Chapter 8
Phycoremediation: A Green Technology for Nutrient Removal from Greywater

A. A. Wurochekke, Radin Maya Saphira Radin Mohamed, Adel Ali Saeed Al-Gheethi, Efaq Ali Noman and Amir Hashim Mohd Kassim

Abstract Phycoremediation as a green technology relies on microalgae which have high potential to grow in greywater. The presence of high levels of nutrients is necessary for microalgae growth to improve the efficiency of this process. However, the main consideration of the phycoremediation process of greywater lies in the wastewater composition, the selection of microalgae strains with high potential to compete with the indigenous organisms in the greywater and remove nutrients and elements from greywater as well as microalgae, which possess the ability to survive under stressful environmental conditions. Besides, this process can be applied to individual houses. The cost of the phycoremediation process, source of microalgae and energy required are the main points which need to be discussed further. The study indicated that the phycoremediation process is most effective for the treatment of greywater. However, many aspects have to be evaluated in order to achieve the high-quality-treated greywater. In this chapter, the effectiveness of phycoremediation and the mechanism of nutrient removal are discussed. Most microalgae species exhibited greater efficiency in removing nitrogen compared to phosphorous due to the nature of the anabolic pathway of microalgae cells and the ability of nitrogen compounds to diffuse through the cell membrane faster than phosphorous compounds.

A. A. Wurochekke · R. M. S. Radin Mohamed (✉) · A. A. S. Al-Gheethi (✉)
A. H. Mohd Kassim
Micro-Pollutant Research Centre (MPRC), Department of Water and Environmental Engineering, Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Batu Pahat, Johor, Malaysia
e-mail: maya@uthm.edu.my

A. A. S. Al-Gheethi
e-mail: adel@uthm.edu.my

E. A. Noman
Faculty of Applied Sciences and Technology (FAST), Universiti Tun Hussein Onn Malaysia (UTHM), Pagoh, Johor, Malaysia

E. A. Noman
Department of Applied Microbiology, Faculty Applied Sciences, Taiz University, Taiz, Yemen

R. M. S. Radin Mohamed et al. (eds.), *Management of Greywater in Developing Countries*,
Water Science and Technology Library 87,
https://doi.org/10.1007/978-3-319-90269-2_8

Keywords Algae · Treatment · Nutrient removal · Alternative technology

8.1 Introduction

Due to the growth of the human population, people have begun to live in larger and more densely populated groups. Subsequently, the removal of human waste has become a serious issue. The lack of treatment plants for carbon, ammonia and nitrogen, as well as pathogen removal, is common in recent times due to the scarcity of land for treatment facilities which are mostly centralised with a broad range of consented pollutants. In a highly populated area, it is difficult to install individual treatment systems and this has led to the installation of pumps and pipes to efficiently transport waste to centralised outlets. Currently, European countries have set regulations to maintain the natural quality of wastewater streams without affecting biodiversity.

Domestic and industrial waste sewage discharges contain dissolved and suspended organic and inorganic constituents, faecal and other potentially pathogenic bacteria. Presently, wastewater has to be treated prior to disposal due to a number of reasons. For example, nutrients in wastewater such as nitrogen, phosphorus and sulphur pose a threat to the environment and its ecological sustainability. Besides that, wastewater also emits foul odours due to anaerobic digestion and can also cause potential health risks when it comes into contact with potable water. Reclaimed wastewater is now an important constituent of water supply (5–10%), which can be reused for non-drinking purposes (Wurochekke et al. 2016).

The operational characteristics of a common wastewater treatment plant consist of a few processes such as preliminary, physical, chemical and biological processes. However, the required effluent standard for the discharge of wastewater depends on the flow rate of receiving water. Wastewater preliminary treatment consists of two stages. First, a screening process will be carried out to reduce and remove coarse, medium and fine solids using different screen sizes. Second, the removal of grit and sand will occur in a grit chamber which settles dense materials easily and quickly. The organic matter remains suspended in downstream units for treatment (Al-Gheethi et al. 2015).

The purpose of primary treatment is to remove most of the suspended solids which thus reduces and regulates BOD (typically by 30%) before proceeding with the secondary treatment. This is achieved using gravitational settlement tanks where the residual part of solids is the raw primary sludge. The materials which possess less density than water such as detergents will move up to the surface of the sedimentation tank. They will be collected and removed prior to the next treatment. This process could be improved by using phosphate-precipitating chemicals like Al and Fe ions.

The secondary treatment is purposely designed to remove dissolved organic matter and other fine suspended organic matter. This treatment technique is predominantly controlled and enhances natural decomposition mechanisms in bioreactors. In this situation, the controlled condition ensures shorter treatment time. The organic matter is removed by bacteria that adapt to the environment such as ammonia oxidizers. The secondary process needs a sufficient supply of oxygen so that nitrifying microorganisms are kept in contact with the aerobic process. Besides the process described previously, there is a wide variety of secondary treatment processes available. The main ones include algal stabilisation ponds, land disposal systems, anaerobic reactors, activated sludge systems and aerobic biofilters (Jais et al. 2017).

Lastly, the tertiary treatment is designed to achieve low solid values and to remove pathogenic organisms, heavy metals and nutrients such as nitrogen and phosphorus. This tertiary treatment is a treatment process for wastewater that is expected to achieve the highest degree of effluent quality through the use of sand filters or UV lamps to remove or eliminate pathogenic organisms. These processes are capital intensive especially the backwashing of the sand filter. It requires large amounts of power. However, the chemical precipitation process is widely used for nutrient removal because biological nutrient removal organisms used in absorbing nutrients may not necessarily attain the consistency of chemical treatment even though they are more sustainable (Atiku et al. 2016).

Apparently, wastewater treatment processes are designed to achieve improvement in effluent quality. These processes perform well and meet the required quality standards. However, tertiary treatment such as nutrient removal faces some limitations due to the high costs it incurs. This is especially true for the removal of phosphorus.

For phosphorus, a normal 1 mg/L PO_4 is required to meet 95% of the time to meet UWWTD or WFD standards which are challenging and capital intensive compared to traditional chemical processes. Achieving N and P effluent standards is the key to eutrophication control and prevention. In terms of eutrophication, P is considered as the most problematic element in natural waters that causes point source pollution as the average concentration is below 0.5 mg/L. The eutrophic condition of natural waters and microalgae concentration agree with the phosphorus level. An environment that receives more nitrogen than what plants require for growth is called a nitrogen-saturated environment. However, phosphorus in the environment is less soluble in water compared to nitrogen. Therefore, it is considered as a much more significant growth-limiting nutrient in the aquatic system.

Microalgae growth in water bodies can lead to unwanted effects. Though waters with abundant nutrients (N and P) known as eutrophic waters grow algae well, waters with a lower quantity of nutrients limit growth. The eutrophic environment is characterised by cool, dark and deep waters with depleted levels of oxygen, especially in temperate and tropical areas. On the other hand, algae decolourise the water which affects the aesthetic and recreational values of water. Algae also change the taste of water and produce another toxin that is harmful to higher forms of life in the food chain. Yet, they are considered a good bio-treatment technique in the control treatment process. This lack of oxygen in the water makes it difficult for aquatic animals to survive.

The effect of oxygen-depleted water forms a microbial breakdown from the sediment of dead algae and animal waste in environments with excess nutrients such as eutrophic waters. Human activity also affects lakes and rivers through the discharge of P from detergents to surface waters although some waters are already eutrophic in nature. Besides that, the upper layer of water in a stratified lake in autumn cools to a lower temperature less than the deep lower layer of a stratified stagnant lake where mixing occurs in the stratified layers. Thus, the oxygen-depleted water from the bottom rises to the surface replacing the cooler water. Consequently, aquatic organisms that need oxygen sometimes suffocate and die during this process.

Bio-treatment with microalgae is an appropriate method because of their photosynthetic capabilities, changing solar energy into biomasses yields and embracing phosphorus and nitrogen content which inflicts eutrophication (Abdel-Raouf et al. 2012).

This chapter focused on the phycoremediation process as a green technology for nutrient removal from greywater. The selection of the most potent microalgae strain and the process used to enhance removal efficiency are discussed.

8.2 Nutrient Removal Techniques from Wastewater

Biomass is another technique used in wastewater treatment. Microalgae and duckweed are used in lagoon wastewaters, while reed beds are commonly used for non-bacterial options. The presence of nutrients in wastewater makes it an ideal place for the optimal growth of microalgae. Artificial wetlands planted with specific species of reeds are mostly used in rural areas where there are no wastewater treatment facilities. This is a biological process that treats wastewater completely. They do not require chemicals, are inexpensive to run, produce reeds for compost after harvest and are very effective in treatment (See “Reed Beds for the Treatment of Domestic Wastewater, Grant and Griggs”). Wastewater lagoons are also used for the removal of N and P. Typically, wastewater lagoons are involved in the final stage in wastewater treatment system. Wastewater lagoons refer to large ponds or tanks planted with plants which possess properties for nutrient removal like duckweed where the removal efficiency is proportional to plant biomass growth. According to a previous study by Al-Nozaily et al. (2000), N and P absorption rates and the growth rate of duckweed at high ammonia levels were inhibited. However, the tank depth does not affect N removal and P removal is less than that of algae-based pounds (Arceivala 1981). It was noted that duckweed is considerably easier to harvest than algae.

Nitrification is a process whereby reduced forms of inorganic and organic nitrogen, particularly ammonium, are oxidised to nitrate. Ammonia-oxidizing bacteria first oxidise ammonia to nitrite, followed by the oxidation of nitrite to nitrate by the nitrite-oxidizing bacteria. The oxidising bacteria *Nitrosomonas* and *Nitrobacter* are the main organisms responsible for the reaction, however, the process produces acid and lowers pH. Therefore, alkalinity needs to be added. Hence, gaseous nitrogen is formed through denitrification by the biological conversion of nitrate.

Biological treatment amid other physical and chemical treatments has more advantages. Chlorine is added to the wastewater stream to oxidise ammonia–nitrogen, which later becomes gaseous nitrogen. Ammonia stripping occurs when pH increases up to 11.5 during the treatment process with plant growth when CO_2 is reduced. The solution with high pH predominantly has ammonia as dissolved gas while enough air–water contact strips ammonia gas from the solution. Hence, the phycoremediation technique is viable for wastewater treatment.

8.3 Phycoremediation of Wastewater

The phycoremediation technique is defined as a bio-treatment process for wastewater using microalgae species. This process mainly aims to remove nutrients such as nitrogen and phosphorus from wastewater through the assimilation process of microalgae cells. The nutrients absorbed through the cell membrane of microalgae cells are transformed in the cytoplasm to be used in anabolic pathways (Atiku et al. 2016). The phycoremediation process is quite different from phycoremediation in which specific plants are used for the bioremediation of pollutants from wastewater. The potential of several microalgae species in the phycoremediation process of different types of wastewater has been reported in the literature. The phycoremediation process is recommended for the individual users due to the low operation costs, the absence of the toxic by-products, high efficiency in nutrient removal, increase in dissolved oxygen as well as the production of the microalgae biomass with high nutrient values. Besides, this process might also contribute to the inactivation of pathogenic bacteria due to the antibacterial properties of some microalgae species (Al-Gheethi et al. 2017).

Phycoremediation has been shown to exhibit high efficiency in the removal of nutrients from different types of the wastewater such as domestic, brewery and dairy wastewater (Mohamed et al. 2017). Therefore, it has high potential to produce high-quality-treated wastewater compared to those generated during the primary and secondary treatment processes (Abou-Shanab et al. 2013). Microalgae are photoautotrophic as they have the ability to obtain energy and carbon sources. However, these organisms still need some nutrients in form of nitrogen and phosphorus as well as trace elements for the metabolic and anabolic pathways. Hence, during the inoculation of microalgae in the wastewater, nutrients can be absorbed through the assimilation process. Moreover, microalgae growth in wastewater depends on environmental conditions. Therefore, the best option to achieve high efficiency in the removal of nutrients is by using indigenous strains since these strains have been acclimatised to the surrounding conditions and are able to survive and compete with other indigenous bacteria in greywater. Several species of microalgae such as *Scenedesmus dimorphic*, *Botryococcus braunii*, *Chlorella vulgaris*, *Spirulina* sp., and *Phormidium* sp., have exhibited high efficiency in the phycoremediation process due to their potential to tolerate harsh environmental conditions. Another effective option is by subjecting the microalgae to the starvation process in which the microalgae are harvested from the culture medium and then dried at room temperature. The deficiency in nutrients would induce the microalgae cells to transform from a vegetative state to form cysts (dormant state). Thereafter, the microalgae inoculum used in the phycoremediation process of greywater added as a dry biomass. The starvation process makes the microalgae biomass more effective in the uptake of nutrients and accelerates the removal process (Mohamed et al. 2017).

8.4 Controlled Eutrophication of Microalgae for Phycoremediation

To control the release of wastewater with high nutrient content especially for P, a standard limit needs to be achieved to prevent effluent from of causing eutrophication in water bodies. The growth of microalgae indicates water pollution since they typically respond to many types of ions and toxins. Green algae play a dual role in the treatment of wastewater as they enable the effective utilisation of different constituents essential for growth which further leads to enhanced biomass production for green products (Rawat et al. 2011).

A controlled environment can be a viable place for microalgae isolated specifically to grow in wastewater in which they consume P and other pollutants for their survival which is termed as phycoremediation. They are used for the removal of pollutants prior to discharge into rivers and lakes. These microalgae are not discharged together with the treated water as they are used for the continuous flow treatment of wastewater and are often harvested to sustain the optimal value of microalgae concentration. The collected biomass has the potential to produce valuable products such as biofuel, biodiesel and fertilisers due to the high content of carbon and nutrients.

Microalgae absorb a large amount of atmospheric CO_2 and release oxygen during its growth period. For additional microalgae growth, additional CO_2 is required though it affects the condition of bacterial growth. Waters that contain microalgae give out foul odour and may cause a change in how they taste. Nevertheless, freshwater microalgae have absorption abilities where they utilise nutrients and metals found in wastewaters for photosynthesis and thus purifies the water. However, this purified water is not suitable for drinking purposes until it undergoes natural purification after being discharged into rivers and lakes. Furthermore, the water can be drinkable if it undergoes another treatment process using activated carbon to further remove dissolved organic pollutants.

Furthermore, the role of microalgae is to accumulate and convert wastewater nutrients into biomass and lipids. The capability of microalgae to remove or degrade hazardous organic pollutants is well known (Abeliovich 1986). The usage of microalgae is summarised in Table 8.1. The examples given demonstrate that algae are indeed capable of contributing to the degradation of environmental pollutants, either by directly transforming the pollutant in question or by enhancing the degradation potential of the microbial community present. The biomass resulting from the treatment of wastewater can be easily converted into sustainable products. Depending on the species used for this purpose, the resulting biomass can be applied and used in many different ways. For instance, it can be used as an additive for animal feed as well as for the extraction of value-added products like carotenoids, bio-molecules or the production of biofuel. Microalgae biomass is, therefore, useful for both biofuel production as well as wastewater treatment. The successful implementation of this strategy would allow the use of freshwater to be minimised.

Table 8.1 Microalgae contributing to the degradation of environmental pollutants

Microalgae	Type of microalgae	Source of wastewater	Reference
Prototheca zopfii	Freshwater	Degraded petroleum hydrocarbons found in Louisiana crude and motor oils waste	Walker et al. (1975)
Chlamydomonas species	Freshwater	Meta cleavage in wastewater	Jacobson and Alexander (1981)
Chlorella pyrenoidosa	Fresh and brackish	Degradation of azo dyes wastewater	Jinqi and Houtian (1992)
Spirulina platensis	Freshwater and brackish water	Domestic wastewater treatment	Laliberte et al. (1997)
Chlorella sorokiniana	Freshwater	Wastewater treatment under aerobic dark heterotrophic condition	Ogbonna et al. (2000)
Scenedesmus sp.	Freshwater	Removal of ammonia from effluents containing high alkaline and ammonium levels	Jin et al. (2005)
Chlorella sp.	Fresh and marine water	Anaerobically digested dairy waste	Wang et al. (2010)
Ankistrodesmus and *quadricauda*	Freshwater	Olive-oil mill wastewaters and paper industry wastewaters	Tran et al. (2010)

8.5 Wastewater Treatment Potential of Microalgae

Microalgae have the potential to survive in a broad range of environmental conditions. Therefore, it represents a good source of biomass (Xin et al. 2010; Xu et al. 2013). The utilisation of wastewater as a production medium for microalgae biomass leads to a reduction in nitrogen and phosphate content (Mata et al. 2010; Xin et al. 2010). In addition, microalgae biomass can be used as feedstock for many industries (Spolaore et al. 2006; Harun et al. 2010).

It has been argued that biodiesel production with wastewater treatment is the most reasonable area to be commercialised in the short term. They provide a way to remove chemical and biological contaminants, heavy metals and pathogens from wastewater while producing biomass for biodiesel production. Wastewater rich in CO_2 provides a conductive growth medium for microalgae because CO_2 balances the wastewater by allowing higher microalgae production rates, reduced nutrient levels in the treated wastewater, decreased harvesting costs and increased lipid production (Brennan and Owende 2010).

Microalgae have the ability to capture sunlight and use that energy to store carbon. According to Alabi et al. (2009) the amount of carbon found in microalgae biomass is about 45–50%. Algae can have a doubling time of as little as 4 h to accumulate biomass. The microalgae growth will be limited if the culture is being supplied with CO_2 from the air because the amount of CO_2 found in air is small (0.033%). Therefore, extra CO_2 can be mixed with air and later added into the culture to facilitate microalgae growth (Mata et al. 2010). The efficiency of CO_2 can be improved by introducing deep level subaquatic through air stones, or through CO_2-rich industrial flue gas into the cultures.

In the photosynthesis process, O_2 is being generated and released into the air. However, if the O_2 gas concentration increases and gets trapped within the cell, it will cause damage to the chlorophyll reaction centres thus leading to a decrease in the production of biomass (Alabi et al. 2009). This problem may occur only in a closed system such as PBRs. In order to avoid such problems, a gas exchanger is needed to help release the O_2 gas. In open systems, however, this is not necessary because the O_2 gas can be automatically released into the atmosphere (Mata et al. 2010).

According to a previous study by Sawayama et al. (1995), *Botryococcus* sp. was used to remove nitrate and phosphate from sewage after primary treatment along with the production of hydrocarbon-rich biomass while Martinez et al. (2000) achieved a significant removal of phosphorus and nitrogen from urban wastewater using the microalgae *Scenedesmus obliquus*. They were able to eliminate 98% of phosphorus and completely remove ammonium (100%) in a stirred culture at 25 °C over 94 and 183 h retention time, respectively. To further strengthen the potential of microalgae in wastewater treatment, Hodaifa et al. (2008) recorded a 67.4% reduction in BOD_5 with *S. obliquus* cultured in diluted (25%) industrial wastewater from olive-oil extraction. The percentage of elimination reduced to 35.5% with undiluted wastewater because of low nitrogen content which inhibited microalgae growth during the exponential phase.

In addition, Yun et al. (1997) successfully grew *Chlorella vulgaris* in wastewater discharged from a steel plant to achieve an ammonia bioremediation rate of 0.022 g NH_3 per day. Munoz et al. (2009) found that the use of a biofilm attached to the reactor walls of flat plate and tubular photobioreactors improved BOD_5 removal rates by 19 and 40%, respectively, as compared with a control suspended bioreactor for industrial wastewater effluent. The retention of algal biomass showed remarkable potential in maintaining optimum microbial activity while remediating the effluent. To absorb heavy metal ions, Chojnacka et al. (2005) found that *Spirulina* sp. acted as a biosorbent where the biosorption properties of microalgae depended strongly on cultivation conditions with photoautotrophic species showing greater biosorption characteristics.

Mohamed et al. (2017) used *Botryococcus* sp. for the removal of BOD_5, COD, ammonia (NH_3), nitrate (NO_3^-) and orthophosphate (PO_4^{3-}) as well as K, Ca and Na ions from bathroom greywater by using a photo-reactor system at village houses. The phycoremediation process was conducted for 21 days. The study revealed that *Botryococcus* sp. reduced BOD_5, by 85.3 to 98%, COD by 71.22 to 85.47%, NH_3 by 86.21 to 99% and PO_4^{3-} by 39.12 to 99.3% after 21 days. The reduction of NO_3^- was recorded after 18 days of the treatment period at an efficiency of 98%. Moreover, *Botryococcus* sp. removed 97% of K after 3 days and 95% of Ca at the end of the phycoremediation process. Al-Gheethi et al. (2017) claimed that the kinetic coefficient of *Scenedesmus* sp. for the removal of NH_4^- was $k = 4.28$ mg NH_4^{-1} log_{10} cell mL^{-1} d^{-1} with 94% of the coefficient and $km = 52.01$ mg L^{-1} ($R^2 = 0.94$) while the removal of NH_4^- was $k = 1.09$ mg NH_4^- log_{10} cell mL^{-1} d^{-1} for PO_4^{3-} and $km = 85.56$ mg L^{-1}, with 92% of the efficiency. Both studies by Al-Gheethi et al. (2017) and Mohamed et al. (2017) indicated that microalgae species have high potential in the removal of the nutrients from wastewater. Most of the microalgae species exhibited more effectiveness in the removal of nitrogen compared to phosphorus. This is due to the role of nitrogen in anabolic activities and the building of amino acids. Therefore, nitrogen represents between 7 and 10% of the microalgae cells by dry weight (Richmond 2004). Phosphorus is also necessary for the microalgae genome (DNA and RNA), phospholipids, and ATP (Yao et al. 2015). The removal percentages for different wastewater parameters via the phycoremediation process using microalgae species are presented in Table 8.2.

Temperature condition has a strong correlation with the biochemical reactions which affect microalgae growth as maximal productivity can only be achieved when nutritional needs are met at correct optimal temperatures (Richmond 2004). Temperature optimal for the growth of microalgae are usually between 20 and 30 °C while temperatures lower than 16 °C decrease growth rate as many microalgae die at temperatures above 35 °C. There is a relationship between temperature and light intensity since lamps and sunlight emit heat (Richmond 2004).

The polyunsaturated fatty acids within the membranes and the fluidity of the membrane system increase at low temperature and this is essential for protecting the thylakoids and the photosynthetic machinery of microalgae cells from photoinhibition. Therefore, lipid classes and composition are affected by temperature instead of the total lipid content. However, in any algae media, the value of the pH that is suitable for cultivation ranges from 6 to 8 (Zeng et al. 2011). Although each media may have a different pH value since the values are not fixed during the cultivation process, it can be changed. Whitacre (2010) stated that the general pH value for most freshwater microalgae species ranges between 7 and 9 but the optimum pH is around 7.5. Microalgae species seem to be more tolerant of the broad range of pH values (Lam and Lee 2012). The growth of *Botryococcus* species has shown its tolerance to different pH conditions ranging from 6 to 8.5. The genus *Botryococcus* race A strains has been observed to yield biomass with high lipid content (15–35% by dry weight) and when the fatty acids were analysed, the oleic, linoleic, stearic and palmitic acids were the major fatty acids found with traces of pharmaceutically important alkyl substituted fatty acids such as 12-methyl hexadecanoic acid, 14-methyl tetradecanoic acid and 16-methyl heptadecanoic acid (Jin et al 2005). Thus, the algae *Botryococcus* appears to be a potential organism for lipid-rich biomass production under varying pH conditions. The failure to maintain the correct pH can lead to the slow growth of microalgae or eventual culture collapse because pH can affect the availability and solubility of CO_2 and minerals in the medium.

Therefore, one of the most important points in the phycoremediation process is the source of microalgae species. Microalgae species obtained from fresh water

Table 8.2 Removal of pollutants from different wastewater samples via the phycoremediation process using microalgae species

Microalgae species	Wastewater	Removal efficiency (%)	References
Botryococcus sp.	Household greywater	COD 88, BOD 82, TN 52, TOC 76	Gani et al. (2015)
	Men hostel greywater	COD 85.6, BOD 66.7, TSS 12.3	Gokulan et al. (2013)
	Aerated Swine wastewater	TP 93.3, TN 40.8	Liu et al. (2013)
	Greywater	BOD_5 85.3–98, COD 71.22–85.47, NH_3 86.21–99, $PO4^{3-}$ 39.12–99.3, NO_{3-} 98, K 97, Ca 95	Mohamed et al. (2017)
Chlorella sp.	Secondary wastewater from municipal	N 96, P 84	Jing (2009)
	Dairy wastewater	NO_3^- 49.09, NO_2^- 79.06, TP, 83.23, Fe 32.0	Khothari et al. (2012)
	Textile wastewater	BOD 81, NO_2 62, PO_4 87	Pathak et al. (2014)
	Wastewater	TN 83.2–88.1	Yao et al. (2015)
	Central municipal wastewater	COD 70, TN 61, TP 61	Min et al. (2011)
	Rubber latex concentrate processing wastewater	COD 93.4, TN 79.3	Bich et al. (1999)
	Drainage solution from greenhouse production	TP 99.7, TN 20.7	Hultberg et al. (2013)
	Leather processing chemical manufacturing facility	BOD 22, COD 38, NH_4 80, Ca 63, Mg 50, Na 14, K 18, Ni 89, TN 29–73	Rao et al. (2011)
Nostoc sp.	Dairy effluent	BOD 40.4, COD 40.3, PO_4 21, TSS 53	Kotteswari et al. (2012)
Pithophora sp.	Dairy wastewater	NH_3 99.01, NO_3^- 84.56, P = 97.98	Silambarasan et al. (2012)

(continued)

Table 8.2 (continued)

Microalgae species	Wastewater	Removal efficiency (%)	References
Scenedesmus sp.	Anaerobically digested palm oil mill effluent	TN 99.5, TP 98.8, COD 86, BOD 86.5	Kamarudin et al. (2013)
	Swine wastewater	TN 59, TP 24, IC 27	Abou-Shanab et al. (2013)
	Tannery wastewater	NO_3 44.3, PO_4 95, Cu 73.2–98, Zn 65–98, Pb 75–98	Ajayan et al. (2015)
	Animal wastewater	N 87, P 83.2	Kim et al. (2006)
	Wastewater	N > 99, P > 99	Li et al. (2010)
	Wet market wastewater	NH_{4-} 91, PO_4^{3-} 92.27	Al-Gheethi et al. (2017)
	Wet market wastewater	TOC 71.73, TN 73.01, PO_4^{3-} 87.60, Zn 79.65, Fe 59.33, Cu 100	Jais et al. (2015)
	Fermented swine wastewater	TP 83.2, TN 87, TC 12.9	Kim et al. (2007)
Spirulina platensis	Sago starchy wastewater	TN 99.9, TP 99.4, COD 98	Phang et al. (2000)

might be suitable to be used for the phycoremediation of wastewater. Laboratory observations indicated that most microalgae obtained from freshwater survive and grow in various type of wastewater. Based on the literature, it appears that most microalgae have high efficiency in reducing nitrogen and phosphorous in wastewater during the phycoremediation process. Therefore, phycoremediation as a treatment process could enhance the quality of wastewater which would then be reused for unrestricted irrigation purposes or discharged into surface waters.

8.6 Conclusions

Microalgae species possess high potential to be used in the phycoremediation process of greywater. However, the selection of microalgae strains should be considered based on its ability to survive, grow and remove nutrients from waste. Moreover, the use of indigenous strains might be the best option to achieve high effectiveness for the phycoremediation process. Moreover, the starvation process might enhance the efficiency of the phycoremediation process within a short time.

Acknowledgements The authors wish to thank the Ministry of Higher Education (MOHE) for supporting this research under FRGS vot 1574 and also the Research Management Centre (RMC) UTHM for providing grant IGSP U682 for this research.

References

Abdel-Raouf N, Al-Homaidan A, Ibraheem IBM (2012) Microalgae and wastewater treatment. Saudi J Biol Sci 19:257–275

Abeliovich A (1986) Algae in wastewater oxidation ponds. In: Richmond A (ed) Handbook of microbial mass culture. CRC Press, Boca Raton, pp 331–338

Abou-Shanab RA, Ji MK, Kim HC, Paeng KJ, Jeon BH (2013) Microalgal species growing on piggery wastewater as a valuable candidate for nutrient removal and biodiesel production. J Environ Manage 115:257–264

Ajayan KV, Selvaraju M, Unnikannan P, Sruthi P (2015) Phycoremediation of tannery wastewater using microalgae *Scenedesmus* species. Int J Phytoremed 17(10):907–916

Alabi AO, Bibeau E, Tampier M (2009) Microalgae technologies & processes for biofuels-bioenergy production in British Columbia: current technology, suitability & barriers to implementation. British Columbia Innovation Council, Vancouver

Al-Gheethi AA, Ismail N, Efaq AN, Bala JD, Al-Amery RM (2015) Solar disinfection and lime stabilization processes for reduction of pathogenic bacteria in sewage effluents and biosolids for agricultural purposes in Yemen. J Water Reuse Des 5(3):419–429

Al-Gheethi AA, Mohamed RM, Jais NM, Efaq AN, Abdullah AH, Wurochekke AA, Amir-Hashim MK (2017) Influence of pathogenic bacterial activity on growth of *Scenedesmus* sp. and removal of nutrients from public market wastewater. J Water Health. Online

Al-Nozaily F, Alaerts G, Veenstra S (2000) Performance of duckweed-covered sewage lagoons II. Nitrogen and phosphorus balance and plant productivity. Water Res 34(10):2734–2741

Arceivala SJ (1981) Wastewater treatment and disposal; engineering and ecology in pollution control, vol 15. M. Dekker, New York

Atiku H, Mohamed RMSR, Al-Gheethi AA, Wurochekke AA, Kassim AHM (2016) Harvesting of microalgae biomass from the phycoremediation process of greywater. Environ Sci Poll Res 23(24):24624–24641

Bich NN, Yaziz MI, Bakti NAK (1999) Combination of *Chlorella vulgaris* and *Eichhornia crassipes* for wastewater nitrogen removal. Water Res 33:2357–2362

Brennan L, Owende P (2010) Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products. Renew Sustain Energy Rev 14(2):557–577

Chojnacka K, Chojnacki A, Gorecka H (2005) Biosorption of Cr^{3+}, Cd^{2+} and Cu^{2+} ions by blue-green algae *Spirulina* sp.: kinetics, equilibrium and the mechanism of the process. Chemosphere 59(1):75–84

Gani P, Sunar NM, Matias-Peralta HM, Abdul Latiff AA, Kamaludin NS, Parjo UK, Er CM (2015) Experimental study for phycoremediation of *Botryococcus* sp. on greywater. Appl Mech Mater 773:1312–1317

Gokulan R, Sathish N, Kumar RP (2013) Treatment of grey water using hydrocarbon producing *Botryococcus braunii*. Int J Chem Tech Res 5(3):1390–1392

Harun R, Singh M, Forde GM, Danquah MK (2010) Bioprocess engineering of microalgae to produce a variety of consumer products. Renew Sustain Energy Rev 14(3):1037–1047

Hodaifa G, Martinez ME, Sanchez S (2008) Use of industrial wastewater from olive oil extraction for biomass production of *Scenedesmus obliquus*. Biores Technol 99(5):1111–1117

Hultberg M, Carlsson AS, Gustafsson S (2013).Treatment of drainage solution from hydroponic greenhouse production with microalgae. Biores Technol 136:401–406

Jacobson SN, Alexander M (1981) Enhancement of the microbial dehalogenation of a model chlorinated compound. Appl Environ Microbiol 42:1062–1066

Jais NM, Mohamed RMSR, Apandi WA, Matias-Peralta H (2015) Removal of nutrients and selected heavy metals in wet market wastewater by using microalgae *Scenedesmus* sp. Appl Mech Mater 773–774:1210–1214

Jais NM, Mohamed RMSR, Al-Gheethi AA, Hashim MA (2017) The dual roles of phycoremediation of wet market wastewater for nutrients and heavy metals removal and microalgae biomass production. Clean Technol Environ Policy 19(1):37–52

Jin Y, Veiga MC, Kennes C (2005) Bioprocesses for the removal of nitrogen oxides from polluted air. J Chem Technol Biotechnol 80:483–494

Jing S (2009). Removal of nitrogen and phosphorus from municipal wastewater using microalgae immobilized on twin-layer system. Ph.D. thesis, Universitätzu Köln, Germany

Jinqi L, Houtian L (1992) Degradation of azo dyes by algae. Environ Pollut 75:273–278

Kamarudin KF, Yaakob Z, Rajkumar R, Takriff MS, Tasirin SM (2013) Bioremediation of palm oil mill effluents (POME) using *Scenedesmus dimorphus* and *Chlorella vulgaris*. Int J Adv Sci Lett 19:2914–2918

Kim MK, Park JW, Park CS, Kim SJ, Jeune KH, Chang MU, Acreman J (2007) Enhanced production of *Scenedesmus* spp. (green microalgae) using a new medium containing fermented swine wastewater. Biores Technol 98(11):2220–2228

Kothari R, Pathak VV, Kumar V, Singh DP (2012) Experimental study for growth potential of unicellular alga *Chlorella pyrenoidosa* on dairy waste water: an integrated approach for treatment and biofuel production. Biores Technol 116:466–470

Kotteswari M, Murugesan S, Ranjith Kumar R (2012) Phycoremediation of dairy effluent by using the microalgae *Nostoc* sp. Int J Environ Res Dev 2(1):35–43

Laliberte G, Olguin EJ, Noue JDL (1997) Mass cultivation and wastewater treatment using Spirulina. In: Vonshak A (ed) *Spirulina platensis*-physiology, cell biology and biotechnology. Taylor and Francis, London (UK), pp 59–73

Lam MK, Lee KT (2012) Microalgae biofuels: a critical review of issues, problems and the way forward. Biotechnol Adv 30(3):673–690

Li X, Hu H, Gan K, Sun Y (2010) Effects of different nitrogen and phosphorus concentrations on the growth, nutrient uptake and lipid accumulation of a freshwater microalga *Scenedesmus* sp. Biores Technol 101:5494–5500

Liu J, Ge Y, Cheng H, Wu L, Tian G (2013) Aerated swine lagoon wastewater: a promising alternative medium for *Botryococcus braunii* cultivation in open system. Biores Technol 139:190–194

Martinez ME, Sanchez S, Jimenez JM, Yousfi EF, Munoz L (2000) Nitrogen and phosphorus removal from urban wastewater by the microalga *Scenedesmus obliquus*. Biores Technol 73(3):263–272

Mata TM, Martins AA, Caetano NS (2010) Microalgae for biodiesel production and other applications: a review. Renew Sustain Energy Rev 14:217–232

Min M, Wang L, Li Y, Mohr MJ, Hu B, Zhou W, Chen P, Ruan R (2011) Cultivating *Chlorella* sp. in a pilot-scale photobioreactor using centrate wastewater for microalgae biomass production and wastewater nutrient removal. Appl Biochem Biotechnol 165:123–137

Mohamed RM, Al-Gheethi AA, Aznin SS, Hasila AH, Wurochekke AA, Kassim AH (2017) Removal of nutrients and organic pollutants from household greywater by phycoremediation for safe disposal. Int J Energy Environ Eng:1–14

Munoz R, Kollner C, Guieysse B (2009) Biofilm photobioreactors for the treatment of industrial wastewaters. J Hazard Mat 161(1):29–34

Ogbonna JC, Yoshizawa H, Tanaka H (2000) Treatment of high strength organic wastewater by a mixed culture of photosynthetic microorganisms. J Appl Phycol 12:277–284

Pathak VV, Singh DP, Kothari R, Chopra AK (2014) Phycoremediation of textile wastewater by unicellular microalga *Chlorella pyrenoidosa*. Cell Mol Biol 60(5):35–40

Phang SM, Miah MS, Yeoh BG, Hashim MA (2000) Spirulina cultivation in digested sago starch factory wastewater. J Appl Phycol 12:395–400

Rao HP, Kumar R, Raghavan BG, Subramanian VV, Sivasubramanian V (2011) Application of phycoremediation technology in the treatment of wastewater from a leather-processing chemical manufacturing facility. Water SA 37(1):07–14

Rawat I, Kumar RR, Mutanda T, Bux F (2011) Dual role of microalgae: phycoremediation of domestic wastewater and biomass production for sustainable biofuels production. Appl Energy 88:3411–3424

Richmond A (2004) Environmental effects on cell composition. In: Handbook of microalgae culture—biotechnology and applied phycology. Blackwell publishing, Oxford, UK, pp 83–93

Sawayama S, Inoue S, Dote Y, Yokoyama SY (1995) CO_2 fixation and oil production through microalga. Energy Convers Manage 36:729–731

Silambarasan T, Vikramathithan M, Dhandapani R, Mukesh DJ, Kalaichelvan PT (2012) Biological treatment of dairy effluent by microalgae. World J Sci Technol 2(7):132–134

Spolaore P, Joannis-Cassan C, Duran E, Isambert A (2006) Commercial applications of microalgae. J Biosci Bioeng 101:87–96

Tran NH, Bartlett JR, Kannangara GSK, Milev AS, Volk H, Wilson MA (2010) Catalytic upgrading of biorefinery oil from micro-algae. Fuel 89:265–274

Walker JD, Colwell RR, Petrakis L (1975) Degradation of petroleum by an alga, *Prototheca zopfii*. Appl Microbiol 30:79–81

Wang L, Li YC, Chen P, Min M, Chen YF, Zhu J, Ruan RR (2010) Anaerobic digested dairy manure as a nutrient supplement for cultivation of oil-rich green microalgae *Chlorella* sp. Biores Technol 101:2623–2628

Whitacre JM (2010) Degeneracy: a link between evolvability, robustness and complexity in biological systems. Theoretical Biol Med Model 7(1):6

Wurochekke AA, Mohamed RMS, Al-Gheethi AA, Atiku H, Amir HM, Matias-Peralta HM (2016) Household greywater treatment methods using natural materials and their hybrid system. J Water Health 14(6):914–928

Xin HS, Schaefer DM, Liu QP, Axe DE, Meng QX (2010) Effects of polyurethane coated urea supplement on in vitro ruminal fermentation, ammonia release dynamics and lactating performance of Holstein dairy cows fed a steam-flaked corn-based diet. Asian-Aust J Anim Sci 23:491–500

Xu Y, Purton S, Baganz F (2013) Chitosan flocculation to aid the harvesting of the microalga *Chlorella sorokiniana*. Biores Technol 129:296–301

Yao L, Shi J, Miao X (2015) Mixed wastewater coupled with CO_2 for microalgae culturing and nutrient removal. PLoS ONE 10(9):e0139117. https://doi.org/10.1371/journal.pone.0139117

Yun YS, Lee SB, Park JM, Lee CI, Yang JW (1997) Carbon dioxide fixation by algal cultivation using wastewater nutrients. J Chem Technol Biotechnol 69:451–456

Zeng J, Singh D, Chen S (2011) Thermal decomposition kinetics of wheat straw treated by *Phanerochaete chrysosporium*. Int Biodeterior biodegradation 65(3):410–414