Review on hybrid energy systems for wastewater treatment and bio-energy production

Sharma S. [1], Verma A. [2].
Department of Zoology, University of Rajasthan, Jaipur, Rajasthan

Abstract
Access to clean water has been a great challenge around the globe due to the high pollutant contents in the water. Therefore, there is a high demand of freshwater resources or a dire need of clean recycle wastewater as a new source of water supply. In order to accomplish this, new concept or engineering systems need to be developed where hybrid wastewater treatment system can be an effective pollutants removal. Wastewater contains energy in the form of biodegradable organic matter. The concept of accomplishing wastewater treatment and generate energy simultaneously has been a trend recently and can be done with hybrid wastewater treatment system. Energy gained from such hybrid system is therefore both sustainable and environmental friendly which may be good source of bio-energy to compliment the power of a treatment plant. In this paper, we classify hybrid wastewater systems typically include physical–biological hybrid, physical–chemical hybrid, chemical–biological hybrid and physical–chemical–biological hybrid system. From the detailed literature gathered thus far, hybrid sys-tems demonstrated some potential advantages compared to stand-alone systems such as: more stable and sustainable in the voltage generated, better overall treatment efficiency and energy savings.
Keywords engineering systems; wastewater treatment; generate energy; hybrid wastewater treatment system

1. Introduction

Waater becomes the scarest thing in some parts of the world as the availability is become limited due to the increasing contamination and environmental activities around the globe [1,2]. There are 1.2 billion people living on this earth today with no access to safe drinking water; typically two million people die annually of diarrhoea and about one third of the world's popula-tion lack satisfactory sanitation [3]. The high demand of fresh-water resources and growing environmental awareness give rise to the use of reclaimed wastewater as a new source of water supply [4].

Wastewaters are commonly categorized as domestic waste-water or industrial wastewater. Domestic wastewater refers to wastewater generated from "non-manufacturing activities" occurring in residential homes which includes sewage (from toi-lets) and grey water (from bathrooms and kitchens). There are many types of industrial wastewater based on the different industries and contaminants; each sector produces its own parti-cular combination of pollutants. Wastewaters are typically con-taminated with physical, chemical and biological composition which has tremendous negative impact on environment, where it has the ability to destroy many animal habitats, and cause irre-parable damage to many ecosystems. Wastewater treatment pro-cesses are designed to achieve improvements of the wastewater quality. The two main reasons for collecting and treating waste-water are to prevent water-borne transmission of disease and to preserve the aquatic environment [5]. Physical composition in wastewater such as suspended solids can lead to the development of sludge deposits and anaerobic conditions when untreated wastewater is discharged in the aquatic environment.

On the other hand, constituents such as biodegradable organics can lead to depletion of natural oxygen resources and to the development of septic conditions. Nutrients such as nitrogen and phosphorus, when discharged to the aquatic environment can lead to the growth of undesirable aquatic life and cause groundwater pollu-tion when discharged in excess. Many compounds found in was-tewater have characteristics of carcinogenic, mutagenic, tetra-togenic or have high acute of toxicity [5].

Therefore, an advance treatment method such as hybrid was-tewater treatment system has gained much attention in recent years for a more effective removal of pollutants from wastewater [6]. The concept of microbial fuel cell (MFC) in accomplishing wastewater treatment and to generate bioenergy simultaneously has also been a trend where much effort has been put in to maximize the power generation [7,8]. Wastewaters contain energy, in the form of biodegradable organic matter, that we expend energy to remove rather than trying to recover it [9]. Besides, there is a continuous global concern on environments and shortage of energy from fossil fuels like pollution and global warming with the exponential growth of population [10,11]. This trend has triggered global movement towards the generation of renewable energy by developing new technology and engineering systems which are not only sustainable but clean and environmental-friendly. There are some hybrid technologies which are promising and yet completely different approach to wastewater treatment as the treatment process can become a method of capturing energy in the form of electricity or hydrogen gas, rather than a drain on electrical energy.

Even though the energy generated from hybrid wastewater treatment system is not significant to support the energy demand of a city, it is however sufficient to run a treatment plant [9]. With advances, capturing this power could achieve energy sustainability of the water infrastructure.

This paper is not a review on MFC alone but on the hybrid of wastewater treatment systems. MFC is just one of them which is categorized under chemical–biological hybrid system; therefore this review paper is geared towards this method of classification i.e. based on “hybrid” schemes. We have classified all the possible hybrid wastewater treatment systems which can be applied in the treatment process. Furthermore, the advantages and dis-advantages of the hybrid system are discussed in detail. The notable advantages of the hybrid wastewater treatment system are more stable and sustainable voltage generated, better overall efficiency and energy saving. Nevertheless, some hybrid system may require high operating cost and is discussed in this paper. The future trend of the treatment process was reviewed and predicted. This paper can be a great source of information to the readers to consider the possible combinations of hybrid systems available which can help to improve the efficiency in the treatment system and at the same time, some combinations can even generate bio-energy which can be possibly fed to the plant for energy savings.

2. Hybrid system for wastewater treatment

A hybrid energy system usually consists of two or more energy sources or methods used together, via suitable energy conversion techniques, to provide fuel savings, energy recovery and increase overall system efficiency [12].

In terms of wastewater hybrid systems, there are various types of possible combination methods used for wastewater treatment. The hybrid system in this context is defined as the combination of two or more treatment methods, either two or more of the fol-lowing: Biological unit processes, chemical unit processes and physical unit operations.

There are basically four types of hybrid system available which are: (1) Physical–biological hybrid system, (2) Physical–chemical hybrid system, (3) Chemical–biological hybrid system, and (4) Physical–chemical–biological hybrid system.

The hybrid treatment system can be a combination of various unit operations and processes in order to improve the wastewater effluent quality. Fig. 1 shows a broad spectrum of the possible combinations of the hybrid system between physical, chemical and biological processes. Hybrid system can be defined as any processes which fall inside the green region. Unit operations and processes are grouped together to provide various levels of treat-ment usually known as preliminary, primary, advanced primary, secondary (without or with nutrient removal) and advanced (or tertiary) treatment. Generally, preliminary, primary and advanced primary treatment may utilize physical and/or chemical processes to prepare the effluent for the next stage of treatment that is biological treatment processes. Tertiary and advanced treatment using chemical or/and physical processes is normally warranted to further polish the treated effluent to comply with more stringent discharge standards [5].

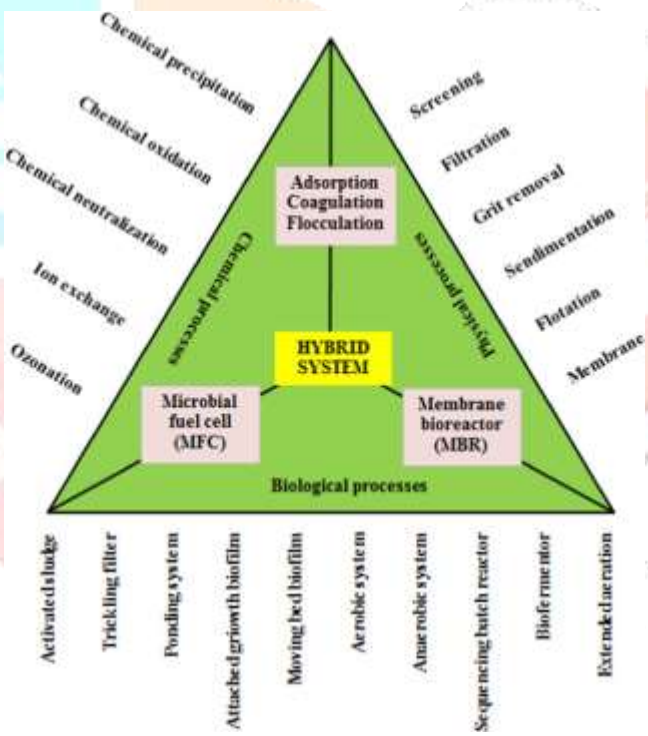

Fig. 1. Broad spectrum of combinations of possible hybrid processes.

Selection of the types of hybrid wastewater systems depend on the types of pollutants that are in the wastewater. Normally, bio-logical treatment processes are required in order to get rid of pollutants such as degradable organics, volatile organics, nitrogen, phosphorus or refractory toxic organics from the wastewater. Pollutants such as suspended solids normally involve physical processes like membrane filtration, flotation and screening. On top of that, pollutants such as metal will normally required chemical treatment process. Most of the wastewater consists of more than one pollutant and therefore, will normally call for hybrid waste-water treatment for a more complete removal. The aim of the hybrid wastewater treatment system implementation is to treat the wastewater at least up to the quality which can be used as a reclaimed wastewater as a new source of water supply.

2.1. Physical–biological hybrid system

Physical–biological hybrid system can be applied when pollu-tants consist of high suspended solids, oil and grease, organic and inorganic components. Membrane bioreactor (MBR) is one of the most common physical–biological hybrid systems where it is increasingly applied in wastewater treatment plants. The advan-tages of using MBR technology for wastewater include: (1) cap-ability of dealing with high volumetric organic loading rates [13,14]; (2) improved effluent water quality for water reuse since bacteria and suspended solids which are larger than the mem-brane pore size will be retained by membrane [15–17]; and complete and stable nitrification owing to the retention of slow-growing nitrifying bacteria at a prolonged solids retention time [18–19].

Table 1 represents a comprehensive list of various types of physical–biological hybrid system that has been studied so far with different type of wastewaters. Membrane bioreactors (MBRs) can be a great technology to replace activated sludge process and the final clarification step in municipal wastewater treatment [30]. The technique utilizes the suitable membranes in retaining unwanted pollutants while allowing clean filtered water to flow through. The combination of biological degradation with mem-brane filtration allows for high reduction of chemical oxygen

demand (COD), biochemical oxygen demand (BOD), and ammonia nitrogen (NH_3–N) [30]. Fig. 2a shows the schematic diagram of a membrane bioreactors (MBRs) hybrid system. Ultrafiltration (UF) and microfiltration (MF) membranes are two common types of membrane used in a MBR hybrid system, in which UF having finer pores compared to MF. Thus UF can capture smaller size pollutant
compared to MF system.

Physical–biological hybrid system can achieve significant energy saving with design such as the upflow anaerobic sludge blanket (UASB) reactors with submerged aerated biofilters hybrid system as shown in Fig. 2b [31]. UASB has the ability to stabilize anaerobically 70% of the organic substrate that is flowing to the plant. Consequently, there will be low sludge production and a significant energy saving will be achieved with such hybrid sys-tem. Biofilter serves as the post-treatment for UASB effluent and able to further degrade the soluble compounds thus filtered the balanced suspended solid. The average overall removal efficiencies of the hybrid system for SS, BOD and COD were 95%, 95% and 88%, respectively, which resulted from compact, efficient and low energy high rate reactor.

Table 1
Different types of physical and biological hybrid systems with the pollutants removal percentage (%).

Physical–biological hybrid system	Types of wastewater	Pollutants and removal percentage (%)	Reference
Extended aeration with filtration	Sago	COD – 88% BOD – 84% TSS – 73%	[20]
Membrane-aerated activated sludge	Synthetic	TN – close to 100%	[21]

Anaerobic-oxic-anoxic biofilm filtration (AOBF) with membrane filtration (MF) (AOBF/MF)	Blended wastewater (domestic wastewater, black water, and landfill leachate)	TSS, COD and soluble nutrients – more than 90–95%	[22]
Submerged membrane bioreactor with mixed liquor recirculation (MLR/MBR)	Synthetic	COD – 497.7% TN – 67%	[23]
Membrane bioreactor and packed-bed biofilm reactor (MBR-PBBR)	Synthetic	TN – more than 99%	[24]
Hydrogen-based membrane biofilm reactor	Synthetic	TN – more than 99%	[25]
Membrane aerated biofilm reactor	Leachate	COD – 50–93% TN – 80–99%	[26]
Membrane distillation combined with an anaerobic moving bed biofilm reactor	Municipal	TP – 100% Dissolved organic carbon – more than 98% Organic matter – almost 100%	[27]
Membrane-aerated biofilm reactor (FT-MABR)	Synthetic	TN – 83.5%	[28]
Membrane aerated biofilm reactor	Synthetic	COD - 85% Nitrification – 93%] Denitrification – 92%	[29]
Membrane bioreactors	Municipal	COD – 97.8 to 99.9%, BOD – 98.9 to 99.9% AN – 91.0 to 99.9%	[30]
Upflow anaerobic sludge blanket (UASB) reactors and submerged aerated biofilters	Municipal	SS – 95% BOD – 95% COD – 88%	[31]
Bioreactor with pressurized aeration and dissolved air flotation	Domestic wastewater	COD – 86% NH_4^{p} –N – close to 100% (C/N ratio of 3) TN – 80% (C/N ratio of 5)	[32]
Anaerobic hybrid membrane bioreactors (AnHMBR) with mesh filter	Synthetic wastewater	COD – 82.473.4 2-chlorophenol – 96.875.2	[33]

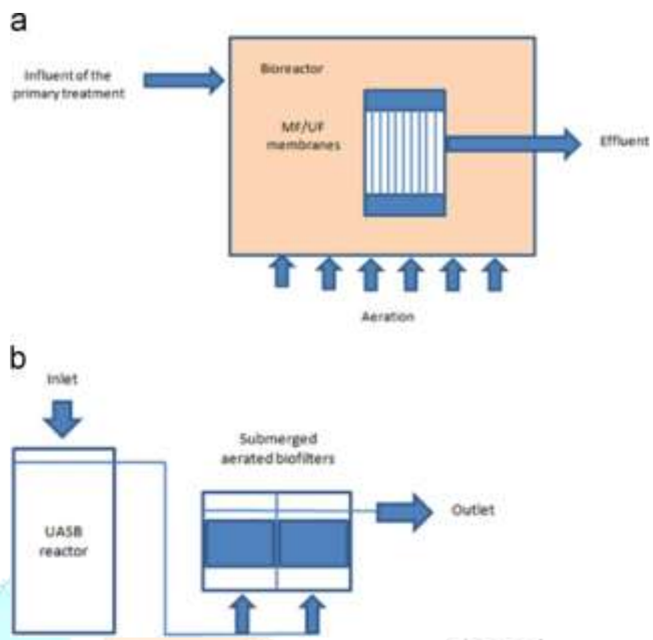

Fig. 2. Schematic diagrams on different types of physical–biological hybrid system.
(a) Membrane bioreactors (MBRs) hybrid system. (b) UASB reactor and submerged aerated biofilter hybrid system.

2.2. Physical–chemical hybrid system

The adoption of physical–chemical hybrid system is typically for wastewaters that are rich in suspended solids, oil and grease, turbidity, metals or ions content. Chemical coagulation and floc-culation is known as an integration of physical and chemical processes which thoroughly mix the chemicals with the waste-water to promote aggregation of wastewater solids into particles large enough to be separated through physical processes [34]. Most of the wastewaters are unlikely to settle readily without the aid in the form of chemical coagulation and flocculation. Chemical coagulation and flocculation are the most important steps to remove colloidal particles and turbidity from wastewater and are known to aggregate wastewater constituents within the size ran-ging from 0.1 mm to 10 mm [35]. Table 2 represents a list of phy-sical–chemical hybrid systems that has been researched with pollutants removal percentage (%). From Table 2, it is reported that any integration of coagulation and flocculation systems with any physical unit operations is able to remove 90% or more of turbidity.

Adsorption is one of the most common techniques for remov-ing contaminants from wastewater. It has been shown that adsorption using activated carbon is able to cope with a wide range of contaminants due to its large surface area characteristic [36]. Therefore, any integration with adsorption unit processes can be a great hybrid system to improve the wastewater quality. As presented in Table 2, adsorption–coagulation–dissolved air flota-tion hybrid is able to get rid of high percentage of oil and grease (91.6 to 94.4%) in the hydrocarbon reservoir, known as produced water. The schematic diagram of adsorption–coagulation–dis-solved air flotation hybrid is as shown in Fig. 3a.

Ozonation is a common treatment process used for bacteria disinfection and organic pollutant oxidation in drinking water treatment [37] based on the use of active ozone gas (O_3). Based on Table 2, it is reported that the autotrophic nitrogen removal (ANR) process with ozonation–adsorption (activated carbon) hybrid system has successfully removed 82.6% of COD and 78.4% of TN in landfill leachate. In comparison with ANR stand-alone system, the removal is much lower compared to hybrid system where the removal of COD and total nitrogen is achieved is only 13.2% and74%, respectively [37]. Schematic diagram of an autotrophic nitrogen removal (ANR) process with ozonation–adsorption (activated carbon) hybrid system is as shown in Fig. 3b.

Table 2
List of physical–chemical hybrid systems with pollutants removal percentage (%).

Physical–chemical hybrid system	Types of wastewater	Pollutants and removal percentage (%)	Reference
Coagulation with dissolved air flotation (DAF)	Raw water	Turbidity – 96.5% TDS – 14.6%	[38]
Adsorption–coagulation–dissolved air flotation	Produced water (hydrocarbon reservoir)	Oil and grease – 91.6–94.4%	[39]
Coagulation–flocculation and flotation	Refinery wastewater	COD – 87% TOC – 84% Turbidity – 90%	[40]
Autotrophic nitrogen removal (ANR) with ozonation and activated carbon filtration	Landfill leachate	COD – 82.6% TN – 78.4%	[41]
Coagulation/flocculation and membrane filtration	Surface water	Turbidity – 99.39% Colour – 100% Giardia (protozoan parasites) – 100% Cryptosporidium oocysts (protozoan parasites) – 100%	[42]
RO process and ion exchange -membrane filtration	Seawater	Boron (microfiltration membrane) – 95–98% Boron (ultrafiltration membrane)- 92.8–93.8%	[43]
Reverse electrodialysis (RED) and reverse osmosis	Seawater	Not reported (modelling)	[44]

Integrated reverse osmosis (RO) process with the sorption-membrane filtration (MF) hybrid system was implemented for boron removal from seawater [43]. Ion exchange resin with a particle size of 0–20 mm was employed for removal of boron from RO permeates. Sorption of boron was performed on a fine pow-dered boron selective ion exchange resin and boron loaded resin was separated by submerged membranes later on. The main advantage of sorption-membrane filtration hybrid process is the opportunity of using very fine particles of the resin, which increases specific surface and results in faster kinetics. RO-ion exchange-MF hybrid system has effectively removed boron by 95 to 98% from microfiltration membrane and 92.8–93.8% from ultrafiltration membrane.

A hybrid desalination system that combines reverse electro-dialysis (RED) and reverse osmosis (RO) processes is another example of a physical–chemical hybrid system. In this hybrid process the RED unit harvests the energy in the form of electricity from the salinity gradient between a highly concentrated solution (e.g., seawater or concentrated brine) and a low salinity solution (e.g., biologically treated secondary effluent or impaired water) [44]. The RED-treated high salinity solution has a lower salt con-centration and serves as the feed solution for the RO unit to reduce the pump work. The concentrated RO brine provides the RED unit a better high salinity source for the energy recovery compared to seawater. In addition, the concentration of the discharged brine can be controlled by the RED unit for improving the water recovery and minimizing the impact on the environment. Such hybrid system is able to gain energy from the RED unit and meanwhile save on the energy consumption on the RO system. Fig. 3c shows a schematic diagram of an RED stack connected with an external electric load. The cations and anions are driven through the cation- and anion-exchange membranes (CEM and AEM), respectively by the salinity gradient. The schematic diagram of the RED-RO hybrid system is shown in Fig. 3d.

2.3. Chemical–biological hybrid system

The combination of chemical–biological system is normally applied to eliminate contaminants such as nitrogen, phosphorus, refractory toxic organic which normally reflected as COD level, BOD and TOC from the wastewater. The percentages of pollutants removal for different types of chemical–biological hybrid systems are presented in Table 3.

MBBR with ozone pretreatment hybrid has shown better per-formance compared to stand-alone MBBR without any ozone pretreatment. Stand-alone MBBR has reported removals of 18.3% of acid-extractable fraction (AEF) and 34.8% of naphthenic acids (NAs), while the ozonation combined MBBR process showed higher removal of AEF (41.0%) and NAs (78.8%).

Hybrid systems with oxidative system integration have the potential in reducing toxicity and enhancing biodegradability of wastewater within a shorter reaction time [46]. Amongst advanced oxidation processes, Fenton is a well-proven oxidative system that oxidizes recalcitrant organic contaminants in effluents by utilizing strong hydroxyl radical generated in-situ through the reaction of iron with hydrogen peroxide. However, by using Fenton oxidation as a stand-alone approach is generally not lucrative due to the accompanying high reagent consumption [47]. Accordingly, combined Fenton–SBR has been an effective and economical method for recalcitrant wastewaters treatment [48]. From Table 3, it has been reported that chemical oxidation with SBR is able to accomplished removal of 76.5% of COD, 45% of TOC and 96% of phenol from petroleum refinery wastewater. The schematic dia-gram of Fenton–SBR hybrid is as shown is Fig. 4.

Microbial fuel cell (MFC) on the other hand is another system that involved both chemical and biological treatment processes. Microbial fuel cells (MFCs) have gained a lot of attention in recent years as a mode of converting organic waste including low-strength wastewaters and lignocellulosic biomass into electricity. Much research papers have been published on MFC stand-alone system but none has actually come to discuss on the effort of integrating MFC with other unit operations and processes. Table 4 shows a comprehensive list of MFC hybrid system with chemical and biological unit processes for wastewater treatment and bio-energy generation that has been researched this far. One of the most common units is power density, which is either represented as the power generated per unit area of the anode or cathode surface area (mW/m^2) or current generated per unit volume of cell (mW/m^3).

Wastewaters are rich in biodegradable organic matter, which are ready to be converted into energy. Microbial fuel cell (MFC) technologies are a promising and yet completely different approach to wastewater treatment as the treatment process can become a method of capturing energy in the form of electricity or hydrogen gas, rather than a drain on electrical energy [9].

For MFC-Anaerobic Fludized Bed (AFBMFC) hybrid system, fluidized media such as graphite-granule particles were used as a comparison as a fluidized media in the MFC [50]. It was observed that the use of both material can shorted the start-up time, as well

as enhances power density and removal of COD. The start-up time was shortened and removal of COD was higher when activated carbon was applied in the AFBMFC because of its higher specific surface and the wearability is better comparatively. In terms of power generation, maximum power density production of granule-graphite AFBMFC was 530 mW/m^2, much higher than 410 mW/m^2 using a granular activated carbon AFBMFC in the same reactor. The schematic diagram of an anaerobic fluidized bed with MFC (AFBMFC) hybrid is as shown in Fig. 5a.

An integrated MFC-sequencing batch reactor (SBR) hybrid had resulted high COD removal in the wastewater with COD removal efficiency of over 90%. Besides, this integrated system is low in capital and operating cost [51]. In a lab-scale integrated SBR-MFC system, the maximum power production of the MFC was 2.34 W/m^3 for one typical cycle. The schematic diagram of anaerobic sludge and mixed liquor suspended solid MFC with sequencing batch reactor (SBR) hybrid system is shown in Fig. 5b.

MFC-Anaerobic Digestor (AD) hybrid system was reported to operate effectively together. MFC was more susceptible to high acetic acid load than AD. Low pH had a relatively delayed effect on the MFC compared to AD, allowing the hybrid system, to have a more stable energy output. At low pH, when operating as hybrid, the AD compartment was able to recover pH to normal levels when the MFC component failed. These results demonstrate that there are synergies that can be gained from this hybrid system [53]. The schematic diagram of an anaerobic digester (AD) with MFC hybrid system is as shown in Fig. 5c.

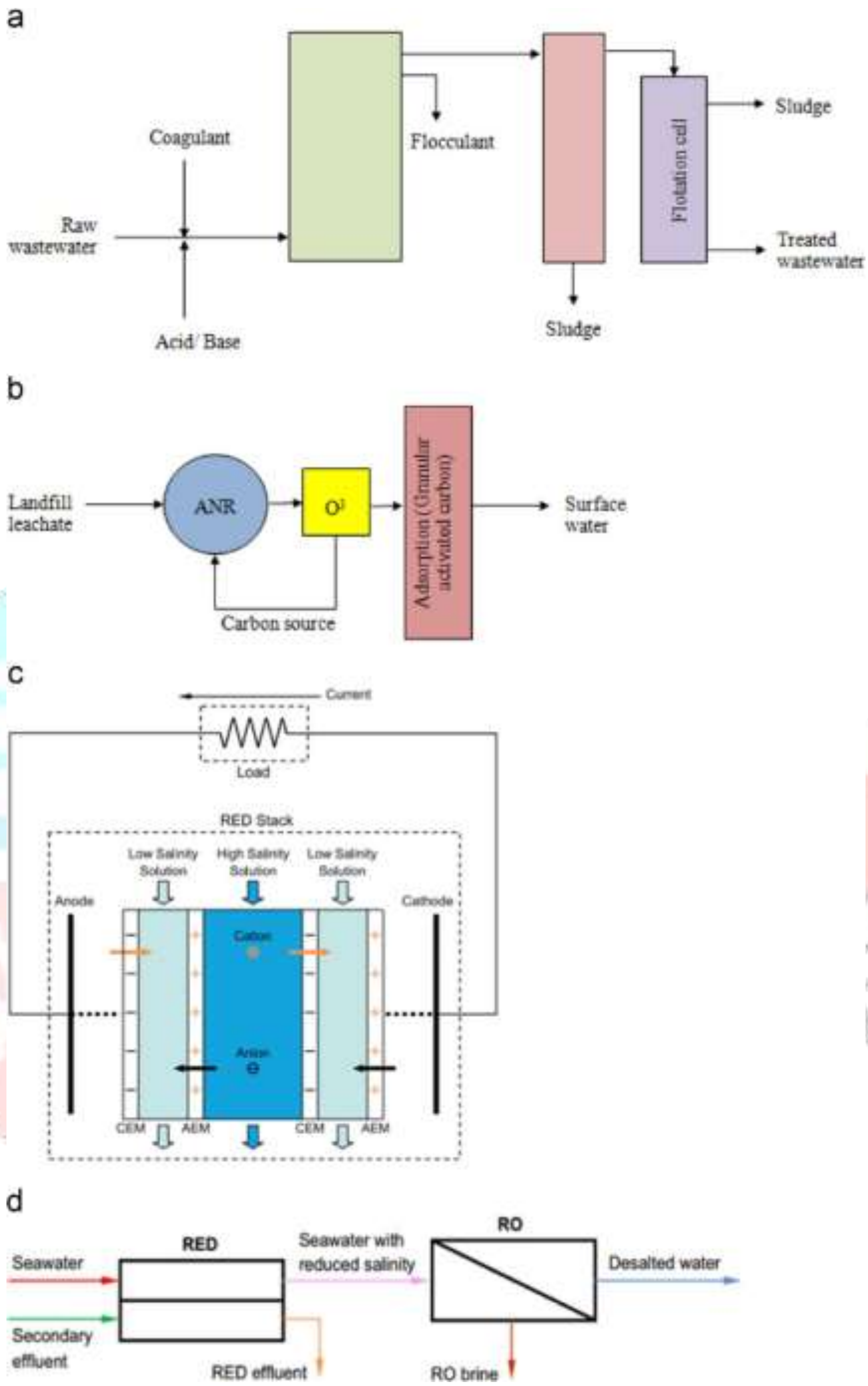

Fig. 3. Schematic diagrams on different types of physical–chemical hybrid systems. (a) Coagulation-flocculation and flotation hybrid system. (b) Autotrophic nitrogen removal (ANR) with ozonation and activated carbon filtration hybrid system. (c) Reverse electrodialysis (RED) stack [44]. (d) Reverse electrodialysis (RED) and reverse osmosis (RO) hybrid system [44].

Table 3 List of chemical–biological hybrid systems with pollutants removal percentage (%).

Chemical–biological hybrid system	Types of wastewater	Pollutants and removal percentage (%)	Reference
Moving bed biofilm reactors (MBBR) with ozone pretreatment	Oil sands process-affected water	Acid-extractable fraction - 41.0% Naphthenic acids - 78.8%	[45]
Chemical oxidation with sequencing batch reactor (SBR)	Petroleum refinery wastewater	COD – 76.5% TOC – 45% Phenol – 96%	[46]

2.4. Physical–chemical–biological hybrid system

Typically, when the wastewater comprises a wide range of pollutants such as suspended solids, oil and grease, volatile organics, degradable organics, ions, nutrients such as nitrogen or phosphorus and metals, a physical–chemical–biological hybrid system is required for the removals of these pollutants. A few examples of the integration of physical unit operations with che-mical and biological unit processes are presented in Table 5.

An integrative membrane coagulation adsorption bioreactor (MCABR) with simultaneous dosing of polyaluminium chloride (PACl) as the coagulant and powdered activated carbon (PAC) as adsorbent into the bioreactor has demonstrated a great capacity of removal of organic matter from the slightly polluted surface water [54]. In the MCABR, four kinds of mechanism, i.e. separation by membrane, biodegradation by micro-organisms, coagulation by PACl, and adsorption by PAC jointly contributed to the removal of the dissolved organic matter and UV_{254}. Such hybrid system is able to remove significant amount of pollutants such as DOC, UV_{254}, TOC, chemical oxygen demand (COD_{Mn}), THMFP, HAAFP, BDOC and AOC with removal percentage of 63.2%, 75.6%, 68.3%, 72.7%, 55.3%, 56.2%, 67.4%, 75.5%, respectively. Fig. 6a shows the schematic diagram of an integrative membrane coagulation adsorption bioreactor (MCABR).
A lab-scale advance wastewater treatment system that consists of sequencing batch reactor (SBR), chemical-dissolved-air flotation (DAF) and ultraviolet (UV) disinfection hybrid system was devel-oped for poultry slaughterhouse reclamation [55]. The SBR was operated to remove nitrogen and the chemical–DAF system was operated to remove phosphorus and remaining suspended solids. The floated effluent was submitted to UV disinfection. The pollu-tants and removal percentage for SBR, chemical-DAF and UV hybrid in poultry slaughterhouse wastewater is reported in Table 5.

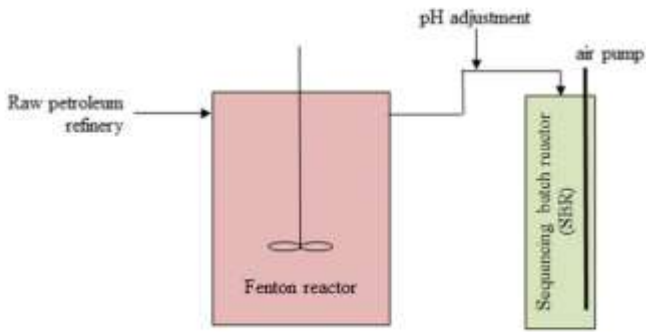

Fig. 4. Chemical oxidation (Fenton) with sequencing batch reactor (SBR) hybrid mixed liquor suspended solid MFC with sequencing batch reactor (SBR) hybrid system.

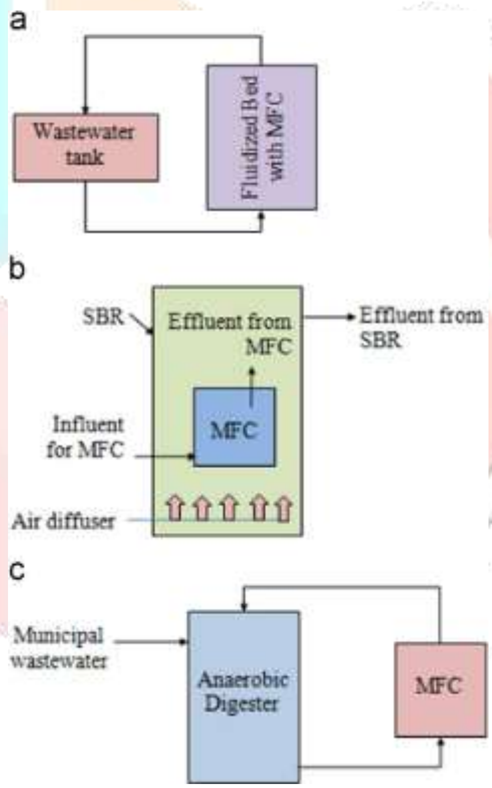

Fig. 5. Schematic diagrams on various types of chemical–biological MFC hybrid systems. (a) Anaerobic fluidized bed with MFC hybrid. (b) Anaerobic sludge and system. (c) Anaerobic digester (AD) with MFC hybrid system.

Table 4
List of chemical–biological MFC hybrid systems with pollutants removal percentage (%) and bio-energy generated.

Chemical– biological MFC hybrid system	Types of wastewater	Pollutants and removal percentage (%)	Power density (mW/m^3 or mW/m^2) and bioe-nergy generated	Reference
Biofermentor with MFC	Glucose	COD – 71%	4200 mW/m^3 Hydrogen production¼2.85 mol H_2/mole glucose	[49]
Anaerobic fluidized bed with MFC (AFBMFC)	Sanitary wastewater	88	530 mW/m^2 (graphite graule) 410 mW/m^3 (activated carbon)	[50]
Anaerobic sludge and mixed liquor suspended solid MFC with sequencing batch reactor (SBR)	Synthetic wastewater	490	2.34 W/m	[51]
Up-flow constructed wetland integrated with MFC	Synthetic wastewater	COD – 100% NO3 – 40% NH_4^+ – 91%	6.12 mW/m^2	[52]
Anaerobic digester (AD) with MFC	Municipal wastewater	Not reported	0.13 mW/m^2 Methane produced ¼ (3.9L) 76.7%	[53]

A submerged membrane adsorption bioreactor (MABR) hybrid system as shown in Fig. 6b was reported to be able to achieve high removal efficiency for organic matter in the surface water. The removal of dissolved organic matter in MABR was accomplished through the combination of three unit effects: rejection by ultra-filtration (UF) membrane, biodegradation by microorganism, and adsorption by powdered activated carbon (PAC) [56]. When pow-dered activated carbon (PAC) was added to the bioreactor, the MABR achieved much higher removal efficiency for organic matter in the raw water as compared to membrane bioreactor (MBR) without PAC.

Partially saturated vertical-flow constructed wetland with trickling filter with filtration and chemical precipitation hybrid system was developed in order to improve denitrification and dephosphatation as compared to conventional vertical flow con-structed wetlands (VFCW) in a municipal wastewater [57]. For chemical precipitation, ferric chloride ($FeCl_3$) was added for phosphorus treatment. Results revealed good performances of the overall treatment where most of the dissolved carbon and nitri-fication were removed by trickling filter. The main part of the treatment was from the first stage known as filtration unit. Nitrate removal was achieved principally at the second filtration stage. Phosphorus migration through the first stage and its slight retention at the second stage was observed. The schematic diagram of the partially saturated vertical-flow constructed wet-land with trickling filter with filtration and chemical precipitation hybrid system is shown in Fig. 6c.

In their earlier study, Leyva-Díaz et al found that the standalone membrane basaed reactor (MBR) had a better performance com-pared with the moving bed biofilm reactor combined with mem-brane bioreactor (hybrid MBBR–MBR) from the point of view of the kinetic parameters [58]. However, the hybrid moving bed biofilm reactor-membrane bioreactor assisted with advanced oxi-dation which is presented in Fig. 6d was reported to have the best kinetic behaviour for the heterotrophic and autotrophic biomass as compared to the one without the moving bed biofilm reactor [59]. The application for the advanced oxidation process (AOP) is recommended when wastewater components have a high che-mical stability and/or low biodegradability. In this sense, a com-bination of biological process and chemical oxidation method is usually required for an effective treatment [60,61] since biological system are not adequate as the sole treatment of wastewater due to the fact that the persistent pollutants pass unaltered through the wastewater treatment plant [62]. The removal percentage of the pollutants from municipal wastewater with this hybrid system is as shown in Table 5. Also, it was reported that Hybrid MBBR– MBR systems have shown to demonstrate highest potential capacity to remove total nitrogen [63].

3. Advantages of hybrid system versus stand-alone system

Some of the prior studies on hybrid schemes of fuel cell systems by Abdullah et al. had demonstrated the feasibility and superiority of hybrid systems compared to stand-alone systems for various applications other than effluent or waste water treatment
[64,65]. Some of the notable advantages are:

(1) more stable and sustainable voltage generated,
(2) better overall treatment efficiency, and
(3) energy saving potential [66]

MFCs are capable of recovering the potential energy present in wastewater and converting it directly into electricity [67]. Using MFCs may help offset wastewater treatment operating costs and make advanced wastewater treatment more affordable for both developing and industrialized nations [68].

4. Limitations of hybrid systems

Hybrid treatment system can be a great choice of treatment options in wastewater in terms of effectiveness. Nevertheless, the overall cost of the hybrid system has to be taken into consideration in terms of capital costs, the operating costs and maintenance costs [69]. Most costs are very site-specific, and for a full-scale system these costs strongly depend on the flow rate of the efflu-ent, the configuration of the reactor, the nature (concentration) of the effluent as well as the pursued extent of treatment.

Hybrid system with a combination of physical treatment such as membrane may pose a challenge because of the high operating cost in terms of energy consumption. If the hybrid system is not designed in a way to have positive energy gained in the overall system, therefore membrane based hybrid system may not be worth to invest. Besides, membrane technologies may require high maintenance cost depending on fouling frequency and the appli-cation of the membrane based hybrid system. Frequent membrane replacement can be very costly.

The physical–chemical precipitation is simple to implement, reliable and efficient but presents several disadvantages such as increased operating costs due to the consumption of chemical reagents and corrosiveness of some of the coagulants which may lead to other problems [70]. Besides, excess sludge production through coagulation, flocculation and precipitation may be lead to problem in terms of disposal unless the sludge produced is able to be recycled for other purposes.

Table 5
List of physical–chemical–biological hybrid systems with pollutants removal percentage (%).

Physical–chemical–biological hybrid system	Types of Wastewater	Pollutants and removal percentage (%)	Reference
Membrane coagulation adsorption bioreactor (MCABR)	Slightly polluted surface water	DOC– 63.2% UV_{254} – 75.6% TOC– 68.3% COD_{Mn} – 72.7% THMFP – 55.3% HAAFP – 56.2% BDOC – 67.4% AOC – 75.5%	[54]
SBR, chemical–DAF and UV Disinfection	Poultry slaughter-house wastewater	Phosphorus – 99% SS _ 65725%	[55]
Membrane adsorption bioreactor (MABR)	Surface water	TOC – 42.7% DOC – 37.5% COD_{Mn} – 59.5 % UV_{254} – 54.6 % $NH_4{}^{þ}$ -N – 96.7% NO_2^--N – 76.2% Turbidity – 97.8% Total coliform – 100%	[56]
Partially saturated vertical-flow constructed wetland with trickling filter with filtration and chemical precipitation	Domestic and winery wastewater	SS – 99% BOD – 98% COD – 94% TKN – 97% TN – 71% TP – 60%	[57]
Hybrid moving bed biofilm reactor-membrane bioreactor with advanced oxidation processes	Municipal	COD – 87.98% BOD_5 – 96.89% TOC – 85.36% TSS – 93.03% TP – 45.30% TN – 72.39 %	[58]

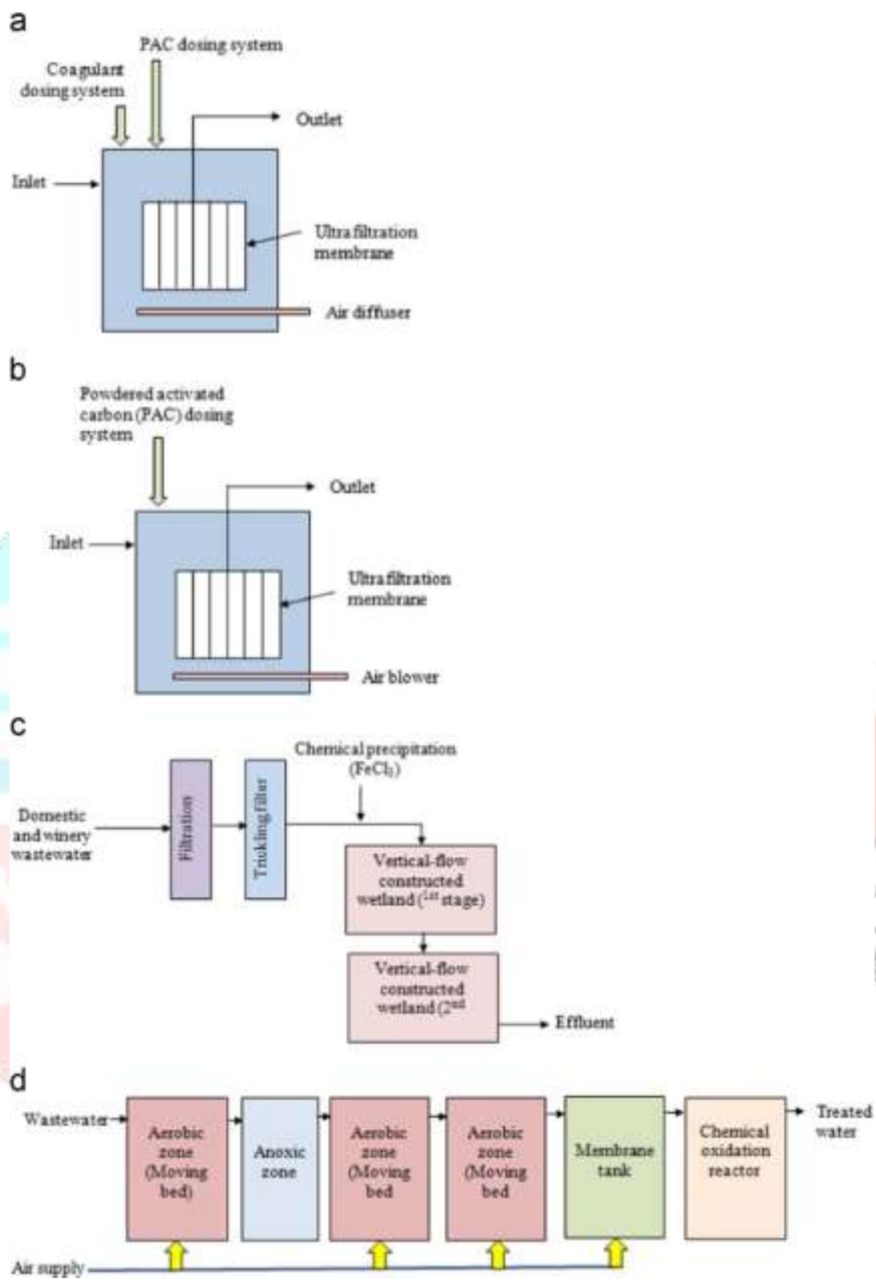

Fig. 6. Schematic diagrams on various types of physical–chemical–biological hybrid systems. (a) Membrane coagulation adsorption bioreactor (MCABR) hybrid system. Submerged membrane adsorption bioreactor (MABR) hybrid system. (c) Partially saturated vertical-flow constructed wetland with trickling filter with filtration and chemical precipitation hybrid system. (d) Hybrid moving bed biofilm reactor-membrane bioreactor with advanced oxidation processes.

Some of the biological process combinations such as activated sludge process may require large amount of oxygen supply for the biological process. Such hybrid system may require high operating cost which makes the overall hybrid system not worth to be invested. There must be a balance made between the energy consumed with the energy gain from the hybrid system in other to make the overall system worthwhile. The summary of the advantages and disadvantages for each of the different types of hybrid treatment system is presented in Table 6.

Physical–biological	• Integration with membrane or RO for such hybrid system is able to remove particles and suspended solids effectively. • Generally, pollutants such as COD, BOD, TSS and TN are able to be removed effectively by such hybrid system.	• Integration with biological unit process which requires aeration will incur high operating cost due to high power consumption to aerate the column. • Biological treatment system integrated with membrane or RO require high operating due to energy consumption. Besides, it may also require high maintenance cost due to fouling.
Physical–chemical	• Able to remove colloidal particles, turbidity, ions and metals. • Integration with adsorption unit for such hybrid system is able to remove various types of pollutants such as COD, BOD, colour, oil and grease, TOC and TDS effectively. • Such hybrid has the benefit of disinfection when integrated with ozonation. • RED integrated treatment system is able to accomplished energy generation	• Coagulation and flocculation treatment system may incur high operating cost due to the coagulants and flocculants used. Such system may not be economical if the dosing system is not optimized as overdosing of chemical may happen. Besides, sludge disposal may be another problem as such hybrid system tends to generate a lot of sludge. • Ozonation is not a cost effective treatment method as it requires high energy consumption. • Membrane or RO related integration may incur high operating and maintenance cost.
Chemical–biological	• Ozonation is able to remove pollutants such as AEF and NAs effectively. Combination of such hybrid is more economical when combining with SBR by reducing the reagent consumption for Fenton oxidation process. • MFC is able to accomplish wastewater treatment and generate power simultaneously. Such system generally tends to generate less sludge as compared to typical biological treatment systems.	• Ozonation is not a cost effective treatment method as it requires high energy consumption. • None air-cathode MFC can be very costly due to the aeration system at the cathode compartment in order to complete the chemical reaction. If MFC is constructed with typical CEM such as Nafion can incur high investment cost. • Integration with SBR can be costly due to aeration system.
Physical–chemical–biological	• Able to remove wide range of pollutants. Removal efficiency may be higher as compared to the other three types of hybrid system as listed above.	• If such hybrid involves ozonation, membrane or reverse osmosis, coagulation and flocculation, none air-cathode MFC and aeration units, therefore it will definitely incur high operating and maintenance cost.

MFC into hybrid treatment system has several advantages which are listed below:

(1) Bioenergy generation together with pollutant removal, where the current generated is dependent on the wastewater strength and the coulombic efficiency.
(2) Elimination of aeration unit. For air-cathode MFC system, no aeration is required. Aeration system in AS is very costly where such system can consume 50% of the electricity used at a treatment plant.
(3) Reduction of solids production. As compared to the aerobic system such as TF and AS, bacterial biomass production by MFC is much lower due the anaerobic condition of MFC.
(4) Minimize odour problem in the treatment system. MFC is a closed system where odor will not be a major problem in the overall treatment system.

There are four possible treatment process flows that can be envisaged in the near future. First, it is expected that the MFC process could be integrated into the process flow of a conventional system replacing the AS or TF systems. In this case, the MFC would be used in a manner similar to that of a TF in a TF/solids contact (SC) arrangement (see Fig. 7a). Second, MFC can be a pretreatment unit for a membrane bioreactor (MBR) process (Fig. 7b). In present paper, it has been predicted that MFC-adsorption hybrid system can be a great hybrid treatment system in the near future due to the great ability of the adsorption column in removing various types of pollutants in wastewater. MFC-adsorption hybrid system can be presented in the form of either ex-situ (Fig. 7c) or in-situ system configurations (Fig. 7d).

On the other hand, energy production from salinity gradient can be a popular trend in the near future. Energy can be produced from a reverse electrodialysis (RED) due to the salinity gradient [71]. It is reported that electrical potential of 0.1–0.2 V per pair of membrane can be produced from seawater and freshwater (or treated wastewater) through pairs of ion-exchange membranes in a RED. Globally, up to 980 GW of power could be generated from salinity gradient energy where freshwater flows into the sea [72]. A RED stack can be placed between the anode and cathode chambers of an MFC or microbial electrolysis cell (MEC), creating a hybrid technology called a microbial reverse electrodialysis cell (MRC).

6. Conclusion

In the present paper, we have classified the hybrid wastewater treatment systems into 4 types, i.e.

(1) Physical–biological hybrid;
(2) Phycial–chemical hybrid;
(3) Chemical–biological hybrid; and
(4) Physical–chemical and biological hybrid

There are both advantages and disadvantages associated with hybrid system. Generally, hybrid systems are more stable and sustainable in terms of voltage generation and treatment effi-ciency as compared to stand-alone system. Bioenergy generated can help to offset the treatment operating costs of the overall system. In terms of energy balance, bio-energy generated from the hybrid system must be at least equal or greater than the energy used to operate the overall system. Conversion of wastes in to bioelectricity by using microbial electrochemical technologies is predicted to be the future trend of the hybrid system. It is predicted that MFC could be replacing the AS or TF systems or even have it as a pretreatment process for MBR. Energy production from salinity gradient such as RED can be another popular trend in the near future. Yet, integration of MFC with adsorption column can be an interesting option.

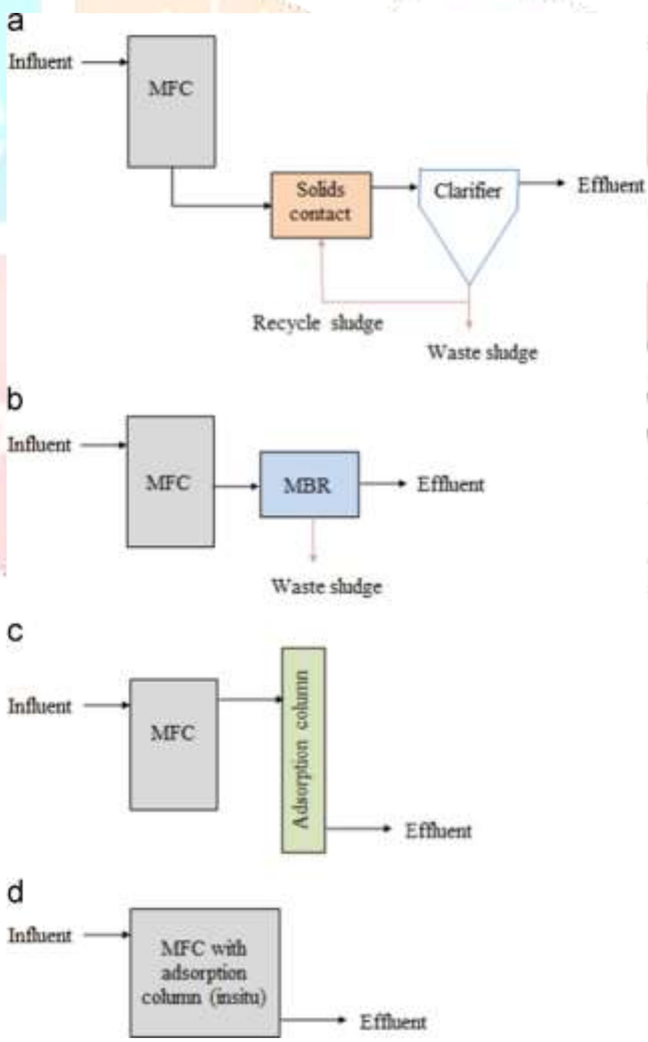

Fig. 7. Flow diagrams for using an MFC reactor as the biological treatment process. (a) A conventional treatment train with a downstream solids contact tank, sludge recycle line, and clarifier. (b) Combined with a MBR using the MFC as a pretreat-ment

method to provide power for the MBR reactor (c) A hybrid of MFC with ex-situ adsorption column (d) In-situ hybrid of MFC with adsorption column.

Acknowledgements

This present study was supported by the Department of Zoology, University of Rajasthan, Jaipur. The authors would like to thank all staff for their continuous encouragements throughout this project.

References

[1]Guthrie P. Global water security – an engineering perspective;. London: The Royal Academy of Engineering; 2010.
[2]Hanjra MA, Qureshi ME. Global water crisis and future food security in an era of climate change. Food Policy 2010;35(5):365–77.
[3]Jury WA, Vaux HJ. The emerging global water crisis: managing scarcity and conflict between water users. Adv Agron 2007;95:1–76.
[4]Yang H, Abbaspour KC. Analysis of wastewater reuse potential in Beijing. Desalination 2007;212(1):238–50.
[5]Tchobanoglous G, Burton FL, Stensel HD. Wastewater engineering treatment and reuse; Metcalf and Eddy. 4th ed.. New York: McGraw-Hill; 2003.
[6]Vymazal J. Horizontal sub-surface flow and hybrid constructed wetlands systems for wastewater treatment. Ecol Eng 2005;25(5):478–90.
[7]Zhang L, Li J, Zhu X, Ye D, Liao Q. Anodic current distribution in a liter-scale microbial fuel cell with electrode arrays. Chem Eng J 2013;223:623–31.
[8]Zhou M, Chi M, Luo J, He H, Jin T. An overview of electrode materials in microbial fuel cells. J Power Sources 2011;196(10):4427–35.
[9]Logan BE. Microbial fuel cells. New Jersey: John Wiley & Sons; 2008.
[10] Jana PS, Behera M, Ghangrekar MM. Performance comparison of up-flow microbial fuel cells fabricated using proton exchange membrane and earthen cylinder. Int J Hydrog Energy 2010;35(11):5681–6.
[11] Lovley DR. The microbe electric: conversion of organic matter to electricity. Curr Opin Biotechnol 2008;19(6):564–71.
[12] Abdullah MO. Applied energy: an introduction. Florida: CRC Press; 2013.
[13] Ben Aim RM, Semmens MJ. Membrane bioreactors for wastewater treatment and reuse: a success story. Water Sci Technol 2003;47:1–5.
[14] Chu HQ, Cao DW, Jin W, Dong BZ. Characteristics of bio-diatomite dynamic membrane process for municipal wastewater treatment. J Membr Sci 2008;325(1):271–6.
[15] Krauth K, Staab KF. Pressurized bioreactor with membrane filtration for wastewater treatment. Water Res 1993;27(3):405–11.
[16] Pollice A, Laera G, Saturno D, Giordano C. Effects of sludge retention time on the performance of a membrane bioreactor treating municipal sewage. J Membr Sci 2008;317(1–2):65–70.
[17] Rosenberger S, Kruger U, Witzig R, Manz W, Szewzyk U, Kraume M. Perfor-mance of a bioreactor with submerged membranes for aerobic treatment of municipal waste water. Water Res 2002;36(2):413–20.
[18] Davies WJ, Le MS, Heath CR. Intensified activated sludge process with sub-merged membrane microfiltration. Water Sci Technol 1998;38(4–5):421–8.
[19] Li H, Yang M, Zhang Y, Yu T, Kamagata Y. Nitrification performance and microbial community dynamics in a submerged membrane bioreactor with complete sludge retention. J Biotechnol 2006;123(1):60–70.
[20] Rashid WA, Musa H, King WS, Bujang K. The potential of extended aeration system for sago effluent treatment. Am J Appl Sci, 7; 2010. p. 616–9.
[21] Downing LS, Nerenberg R. Total nitrogen removal in a hybrid, membrane-aerated activated sludge process. Water Res 2008;42(14):3697–708.
[22] Hyun K, Lee S. Biofilm/membrane filtration for reclamation and reuse of rural wastewaters. (Water Sci Technol 2009;59(11):2145–52.
[23] Liang Z, Das A, Beerman D, Hu Z. Biomass characteristics of two types of submerged membrane bioreactors for nitrogen removal from wastewater. Water Res 2010;44(11):3313–20.

[24] Zhang Y, Zhou Jiti, Zhang J, Yuan Shouzhi. An innovative membrane bioreactor and packed-bed biofilm reactor combined system for shortcut nitrification-denitrification. J Environ Sci 2009;21(5):568–74.

[25] Xia S, Wang C, Xu X, Tang Y, Wang Z, Gu Z, Zhou Y. Bioreduction of nitrate in a hydrogen-based membrane biofilm reactor using CO 2 for pH control and as carbon source. Chem Eng J 2015;276:59–64.

[26] Syron E, Semmens MJ, Casey E. Performance analysis of a pilot-scale mem-brane aerated biofilm reactor for the treatment of landfill leachate. Chem Eng J 2015;273:120–9.

[27] Kim HC, Shin J, Won S, Lee JY, Maeng SK, Song KG. Membrane distillation combined with an anaerobic moving bed biofilm reactor for treating muni-cipal wastewater. Water Res 2015;71:97–106.

[28] Wei X, Li B, Zhao S, Qiang C, Zhang H, Wang S. COD and nitrogen removal in facilitated transfer membrane-aerated biofilm reactor (FT-MABR). J Membr Sci 2012;389:257–64.

[29] Liu H, Yang F, Shi S, Liu X. Effect of substrate COD/N ratio on performance and microbial community structure of a membrane aerated biofilm reactor. J Environ Sci 2010;22(4):540–6.

[30] Mohammed TA, Birima AH, Noor MJMM, Muyibi SA, Idris A. Evaluation of using membrane bioreactor for treating municipal wastewater at different operating conditions. Desalination 2008;221(1):502–10.

[31] Gonçalves RF, de Araújo VL, Bof VS. Combining upflow anaerobic sludge blanket (UASB) reactors and submerged aerated biofilters for secondary domestic wastewater treatment. Water Sci Technol 1999;40(8):71–9.

[32] Zhang Q, Liu S, Yang C, Chen F, Lu S. Bioreactor consisting of pressurized aeration and dissolved air flotation for domestic wastewater treatment. Sep Purif Technol 2014;138:186–90.

[33] Wang YK, Pan XR, Sheng GP, Li WW, Shi BJ, Yu HQ. Development of an energy-saving anaerobic hybrid membrane bioreactors for 2-chlorophenol-contained wastewater treatment. Chemosphere 2014;140:79–84.

[34] Norulaini N, Norulaini N, Zuhair A, Zuhair A, Hakimi M, Hakimi M, Omar M, Omar M. Chemical coagulation of setileable solid-free palm oil mill effluent (Pome) for organic load reduction. Journal of Industrial Technology 2001;10 (1):55–72.

[35] Adin A, Asano T. The role of physical–chemical treatment in wastewater reclamation and reuse. Water Sci Technol 1998;37(10):79–90.

[36] Dias JM, Alvim-Ferraz MC, Almeida MF, Rivera-Utrilla J, Sánchez-Polo M. Waste materials for activated carbon preparation and its use in aqueous-phase treatment: a review. J Environ Manag 2007;85(4):833–46.

[37] Li W, Lu X, Xu K, Qu J, Qiang Z. Cerium incorporated MCM-48 (Ce-MCM-48) as a catalyst to inhibit bromate formation during ozonation of bromide-containing water: Efficacy and mechanism. Water Res 2015.

[38] Rozainy MMR, Hasif M, Puganeshwary P, Afifi A. Combination of chitosan and bentonite as coagulant agents in dissolved air flotation. APCBEE Procedia 2014;10:229–34.

[39] Younker JM, Walsh ME. Bench-scale investigation of an integrated adsorption– coagulation–dissolved air flotation process for produced water treatment. J Environ Chem Eng 2014;2(1):692–7.

[40] Santo CE, Vilar VJ, Botelho CM, Bhatnagar A, Kumar E, Boaventura RA. Opti-mization of coagulation–flocculation and flotation parameters for the treat-ment of a petroleum refinery effluent from a Portuguese plant. Chem Eng J 2012;183:117–23.

[41] Gao JL, Oloibiri V, Chys M, De Wandel S, Decostere B, Audenaert W, He YL, Van Hulle SWH. Integration of autotrophic nitrogen removal, ozonation and acti-vated carbon filtration for treatment of landfill leachate. Chem Eng J 2015;275:281–7.

[42] Nishi L, Vieira AMS, Vieira MF, Silva GF, Bergamasco R. Application of hybrid process of coagulation/flocculation and membrane filtration for the removal of protozoan parasites from water. Procedia Eng 2012;42:148–60.

[43] Güler E, Kabay N, Yüksel M, Yiğit NÖ, Kitiş M, Bryjak M. Integrated solution for boron removal from seawater using RO process and sorption-membrane fil-tration hybrid method. J Membr Sci 2011;375(1):249–57.

[44] Li W, Krantz WB, Cornelissen ER, Post JW, Verliefde AR, Tang CY. A novel hybrid process of reverse electrodialysis and reverse osmosis for low energy seawater desalination and brine management. Appl Energy 2013;104:592–602.

[45] Shi Y, Huang C, Rocha KC, El-Din MG, Liu Y. Treatment of oil sands process-affected water using moving bed biofilm reactors: with and without ozone pretreatment. Bioresour Technol 2015;192:219–27.

[46] Diya'uddeen BH, Pouran SR, Aziz AA, Nashwan SM, WMAW Daud, Shaaban MG. Hybrid of Fenton and sequencing batch reactor for petroleum refinery wastewater treatment. J Ind Eng Chem 2014;25:186–91.

[47] Martins RC, Rossi AF, Quinta-Ferreira RM. Fenton's oxidation process for phenolic wastewater remediation and biodegradability enhancement. J Hazard Mater 2010;180(1):716–21.

[48] Lin SH, Jiang CD. Fenton oxidation and sequencing batch reactor (SBR) treat-ments of high-strength semiconductor wastewater. Desalination 2003;154 (2):107–16.

[49] Sharma Y, Li B. Optimizing energy harvest in wastewater treatment by com-bining anaerobic hydrogen producing biofermentor (HPB) and microbial fuel cell (MFC). Int J Hydrog Energy 2010;35(8):3789–97.

[50] Kong W, Guo Q, Wang X, Yue X. Electricity generation from wastewater using an anaerobic fluidized bed microbial fuel cell. Industrial Engineering Chem-istry Research 2011;50(21):12225–32.

[51] Liu XW, Wang YP, Huang YX, Sun XF, Sheng GP, Zeng RJ, Li F, Dong F, Wang SG, Tong ZH, Yu HQ. Integration of a microbial fuel cell with activated sludge process for energy-saving wastewater treatment: Taking a sequencing batch reactor as an example. Biotechnology and bioengineering 2011;108(6):1260–7.

[52] Oon YL, Ong SA, Ho LN, Wong YS, Oon YS, Lehl HK, Thung WE. Hybrid system up-flow constructed wetland integrated with microbial fuel cell for simulta-neous wastewater treatment and electricity generation. Bioresour Technol 2015;186:270–5.

[53] Weld RJ, Singh R. Functional stability of a hybrid anaerobic digester/microbial fuel cell system treating municipal wastewater. Bioresour Technol 2011;102 (2):842–7.

[54] Tian JY, Chen ZL, Nan J, Liang H, Li GB. Integrative membrane coagulation adsorption bioreactor (MCABR) for enhanced organic matter removal in drinking water treatment. J Membr Sci 2010;352(1):205–12.

[55] De Nardi IR, Del Nery V, Amorim AKB, dos Santos NG, Chimenes F. Perfor-mances of SBR, chemical–DAF and UV disinfection for poultry slaughterhouse wastewater reclamation. Desalination 2011;269(1):184–9.

[56] Tian JY, Liang H, Yang YL, Tian S, Li GB. Membrane adsorption bioreactor (MABR) for treating slightly polluted surface water supplies: as compared to membrane bioreactor (MBR). J Membr Sci 2008;325:262–70.

[57] Kim B, Gautier M, Prost-Boucle S, Molle P, Michel P, Gourdon R. Performance evaluation of partially saturated vertical-flow constructed wetland with trickling filter and chemical precipitation for domestic and winery waste-waters treatment. Ecol Eng 2014;71:41–7.

[58] Leyva-Díaz JC, Calderón K, Rodríguez FA, González-López J, Hontoria E, Poyatos JM. Comparative kinetic study between moving bed biofilm reactor-membrane bioreactor and membrane bioreactor systems and their influence on organic matter and nutrients removal. Biochem Eng J 2013;77:28–40.

[59] Leyva-Díaz JC, López-López C, Martín-Pascual J, Muñío MM, Poyatos JM. Kinetic study of the combined processes of a membrane bioreactor and a hybrid moving bed biofilm reactor-membrane bioreactor with advanced oxi-dation processes as a post-treatment stage for wastewater treatment. Chem Eng Process: Process Intensif 2015;91:57–66.

[60] Wiszniowski J, Robert D, Surmacz-Gorska J, Miksch K, Weber JV. Landfill leachate treatment methods: a review. Environ Chem Lett 2006;4(1):51–61.

[61] Renou S, Givaudan JG, Poulain S, Dirassouyan F, Moulin P. Landfill leachate treatment: Review and opportunity. J Hazard Mater 2008;150(3):468–93.

[62] Badawy MI, Wahaab RA, El-Kalliny AS. Fenton-biological treatment processes for the removal of some pharmaceuticals from industrial wastewater. J Hazard Mater 2009;167(1):567–74.

[63] Leyva-Díaz JC, González-Martínez A, González-López J, Muñío MM, Poyatos JM. Kinetic modeling and microbiological study of two-step nitrification in a membrane bioreactor and hybrid moving bed biofilm reactor–membrane bioreactor for wastewater treatment. Chem Eng J 2015;259:692–702.

[64] Abdullah MO, Gan YK. Feasibility study of a mini fuel cell to detect inter-ference from a cellular phone. J Power Sources 2006;155:311–8.

[65] Abdullah MO, Yung VC, Anyi M, Othman AK, Ab. Hamid KB, Tarawe J. Review and comparison study of hybrid diesel/solar/hydro/fuel cell energy schemes for a rural ICT telecenter. Energy 2010;35:639–46.

[66] Abdullah MO, Tay KM, Gan YK. A multi-purpose mini hybrid fuel cell- solar portable device for rural application: laboratory testing (paper accepted for publicaion in International Journal of Research and Review in applied Sci-ences, Special Editon entitled “Energy sustainability for global techno-economic uplift”); 2011.

[67] Manickam SS, Karra U, Huang L, Bui NN, Li B, McCutcheon JR. Activated carbon nanofiber anodes for microbial fuel cells. Carbon 2013;53:19–28.

[68] Liu H, Ramnarayanan R, Logan BE. Production of electricity during wastewater treatment using a single chamber microbial fuel cell. Environ Sci Technol 2004;38(7):2281–5.

[69] Hai FI, Yamamoto K, Fukushi K. Hybrid treatment systems for dye wastewater. Crit Rev Environ Sci Technol 2007;37(4):315–77.

[70] Balamane-Zizi O, Ait-Amara H. Study of the simultaneous elimination of phosphates and heavy metals contained In dairy wastewater by a physical– chemical and biological mixed process; consequences on the biodegradability. Energy Procedia 2010;18:1341–60.

[71] Ramon GZ, Feinberg BJ, Hoek EM. Membrane-based production of salinity-gradient power. Energy Environ Sci 2011;4(11):4423–34.

[72] Kuleszo J, Kroeze C, Post J, Fekete BM. The potential of blue energy for redu-cing emissions of CO2 and non-CO2 greenhouse gases. J Integr Environ Sci 2010;7(S1):S89–96.