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Review Paper

Potential Use of High Rate Algae Ponds for Resource Recovery in the Water-Food-Energy Nexus for Tanzania: A Review

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ABSTRACT

The use of High Rate Algal Ponds (HRAPs) for the treatment of wastewater and resource recovery has raised interest in recent years. Treatment of wastewater through this technology has proved to have high efficiency in reducing the level of pollution, nutrients, dissolved solids as well as pathogens. HRAPs are more efficient than conventional Wastewater Stabilization Ponds (WSPs) due to their design approach that provides room for high rate bio-chemical processes, which increase the mechanisms of nutrients and pathogens removal as well as the rate of micro-algae production for purposes of resource recovery. This paper reviews the upgrading potential of existing WSPs to HRAPs for resource recovery from products of wastewater for biofuel production, as a plant nutrient or for irrigation purposes and animal feeding. Several results have reported HRAPs to have efficiency in reducing bacterial contamination in excess of 99% while the removal of organic matter of up to 84% for Chemical Oxygen Demand (COD) and 88% for Biochemical Oxygen Demand under normal conditions have been reported. The removal for nitrogen was indicated to vary from 50 to 98% while that of phosphorus varies from 32 to 99% depending on the culture conditions. It was further noted that, the potential for resource recovery from HRAPs is high in terms of energy and nutrients recovered through algae biomass, particularly for biofuel and animal feed production. Whereas among the dominant algal species of the HRAP Chlorella vulgaris revealed to have suitability in both treatment of wastewater and achieved a higher effluent quality and having nutrients contents essential for lipid extraction for biofuel and as a protein source for animal feeding which is largely attributed by their ability to grow very rapidly and to tolerate varieties of cultural conditions. To date, limited research attention has been given to studying the re-use potential of wastewater for irrigation purposes in Africa.

Keywords: *High rate algal ponds, Wastewater Treatment, Micro-algae, Resource Recovery.*

INTRODUCTION

The application of High Rate Algal Ponds (HRAPs) for the treatment of wastewater has raised interest and caught global attention in recent years (Pittman *et al.*, 2011) although numerous studies on use of

high rate ponds for nutrients removal for resource recovery have been carried out for over 60 years (Oswald *et al.*, 1957; Oswald and Golueke, 1960; García *et al.*, 2000; Craggs *et al.*, 2014; Drira *et al.*, 2016). HRAPs were first developed in the United States of America in the middle of the 20th century for wastewater treatment (Oswald et al., 1957; Oswald and Golueke, 1960). They are now being used in different parts of the world including Israel, South Africa (Azov et al., 1982; Abeliovich, 1986; Buhr and Miller, 1983; Shelef and Azov 1987), Morocco (Bouchaib, 2009), Australia (Young et al., 2016), France (Picot et al., 1991), the United Kingdom (Fallowfield and Garrets, 1985), Spain (García et al., 2008), China, and New Zealand (Craggs et al., 2012; Craggs et al., 2014).

Previous studies have shown that HRAPs are more efficient than conventional Waste Stabilization Ponds (WSPs) for the treatment of wastewater and algae production that can be used for various resource recovery applications (Sayre, 2010; Craggs et al., 2014; Butler et al., 2017). They are considered as effective reactors that reclaim water; nutrients and energy from organic wastewater (Young et 2017). Micro-algae possess the al., potential to produce bio-oils as a source of energy, carbohydrates, proteins, amino acids and other value-added products (Cooney et al., 2011). In accordance with Burlew (1953), the first micro-algae cultivation started in early 19th century with Chlorella vulgaris. The mass cultivation of micro-algae began in the 1940s in the United States, Germany, and Japan, while the first commercial largescale micro-algae culture system using Chlorella was developed in the 1960 (Park et al., 2018).

In most of urban centres, management of both faecal sludge and wastewater is posing a lot of challenges (Brandes *et al.*, 2015). Due to high rates of urbanisation, population growth and economic development, the generation of wastewater is increasing rapidly, especially in the Global South (Phuntsho *et al*, 2017). It has been estimated that 80% of wastewater generated globally, is directly discharged into the environment without being treated or being re-used, with 90% in developing countries (D'Andrea *et al.*, 2015). Several technologies for the treatment of faecal sludge and wastewater are practiced, but the most common treatment technology used in tropical climate is Wastewater Stabilization Ponds (WSPs) because of the favourable climatic conditions (Mara, 2013; Craggs *et al.*, 2003). This enables most of the biological systems to function effectively without human interference (Mayo, 2013).

The conventional WSPs systems discharge high levels of nutrients in their effluents, which contribute to water eutrophication, which in turn can affect the aquatic life of receiving water bodies (Garcia and Marine, 2000). High levels of nutrients in the effluents also accelerate the growth of algae blooms on the surface of the storage ponds (Mbwele, 2006). Some scholars have reported that excessive nitrogen in water in form of nitrate can cause methaemoglobinemia infants in and susceptible populations, and in the form of ammonia it is toxic to fish and exerts oxygen demand in receiving water by nitrifiers (Mayo, 2013; Picot et al., 2009). In accordance with Liu et al. (2017) several pathogens, such as bacteria and helminths, responsible for causing communicable diseases are found in effluents of conventional ponds, and their values generally exceed the permissible limits that pose risks to public health. Unfortunately, many of the pond systems are not designed to optimise the recovery of resources from wastewater.

HRAPs are closed-loop, paddlewheelmixed ponds, which can take a few metres of an area in which a typical design consist of a series of parallel meandering channels (Figure 1). Among the operational features of HRAPs, depth has been taken as a crucial input for the pond performance (García and Marine, 2000; Craggs *et al.*, 2012; Sutherland *et al.*, 2014). Basing on various recommendations from literature,

HRAPs should maintain a shallow depth as much as possible since shallow depth allows much light to penetrate throughout the pond system whereby micro-algae cells are exposed to optimal light. The optimal range of depth reported in literature ranges from 0.2 to 0.5 m. The technology essentially consists of shallow race track reactors with mechanical mixing which recirculate the contents of the pond in which the interchange of CO_2 and O_2 is promoted between algae and aerobic organisms (Buhr and Miller, 1983).

Studies show that high rate pond systems have incorporated many improvements of

conventional ponds (Young *et al.*, 2017). Their designs provide room for high rate bio-chemical processes, which speeds up the removal of sludge disposal, minimizes bad odours and increases the mechanism of nutrients and pathogens removal (Craggs *et al.*, 2014). They are more economic than conventional ponds and they provide micro-algae for biofuel production, food and animal feed (Paulo *et al.*, 2009; Sayre, 2010; Rupiper, 2016). The purpose of this paper is to review the potential uses of HRAPs with focus on opportunities of re-using the resources recovered from wastewater.



Figure 1: A laboratory-scale High Rate Algal Pond at New Mexico State University (source: https://www.google.com/search?q=Photos+of+high+rate+algal+pond

PERFORMANCE OF HRAPs IN WASTEWATER TREATMENT

Operational factors that manage the performance of HRAPs include the pond depth and its influence on light penetration which account for the light regime to which the photosynthetic organism has to be exposed, Hydraulic Retention Time (HRT) of the effluent in the pond as well as effect of turbulence on nutrients availability and exposure to light intensity. The operating characteristics of HRAPs are largely determined by the various interactions between the several chemicals and the biological processes within the system as well as the environmental factors.

Removal of Chemical and Biochemical Oxygen Demand

The organic compounds of wastewater comprise of a large number of compounds

with all having at least one carbon atom. The carbon atom in these compounds can be oxidized biologically by bacteria to yield CO₂. Some of the algae species have been reported to have high efficiency of removing organic matter. In accordance with literature (Choi and Lee, 2012) the removal efficiency of organic matter increased with an increased amount of *Chlorella vulgaris*. By increasing *Chlorella vulgaris* concentration from 1 to 10 g/L, the removal efficiency of organic matter increased from 80.4% to 82.9% for BOD₅ and 78.3% to 82.3% for COD (Table 1).

 Table 1: Chemical and Bio-chemical Oxygen Demand Percentage Removal Efficiency in

 High Rate Ponds

Algal Specie		COD		BOD ₅	Reference		
	% Removal	Condition/addition	%Removal	Condition/addition			
Micractinium	77.4%	Normal	N/A	N/A	Nurdogan and		
	84%	80mg/l CaO N/A N/A		Oswald (1995)			
Not Specified	35%	HRT = 4 days	N/A	N/A	García et al. (2006)		
	38%	HRT = 7 days	HRT = 7 days N/A N/A				
Chlorella vulgaris	10%	HRT = 4 days	N/A	N/A	Cromar and		
Phormidium Sp	30%	HRT = 7 days	N/A	N/A	Fallowfield (1997)		
Scenedesmus Sp							
Chlorella vulgaris	67.2%	Normal	68.4%	Normal	Colak and Kaya.		
					(1988)		
Fragilaria,							
Euglena,	50%	Normal	N/A	N/A	Chen <i>et al.</i> (2003)		
Chlorella,							
Micratinium,							
Cyclotella,							
Navicula							
Not Specified	N/A	N/A	~ 50%	BOD ₅	Craggs <i>et al.</i> (2012)		
	N/A	N/A	~ 87%	fBOD ₅			
Scenedesmes	31%	Normal	32%	Normal	Doma et al. (2015)		
obliquus and							
Micracitinium							
pusillum							
Chlorella vulgaris	66%	Normal	70%	Normal	Sahu (2014)		
Chlorella vulgaris	78.3%	1 g/L C. vulgaris	80.4%	1 g/l C. vulgaris			
	82.3%	10g/L C. vulgaris	82.9%	10g/1 C. vulgaris	Choi and Lee (2012)		
Not Specified	N/A	N/A	88%	Normal	Hamouri et al. (1994)		

HRT= Hydraulic retention time, BOD_5 = Biochemical oxygen demand after five days, $fBOD_5$ = Filtered Biochemical oxygen demand after five days COD = Chemical oxygen demand and N/A = Not applied

Nutrients Removal

Nutrients like nitrogen and phosphorous can be removed in HRAPs through biological treatment of wastewater. In sewage effluent, nitrogen primarily arises from metabolic inter-conversions of several compounds, while 50% or more of the phosphorus arises from synthetic Principally, detergents. nitrogen in wastewater occurs in form of NH4⁺ (Ammonia), NO_2^- (nitrite), NO_3^- (nitrate) and phosphorus in most cases is in the

form of PO_4^{3-} (orthophosphate). The removal of these two elements is by nutrients stripping, uptake by microorganisms and precipitation. When these nutrients are in excess in receiving water bodies, they cause eutrophication which in turn leads to excessive growth of harmful microalgal blooms (Abdel-Raouf et al., 2012). However, several studies have shown that a HRAP fed with clarified domestic wastewater with CO_2 supplement, can remove nutrients to levels of concentration better than those achieved

in conventional ponds (Woertz *et al.*, 2009; Craggs, 2012; Batter, 2013).

Nitrogen transformation and removal in High Rate Algal Ponds

Organic nitrogen and NH₃ enter into the system of HRAPs with the influence of wastewater. Organic nitrogen in faecal other organic matter and materials undergoes conversion to NH₃ and ammonium ion (NH⁺₄) by microbial activity. When HRAPs efficiently operate in treating wastewater, nitrogen is effectively removed (Jones et al., 2016). The concentration of nitrogen is lowered in the effluent by bacteria, denitrification, algal assimilation and NH₃ volatilization when pH is very alkaline. The major mechanisms for removal of nitrogen are of ammonia by uptake algae and nitrification-denitrification process and to some extent stripping of ammonia (NH₃) (Mayo, 2013; Mayo and Mutamba, 2004). Nutrient removal is highly influenced by massive growth of micro-algae and chlorophyll concentration whereby pH and temperature are the main contributing factors (Mayo et al., 2018). For example, in summer, higher temperatures favour algal productivity and performance of HRAP in reducing NH₄-N in the effluent and with high pH, a large portion of the nitrogen is removed through ammonia volatilization. High daytime pH generated in the ponds due to algal uptake of bicarbonates, shifts the equilibrium in favour of NH₃, which may volatilize into the atmosphere when pH exceeds 9.0.

According to Chen *et al.* (2003), in a study, ammonia in the influent was by 71% while in the effluent concentration reduced to less than 12% and also the oxidized forms, the nitrite and nitrate appeared to be 19.3% with the mass balance showing a loss of nitrogen by 44.6%.

Micro-algae normally lower the concentration of nitrogen in the effluent through algal assimilation when the algae harvesting is incorporated and in turn contributes to the conditions that are favourable for the massive growth of algae whereby algal biomass and chlorophyll increase (Abdel-Raouf et al., 2012). On the other hand, bacteria nitrification also plays a role of oxidation of NH₄-N into NO₂-N and NO₃-N in the pond system. Ammonium is nitrified to nitrite (NO_2) by Nitrosomonas bacteria then to nitrate (NO_3) by Nitrobacter (USEPA, 2011). In anoxic conditions nitrate may by bacteria as an electron acceptor of electrons released by organic matter, thus reducing it to nitrogen gas.

Mechanism of phosphorous removal

In wastewater, phosphorus can be found in three forms; Organic phosphorus compounds, polyphosphates or condensed phosphates and orthophosphates, which carries 80% of the total phosphate in wastewater. Organic phosphorus compounds are mainly insoluble phosphor-proteins, nucleic acids and polysaccharides. Polyphosphates are in form of polymers of phosphoric acid while orthophosphates in HRAPs is as a result of complete hydrolysis of polyphosphates and total decomposition of organic phosphorus compounds through biological treatment of sewage (Nurdogan and Oswald, 1995). There are several forms of orthophosphates which is as a result of function values of pH. At the neutral pH of the domestic wastewater; the predominant form of pH is HPO₄²⁻. At high rate of photosynthesis, the pH of wastewater in HRAPs may raise up to 11 in the afternoons of the summer days and around 9 during winter seasons. However, pH can increase in the pond due to photosynthetic depletion of dissolved CO₂ under inorganic - carbon limited growth of algae (Woertz et al., 2009).

Orthophosphates are essential for growth of algae and other macrophytes. To avoid eutrophication in receiving water bodies, they have to be removed during wastewater treatment process. In algal cells, phosphates typically fall within the range of 0.35 to 1% (Craggs *et al.*, 2012) and may also reach 3.16% when there is luxury uptake. Phosphorus may be removed from wastewater by precipitation resulting from chemical addition or elevated pH levels (Chen *et al.*, 2003; Rodrigues, 2013) and sometimes with longer Hydraulic Retention Time (HRT) (Table 2). Polyphosphates and organic phosphorus are known to be removed by adsorption on CaCO₃ crystals, which are formed in significant amounts in the pH range of HRAP operation. Precipitation is the main cause of phosphate removal in calcium – rich ponds. Therefore, calcium must be added in ponds with low concentration of calcium (Picot *et al.*, 1991).

Algal Specie	Nitrogen		Pl	osphorus	Reference	
	% Removal	Condition/addition	% Removal	Condition/addition		
Chlorella vulgaris	86%	Normal	78%	Normal	Lau et al. (1996)	
Not Specified	50%	Normal	85.7%	Normal	Colak and Kaya. (1988)	
Micractinium	85%	Normal	45-55%	20-40mg/l CaO	Nurdogan and Oswald	
	90%	60-80mg/l CaO	99%	60mg/l CaO	(1995)	
Not Specified	73%	HRT = 7 days	43%	HRT = 7 days	García et al. (2006)	
	57%	HRT = 4 days	32%	HRT = 4 days		
Multiple species	69%	HRT = 4 days	17% Con P	HRT = 4 days	Cromar and	
Chlorella vulgaris	69% ~	HRT = 4 days	45% Ex P	HRT = 4 days	Fallowfield (1997)	
Phormidium Sp	78% ~	HRT = 7 days	69% Con P	HRT = 7 days		
Scenedesmus Sp	78% ~	HRT = 7 days	93% Ex P	HRT = 7 days		
Not Specified	94%	Normal	71%	Normal	Picot et al. (1991)	
Fragilaria, Euglena, Chlorella, Micratinium,	87%	Normal	40%	Normal	Chen et al. (2003)	
Cyclotella, Navicula						
Mixed cultures	>98%	CO ₂	>96%	CO ₂	Woertz et al. (2009)	
Not Specified	~65%	CO ₂	~19%	CO ₂	Craggs et al. (2012)	
Not Specified	~60%	CO ₂	N/A	N/A	Park and Craggs (2010)	
Scenedesmes obliquus and Micracitinium pusillum	56%	Normal	N/A	N/A	Doma et al. (2016)	
Chlorella vulgaris	71%	Normal	67%	Normal	Sahu (2014)	
Chlorella vulgaris	81.04%	1g/L C. vulgaris	32.26%	1g/L C. vulgaris	Choi and Lee (2012)	
	84.81%	10g/L C. vulgaris	50.12%	10g/L C. vulgaris		
Not Specified	69%	Normal	52%	Normal	Hamouri <i>et al.</i> (1994)	

 Table 2: Nutrient Percentage Removal Efficiency in High Rate Ponds

HRT = Hydraulic retention time, Con p = Control pond, Ex p Experimental pond and N/A = Not applied

Mortality of Faecal Bacteria

There are several pathogenic organisms in wastewater including bacteria such as *Salmonella* and *Shigella*, protozoa, viruses and helminth eggs (Abdel – Raouf *et al.*, 2012). Several results have reported that HRAPs are efficient in reducing bacterial contamination and the number of nematodes eggs. Apart from HRAPs being used for resource recovery attributed by massive growth of algae, it is also very important in treatment of wastewater (Oswald and Goueke, 1960; Oswald,

1995). Algae supply the oxygen demanded for bacteria degradation of organic matter, and bacteria excrete mineral compounds that provide the algae with nutrition which accelerate in turn the rate of photosynthesis. High rate of photosynthesis increases the level of pH which increase the mortality rate of pathogens. Among the pathogenic organisms, bacteria provide a large number of microbial communities in all biological wastewater treatment processes and several studies have reported the number in the range of 10^6 and above (Hamouri *et* al., 1994; Bahlaoui, and Troussellier, 1997; Abdel - Raouf et al., 2012; Doma et al., 2015). However, considerable pathogen removal of more than 99% can be achieved in HRAPs (Bahlaoui and Troussellier, 1997).

At rapid growth of algae, the pH can rise up to and above 9, which is favourable for bacterial removal (Parhad and Rao, 1974; Young et al., 2017). When algal activity is at its peak, carbonate and bicarbonate ions react to provide more carbon dioxide for algae, leaving an excess of hydroxyl ions. A pH above 9 for 24 hours ensures nearly 100% killing of *E. coli* and presumably most pathogenic bacteria (Young et al., 2017). Other factors for faecal bacteria die-off include high temperature with increased time (Marais, 1974; Mancini, 1978; Mills et al., 1992), starvation (Gann et al., 1968), microbial antagonism (Polprasert et al., 1983), production of toxic substances by algae (Merz et al., 1962) as well as high light intensity due to shallow depth (Mayo, 1989; Mayo, 1995). Light of wavelength 425-700 nm can damage faecal bacteria. Ultraviolet radiation is known to disinfect bacterial cells, even those resistant to antibiotics. Meckes (1982) reported that total coliform resistant streptomycin, isolates to tetracycline, and chloramphenicol were disinfected by ultraviolet radiation. Fujioka et al. (1981) and Kapuscinski and

Mitchell (1983) have reported that visible light can also disinfect coliforms.

MICRO-ALGAE BIOMASS PRODUCTION

Among other plants, algae have been mentioned to have more efficiency to utilize energy from visible light. Microalgae have the ability to grow very fast and yield high biomass, using non-fresh water streams as substrate (Park et al., 2013). They do not interfere with food security if produced for biofuels, and can be harvested daily. The generated fuel has less emission of CO₂ compared to petroleum-based fuels, and therefore might reduce greenhouse gas emissions (Park et al., 2018). In high rate algal ponds, up to 30 tons/ha/year of algae can be produced and their yield may increase up to 60 tons/ha/year if CO₂ is artificially applied for extra carbon supply. In conventional WSPs, the algae production is much lower, and can only go up to 10 tons/ha/year (Craggs et al., 2011; Craggs et al., 2014; Montemezzani et al., 2015).

The key input for the algae growth include wastewater, sunlight and high solar radiation, sustainable source of CO₂ and nutrients (Batten, 2013). Production of algae is more reliable compared to other traditional plants as algae have the ability to operate in two distinct environments. This is aerobic and anaerobic alteration of photosynthesis-respiration relationship. which turn leads continous in to production of massive microalgae (Bala-Amutha and Murugesan, 2011). Several studies have reported that the mutual interaction between algae and bacteria has a significant impact on algal growth (Buhr and Miller, 1983; Medina and Neis, 2007; Fuentes et al., 2016), since the presence of symbiotic relationship between bacteria and algae is beneficial to the massive production of micro-algae and algal products. Both algae and bacteria alter their metabolism to meet each other's needs, micronutrients like vitamins and macronutrients like nitrogen and carbon are usually exchanged between algae and bacteria (Medina and Neis, 2007), and plant hormones excreted from bacteria also promote algal growth. A typical example showing the mutual relationship is when bacterial species supply vitamin B12 to an algae as an exchange for fixed carbon. When some algae are grown with an of artificial consortium mutualistic bacteria, they supply fixed organic carbon to the consortium and in return, they show enhanced growth (Wrede et al., 2014; Fuentes *et al.*, 2016).

Efficiency of algal biomass production also depends on haversting and dewatering mechanisms (Golueke and Oswald, 1965). The mechanisms involved include centrifugation, flocculation, filtration, gravity sedimentation, screening. floatation and electrophoresis techniques. Haversting techniques depend on the properties of the microalgae such as size, shape, density and also uses of the targeted outputs. Dewatering process is important for the equally biomass production according to the study done by Batten et al. (2013).

Several methods for drying can be deployed for the achievement of concentration of 99% to 100% suspended solids before the biomass being used for targeted purposes (Christi, 2008; Cooney et al., 2009). Upon drying, extraction can be followed whereby the internal triglycerides and free fatty acids can be extracted from the algal biomass into biofuel such as biodiesel or jet fuel (Cooney et al., 2011). To some of algae species such as Nannochloropsis ssp, Chlorella spp, and Scenedesmus spp., 100% extraction has to be taken into consideration as most of the oleaginous microalgae possess hard cell walls that coupled with small cell sizes hinder the total oil extraction in strains. (Cooney et al., 2009).

In a single use energy stream, the fuel would be a final valuable product and the nutrients and energy would be lost while in a closed energy loop system, the products feed back into the production e.g. burning biofuels result in production of carbon doxide, which can be recycled for algal growth. Therefore, since carbon and nutrients are cycled with the use of energy from the sun, the system is renewable and carbon neutral (Rupiper, 2016).

MICRO-ALGAE BIOMASS UTILIZATION

Little attention has been paid in utilization of micro-algae that can be generated in wastewater ponds (Craggs *et al.*, 2014; Young *et al.*, 2017). The harvested algal biomass can be potentially used as fertilizer, protein-rich animal feed, or can be converted into biofuel; like biogas via anaerobic digestion (Heubeck *et al.*, 2007), bio-ethanol via carbohydrate fermentation (Hwang *et al.*, 2016), bio-crude oil via high temperature liquefaction (Jegathese and Farid, 2014), or biodiesel via lipid trans-esterification (Craggs *et al.*, 2011; Montemezzani *et al.*, 2015; Driver *et al.*, 2014).

Micro-algae for Bio-fuels

The consumption of fossil fuels is increasing at an alarming rate globally. Petroleum reserves are shrinking at a fast in turn creating demand for pace. alternative sources of fuel (Mutanda et al., 2011). The current systems for production of alternative energy do not account for the water and energy crisis, neither for the food security since the production of traditional crops for biofuel and feed e.g. terrestrial oil seed plants, soybeans, corn, sunflower, palm, Jatropha, cassava, coconut, rice straws, witch grass, need arable land for their cultivation and hence conflicting with agricultural land used for food crops (Park et al., 2018). All these

challenges ought to have alternative source of nutrients and energy, which can be obtained from the utilization of microalgae.

Due to the current consumption trend, fossil fuels may run out within several decades (Khan et al., 2017; Park et al., 2018). Over 80% of energy consumption comes from fossil fuels, which is not only non-renewable energy, but it is also one of the main contributors of global climate change (Pittman, 2011; Jegathese and Farid, 2014; Mehrabadi et al., 2016; Young et al., 2017). It is factual that, in life cycle while algal biodiesel reduces carbon emmissions and 50% loss life cycle production of greenhouse gases, petrol based fuel release it (Slade and Bauen, 2013). Algae can sequester CO_2 about 10 to 50 times more efficiently than land crops (Maity et al., 2014; Rupiper, 2016). It is prospected that algae biodiesel will almost completely replace conventional biodiesel by 2040, to reduce global warming and achieve CO₂ emission (Khan et al., 2017). One of the objectives of the Copenhagen Accord which took place in the past few years, was to promote the use of renewable energy to replace the fossil fuels since they are environmentally friendly and carbon neutral (Lee, 2011; Lau et al., 2012). It is important to understand that, micro-algae for bio-fuel production are advantageous because apart from contributing to alternative energy, they avoid using food crops for fuel production, hence enhances food security. In accordance with Khan et al. (2017), algae species such as tribonema, ulothrix and euglena have good potential of biodiesel production and it is estimated that the use of HRAPs for wastewater treatment could save up to 50% of energy that typical mechanical systems use (Rupiper, 2016).

One of the strongest facts in comparison between cost-benefit analysis of using algal biofuel to petrol-diesel is that, biofuel

is a renewable fuel while petrol-diesel have a limited and diminishing supply. Therefore, as time goes on, the cost implications of petrol-diesel will be increase because of limited supply whereas algal biofuel production from wastewater will not face that shortfall (Maity et al., 2014; Rupiper, 2016). Therefore, the use of biodiesel from wastewater algae is promising and potentially cost effective compared to petro-diesel (Craggs et al., 2011; Pittman, 2011). The petrol-diesel market price is still more expensive, even at the average cost it is almost four times more expensive than biodiesel by as much as US\$ 2.67 per gallon (Slade and Bauen, 2013; Maity et al., 2014; Rupiper, 2016). A study done by Rupiper (2016) found that biodiesel is more cost-effective than petroleum-diesel based fuel.

Several studies have indicated that algae have oil content with different composition depending on the species (Greenwell et al., 2010; Park et al., 2013). Some have good fatty acid value, hence highlighting the potentials of their utilization (Khan et al., 2017). A study done by Drira (2016) found out that *Chlorella sp* have high fatty acid content, almost 70% of lipids extracted from the harvested biomass with more palmitic and stearic acids. In accordance with several researchers the algae harvested from full-scale HRAP treating domestic wastewater through increase of pH, performs the recovery of more than 96% of biomass chlorella vulgaris, Dunaliella tertiolecta. Tibonoma minus. Nannochloropsis and *Tetraselmis* (Greenwell et al., 2010; Mutanda et al., 2011; Jegathese and Farid, 2014; Milledge et al., 2014; Wrede et al., 2014; Hwang et al., 2016; Mehrabadi, 2016).

The high oil content and rapid production of algal biodiesel cycle can ensure stable supply (Dermibas, 2010). Many studies using micro-algae conducted to produce biofuels most especial biodiesel and this is because generally micro-algae contain relatively low carbohydrate contents but high lipid contents in their cells (Mata *et al.*, 2011). Micro-algae contain glucose based carbohydrates, which is suitable sugars for bioethanol production. From the study done by Mehrabadi *et al.* (2016), *Chlorella vulgaris* is a prominent algae specie that is appropriate for all bio-fuel production types (Table 3).

Biofuel Type	Microalgae species	Algae composition (%)			Reaction Temperature	Time	Yield	
rype		L	Р	С	(°C)			
Biodiese	1				· · · · · · · · · · · · · · · · · · ·	Minutes	g biodiesel/	
			,				g biomass	
	Dunaliella tertiolecta	19	NG	NG	340	0.5	NG	
	Chlorella vulgaris	38.9	NG	NG	60	120	0.3	
	Chlorella sp	12	NG	NG	60	1140	NG	
	Nannochloropsis oceanic	24.8	NG	NG	60	2880	0.2963	
Biogas						Days	CH ₄ in biogas %	
	Scenedesmus spp & Chlorella ssp (50%) and 50% of waste paper.	NG	NG	NG	35	10	68-72	
	Scenedesmus (30%) and 70% Chlorella	NG	NG	NG	37	23	56-60	
	Scenedesmus (40%) and 40% Chlamydomonas	NG	NG	NG	35	NG	40-60	
Scenedesmus obliquus		NG	NG	NG	33	30	0.61	
Bio-etha	nol					Days	g bio-ethanol / g biomass	
	Chlorococum sp	NG	NG		30-40	60	0.23-0.37	
	Chlorococum humicola	NG	NG	32.52	30	50	0.027-0.52	
	Scenedesmus obliquus	NG	NG	29	30		0.023	
	Spirulina platensis	NG	NG	58	30	24	0.13-0.16	
	Chlorella vulgaris	NG	NG	55	33	26	0.167	
Bio-crude oil						Minutes	g bio-oil/ g biomass	
	Chlorella vulgaris	25	55	9	350	60	0.28-038	
	Chlorella pyronoidosa	0.1	71.3	NG	280	120	0.359	
	Scenedesmus obliquus	16.8	28		250-375	5	0.176-0.505	
	Nanochloropsis oceania	24.8	19.1	22.7	300	30	0.40	
	Dunaliella tertiolecta	23.4	50.8	NG	250-275	5	0.553	

Table 3: Recently Published Results of Biofuel Production from Algal Biomass

Modified from Mehrabadi et al. (2016)

NG = not given, L= lipids, C= Carbohydrates, P= Proteins

Micro-Algae for Food and Feed

Organisms require food to supply the energy that they need for movement and other activities in which they engage, as well as building blocks for their growth. The rise in global population has led a concern of exploring alternative sources of food. Corn and soybean remain to be the main staple food crops in so many human societies, as a dominant source of energy and protein (Lum *et al.*, 2013). However, food processing for animals directly competes with the human consumptions. From several studies (Benemann, 2013; Lum *et al.*, 2013; Norambuena *et al.*, 2015), it is seen that the micro-algae biomass has been generated for potential biofuel production may be a viable replacement of food crops due to their high level of protein, relatively well balanced amino acids and rich contents of minerals and vitamins together with bioactive compounds (Lum *et al.*, 2013). Microalgae and cyanobacteria are a promising source of protein for food and feed purposes, (Craggs et al., 2014; Smetana et al., 2017). Several researchers have reported that paddle-wheel mixed algal growth ponds are not only costeffective for wastewater treatment, but are also very efficient for reclaiming nutrients in algal biomass, which in turn can be used for animal feed (Oswald 1995; Batten, 2013; Hwang et al., 2016). Considerable efforts have been directed towards removal of algae from the effluent polishing pond for the purposes of upgrading the quality of effluent, and recovering a valuable source of food for animals (Golueke and Oswald, 1965, García et al., 2000).

Micro-algae are a main source of omega-3 (n-3) polyunsaturated fatty acids, including docohexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which can also be obtained in eggs, meat and milk. They also contain -linoleic acid (Austic et al., 2013; Benemann, 2013) and have high iodine content (He et al., 2002). The biomass has high crude protein content and could be used as animal feed with proper processing, and could thus be considered as an attractive alternative for animal feedstocks (Norambuena *et* al., 2015). However, recent studies have shown that sewage grown algae such as chlorella and scenedesmus sp, have drawn attention as potential nutrients sources due to their high crude protein and carotenoid contents, and the recent estimates indicate that 30% of the global algae production is used by the animal feed industry (Becker, 2004). Since protein is considered to be the most expensive nutrient in animal feeding (Rezael et al., 2013), proper utilization of algae can be of great benefits.

The advantage of harvesting micro-algae is that the same harvested product can be used for two purposes. Firstly, for the extraction of lipids and secondly, the remaining product serve as animal feed (Lum *et al.*, 2013). The remaining microalgae skeletons after lipid extraction, the so-called de-fatted micro-algae biomass can be used as animal feed and adjusting the current competition with human food crops supply.

Micro-algae Value for Animal Nutrition

Several studies have reported different potentials of cultivated algae as effective maintaining animal growth, in performance and sometimes improve daily body weight gain. It is reported that 10% supplement of chlorella sp. into a diet deficient in riboflavin and vitamin A improve feed efficiency and growth of chicks (Combs, 1952). Blue-green algae (e.g. spirulina sp) seem to have positive impacts on overall growth performance, organ health, and reproductive characteristics of animals. Some of the blue-green algae can supplement diets for broiler chickens with up to 20% as to that of conventional crops. However, over the past few decades, pond-grown algae were found to sustain fish growth in aquaculture while today; algae from ponds are used for feeding various animal species (Shields, 2012). De-fatted biomass of micro-algae species derived from the biofuel production has of recently shown feasibility in replacement of corn and soybean meal in diets for poultry, swine, cattle, and sheep (Austic et al., 2013; Lum et al., 2013). Although some studies have reported supplementing the de-fatted biomass from straurospiro sp. to replace 7.5% corn and soya bean meal in diet for weanling pig cannot affect their overall grown growth?) performance, (or Supplementation of micro-algae to the increases diets of ruminants, the concentration of n-3 PUFA in milk. In lambs and horses, dietary microalgae increased the n-3 fatty acid content in a meat and blood, respectively, while in pigs, dietary microalgae increased DHA concentration in the ion and subcutaneous fat (Sard et al., 2006; He and Rambeck 2002; Hess *et al.*, 2012) and they are greatly used in dairy cows as source of n-3 fatty acid.

Nutritional profiles of micro-algae vary with different algal species although the majority are characterized by proteins, carbohydrates, and lipids contents, which similar; they are in other ways closely related to the conventional feed (Norambuena, 2015). This diversity of nutritional contents makes certain algae species have potential for cultivation of diet-needs for humans and animals (Table 4). For example, a commonly cultivated algae species for human consumption is Spirulina maxima, which are rich in vitamin B1. B2 and -carotene and crude protein of up to 71% which is more compared to the dietary soybean which contains 48% crude protein (Lum et al., 2013).

Focusing on nutritional value, micro-algae contain large amounts of the most limited amino acids, lysine and methionine, hence become potential for all dietary amino acids although they are somehow deficient in the sulphur-containing amino acids like cysteine. Therefore, in order to balance and maximize amino acid utilization by animals, diets can be typically generated by mixing different feedstuffs to balance amino acids to meet their nutrients requirement. For example, it is reported by Austic et al. (2013) that the decreased growth performance of broilers fed by the de- fatted staurospira sp biomass in the first three weeks was prevented by the supplementation of essential amino acids (Lum et al., 2013).

Another study on laying hens reported that inclusion of 10% *Polphyridium sp* Red algal biomass did not affect their body weight, egg production rate, or egg weight, but lowered egg yolk cholesterol level by 24% (Ginzberg *et al.*, 2000). Fish from ponds, or fish product from reared fish ponds represent the major source of n-3

fatty acid while marine fish species are incapable of synthesizing n-3 fatty acids by themselves; they may obtain n-3 fatty acids by consuming micro-algae or other consuming fish. Micro-algae algae biomass or oil may be supplied in the feed of ruminant to manipulate their milk fatty acid composition. From the study that was conducted to compare algae and cosupplementation with sunflower oil in sheep diet, nutrition profile of milk showed the milk DHA concentration was increased as dietary algae concentration rose (Lum *et al.*, 2013).

REUSE OF WASTEWATER FOR IRRIGATION

Wastewater treatment has no alternative option since it can have several impacts on human health and the environment. Treated wastewater can be potentially useful agricultural purposes for (Michunaka et al., 2017). The use of high rate algal ponds becomes of paramount importance as their aim is to maximize wastewater treatment conditions for massive growth of algae and sufficient oxygen which are the key factors for the removal of organic matter, nutrients and pathogens (Young et al., 2017). Since recovered wastewater nutrients can be used as fertilizer, the treated wastewater can be used for irrigation purposes (Paulo et al., 2009). However, reclaimed water from the HRAP, present two options; one reduces consumption of the processed water for domestic purposes and the second is to reduce the cost of nutrients as well as avoid environmental impacts that arises with the discharge of large volumes into the receiving environment (Young et al., 2017; Cooney et al., 2011).

Basing on problem of water scarcity, urban wastewater use in agriculture is now considered as an important practice (Rivera, 2016). Water shortage, threats to food security among urban dwellers, has limited farmers from practicing urban

agriculture (Zhang and Shen, 2017). This raises concerns against using wastewater and it is obvious that urban utilities generate a lot of wastewater from their treatment plants, which in most cases they face many operational problems (Keraita and Akatse, 2012). It is been estimated that more than 20 million hectares are currently being irrigated with wastewater worldwide by about 200 million farmers and the large part of it is practiced in Latin America (D'Andrea *et al.*, 2015). Based on various literature, the situation shows the HRAPs are now merely applied for biofuels production, whereas the focus on the final effluent being used for irrigation purposes is still not very promising. Although they can also be utilized as food supplements for humans and animal dietary, there is little exploration in this area, which indicates there is still little attention on re-use of reclaimed wastewater for agricultural purposes.

Algae species	Nutrients contents			Conventional feed staffs	Nutrients contents		
	Р	С	L		Р	С	L
Synechococcus sp	73	15	11	Egg	49.8	2.7	47.4
Spirulina maxima	71	NG	18	Soybean	48	NG	2
Arthospira maxima	60-70	13-16	6-7	Meat	43	1	34
Spirulina plantesis	61-64	15-16	7-8	Soybean	37	30	20
Apharizomenon flos-aquae	62	23	3	Peas (green)	28.8	47.1	3.7
Chlorella vulgaris	51-58	12-17	14-22	Milk	26	38	28
D. salina	57	32	6	Tomato	14.5	58.3	3.5
Chlorella pyrenoidosa	57	26	2	Wheat	14	84	2
Scenedesmus obliquus	50-56	10-17	12-14	Carrot	11.0	63.3	1.8
Anabaena cylindrical	43-56	25-30	4-7	Rice	10	77	2
Chlamydomonas	48	17	21	Corn	9	85	4

Table 4: Nutritional Values for Microalgae close Related to Conventional Crop based

Modified from Mehrabadi et al. (2016); Lum et al. (2013).

NG = Not Given, P = Protein, C = Carbohydrates, L = Lipids

POTENTIAL OF APPLICATION OF HRAPs IN TANZANIA

Application of this type of technology in Tanzania is significant since it is going to solve problems in several areas. Proper wastewater management contributes to improved public health, environmental protection as well as economic benefits.

i. Environmental benefits

Due to HRAPs efficiency in treating wastewater through reduction of nutrients, receiving water bodies are protected against pollution, which can lead to eutrophication (Garcia and Marine, 2000). Removal of organic matter, pathogens and nutrients from wastewater produces cleaner water and has several indirect environmental benefits including safer and more stable aquatic ecosystems. Wastewater being released into the environment without any treatment can pollute drinking and recreational waters and become less potential for multiple uses and increase costs of treatment of drinking water (Slovak Republic, 2018).

ii. Health benefits

Treatment of wastewater and re-use will reduce the health risks of diseases causing organisms responsible for water borne diseases like cholera, diarrhea, typhoid fever, dysentery and hepatitis that are normally found in effluents of conventional ponds (Liu *et al.*, 2017). Reduction of pathogens and pollutants in the water cycle decreases the morbidity and mortality among the population using water for domestic use. In accordance with the World Health Organization (2017), contaminated drinking water is estimated to cause 502,000 diarrhea deaths each year. Since it has been reported by United Nations Environmental Program, (2010) that 88% of all diarrhea incidents globally are connected to poor hygiene and drinking of unsafe water, the country has no option in adopting a proven technology that will work appropriately to protect public health as well as minimize costs that are associated with healthcare for water-borne disease, hospitalization as well as preventing the productivity losses due to sickness.

iii. Social Economic benefits

HRAPs offers opportunities through resources recovery, and thus the reclaimed wastewater will substitute the use of potable waters particularly in urban farming through irrigation of horticulture crops and gardening which in turn reduces Government costs for treating water for potable uses and reduces the water stress.

Currently, wastewater from waste stabilization ponds is being used for irrigation of horticultures by small scale farmers in some part of the country such as Arusha and Moshi municipalities. To some communities, wastewater from this type of the source is used to grow food products like maize, beans and banana (Paulo et al., 2009) which has helped in generating selfemployment and increase income for low earning communities. Moreover, since the treated water is rich in nutrients, using it for irrigation reduces the need for chemical fertilizers subject to quality checks. This results in a reliable source of water and an improved food security. As reported by World Health Organization (2017).wastewater might be a key to solve the global water crisis and by 2025, half of the world's population will be living in waterstressed countries (Michinika et al., 2017). Application of HRAP has a potential of

reducing water shortages in water-stressed areas through its re-use in aquaculture, agriculture and other uses.

Utilizing algae for biofuel production will sector through improve the energy minimizing the costs of fossil fuel. Energy challenges in Tanzania affect seriously the performance of the country's social and economic sector (Felix and Gheewala, 2011). Poor income, poor health, and education indicators can greatly be improved with adaptation of clean and modern energy (Mkiramweni, 2012). It is estimated that 80% of Tanzanians depend on biomass as a source of energy by burning firewood and charcoal. Application of algae as a source of biofuel will potentially reduce the burden on the forest resources as well as consequences of pollution which can lead air to complications of breathing, chronic respiratory diseases and stinging eyes due to indoor air pollution that comes from burning charcoal and firewood inside homes (Mkiramweni, 2012). Nutrients from wastewater through utilization of microalgae for animal feed will improve individual's incomes since algal products will supplement the conventional source of food which is always expensive. Since microalgae and cyanobacteria have proved to have good source of proteins, omega-3 which can also be obtained in eggs, meat and milk, adopting HRAP will improve animal nutrition (Craggs et al, 2014; Smetana et al., 2017).

CONCLUSIONS & IMPLICATIONS

The high-rate algal pond is a low-cost wastewater treatment system designed to achieve two goals. Secondary wastewater treatment and algal biomass production that can be used for resource recovery like, energy as biofuel, microalgae nutrients as protein-rich animal or fish feed in aquaculture and human food, and reclamed water for irrigation purposes. Use of HRAP has economic impact through

generating self employment, increase income to low earning communities as well as minimizing the issues of food, energy and water crisis and reduce the emission of green house gases. However, since there is partial utilization of microalgae for food and feed, it is necessary to determine limiting factors of the microalgae biomass that hinder its digestion and utilization by animal. The tremendous potential of using the reclaimed wastewater should be fully explored.

AREAS FOR FURTHER RESEACH

For the upcoming research the focus should also include the removal of pathogens in large scale; protozoa, nematode eggs and all prominent pathogens that pose threat to public health rather than just E. coli and faecal indicator bacteria (Young et al., 2017). Reclaimed wastewater for resource recovery should be given much attention. However, since there is partial utilization of microalgae for food and feed, It is necessary to determine limiting factors of the microalgae biomass that hinder its digestion and utilization by animals.

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