-2% loss for every degree below 25 ^{o} C) Efficiency depends on membrane properties, concentration of pollutants, feed rate and temperature

Removes all dissolved non-ions Reduce salt and hardness Produces high quality water that meets the most demanding specifications Insensitive to floe and TDS levels Suitable for small operation with high degree of fluctuation in water demand Does not require external addition of chemicals Required reactive species are generated at the anode surface Pollutants are converted to CO_2 and H_2O Has no environmental and health hazard	

Table 6. Advantage and disadvantages of chemical coagulation-flocculation.

Advantages	Disadvantages
Effective (Reductions of 88-99% in COD, 74-100% in turbidity, 77-100% in surfactans and 65-100% in phosphorus) Produces water with low trbidity Removes pathogens, virus, phosphorous and flouride Easy to handlee and control High stability and flexibility Short residence time (30-60 minutes) Coagulants are available in solution, powder, beads, oil and water-based emulsion Availability of natural polymers Natural polymers are free of toxins Natural polymers are easy to control Natural polymers are biodegradable Al-Fe blends function over wide range of pH and temperature Al-Fe blends produce fewer netalic residues	Use of expensive chrmical Must be combined with other technologies (sedimentation, filtration, chlorination, ozonation or biological conversion) Produce non biodegradable sludge Synthetic polymers produce toxic compounds Efficiency depends on type of coagulant, coagulant feed concentration, dosage of chemical additives, sequence of chemical addition, pH, temperature, duration of mixing, stirring device and flocculator geometry

Table 7. Advantage and disadvantages of electrocoagulation.

Advantages	Disadvantages
Effective (reductions of 88-99% in COD, 68-98% in oil and grease, 50% in chlorine, 96-100% in turbidity30% in TDS and 20% in EC) Effluenthas low TDS content copared to chemical coagualtion Low capital and operating costs Removes oil and grease, heavy metals, suspended solids and emulsified organics Produces clean, colorless amd odorless water	Uses electricity Increases pH Must be combined with other technologies (filtration, chlorination, ozonation or biological conversion) Efficiency depends on pH, retention time, type of electrode and device geometry There is no standardized testing procedure for the design

Short residence time (30-90 minutes) Produces settlable sludge easy to dewater Gas bubbles cary pollutants to the surface where they can be easily concentratedand collected by skimmer Flocs tend to be larger and contain less water, stable and can be separated faster by filtration Easy operation of equipment (no daily maintenance) Easy to automate and control Flocculation, flotation and separation are performed in a single reactor (no polymer and additives addition and no settling andflotation tanks) Use electricity instead of expensive chemicals Addreses any size of SS Has no impact on Na and K ions in solution Has no environmental and health hazard Electrodes are easier to remove, and store compared to corrosive chemicals	

Table 8. Advantage and disadvantages of electrooxidation.

Advantages	Disadvantages
Effective (reductions of 82-98% in COD, 87-93% in BOD, 92-100% in oil and grease, 84-92% insurfactants, 80-96% in color, 98-100% in turbidity, and 80% in total nitrogen) Easy to set up Short residence time (25-90 minutes) Treats non-biodegradable contaminants Can treat harmful recalcitrant organic pollutants which are difficult to degrade by other methods Does not require external addition of chemicals Required reactive species are generated at the anode surface Pollutants are converted to CO_2 and H_2O Has no environmental and health hazard	Uses electricity High operating cost Must be combined with other technologies such as biological remediation Produces hydroxide radicals Produces new complex molecules in water causing deterioration of color and decreased efficiency Efficiency depends on concentration of pollutants, type of anodes, pH, time, current density, stirring rate

Table 9. Advantage and disadvantages of photooxidation.

Advantages	Disadvantages
Effective (reductions of 82-98% in COD, 87-93% in BOD, 92-100% in oil and grease, 84-92% insurfactants, 80-96% in color, 98-100% in turbidity, and 80% in total nitrogen) Easy to set up Short residence time (25-90 minutes) Treats non-biodegradable organic and inorganic compounds Can treat harmful recalcitrant organic pollutants which are difficult to degrade by other methods Does not require external addition of chemicals Does not require pre or post treatment Pollutants are converted to CO_2 and H_2O Environmental and economically sustainable Removes cyanide, Zn, nitrogenous compounds, antibiotics, microorganisms, hormones, organochlorides,	Efficiency depends on concentration of pollutants High capital and operating costs Complex chemistry for specific contaminants Need to remove hydrogen peroxide residual

Table 10 Advantage and disadvantages of adsorption.

Advantages	Disadvantages
Effective (reductions of 96% in COD, 100% in SS, 83-93% in DS, 90% in oil and grease, 100% in turbidity) Easy to set up, operate and control Economical (Low cost) God residence time (3h) Easy to make from locally available materials (bentonite, activated carbon, some plant pats, cellulosic matrials) High removal efficiency Removes all organic substances, TDS and oil and grease Does not require external addition of chemicals or expensive equipment Has no environmental and health hazard	Efficiency depends on concentration of pollutants, type of adsorbent, adsorbent particle diameter, HRT, temperature, pH, mixing and adsorbent surface charge

Table 11. Advantage and disadvantages of constracted wetlands.

Advantages	Disadvantages
Effective (reductions of 96% in COD, 100% in SS, 80-90% in DS, 100% in oil and grease, 85-100% in surfactants) Low operation cost Easy to operate and maintain Removes all organic molecules, heavy metals, surfactants, oil and grease and nutrients (N, P) Does not require external addition of chemicals	High capital cost (Initial construction and planting are costly) Long residence time (5-10 d) Require disinfection step Efficiency depends on concentration and type of pollutants, flow rate, temperature, pH, HRT and plant type Disposal of plants containing heavy metals is a problem Not suitable for cold climate regions (sub zero conditions)

Physical, chemical and biological processes (sedimentation, adsorption, sorption and biological assimilation) combine to remove contaminants Works as a sanitation system to remove all pathogenic organisms and viruses Has no environmental and health hazard	

Table 12. Advantage and disadvantages of aerated lagoons.

Advantages	Disadvantages
Effective reductions of COD, SS, DS, oil and grease,and surfactants (80-199%) Simple and rugged in operation and and has l ow operation cost Does not require external addition of chemicals Physical, chemical, and biological processes (sedimentation, adsorption, sorption and biological assimilation) combine to remove contaminants Has specialized microbial population CO_2 produced is utilized by algae Has no environmental and health hazard	High capital cost (Initial construction and aeration equipment) Long residence time No sludge recycling Low microbial population Require disinfection step Efficiency depends on concentration and type of pollutants, flow rate, temperature, pH, HRT and plant type

Table 13. Advantage and disadvantages of rotating biological contactors.

Advantages	Disadvantages
Effective reductions of COD, BOD, nutrients (80-99%) Easy to set up, operate and control s Medium residence time (5-15 h) Removes fecal coliform and heterotrophic bacteria from water Provides homogenous environment that allows constant contact between microorganisms, nutrients, substrate and oxygen Maintains controlled environmental conditions for biological reactions Does not require external addition of chemicals Pollutants are converted to CO_2 and H_2O Has no environmental and health hazard and treated water can be discharged to water courses	High operating costs Efficiency depends on concentration of pollutants, feed rate, pH, temperature, nutrients, and HRT Used as a secondary treatment

Table 13. Advantage and disadvantages of sequencingl batch bioreactors.

Advantages	Disadvantages
Effective (reductions of 94% in COD, 68% in oil and grease, 84-98% in surfactants and 99% in amonium) Easy to set up, operate and control without break-in-periods Medium residence time (5-15 h) Removes all organic substances from water Provides homogenous environment that allows constant contact between microorganisms, nutrients, substrate and oxygen Maintains controlled environmental conditions for biological reactions (pH, temperature andoxygen) Does not require external addition of chemicals Pollutants are converted to CO_2 and H_2O Has no environmental and health hazard	High capital and operating costs Requires disinfection step Efficiency depends on concentration of pollutants, feed rate, pH, temperature, nutrients, HRT, oxygen, mixing and presence of toxic substances

Table 15. Advantage and disadvantages of vertical flow bioreactors.

Advantages	Disadvantages
Effective reductions of COD, BOD, TN, TP, nitrite, Cl and SO_4 (85-100%) Medium residence time (5-15 h) Removes large substances from water in first basin and degrade soluble pollutants in second basin Maintains controlled environmental conditions for biological reactions Vary in size depending on flow Does not require external addition of chemicals	Requires disinfection step Efficiency depends on concentration of pollutants, feed rate, pH, temperature, nutrients, HRT, and presence of toxic substances Subject to clogging

Table 16. Advantage and disadvantages of expanded bed up-flow bioreactors.

Advantages	Disadvantages
Effective reductions of COD, BOD, SS, oil and grease, surfactants and in amonium (90-99%) Faster up-flow velocity and increased flux Compact treatment, easy to set up, operate and control short HRT (6 h) and high SRT Maintains controlled environmental conditions for biological reactions No clogging Does not require external addition of chemicals	Efficiency depends on concentration of pollutants, feed rate, pH, temperature, nutrients, HRT Suitable for low strength wastewaters

Has no environmental and health hazard	

Table 17. Advantage and disadvantages of membrane biofilters.

Advantages	Disadvantages
Effective reductions of COD, BOD, TS, TN and ammonium (90-99%) Low operating cost Operates under aerobic or anaerobic conditions Short residence time Easy to set up, operate and control The internal hydrodynamics and microbial biology and ecology allows robustness of the process and give it the capacity to maintain high performance Allow biomass to become mor specialized (high concentrations of relevant) Bio-clogging can be controlled by back washing with air and/or water to disrupt biomass and recover flow Does not require external addition of chemicals	High operating cost Subject to clogging and flow channeling Relays on microorganisms to break down organic materials which my be affected by environmental and operating conditions (temperature, pH, nutrients, toxicity and oxygen) Detection of pathogens and need for disinfection treatment (chlorination, UV treatment) Efficiency depends on water composition, biofilter hydraulic loading, type of media, feeding strategy, age of biofilter, aeration and temperature

Table 18. Advantage and disadvantages of trickling biofilters.

Advantages	Disadvantages
Effective reductions of 87-95% in COD, 90% in SS, 93% in DS, 99% , 99% in TN , 90% in heavy metals Low operating cost Medium residence time (5-15 h) Easy to set up, operate and control High concentrations of relevant and specialized organisms Bio-clogging can be controlled by back washing with air and/or water to disrupt biomass and recover flow Does not require external addition of chemicals Reduces fecal coliform by up to 4.5 log	High operating cost Subject to clogging and flow channeling Relays on microorganisms to break down organic materials which my be affected by environmental and operating conditions (temperature, pH, nutrients, toxicity and oxygen) Must be supplement with other treatments (chlorination, UV treatment) Efficiency depends on water composition, biofilter hydraulic loading, type of media, feeding strategy, age of biofilter, aeration and temperature

Table 19. Advantage and disadvantages of anaerobic up-flow biofilters.

Advantages	Disadvantages
Effective pollutants reductions (82-93%) Can treat large volumes Effective, robust and economical Short SRT	Suitable for low strength wastewater Subject to clogging and flow channeling Relays on microorganisms to break down organic materials vis biochemical reactions which my be affected by environmental and operating conditions

Easy to set up, operate and control Work at low temperature The internal hydrodynamics and microbial biology and ecology allows robustness of the process and give it the capacity to maintain high performance and tolerate toxic or hydraulic shocks, variable loading and media backwash Does not require external addition of chemicals	Must be supplement with other treatments (chlorination, UV treatment Efficiency depends on water composition, biofilter hydraulic loading, type of media, feeding strategy, age of biofilter,

Table 20. Advantage and disadvantages of up-flow anaerobic sludge blanket.

Advantages	Disadvantages
Effective reductions of COD, BOD, SS, DS and surfactants (95-100%) Easy to set up, operate and control Low operating cost High concentration of microorganisms and high SRT Superior flocculation and settling characteristics Production of biogas Biogas bubbles create sufficient contact between microorganisms and nutrients Improves water quality parameters (pH, oxygen concentration, TS and BOD) The structure of the sludge blanket protects microorganisms from difficult environmental conditions and allows the development of microorganisms with relatively low specific growth rate Does not require external addition of chemicals Has no environmental and health hazard	Relays on microorganisms to break down organic materials vis biochemical reactions which my be affected by environmental and operating conditions (temperature, pH, nutrients, toxicity) Efficiency depends on water composition, hydraulic loading, feeding strategy, age of sludge and temperature

Table 21. Evaluation criteria for greywater treatments.

Criteria	Definition	Score
Cost	Capital and operating costs-Lowest cost has the highest score	15
Maintenance and Control	Complexity of operation and control of treatment method, frequency of fouling and clogging, the need for specialized personnel-Simplicity and lowest maintenance requirement has the highest	15

	score	
Efficiency	90% removal of pollutants with the least energy consumption has full score. 50% or less has zero score	15
Residence Time	Shorter residence time has full score	15
Suitability	Ease of installation, works under various operating conditions without modification and under local climate, no pre-treatment or other treatments required has full score- Robustness and independence of the treatment system has the highest score	15
Value Added Product	Amount of water recovered for reuse in the carwash operation- The greatest amount has the highest score	10
Environmental and Health Impact	Pollutants are not transferred to another phase. Safe storage and use of chemicals. Safe procedure for chemical use and release of toxic compounds from the treatment- The lowest impact has the highest scores	10
Size and Land Requirement	Able to handle wastewater generated on site with minimum space and infrastructure requirements- has full score	5

6.1.1 Costs

Cost is the top category of comparison and includes capital and operating costs. Capital cost is the prime consideration, but lifespan of the equipment was also considered. A low-cost treatment technology/method that must be frequently replaced has no benefit over a moderately high cost but long-lasting treatment method. Secondary considerations were cost of land or building space needed and the required footprint is counted as a cost. Operating costs include electricity, chemical and additives, replacement of parts and labor.

6.1.2 Maintenance and Control

The complexity of treatment method, frequency of fouling and clogging, the need for specialized personnel, whether services could be fee for service or on-site technicians are needed and easiness of monitoring and control.

6.1.3 Efficiency

Efficiency of a method is evaluated based on effectiveness of removing pollutants (SS, DS, COD, oil and grease, surfactants, turbidity, nutrients, heavy metal) and pathogens (bacteria, protozoa, virus) from greywater as well as energy use efficiency.

6.1.4 Residence Time

The residence time required for the treatment process is very important because the treated water will be recycled. A long residence time means that the system footprint would be larger due to increased storage requirements, reducing overall system efficiency and desirability

6.1.5 Suitability

Suitability includes ease of installation, working under various operating conditions without modification, working under local climate, the need for pre-treatment and the need to combine with other treatment in order to achieve the requires results to meet current and future legislations.

6.1.6 Value Added Product

The largest component of value-added product for this system is the recovery of clean (clear, colorless, odorless, and free of pathogens) water for reuse. The objective of the treatment is to recover as much clean water as possible. While this will ultimately at a cost, the benefits to the environment and the conservation of fresh water may outweighs the cost of the treatment. Sludge produced during the process depends on the method used and it may be difficult to find a viable market for sludge produced by chemical treatments.

6.1.7 Environmental and Health Impact

Environmental impact assessment is based the system's contribution to greenhouse (CO_2, CH_4 and NO) gases, production of volatile organics, production of toxins (toxicity issues) and production of nonbiodegradable sludge, production of hydroxide radicals, production of brine solution, improper use and storage of chemicals, and transfer of pollutant to another phase. The treatment system must not be a health hazard to employees and is designed for the safest operation possible based on Canadian and USA guidelines and legislations. Employees should be able to operate the treatment system safely and the use and storage of chemicals must be done in safe way.

6.1.7 Size and Land Requirement

The treatment system must be able to handle the greywater generated on site with minimum space and infrastructure requirements for the storage of chemicals and clean water.

6.2 Evaluation of Treatment Options

For assessing each treatment method, each criterion shown in Table 21 was given score based on the information summarized in Tables 1-20. The total score given to each treatment method was then used to determine the optimum method to be used for treating greywater for reuse. The results shown in Tables 22A&B indicated that granular filter and rotary biological contactors had the highest score (89 each) followed by sequential batch bioreactor (88), reverse osmosis and up-floe anaerobic sludge blanket (84 each),

Table 22A. Evaluation of treatment methods (Physical and Chemical).

Criteria (Score)	Physical Methods					Chemical Methods				Adsorption
	GF	MF	UF	NF	RO	CCF	EC	EO	PO	
Cost (15)	15	13	11	10	9	12	12	12	9	13
Maintenance and Control (15)	14	10	10	10	10	12	12	12	14	11
Efficiency (15)	14	13	14	14	15	13	12	10	15	13
Residence Time (15)	11	12	13	13	13	15	15	15	14	12
Suitability (15)	11	13	13	13	12	13	13	13	12	13
Value Added Product (10)	9	7	8	8	10	5	5	5	5	5
Environmental and Health Impact (10)	10	7	7	7	10	6	6	6	6	7
Size and Land Requirement (5)	5	5	5	5	5	4	5	5	5	4
TOTAL SCORE	**89**	80	81	80	84	79	80	78	78	80

GF=Granular filtration
MF=Microfiltration
UF=Ultrafiltration
NF=Nanofiltration
RO=Revers osmosis
CCF=Chemical coagulation-flocculation
EC=Electrochemical coagulation
EO=Electrooxidation
PO= Photooxidation

Table 22B. Evaluation of treatment methods (Biological).

Criteria (Score)	Biological Methods									
	CWL	AL	RBC	SBBR	VFBR	EBUBR	MB	TB	AUBF	UASB
Cost (15)	10	12	13	13	13	12	13	12	13	13
Maintenance and Control (15)	12	14	14	14	11	13	11	11	12	12
Efficiency (15)	13	14	14	14	11	12	11	12	12	13
Residence Time (15)	8	8	12	12	9	12	10	12	12	12
Suitability (15)	10	11	13	13	11	10	11	11	10	12
Value Added Product (10)	9	7	8	7	7	7	8	7	8	9
Environmental and Health Impact (10)	7	8	10	10	7	10	7	7	8	8
Size and Land Requirement (5)	1	2	5	5	5	5	5	5	5	5
TOTAL SCORE	70	76	89	88	74	81	76	77	80	84

CWL = Constructed wetlands
AL – Aerated lagoons
RBC = Rotary biological contactors
SBBR = Sequencing batch bioreactor
VFBR = Vertical fellow bioreactor
EBUBR = Expanded bed up-flow bioreactor
MB = Membrane biofilter
TB = Trickling biofilter
AUR = Anaerobic up-flow biofilter
UASB - Up-flow anaerobic sludge blanket

ultrafiltration, and expanded bed up-flow bioreactor (81 each), electrocoagulation, microfiltration, nanofiltration, adsorption and anaerobic up-flow biofilter (80 each), chemical coagulation-flocculation (79), electrooxidation and photooxidation (78 each), trickling biofilter (77), membrane biofilter and anaerobic lagoon (76 each), vertical floe bioreactor (74) and constructed wetland (70). The granular filter scored the highest (89) among the physical treatments, the electrochemical coagulation scored the highest (80) among the chemical treatments group and rotary biological contactors scored the highest (89) among the biological treatments group.

A through review of the literature indicated that non of the 20 treatment options can be used alone safely and effectively to treat greywater for reuse. It is, therefore, recommended that a combination of granular filter and rotating biological contactors be used to treat greywater from a large group of houses, apartment complex, large commercial establishment or recreational facility and a combination of granular filter and sequencing bed bioreactor be used to treat greywater from a single house, a school or small business such as a sport center or shopping mall.

The granular filter is to be used as a pre-treatment. Granular filtration will allow greywater to flow through granular material while suspended solids (sand, clay, organic and inorganic particles and heavy metals) are retained and pathogenic microorganisms (bacteria, algae and protozoa) are partially removed from the wastewater. The granular media could be made of sand, fine and course gravels (or synthetic polymers and diatomaceous earth). Granular filter is easy to set up using locally available material, is economical and has a low capital and operating cost and a short residence time. Reductions of of 100% in COD, 100% in TSS, 100% in turbidity, and 80% in total nitrogen can be achieved by the granular filter.

The ssequencing batch bioreactors is to be usedf as a secondary or polishing treatment following primary treatment that involves removal of grit and coarse suspended material and some pathogenic microorganisms. It is designed used for treatment of greywater for small scale operation due its compactness, low cost, simple operation and flexibility, effective nutrient removal and easy-to-use interface. It performs equalization, biological treatment, and secondary clarification in a single tank using a time control sequence. The degradation of pollutants is achieved by the microorganisms in activated sludge and the nonbiodegradable materials settle and can be separated from the effluent. The system can be operated as anaerobic treatment, where organic matter is mineralized into biogas or under anoxic condition, where nitrates are used as the oxidation reagents to produce free nitrogen through denitrification or under aerobic condition, where dissolved oxygen is used for oxidation of the carbonaceous material and nitrification. The performance is influenced by the amount and quality of inoculum, retention time, rate of mixing and flow rate. BOD and COD removal rates are greater than 90%.

The rotationg biological cobtractor is to be usedf as a secondary or polishing treatment following primary treatment that involves removal of grit and coarse suspended material and some pathogenic microorganisms. The RBC allows the greywater to be in contact with a biological film of microbes that are alternatively exposed to the atmosphere allowing both aeration and assimilation of dissolved organic pollutants and nutrients for degradation. The immersed area of the disc in the greywater is about 40%. The removal of BOD_5 and COD is about 99% and the removal of faecal coliforms, heterotrophic bacteria and specific pathogens (Pseudomonas aeruginosa, Staphylococcus aureus.) is 90–100%. Full nitrification is achievable and total phosphorus removal is about 99%.

VII. CONCLUSIONS

In this study, 20 physical, chemical and biological treatment options for greywater treatment for recycling were reviewed and the performance and advantages and disadvantages of each treatment were discussed. These treatments include granular filtration, microfiltration, ultrafiltration, nanofiltration, reverse osmosis, chemical coagulation-flocculation, electrocoagulation, electrooxidation, photooxidation, adsorption, constructed wetlands, aerated lagoons, rotating biological contactors, sequencing batch reactors, expanded bed up-flow bioreactors, vertical flow bioreactor, membrane bioreactors, trickling biofilter, anaerobic up-flow biofilter and up-floe anaerobic sludge blanket. Each treatment method was evaluated and compared with others using a standard set of criteria that were developed based on the performance efficiency and the advantages and disadvantages of the treatment methods with the objective of selecting the most applicable and economically and environmentally feasible system (or systems) that meet the operating requirements of obtaining clean water for recycling. Eight criteria (cost, maintenance and control, efficiency, suitability, value added product, environmental and health impact and size and land requirement) were selected for evaluation and each criterion was assigned a figure based on its relative important. A comparative analysis was performed on 20 treatment methods using the eight criteria. The granular filter scored the highest (89) among the physical treatments, the electrochemical coagulation scored the highest (80) among the chemical treatments group and rotary biological contactors scored the highest (89) among the biological treatments group. The top 3 treatments were granular filter (89), rotary biological contactors (89) and sequential batch bioreactor (88), A through review of the literature indicated that non of the 20 treatment options can be used alone safely to treat greywater for reuse. It is, therefore, recommended that a combination of granular filter and rotating biological contactors be used to treat greywater from a large group of houses, apartment complex, large commercial establishment or recreational facility and a combination of granular filter and sequencing bed bioreactor be used to treat greywater from a single house, a school or small business such as a sport center or shopping mall. The utilization of treated greywater reduces the demand for fresh clean water and provide substantial benefits for the municipal wastewater system by reducing the amount of wastewater to be treated.

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COMPETING INTRESTS

The authors have declared that no competing interests exist.

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