



Cost-benefit Analysis for a Containerized MBR System for Treatment of Fish Processing Wastewater for Industries in Kisumu, Kenya and Comparison to Wastewater Stabilization Ponds and Activated Sludge Process

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Abstract

The study aimed to calculate a cost benefit analysis for a containerized membrane bioreactors (MBR) system with flow capacity of 10m³ per day, suitable for use by fish industries within urban settlements such as Kisumu city in Kenya where land is scarce and expensive. Further a comparative cost analysis for a containerized MBR system, activated sludge process (ASP) and wastewater stabilization ponds (WSP) treatment systems was conducted relative to treatment volume to determine their economic viability. The cost benefit analysis was calculated as the difference between total input and total output. The total input was the sum of capital expenditure (CAPEX) and operation expenditure (OPEX) while the total output was the cost per m³ of treated water generated and reused over the course of the plant life. The comparative analysis was conducted using basic cost model equations. The MBR system had a cost benefit of 13.1 €/m³d⁻¹ which is approximately ≥ 99% with an assumption that all treated water generated is reused on site. The cost per m³ of treated water was estimated at 1.32€/m³d⁻¹. The results obtained from the correlation cost curves demonstrated that MBR systems with flow capacity of 10m³d⁻¹ to 45m³d⁻¹ are more economical in terms of CAPEX relative to ASP and WSP whose investment cost is driven higher by cost of land. Correlation cost curves showed a high OPEX for MBR systems attributed to high energy requirement. However, MBR systems encourage reuse of the treated water thus becomes economical in the long run over the course of the plant life. Containerized MBR systems were found to be more appropriate for use by industries operating in the urban centers in Kisumu where land is expensive, relative to ASP and WSP that require high capital cost for acquiring land and for construction.

Keywords: Cost benefit analysis; membrane bioreactor; Fish industries

Introduction

Lake Victoria is the second world's largest freshwater lake shared mainly between Kenya, Uganda, and Tanzania [1]. It is a host for the African's largest freshwater inland fisheries [2]. The urban and peri-urban centers within the Lake basin are densely populated as they are a major attraction for human settlement with a population of over 40 million people [3]. Such urban centers include Kisumu city that is located in the Kenyan side of the Lake Victoria basin [1]. The city is highly industrialized and characterized by informal settlements that have high population, poorly planned infrastructure for wastewater and inadequate sanitation facilities [4]. Fish trade is a major source of income in the Lake region with several fish industries operating in Kisumu city [5]. However, the sector is phased with a major challenge on sanitation attributed to poor management and disposal of wastewater. Most of these industries lack proper effluent treatment plants due to the huge investment required for construction of effluent treatment plants [6]. The situation is similar in most industries located in urban settlements in many developing and middle-income countries in Africa [7]. In the early 1990's fish trade was doing well with over 15 fish processing industries in operation in Kisumu [3]. However, the sector is currently phased with the threat of extinction with only about 3 fish processing industries remaining and is struggling to stay in business for lack of enough resources to sustain their operations. Continued disposal of industrial effluent to the Lake has resulted to eutrophication and water pollution thus resulting to fish kills and depletion of fish resources in the Lake. (Gidudu, *et al.*, 2018).

Kisumu water and Sewerage Company (KIWASCO) responsible for water supply and sanitation services in the region has an existing facility with sewerage system design capacity of approximately 17,000m³ against an estimated sewage generation of 34,000m³ [1]. The existing sewerage system is inadequate, overloaded and cannot effectively serve the

Article Information

DOI: 10.31021/jwt.20203127
Article Type: Research
Journal Type: Open Access
Volume: 3 **Issue:** 1
Manuscript ID: JWT-3-127
Publisher: Boffin Access Limited
Received Date: 22 July 2020
Accepted Date: 14 August 2020
Published Date: 16 August 2020

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Citation: Mburu J, Gukelberger E, Mwangi P, Kinyua R Hoinkis J. Cost-benefit Analysis for a Containerized MBR System for Treatment of Fish Processing Wastewater for Industries in Kisumu, Kenya and Comparison to Wastewater Stabilization Ponds and Activated Sludge Process. *J Water Technol Treat Methods*. 2020 Aug;2(1):127.

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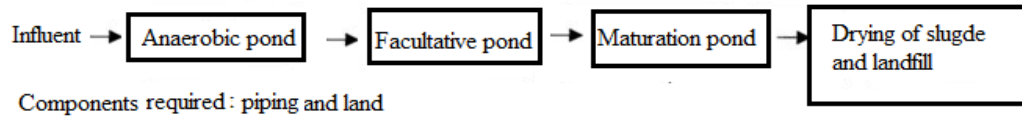


Figure 1: A flow diagram of a typical wastewater stabilization pond (WSP) treatment plant and components

fish industries in the region [8]. Proper management of wastewater is therefore a key issue that requires proper attention thus ensures continued operation of fish industries in Kisumu City [6]. Membrane Bioreactor (MBR) technology is a potential and useful wastewater treatment method used for treatment of various industrial wastewaters [9]. The technology combines the use of biological activated sludge process (ASP) and filtration process to produce highly clarified effluent [10]. The process has advantage over other wastewater treatment methods such as activated sludge process (ASP) and water stabilization ponds commonly used in most African countries as it has a small footprint and encourage water reuse [11]. MBR technology could become a real-time solution to fish processing industries in Kisumu, as they are required to install appropriate effluent treatment plants before being granted a license to discharge their resultant effluent [12]. As MBR technology gets acceptance in treatment of industrial effluent, it is considered as an expensive process due to energy cost and operation expenditure [13]. This has however not been verified as the cost of any treatment method varies according to the nature of the site, size of the treatment plant and nature of installation [14]. In most cases small MBRs can be provided as containerized technology thus is installed without construction or redesigning of the site required [15]. The cost for MBR may be much lower when in comparison to ASP and WSP techniques that requires large areas of land which is inappropriate for urban centers where land is scarce and expensive [16].

Choosing an effluent treatment plant

The choice of the effluent treatment plant suitable for use depends on several factors that include: the type of wastewater, quantity and level of treatment required, treatment plant capacity, capital cost, operational cost, land availability [13]. The strength of the wastewater can be defined by the level of pH, color, turbidity, organic load such as chemical oxygen demand (COD) and biochemical oxygen demand (BOD), suspended solids (SS), soluble phosphates, ammonium nitrogen ($\text{NH}_4^+ \text{-N}$) and heavy metals among other parameters [17]. The quality and quantity of wastewater to be treated determines the most appropriate treatment method and the different levels of treatment required in order to acquire the output effluent quality needed [18]. The wastewater treatment levels are classified as preliminary, primary, secondary and tertiary [13]. Preliminary treatment entails the use of screens to remove rags and big debris from the wastewater [8]. Physical treatment process entails the use of screens and sedimentation tanks to remove medium sized particles and settling suspended solids through the action of gravity [19]. Secondary treatment entails the use of biological process to reduce the organic load in the wastewater [20]. The process is conducted in the aeration tank containing primary effluent mixed with bacteria-rich activated sludge. The air is supplied to the tank in order to provide oxygen to the microorganisms that breakdown organic impurities into biomass, carbon dioxide and water [21]. Tertiary treatment process entails the use of chemical treatment and other methods to remove residual suspended solids and to disinfect the water in the clarification tanks [22].

Types of effluent treatment plants and components required

Wastewater stabilization ponds (WSP): Wastewater stabilization ponds are treatment system constituting large open basins used for

treatment of wastewater through natural processes [23]. The ponds are used in series of three or more for improved level of treatment. The system uses anaerobic pond (approximately 2-5m deep), where microorganisms assimilate organic contaminants for approximately 1-7days and reduce BOD_5 by approximately 60%-70% [16]. Further facultative ponds (approximately 1-2.5m deep) are required for removal of organic matter through the activity of aerobic and anerobic microorganisms, in the upper and lower part of the pond respectively. The process takes 5-30 days with a BOD_5 removal efficiency of about 75-90% [23]. Aerobic (maturation) ponds (approximately 0.5-1.5m deep) are then required for further treatment through removal of pathogens and reduction of nutrient to about 80 and 90% respectively and phosphorus removal of about 50% [18]. However the system further requires additional treatment steps where higher quality effluent is needed. Large land area is needed for construction of ponds, high capital cost for acquiring land and other costs for mosquito control, frequent sludge removal and dewatering [18]. Furthermore the technology takes long periods for a complete process [16]. The system is commonly used in many third world and developing countries as it has low cost of operation and maintenance, and it does not require highly skilled labor. However it is not appropriate in Kisumu urban settlements following the problem of land scarcity and high cost [24]. Typical flow diagram of a WSP and components required is as shown in Figure 1.

Activated sludge process (ASP) ASP: Activated sludge process is a biological wastewater treatment method that uses a bacterial biomass (biological floc) to remove pollutants [25]. The treatment facility requires screens to remove big debris, primary settling tanks for removal of settling suspended solids through action of gravity and a biological reactor (aeration tank) for further removal of biodegradable organic matter. In the aeration tank, primary effluent is mixed with bacteria-rich activated sludge and diffusers are used to supply air to the microorganisms that breakdown organic matter into carbon dioxide, water and biomass [20]. The system requires secondary clarifiers for separation of biological sludge from the treated water through gravity settling process. Clarification tanks are then used for further treatment of resulting effluent [25]. The system produces huge amounts of sludge that is dewatered and disposed in landfills, and there requires sludge drying bed [21]. The system has a relatively higher cost of operation and maintenance than that of WSP due to energy consumption for operation of pumps and diffusers [26]. The system needs skilled man power unlike the WSP system. Further it requires huge areas of land which is not appropriate for industries operating within the urban settlements in Kisumu where land is scarce [24]. The cost of land, construction and the required components adds up to high capital cost which is a challenge for small fish trades in Kisumu. Typical flow diagram of a typical ASP treatment plant and components required is illustrated in Figure 2.

Membrane bioreactor (MBR): Membrane bioreactor (MBR) technology is a wastewater treatment technique that combines the use of activated sludge process (ASP) for biodegradation of waste compounds and membrane filters for physical separation of treated effluent [27]. The treatment system requires a bioreactor (aeration tank) and a denitrification tank for biological treatment of the feed, diffusers for supply of air to the microorganisms, pumps and microfiltration or ultrafiltration membranes [28]. The system is an upgrade of the traditional ASP and does not require the use of sedimentation or clarification tanks for further treatment of the

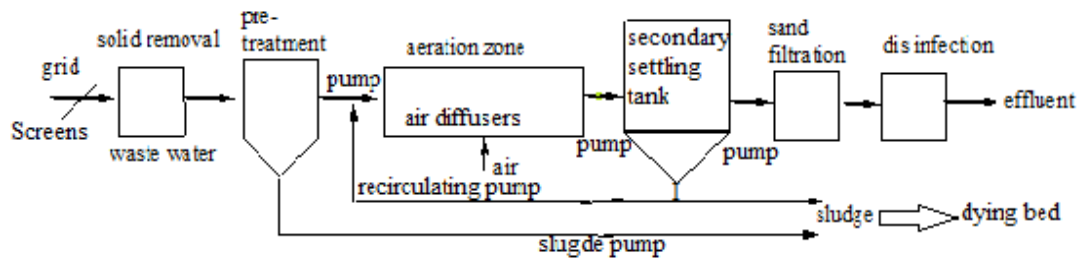


Figure 2: A flow diagram of a typical activated sludge process (ASP) treatment plant and components

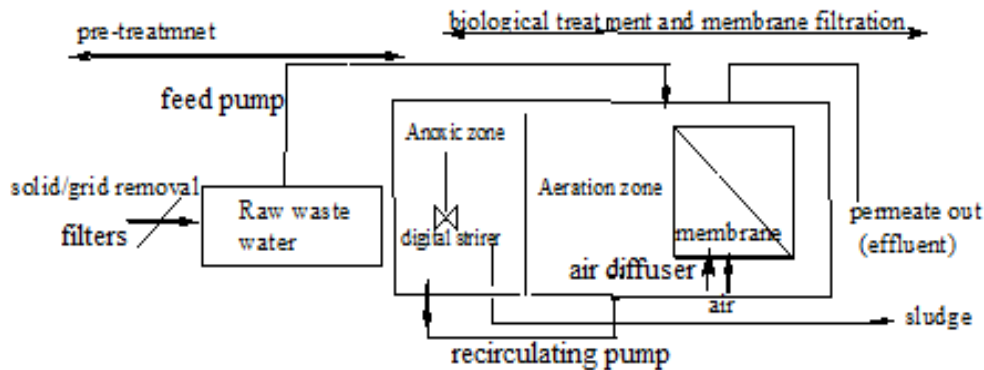


Figure 3: A typical flow diagram of MBR treatment system and components required.

resultant effluent [9]. The technique has many advantages over the ASP and WSP technologies mainly due to its reduced footprint, higher quality effluent that exceeds the capacity of WSP and ASP, low sludge production and ability to encourage reuse of treated water [29]. The capital cost is mainly dependent on plant size, the cost of equipments, membrane and tanks [13]. Small MBR units can be acquired as containerized systems that are installed with no construction required [14]. Figure 3 illustrates a typical flow diagram of MBR treatment system and components required.

The aim of this work was to conduct a cost-benefit analysis, for a containerized MBR system suitable for treatment of fish processing wastewater for fish industries in Kisumu. Further, a comparative analysis for WSP, ASP and MBR treatment plants with the same capacity of between 10m³/d to 100m³/d was conducted using basic cost model equations as estimated by several researchers. The aim was to demonstrate that the cost of using a containerized MBR system is dependent on several factors, and can therefore be a potential option for use by fish industries in Kisumu urban centers where land is scarce. This is in comparison to the other two techniques that require large areas of land and construction expenses.

Methodology

The cost-benefit analysis for a containerized MBR system with a flow capacity of 10m³ per day was proposed for use as a potential method for treatment of fish processing wastewater for fish industries in Kisumu. The cost benefit analysis was calculated by taking into account the capital expenditure (CAPEX) and operation expenditure (OPEX) which adds up to total expenditures (total input). This was compared to the total output which was determined as the cost per m³ of treated water generated and reused on site over the course of the plant life [13]. Capital expenditure was determined by calculating the cost of MBR components and equipments, priced according to the supplier information provided by the various Companies. This is illustrated in equation 1.

$$\text{CAPEX} = E + (L_m/t_{mem})^{t-1} \quad (1)$$

Where: E-cost of equipment

L_m - membrane cost per m² membrane area

t_{mem} -membrane life in years

t = membrane life for PES and PBM coated membranes

The capital expenditure per unit volume for a period of 25 years was calculated as indicated in equation 2.

$$\text{CAPEX} : \{ [E + (L_m/t_{mem})^{t-1}] / m^3 / 25 \text{ years} = x \text{ €/m}^3\text{d}^{-1} \quad (2)$$

Operation expenditure was calculated by taking into consideration the energy input, cost of chemicals, labor, waste management and miscellaneous site services. An MBR having a daily capacity of 10m³ (10,000 L) and expected energy expenditure of 800W was considered. The total specific energy demand was therefore calculated as illustrated in equation 3.

$$E_{tot} = \sum 24Wt / Qp \quad (3)$$

Where: W- rating for sum of the power consumption for each component (in kW)

E_{tot} - total specific energy demand (kWh/m³)

t- hours per day of operation

Qp- permeate flow in m³ / d

The specific energy cost was calculated as shown in equation 4.

$$\text{Specific energy cost} = (E_{tot} \times 18) / 114 \quad (4)$$

Where 1 kWh = 18KSh, with exchange rate of 1€ =114KSh.

The MBR put into consideration had a total membrane area of 16.67 m² (one module), with flux set to 25 L/m²*h at volume flow of 417 L/h.

Operation expenditure (OPEX) was therefore calculated as indicated in equation 5.

Process	Design capacity (m ³ /day)	Capital expenditure (CAPEX) € m ³ /day	Land requirement unit m ² m ³ /d	Operating expenditure (OPEX) US\$ m ³ /day	Reference
MBR	10-100	$y = 1060x^{0.872}$	Non	$y = -0.0509 \ln x + 0.664$	[14]
ASP	10-100	$y = 49,630x^{-0.277}$	$y = 212x^{0.514}$	$y = 578x^{0.190}$	[26]
Waste stabilization ponds	10-100	$y = 474x^{-0.32}$	$y = 326x^{-0.37}$	$y = 995x^{-0.71}$	[26]

Table 1: A cost model of MBR, activated sludge process (ASP), and stabilization ponds treatment systems

Components	Total price KSh.	Euro €
Permeate pump, feed pump Recirculation pump, Blower aeration, Stirrer	Sub total 146,262	1,283
Denitrification tank, Nitrification/ filtration tank, Permeate collection tank, Feed tank	Sub total 42,408	372
Dissolved oxygen sensor, Pressure sensor permeate line, Float switch intake tank/nitrification tank / permeate tank, Volume flow sensor permeate line	Sub total 107,730	945
Infrastructure and other components, Membrane Module	Sub total 268,200	2,353
Total cost	564,642	4,953

Table 2: Total cost for MBR components and equipments

➤ $OPEX = L_E F_{tot} + 365L_M / (Jt_{mem}) + L_C + L_W + L_L$ (5)

Where: L_E is the cost of electrical energy in € /kWh

E_{tot} - total specific energy demand (kWh/m³)

L_M - membrane cost per m² membrane area

J - is the flux in L/m²h

t_{mem} - membrane life in years, t- (8 years)

L_C - chemical cost €/m³

L_W - waste management

L_L - Labor cost

The operation expenditure (OPEX) per unit volume for a period of 25 years was calculated as indicated in equation 26.

➤ $OPEX : (x \text{ €/m}^3) / (364 \text{ days} \times 25 \text{ years}) = \text{€}/x \text{ m}^3 \text{d}^{-1}$ (6)

Where the plant life is 25 years

Total expenditure was calculated as indicated in equation 7.

➤ Total expenditure (TOTEX) for installation and operation using PES/ PBM membrane:
 $CAPEX (x \text{ €/m}^3 \text{d}^{-1}) + OPEX (x \text{ €/m}^3 \text{d}^{-1}) = x \text{ €/m}^3 \text{d}$ (7)

Total output was calculated as the cost per meters cubed of treated water as per the retail price offered by water service provider in Kenya as indicated in equation 8.

➤ Total output: cost per m³ of treated water (x €) × Total volume x m³ per day = x €/day (8)

The difference between total output and total input was calculated to get the total cost benefit as indicated in equation 9.

➤ Total Output (x €/m³d⁻¹) – Total Input (expenditure) (x €/m³d⁻¹) = x €/m³d⁻¹ benefit (9)

Where small MBR systems are assumed to operate with minimal labor cost

Comparative analysis of MBR, activated sludge process

(ASP) and stabilization ponds

A comparative analysis was conducted for the cost of small containerized MBR plants with a capacity of 10m³/d to 100m³/d, activated sludge process (ASP) and stabilization pond treatment systems [14,26]. This was done using basic cost model equations as illustrated in Table 1 [13,14,26].

The costs of CAPEX, OPEX and land requirements were expressed as illustrated in equation 10.

Cost per unit volume (y) = (x)^b (10)

Where: where x, and b are the variable constants

(y) is the capital cost, operation and maintenance cost per unit volume, €/m³/d

(x) is the treatment volume, m³ /d.

(b) is the variation of cost per unit volume relative to size of a process

The costs are not fixed and may vary according to the circumstances of the site design, capacity and nature of installation (eg. a containerized MBR system installed without much construction required) [14]. Capital cost for ASP and stabilization ponds treatment systems included the cost for construction of a screen, grit chamber, sedimentation, equalization, anoxic, aeration and clarification ponds, sludge treatment facility, administrative offices, and other necessary facilities. The operating cost included the cost of labor, power, repair, and chemicals. A graph of CAPEX against treatment volume and OPEX against treatment volume was used to compare the systems.

Results

The cost for all MBR components and equipments put into consideration are presented in Table 2.

The total cost of components and equipments used was 564,642sh. Therefore the capital cost (expenditure) was calculated as indicated in equation 11.

➤ $CAPEX = [564,642sh + (171,00sh/16.67m^2)/(8yrs \times 364days)^{t-1}] = (564,646sh) = 4,953€$ (11)

Where: t = membrane life for PES and PBM coated membranes

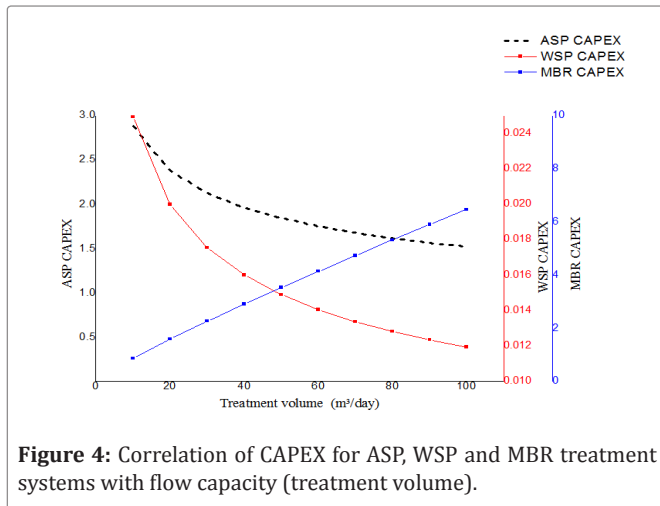


Figure 4: Correlation of CAPEX for ASP, WSP and MBR treatment systems with flow capacity (treatment volume).

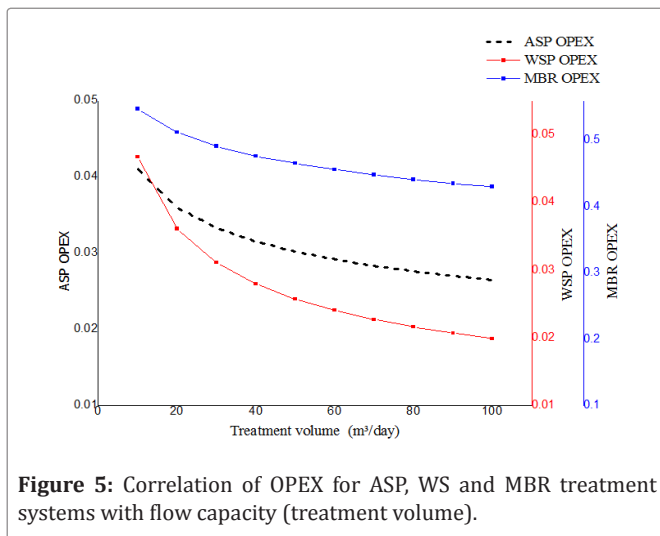


Figure 5: Correlation of OPEX for ASP, WS and MBR treatment systems with flow capacity (treatment volume).

The capital expenditure (CAPEX) per unit volume was as indicated in equation 12

$$\text{CAPEX} = (564,646 \text{ sh}/10\text{m}^3) / (364\text{days} \times 25\text{years}) = (6.2\text{sh}/\text{m}^3\text{d}^{-1}) = 0.05\text{€}/\text{m}^3\text{d}^{-1} \quad (12)$$

Total specific energy demand was calculated as illustrated in equation 13.

$$E_{\text{tot}} = (0.8\text{kWh} \times 24\text{h}) / 10\text{m}^3\text{d}^{-1} = 1.9 \text{ kWh} \quad (13)$$

The specific energy cost was calculated as shown in equation 14.

$$\text{Specific energy cost} = (E_{\text{tot}} \times 18\text{sh}) = (34.2\text{sh}) = 0.3 \text{ €}/\text{m}^3 \quad (14)$$

Where: 1 kWh = 18Ksh, with exchange rate of 1 €=114KSh.

Assumption was made that there was no energy losses and that all input energy was consumed.

Results for OPEX

Operation expenditure (OPEX) was obtained as indicated in equation 15.

$$\text{OPEX} = (34.2\text{sh}/\text{kWh} \times 1.9 \text{ kWh}/\text{m}^3) + \{364\text{days} \times (171,000\text{sh}/16.67\text{m}^2)\} / \{(25 \text{ L}/\text{m}^2\text{h} \times 8\text{yr} \times 364\text{days})\} + 108.9\text{sh} + 49.0\text{sh} + 199.5\text{sh} = (3,705\text{sh}/\text{m}^3) = 32.5 \text{ €}/\text{m}^3 \quad (15)$$

The operation expenditure (OPEX) per unit volume was obtained as indicated in equation 16.

$$\text{OPEX} = (3,705\text{sh}/\text{m}^3) / (364\text{days} \times 25 \text{ years}) = (0.41\text{sh}) = 0.004\text{€}/\text{m}^3\text{d}^{-1} \quad (16)$$

Results for the total output

Total output was obtained as indicated in equation 17.

$$\text{Total output} = \text{cost per m}^3 \text{ of treated water } 150\text{sh} \times \text{Total volume } 10\text{m}^3 \text{ per day} = (1,500\text{sh}/\text{m}^3\text{d}^{-1}) = 13.2\text{€}/\text{m}^3\text{d}^{-1} \quad (17)$$

The total cost benefit analysis was therefore the difference between total input and total output obtained as indicated in equation 18.

$$\text{Total Output } (1,500 \text{ sh}/\text{m}^3\text{d}^{-1}) - \text{Total input } [(CAPEX 6.2\text{sh}/\text{m}^3\text{d}^{-1}) + (OPEX 0.41\text{sh})] = (1493.4 \text{ sh}/\text{m}^3\text{d}^{-1}) = 13.1\text{€}/\text{m}^3\text{d}^{-1} \text{ benefit} \quad (18)$$

Where small containerized MBR plants are assumed to operate with minimal labor cost

If the total output of $1,500 \text{ sh}/\text{m}^3\text{d}^{-1}$ ($13.2\text{€}/\text{m}^3\text{d}^{-1}$) is considered to be 100%, a cost benefit of $13.1\text{€}/\text{m}^3\text{d}^{-1}$ which is approximately 99% was realized with an assumption that all treated water is reused on site. The cost per m^3 of treated water was therefore estimated as $1.32\text{€}/\text{m}^3$. These findings are in agreement with what was reported by Saadia, et al. [10]. The author estimated the cost per m^3 of treated water to be around $\text{€}0.3/\text{m}^3$ [10]. It was evident that despite the higher CAPEX required for installation and operation of MBR systems, it is a profitable treatment system in the long run as it allows reuse of high quality treated effluent.

Results for comparative analysis for MBR, activated sludge process (ASP) and wastewater stabilization ponds (WSP)

A correlation for CAPEX and OPEX for small containerized MBR plants, activated sludge process (ASP) and wastewater stabilization ponds (WSP), treatment systems was conducted and comparative results obtained as illustrated in Figure 4 and 5 respectively.

As presented in Figure 4 a correlation of the cost curves (CAPEX) for ASP, WSP and MBR treatment systems showed a high capital expenditure per unit product water for both ASP and WSP with small flow capacity and a decrease in cost with increasing treatment volume. This was expected as high capital investment is required to construct ponds for the treatment plants with low capacity within the range stated at start phase. Therefore the smaller the flow capacity, the higher the capital expenditure as both systems require large piece of land for pond construction. However the MBR showed low CAPEX with small flow capacity since it would cost less to put up a smaller facility in comparison to the cost required for installation of bigger treatment system with higher flow capacity. From these results, it was more economical to use the MBR for treatment plants with flow capacity within the range of $10\text{m}^3\text{d}^{-1}$ to $45\text{m}^3\text{d}^{-1}$ in comparison to ASP and WSP treatment plants.

Figure 5 illustrates a correlation of the OPEX for ASP, WS and MBR treatment systems with flow capacity of ($10\text{--}100 \text{ m}^3\text{d}^{-1}$). As presented, the WSP and ASP with small flow capacity had high OPEX in comparison to the ones with high capacity $> 60 \text{ m}^3\text{d}^{-1}$. This can be explained by the high OPEX required for operation and maintenance of the treatment plants relative to their flow capacity. The decrease in cost for unit product water for ASP and WSP observed in Figure 5 is therefore associated with the higher returns for treatment systems having higher flow capacity. The MBR treatment system however, had higher OPEX for small size plants with small flow capacity in comparison to ASP and WSP. This was attributed to the high energy requirement for operating MBR in comparison to ASP and WSP treatment systems. However the OPEX for MBR treatment system was decreasing as a function of size and flow capacity. Furthermore, despite the higher operational energy demand required for MBR systems, it encourages reuse of the treated water and is therefore a self-sustaining technology.

Conclusions

MBR system had a cost benefit of a cost benefit of $13.1 \text{ €}/\text{m}^3\text{d}^{-1}$

¹ which is approximately 99. The CAPEX correlation cost curves for demonstrated that MBR system with flow capacity in the range $10\text{m}^3\text{d}^{-1}$ to $45\text{m}^3\text{d}^{-1}$ are more economical to use at the long run. This is in comparison to ASP and WSP treatment plants of similar flow capacity that require large areas of land for construction of ponds thus a high capital cost. The correlation for OPEX demonstrated that MBR systems had higher values attributed to high energy requirement. However, despite the higher operational energy demand for MBR systems, it encourages reuse of the treated water thus cutting cost on water bills associated with water supply from the municipal city council.

Recommendations

A containerized MBR treatment system with flow capacity within the range of $10\text{m}^3\text{d}^{-1}$ to $45\text{m}^3\text{d}^{-1}$ is more affordable relative to ASP and WSP of similar capacity, and can be a better option for treatment of wastewater for the industries operating in the urban centers in Kisumu where land is expensive.

Recommendations for further research: Further research should be carried out to assess the current market demand for MBR technology in Kenya, and further development with respect to the commercialization of the new innovation.

Acknowledgement

This research has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement number 689427 for the project VicInAqua.

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