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Advancements in applicability of microbial fuel cell for energy recovery from human waste

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A B S T R A C T

Microbial fuel cells (MFCs) technology is frequently conferred as a division of wastewater treatment along with electricity generation. Specifically, the application of MFCs for energy recovery from the waste is also great for waste management purpose. Designing bioelectric toilets with MFC technology is an idea to treat sewage wastewater along with disinfection for providing a viable solution for wastewater treatment. Treated water can be reused for toilet flushing after disinfection process, helping to reduce the demand of fresh water. Application of power management systems in MFC will open the possibilities for its real-world application for powering electronic gadgets. This review article encapsulates the discussion on human excreta as a substrate for the MFC attached septic tanks to improve waste management and energy recovery methods. Further, the discussion has been carried on the challenges in the scale-up of the MFC systems and its commercialization issues in the present work.

1. Introduction

Public health practices are epitomizing the excellence of living in a nation or society. In some rural areas, the residents are battling with the scarcity of adequate public health amenities, and a major population is living in the lack of toilet facilities (Ravindra and Mor, 2018). Improper disposal of human feces brings an unpleasant odour, which might be responsible for environmental pollution, waterborne diseases and growth of harmful insects. Adequate toilet facilities are needed to sustain the water quality in water reservoirs. Some new proposals have been instigated in developing countries for well-developed bio-toilet facilities and to get better sanitation index of the population (Ravindra and Mor, 2018). Feces is an organic waste comprising a notable quantity of organic compounds. Approximately 50–70 g COD per capita per day is generated by fecal matter (Harvey, 2007; Shizas and Bagley, 2004; Suhogusoff et al., 2019). Such complex organic composite (containing pathogens) can cause pollution in water bodies, if fecal-urine pretreatment is not effectively managed. In spite of this, anaerobic digestion of fecal matter can only digest 30–40% organic matter approximately, while residual organic matter (with infectious germs) is discarded into the nearby places without prior treatment (Ashok, 2017; Walter et al., 2019). Nowadays, researches are inclined towards utilization of domestic or other wastes as a potential feedstock for renewable energy resources (Jadhav and Chendake, 2019; Jadhav et al., 2017a; Jadhav and Ghangrekar, 2015; Logan, 2008). Microbial fuel cell (MFC) could be referred to as waste-to-energy conversion system that converts biochemical energy stored in the organic waste into electricity. The power generation in MFC is facilitated via electrochemical redox reactions of the microbial metabolism (as anode biocatalyst) (Jadhav et al., 2017b; Jadhav et al., 2017c; Tiquia-Arashiro and Pant, 2019). Several Substrates have been explored for power generation in MFC, which is ranging from simple carbon compounds (like glucose, acetate) to industrial or domestic wastewater. (Pandey et al., 2016; Pant et al., 2010). Table 1 offers a comprehensive view on the efforts of several companies trying to commercialize MFC technology and to make them user-friendly.

A Cambridge- based start-up company, Lebone Solutions, has surveyed sub-Saharan Africa, where 74% of the population spend their life without electricity. Lebone Solutions implemented MFC technology to produce enough current to power LED lamps and charge Li-ion batteries (Grifantini, 2008). Lebone designed an MFC in a 5-gal bucket that consisted of a nutrient-rich mud, graphite-cloth anode, a layer of sand and salt water, and a chicken-wire cathode. The setup is connected to an electronic power-management system (Grifantini, 2008). In June 2009, team members travelled to Namibia and launched a pilot program consisting of 100 MFCs made up of small canvas bags that were stacked

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and connected to each other for enhanced power generation (Grifantini, 2008). Another company in Emefcy (Israel) started the commercialization of MFCs for wastewater treatment. Emefcy's fuel cell technology is perfect for wastewater treatment (typically for wastewater from food and agriculture processing industries) (Katherine, 2012). Trophos Energy is another USA-based company, which is involved in several research areas that influence MFC performance, such as design/architecture, electrode materials, power management systems, and microbial modifications. Trophos Energy developed a Benthic-MFC technology for reliable and sustainable power for wireless sensor networks at the places (such as the marine environment) where other energy generation sources cannot work (Guzman et al., 2010). These Benthic-MFC units generate a power density of 30 mW/m^2 with a maximum power density above 380 mW/m^2 (Guzman et al., 2010). Plant-e, a company in the Netherlands, speculated that the rhizosphere could deliver electricity to electronic appliances. Plant-e company focused on an MFC technology for power generation using soil microorganisms. Plant-e's MFC technology was effectively installed in the Netherlands for lightening LEDs on road barriers (Alex, 2016). Another USA based company Hy-SyEnce Inc. also known as Lucent Wastewater Solutions, is working for the profitable commercialization of a highly scalable multi-module MFC for wastewater treatment, which can substantially reduce pollution by preventing methane (potent greenhouse gas) production and can generate hydrogen and electricity (renewable energy) (Hy-SyEnce Inc). Similarly, IntAct Labs LLC in Cambridge is smearing this technology for power generation and waste recycling during space missions (Efrain, 2008). Human excreta have been a barely investigated substrate for MFC (Colombo et al., 2017; Ieropoulos et al., 2012; Perlow, 2012; Sevda et al., 2018). Previously, cow dung and urine, elephant's urine, swine wastewater has been effectively treated in MFC (Jadhav et al., 2016). Likewise, animal waste, human feces and urine are rich in carbon contents, salts and micronutrients. It contains few residues of medicinal compounds and pathogenic germs equally, which will raise the intricacy of human excreta treatment. The present review article explores the appropriateness of human waste as a feedstock in MFC, which might be useful for power generation source in remote areas or in space. Fecal matter is readily available wherever life exists, so it is feasible to employ it as the cheapest and consistent feedstock. Correspondingly, waste management policies prefer those practices that can harvest energy from waste materials prior to its direct dumping into the environment. MFC toilet technology is two in one approach, which provides sewage treatment along with power generation. The present article summarizes eligibility of urinal wastewater based onsite bioelectric toilet. The article also covers the real-life applicability of urine-powered MFCs and bio-toilets to power electronic devices and their possible outcomes, together with an evaluation of the challenges in operation and in scale-up. Recent advancements in the field-scale application of bioelectric toilet technology and its readiness for commercialization in sanitation infrastructure are evaluated in this review.

1.1. Human waste: a suitable feedstock for MFC

Human waste consists of a hefty amount of organic and nutrient compounds (Jonsson et al., 2005), where approximately 2% urea by weight exists in urine. A normal human urine contains 6–18 g day^{-1} urea, 0.5–0.8 g day^{-1} creatinine, 0.12 g day^{-1} amino acids, 0.5 g day^{-1} peptides, and 1.8 g day^{-1} uric acid. Variable quantities of pentose, hexose, ketone bodies, bilirubin, citric acid and lactic acid are also available in regular urine (Ieropoulos et al., 2012). However, compounds like uric acid and urea could not be utilized as carbon source by microorganisms. Ions like sodium, potassium, chloride and phosphate ion are also present in human urine (Simha et al., 2018). Table 2 represents the concentration of significant components in urine and feces (Simha et al., 2018; J. Lu et al., 2017).

Chemically in urea, each molecule has four weakly bonded H atoms as compared to H^+ present in the water (Simha et al., 2018). These weak chemical bonds in urea require minimum energy input for a breakdown to release H^+ and electrons (e^-) more rapidly (Jadhav et al., 2016). The mean calorific value of one gram of amino-acids, peptides and carbohydrates (metabolizable substrates) has been expected to be 2.08 kcal (Ieropoulos et al., 2012). Jumpertz et al., 2011 analysed energy balance and nutrient absorption in human body and observed that approximately 1–9% of total calorie ingested was lost in human feces. Thus, chemical energy present in the feces and urine can be converted into energy using MFC technology. Consequently, the human feces contain organic compounds that can liberate e^- during microbial substrate oxidation (J. Lu et al., 2017). The concept of a bioelectric toilet is a field-scale approach of MFC technology, in which human waste treatment is achieved through organic carbon elimination (Eq. (1)) and ammonia oxidizes into the nitrogen in an anaerobic environment (Eq. (2)). The conversion of sulfide into elemental sulfur takes place and odour is

Table 2
The concentration of significant components in the urine and feces sample.

Components	Concentration (mg/L)
Urea	19,650
Ammonium (NH_4^+)	495
Sodium (Na^+)	3186
Potassium (K^+)	1498
Chlorides (Cl^-)	5945
Phosphates (PO_4^{3-})	705

Components	Approx. concentration (%)
Cellulose	22
Hemicellulose	2
Lignin	5
Protein	34
Lipids	14

Table 1
The list of companies involved in commercialization of the MFC.

Companies	Country	Design	Benefit	Reference
Lebone Solutions	Cambridge	Implemented MFC technology to produce enough current	Power LED lamps and charge Li-ion batteries in sub-Saharan Africa.	(Grifantini, 2008)
Emefcy	Israel	Emefcy's fuel cell technology	Perfect for wastewater treatment (typically for wastewater from food and agriculture processing industries)	(Katherine, 2012)
Trophos Energy		Benthic-MFC technology	Reliable and sustainable power source for wireless sensor networks for marine environment.	(Guzman et al., 2010)
Plant-e	Netherland	MFC technology for power generation using soil microorganisms	These MFC technology was effectively installed in the Netherlands for lightening LEDs on road barriers	(Alex, 2016)
Hy-SyEnce Inc. (Lucent Wastewater Solutions)	USA	Developed multi-module MFC for wastewater treatment	Substantially reduce pollution by preventing methane (potent greenhouse gas) production and can generate hydrogen and electricity (renewable energy)	Hy-SyEnce Inc
IntAct Labs LLC	Cambridge	MFC technology for power generation	Power generation and waste recycling during space missions	(Efrain, 2008)

eliminated (Eq. (3)) (Ashok, 2017). Reuse of treated sewage water is coupled with simultaneous electricity generation that can illuminate toilets during night. The addition of disinfectants in ultimate effluent eliminates the risk of pathogens (Eq. (4)) (Jadhav et al., 2014). Sludge accumulation is significantly less in the bioelectric toilet, and sludge is a valuable fertilizer as compost/manure. Mechanism of electrochemical reactions in MFC is as follows:

Carbon elimination:

$$CH_3COOH + 2H_2O \rightarrow 2CO_2 + 8H^+ + 8e^- \quad (1)$$

Nitrogen elimination:

$$NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O \quad (2)$$

Odour elimination:

$$2SO_4^{2-} + 18H^+ + 16e^- \rightarrow 8H_2O + 2HS^- \rightarrow 2S^0 + 2H^+ + 2e^- \quad (3)$$

Pathogen elimination:

$$NaOCl + H_2O \rightarrow NH_2Cl + HOCl \rightarrow NHCl_2 + H_2O + \text{pathogen elimination} \quad (4)$$

Oxygen reduction:

$$2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O \quad (5)$$

Fig. 1 demonstrates schematic of MFC based on human excreta. Organic compounds present in human feces release electrons during microbial substrate oxidation (J. Lu et al., 2017). These electrons are collected through an external circuit with a load and generate a direct current. Treated water is circulated towards the cathode chamber for the removal of pathogens. Initially, the settled sludge is hydrolyzed within a septic tank and is fed into the MFC for biocatalytic oxidation (Ghadge et al., 2016). While considering elimination of organic contaminants a two chambered MFC operating with real human feces has been able to remove 71% total COD and 44% $NH4^+$ (Jadhav et al., 2020). Cid et al. (2018a, 2018b) developed an electrochemical toilet for the treatment and recycling of toilet wastewater. This toilet shows 70% ammonia removal efficiency in initial one-month period (Cid et al., 2018b). Approximately 70–80% COD removal was achieved over 42 days (Cid et al., 2018b). Similarly, Castro et al. (2014) evaluated the green latrine for power generation with waste treatment and reported approximately 68% nitrogen removal, 76% nitrate removal and more than 90% COD removal.

1.2. The different biocatalyst used in MFCs

MFCs can utilize a wide variety of inoculation with single pure culture of microorganism or mixed microbial consortia. Recently, mixed microbial communities have been significantly explored in MFCs as mixed culture is easy to adapt and stable. Enriched microbial consortia are more robust as compared to pure microbial culture due to stress resistance and nutrient adaptability. Anaerobic sludge has been usually applied as inoculum for MFCs (Rabaey et al., 2004; Kim et al., 2005). According to Table 3, most of the MFCs are operated using activated sludge or indigenous microorganisms present in human waste. Salar-Garcia et al. (2020) analysed three kinds of microbial inoculum including sludge and stored urine, while working on urine-fed MFC. Microbial analysis of stored urine has been ruled by *Aerococcaceae*, Atopostipes and Oligela community (Salar-Garcia et al., 2020). Analysis of sludge, revealed the presence of *Proteobacteria*, *Actinobacteria*, *Firmicutes* and *Bacteriodetes* (Salar-Garcia et al., 2020).

Table 3 presents the utilization of human waste as a substrate in different MFC configurations for power generation. It is evident from Table 3 that most of the studies are urine-based MFC, whereas very few of them have used fecal matter for MFC feedstock. The reason behind the appreciated use of urine is the weaker chemical bonds present in urea which is its major organic component. Apart from this, most of the experiments are performed using MFC stacks for enhanced power generation because it is not feasible to enlarge reactor size as power density is reduced proportionally with the enlargement of the MFC reactor size (Greenman and Ieropoulos, 2017). Therefore, the stack arrangement of multiple MFC units in a series or parallel combination provides greater power densities (Greenman and Ieropoulos, 2017).

2. Power generation by using urine based MFCs

Electricity generation from waste is a crucial trial while existing energy resources on earth are getting dissipated by humans (Walther, 2013). In 2012, a special issue of Science Attentive proposed an approach of "Working with Waste" that supports the utilization of waste biomass and aims at reducing the consumption of raw and fresh materials for bioenergy generation (Wigginton et al., 2012). Fig. 2 shows different aspects of utilizing bioelectric toilets for sanitation. In the present scenario, proficient recovery of energy from sewage wastewater

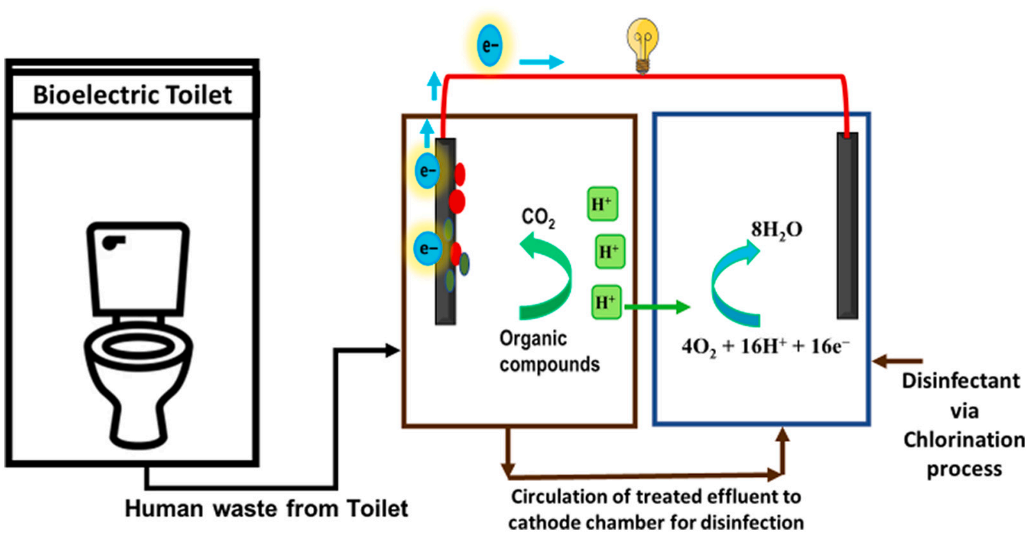

Fig. 1. Schematics of human excreta based MFC.

Table 3
The utilization of human waste as a substrate in different MFC configurations.

MFC configuration	Feed	Anode biocatalyst	Anode	Cathode	Power output	CE	COD removal	Reference
MFCs stack	Urine	Activated sludge	Carbon fiber	Carbon fiber	23 mW m^{-2}	20%	70%	(Cid et al., 2018a)
Air-cathode MFC with N-purging	Urine	Domestic wastewater	Graphite Fiber	Carbon cloth	310.9 ± 1.0 mW m^{-2}	–		(Zhou et al., 2015)
Three Chamber MFC	Artificial Urine	Anaerobic digestion sludge	Carbon brush	Activated carbon	1300 mW m^{-2}	–	97%	(Lu et al., 2019)
Dual-chambered MFCs	Urine	Anaerobic sludge	Carbon felt/Carbon Paper	Carbon paper	332 mW m^{-2}	27%	76%	(Barbosa et al., 2017)
Dual-chambered MFCs	Artificial Urine	Activated Sludge	Graphite felt	Pt/C-Titanium fine mesh,	250 mW m^{-2}	10%	62%	(Kuntke et al., 2012)
Single chamber MFCs	Artificial Urine	Anaerobic sludge	Carbon cloth	Activated carbon-carbon cloth	2500 mW m^{-2}	78%	–	(Y.K. Wang et al., 2017)
Stack of 48 small-scale MFCs	Undiluted urine	Activated anaerobic sludge	Carbon fiber veil	Carbon fiber veil	4.93 mW m^{-2}	–	–	(Ieropoulos et al., 2013)
MFC urine-diverting, composting latrine	Human excreta	–	Graphite granules	Graphite granules	268nW m^{-2}	–	–	(Castro et al., 2014)
Two-chamber MFC	Synthetic human waste	–	Granular graphite with Three graphite rods	Granular graphite with Three graphite rods	3.62 ± 0.04 nW m-2	–	92%	(Castro, 2014)
Two-chamber MFC	Artificial human feces wastewater	Anaerobic sludge	Carbon paper	Pt- Carbon paper	70.8 mW m^{-2}		71%	(Fangzhou et al., 2011)
One-chamber MFC with one MEA	Artificial human feces wastewater	Anaerobic sludge	Carbon paper	Pt- Carbon paper	35 mW m^{-2}	–	–	(Fangzhou et al., 2011)
One-chamber air-cathode MFC	Artificial human feces wastewater	Anaerobic sludge	Carbon fiber	Pt-Carbon paper	217 mW m^{-2}	–	–	(Fangzhou et al., 2011)
Air-cathode MFCs	Urine samples obtained from cannabis users	Mixed microbial culture	Carbon clothes	Platinum powder-Carbon clothes	155 mW m^{-2}		>90%	(Ozdemir et al., 2019)
Dual chamber plate and frame type MFC	Undiluted urine	Anaerobic digestion sludge	Stainless steel mesh	Stainless steel mesh	68 m Wm^{-2}	–	69.97 ± 2.2	(Sharma and Mutnuri, 2019)

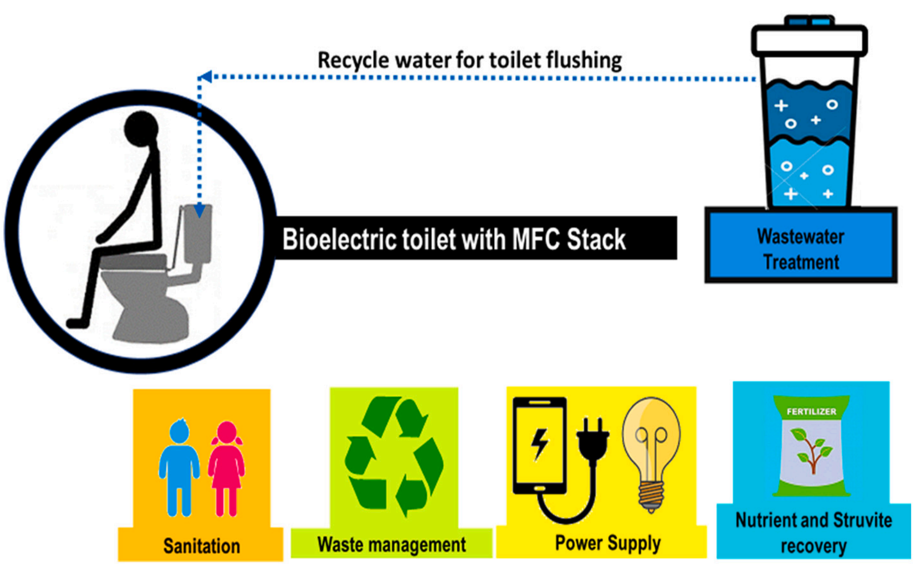

Fig. 2. Multiple aspects of utilizing bioelectric toilets.

is a suboptimal practice as the nutrients of the sewage effluent are extremely diluted in the sewer (Jiang et al., 2011). Different studies focussed on fresh or synthetic urine and showed a COD removal efficiency ranging from 50 to 95% (Table 3), whereas the maximum power density was recorded as 2500 mW m^{-2} using single-chamber MFCs (Y.K. Wang et al., 2017). Some of these urine-powered MFCs are implemented in DC power supply for mobile phone charging, LED bulb lighting, electronic gadgets, and sensors.

2.1. Employing pee power for mobile phone charging

Ieropoulos et al. (2013c) demonstrated the charging of the Samsung mobile phones with a smaller lithium-ion battery (1000 mA/h, 3.7 V) by urine feeding ceramic MFC stack (Ieropoulos et al., 2013c). With urine as a feed, a stack of 24 MFC units was arranged in series of 12, each with 2 parallel combinations. In regular operation, the cut-off voltage is 3.25 V (in switched-off mode), while the target voltage for charging is 3.7 V. Power gained from the MFC stack remained moderately stable and it took approximately 30 h for the complete charging (Ieropoulos et al., 2013c). Walter et al., 2017 scaled-up urine fed MFC stack and used it to charge a cell phone (Samsung GT-E2121B) which had a Li-ion battery (3.7 V and 1000 mA/h) and a smartphone (Samsung Galaxy S I9000) having a Li-ion battery (3.7 V, 1600 mAh). 6 MFCs modules (three modules joined in series with three other modules) were used in this experiment. The Samsung GT-E2121B battery took 42 h for complete charging; the target charge level (3.7 V) was reached within 104 min. The same module was used for charging the 1650 mAh battery of the Samsung Galaxy S I9000. Results showed that the MFC module charged the smartphone fully in 68 h while the phone was switched off. It took an extended time of 82 h to fully charge the battery while the phone was turned on (Walter et al., 2017). The above scenario depicts enhanced possibilities of urine-based MFC implementation in the real world. The neat urine MFC system implemented by Walter et al., 2017 was the first demonstration of smartphone charging. However, at that time, the MFC system had a charge/discharge duty cycle of 2 to 1. In this case, it fulfilled the requirement of a single individual. The results were satisfactory for running power telecommunication devices and it could be helpful in remote areas in natural conditions. Table 4 shows different electronic appliances powered by scaled-up MFCs.

Table 4
Different electronic appliances powered by scaled-up MFCs.

MFC	Electronic devices	Application	Reference
Stack of 4 paper MFC	A red LED (HLMP-P156, Digikey)	Lightning without power management interface circuits	(Fraiwan and Choi, 2014).
Stack of 12 Foot-pumped urine operating wearable MFC	Ran a wireless transmission board.	Wearable transmission MFC systems predict person's location (coordinates) in a case of emergency. Suitable for military and space stations	(Taghavi et al., 2015)
Stack of urine powered 288 MFC	4 LED module (12 V–50 Hz 530 mA 4.5 W 14 W 20)	Urinal lighting through a capacitor bank containing 4 × 3000 F capacitors	(Ieropoulos et al., 2016)
Urine feeding ceramic MFC stack	Lithium-ion battery (1000 mA/h, 3.7 V)	Charging Samsung mobile	(Ieropoulos et al., 2013c)
Urine fed MFC stack	Li-ion battery (3.7 V and 1000 mA/h)	Charging (Samsung GT-E2121B)	(Walter et al., 2017)
Urine fed MFC stack	Li-ion battery (3.7 V, 1600 mAh)	Charging smartphone (Samsung Galaxy S I9000)	(Walter et al., 2017)
Stacks of air cathode MFC	Super-capacitor (240 mF)	To operate automatic integrated motorized air freshener	(You et al., 2016)
Stacks of 15 membrane-less MFC units	2 spotlights, each including 6 LEDs	A direct energy generation set up for remote areas (space, refugee camps)	(Walter et al., 2020)
Stacks of 18 membrane-less MFC units	2 identical LED spotlights with 2 LED electronic controllers	A possible lightning set up for remote areas (space, refugee camps)	(Walter et al., 2020)
12 self-sufficient MFC modules	8 parallel lithium iron phosphate batteries (LFP battery 3.2 V 5 Ah)	To power 6 LED tube light with 6800 mF capacitors	(Walter et al., 2018)
Stack of 112 MFCs	LED bulb (2.6 V)	Strip of 220 LED was light up for some days	(Mateo et al., 2018)
Portable MFC setup	Power lightweight emergency locator transmitters (ELTs)	used in remote areas, military, or aircraft so that the authorities get alert signals related to identifying and locating people and rescuing them in an emergency condition	(Winfield et al., 2015)

2.2. Powering of automatic air freshener

Whenever human waste is used as feed in MFCs or bioelectric toilets, the inherent odour of volatile compounds makes the surroundings unbearable. You et al. (2016) used a stack of urine-fed MFC to operate a motorized air freshener. Usually, two D-size batteries are required to operate such a commercial motorized air freshener. You et al. (2016) arranged stacks of air cathode MFC with 6.25 mL volume of anode chamber. In this stack arrangement, two cascades of 4 MFC units (total 8) were connected in series and parallel combinations. The original electronic circuitry of the air freshener was customized using a super-capacitor (240 mF), which permitted voltage up to 4.2 V. Once the target voltage of the capacitor was achieved (2.8 V), it started the integrated motor (attached with air freshener), which pushed the nozzle of compressed air spray can (You et al., 2016). Later after spraying, the voltage of the capacitor declined to 2.1 V, the system stopped, and the capacitor again started charging. The cycle of charging/discharging is repeated every 15–20 min for 28 days. In the neat urine, COD reduction up to 20% and phosphate removal up to 82% was noticed. The power density of 14.32 Wm^{-3} was obtained for powering the air freshener can. This study depicted how urine-based MFCs could be integrated for power generation, hygiene, sewage water remediation and resource recovery leading to an actual sustainable future (You et al., 2016).

2.3. LED lights powered by urine MFC

The Bill and Melinda Gates Foundation (BMGF) funded a study that reported how to build up an MFC system for continuous power supply for lighting in the public toilets. Walter et al. (2020) arranged two separate stacks of membrane-less MFC, one comprising 15 MFC units and another having 18 MFC units, operated for 6 days, fueled by the urine of festival-goers at Glastonbury Music Festival 2019. The 15-unit stack was directly connected with 2 spotlights, each including 6 LEDs. The 18-unit stack was linked with 2 identical LED spotlights with 2 LED electronic controllers. Later, after 20 h of incubation, MFC stacks fulfilled the power supply requirement of lights directly. The power generated by the 15-unit stack was raised from ≈280 mW to ≈860 mW by the end of the festival. The power generated by the 18-module stack (LED-driven) initially evolved ≈490 mW which increased up to ≈680 mW. The festival, illumination was above the legal standards for outdoor public toilets with the 15-unit stack (≈89 Lx at 220 cm) throughout. It was the first breakthrough in applying the MFC technology as a direct energy generation set up in remote areas (space, refugee camps) (Walter et al., 2020). Another pilot test was sponsored by Oxfam UK and the BMGF, which reported the field investigations of pee power urinal MFCs for urinal lighting (Ieropoulos et al., 2016). This trial was performed during February–May 2015 at Frenchay Campus (UWE, Bristol). Ieropoulos et al. (2016) established the capability of modular MFCs for washroom lighting where students and staff were urinal users. The subsequent trials were conveyed at the Glastonbury Music Festival (Worthy Farm, Pilton) in June 2015 where Ieropoulos et al. (2016) demonstrated the ability of the MFCs for sufficient power generation in urinal lighting of ~1000 urinal users per day (festival audience). The power output recorded for discrete MFC was 1–2 mW and the power output of a 36-MFC stack was appropriate. The real-time electrical output of both bioelectric urinals was proportional to the number of MFCs used, subject to the temperature and flow rate. The urinal lighting at Frenchay campus comprised of 288 MFCs, generated 160–400 mW when the lights were connected directly without super-capacitors whereas the urinal lightning at Glastonbury Music Festival consisting of 432 MFCs, generated 400–800 mW when the lights were connected without super-capacitors. The COD removal efficiency of pee-powered MFC was >95% for the campus urinal and 30% (average) for the Glastonbury urinal (Ieropoulos et al., 2016). A field trial performed at Glastonbury music festival 2016 (England) witnessed the practical implementation of pee power urinals (Walter et al., 2018). Performance of the MFC stack holding of 12 self-sufficient MFC modules with 6800 mF capacitors and regulator system was investigated to power 6 LED tube lights. A battery stack setup of 8 parallel lithium iron phosphate batteries (LFP battery 3.2 V 5 Ah) was used to store the power generated. Approximately ~1200 L of urine is accumulated daily. During the trial, power output progressively improved for 2 days up to 590 ± 12 mW at 217 ± 5 Ma which sustained for 28 h. The power generated through MFC modules was deposited inside battery stacks during the day period which powered the tube lights at night. The duty cycle was of ≈14 h 30 min (charge time) and ≈9 h 30 min (discharge time). However, the voltage level of the battery declined continuously. During 24 h, it was observed that the lighting system dissipated more power as its energy requirement was high whereas power generation by the MFC system was minimal and could not match with the requirement of the lighting system. Field results of the system under uncontrolled usage indicated an optimal retention time for power production between 2 h 30 min and ≈9 h, while at the HRT of ≈11 h 40 min, 48% COD and 13% total nitrogen content reduction were obtained (Walter et al., 2018). Mateo et al. (2018) built up a large module of 112 MFCs which was made up of seven stacks of 16 mini-MFCs. Results showed that individual MFC generated power equivalent to 1.22 mW. Later, it achieved the maximum power of 6.62 mW after optimization of the electric connection. The minimum requirement is an input voltage of 2.6 V and an input current of 0.020 Ma for lighting a LED bulb. However, there is no threshold power requirement. Thus, optimization of the electrical configuration was carried out to satisfy the voltage and current threshold values and a strip of 220 LEDs was illuminated for several days. Besides this, the robustness of the MFC technology was established after operating 112 MFCs simultaneously with a reproducible performance for 30 days (Mateo et al., 2018). Fig. 3 represents the power harvesting setup of the bioelectric toilet.

2.4. Urine-powered electronics

For being an alternative energy source, the flexibility of design and applicability of the system should be the qualifying criteria. Utilization of the MFC technology to power different electronic devices is necessary to improve its applicability. Winfield et al. (2015) applied a portable MFC setup to power lightweight emergency locator transmitters (ELTs). An ELT is an emergency device widely used in remote areas or aircraft so that the authorities get alert signals related to identification and location of people and rescuing them in an emergency condition. Such lightweight ELTs would be preferable due to their robustness and quick response. Urine-driven MFCs could be an ideal system for powering ELTs and assisting in providing a convincing indication for "life rescue." Winfield et al. (2015) developed origami tetrahedron MFCs (TP-MFCs) using photocopier paper to test different urine-based inoculants. A stack of six abiotic MFCs was inoculated with urine, generated suitable working voltage after 3 h 15 min, sufficient to energize a power management system. The anodes of previously used TP-MFCs were thereafter detached and air-dried for a week. Dried anodes were refrigerated and turned-out suitable TP-MFC. After 4 weeks, these MFCs displayed a quick response to fresh urine and attained a purposeful working voltage in just 35 min. Two TP-MFC were allied in parallel combination, which assisted the power supply for transmission of 85 radio signals, though the series configuration of TP- MFCs supported 238 broadcasts for more than 24 h. These results demonstrated that simple, inexpensive and lightweight paper MFCs could be employed as urine-activated "life rescue" reporting systems (Winfield et al., 2015).

2.5. Bioelectricity from MFC toilets

Bioelectric toilet (BET) or Bio-electrochemical septic tank is a novel MFC technology in which fecal matter can be utilized as a substrate for bacterial oxidation to yield electricity during treatment (Ashok, 2017). The bioelectric latrine treats human excreta and generates the following three incentives: effluent treatment, electricity generation, and compost formation. Castro et al. (2014) evaluated the green latrine for power generation and waste treatment. The authors proposed a simple tri-compartment design in which each compartment was hydraulically separated. This eliminated the requirement of a cation exchange membrane. The latrine was made up of concrete blocks and mortar. The design had a composting chamber, where solids were composted aerobically with an arrangement to divert urine from the composting unit. Power generation takes place by the biological treatment mechanism of nitrogen and other organics in the waste stream. Due to this reason, a separate compartment was attached where nitrification reactions took place by ammonia-oxidizing microbial consortia. Nitrifying bacteria oxidize ammonium (NH_4^+) into nitrate (NO_3^-). Effluent from the anode chamber and nitrification chamber flow towards the cathode chamber, where nitrate is reduced to gaseous nitrogen by denitrifying bacteria. The anode and cathode chambers are anoxic and are placed below the ground level, while the nitrification chamber is aerobic and is at the ground (Fig. 4). This MFC latrine was supervised for 1 year and was used regularly (Castro, 2014). This bioelectric latrine was situated in the most populated mid-site of the campus. The expected users were students and

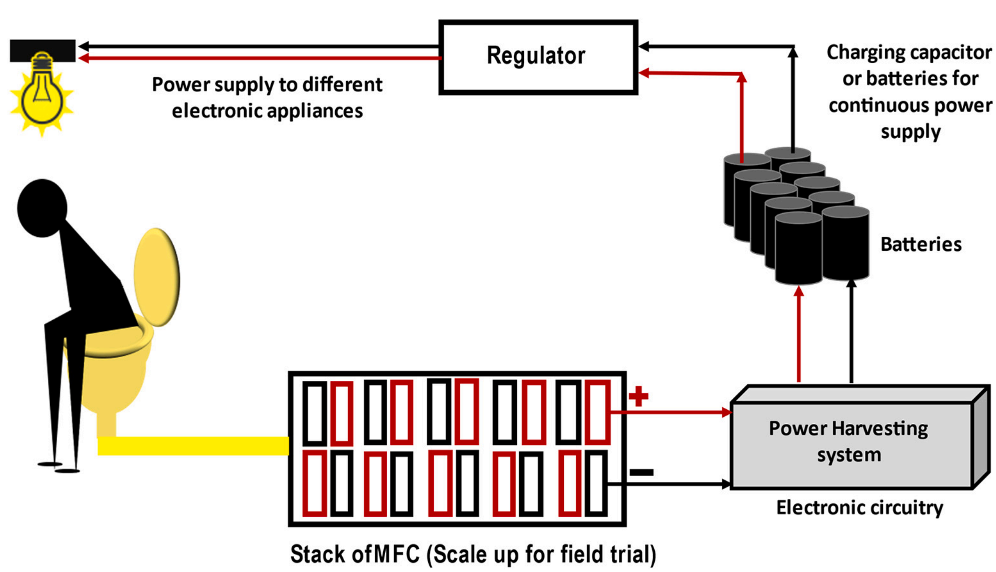

Fig. 3. The schematic diagram for power harvesting setup of bioelectric toilet.

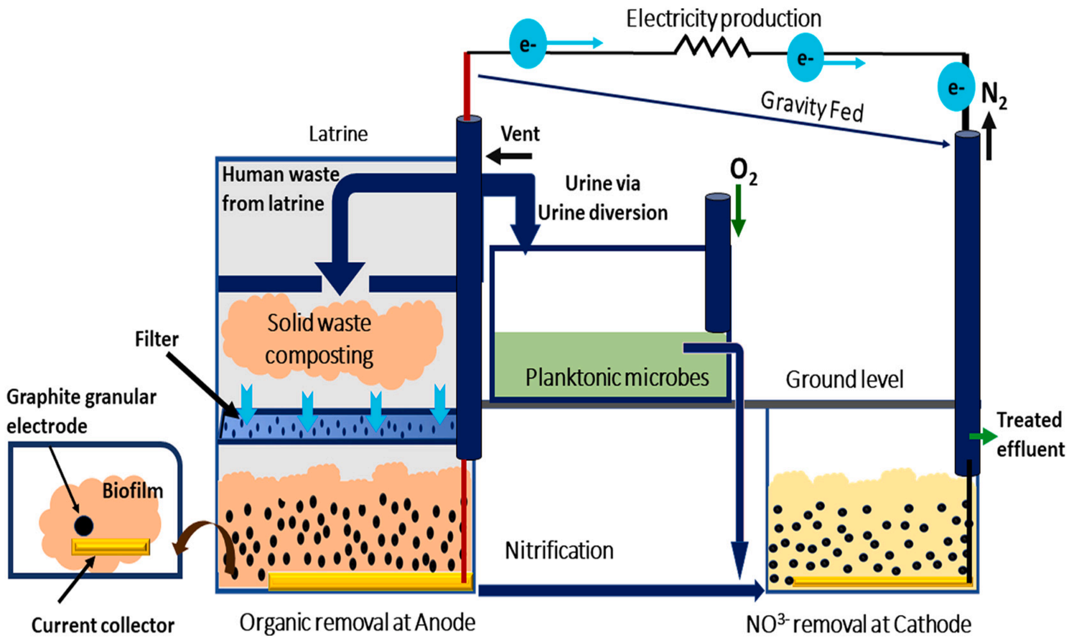

Fig. 4. The green latrine for power generation at NYASTEC campus, Ghana (adapted from Castro et al., 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

faculty members. Elimination of nitrogen and other organic compounds was detected at different time intervals (named as phase I and phase II), COD removal efficiency was found more than 90% in both the phases while nitrate removal in phase I was approximately 75%. The nitrogen removal during Phase II was approximately 68 mg Nitrogen/L. Power generation attained an average of 3.40 nW m^{-2} during phase I. However, in Phase II, it remained at 0.66 nW m^{-2}.

The stacked BET-MFC (100 L volume) was tried for human waste treatment at the Indian Institute of Technology Kharagpur (IIT KGP), India. The fecal matter was collected from the hostels. Stacked BET-MFC exhibited 87–92% of organic matter elimination together with its applicability for charging mobile phone batteries and illuminating LED bulbs (Das et al., 2018). This bioelectric toilet was built up with modified clayware/battery separators and acrylic material having 36 modules of separator-electrode assemblies. It provides a continuous supply of wastewater from the septic tank in an up-flow manner (Das et al., 2018; Mathuriya et al., 2018). IIT KGP, India, developed another BET-MFC of 1.5 m^3 capacity for the treatment of human waste with simultaneous electricity generation (Das et al., 2018). This BET-MFC had a hexagonal middle settling chamber where five outer anodic chambers were fixed with air cathode, and the 6th chamber was for disinfection (cathodic type). The middle settling chamber consisted of 49 pairs of separator-electrode assemblies, where carbon felt was used as both anode and cathode. The separator was made up of 20% montmorillonite mixed clayware ceramic tile (Fig. 3). It was reported to be the most successful continuous operation of BET-MFC for the last few years (Das et al., 2018). This MFC system was capable of removing about 5–6 log scale pathogens from anodic treated effluent using hypochlorite solution feeding in the final aqueous cathodic chamber. The electrical energy gained was capable of powering the LED bulbs for illumination. Bioelectric toilet (BET) or Bio-electrochemical septic tank is a novel MFC technology in which fecal matter can be utilized as a substrate for bacterial oxidation to yield electricity during treatment (Ashok, 2017). The electrical energy gained is capable of powering the LED bulbs for illumination. Cid et al. (2018b) created a self-contained toilet system by the help of the California Institute of Technology, Pasadena, California. The toilet system is integrated with waste treatment before it is released into the environment. The system was designed in such a way that after flushing the toilet, wastewater was released into a tank. Thereafter, the collected wastewater was pumped out into a stack of electrochemical reactors. Inside the electrochemical reactor, microbial oxidation of fecal material took place. The microbial communities inside the reactor were unidentified (Cid et al., 2018b). Indeed, there is the possibility of having pathogens. Chlorination is an inexpensive and effective way for pathogen elimination from water. When the chloride is added to the electrochemical reactor for disinfection, the electrochemical oxidation (anodic) of chloride continuously generated chlorine (in situ chlorine production). Anodic oxidation of fecal material releases electrons to anode which is connected to the cathode via an electrical circuit. H_2O reduction takes place at the cathode and molecular hydrogen is generated (biohydrogen production). Apart from that, the sequential treatment offered COD reduction up to 80% which was apt for the agricultural reuse standards of WHO. Treated black water was restored in flush water reservoirs for its repeated use (Cid et al., 2018b).

2.5.1. Cost evaluation for bioelectric toilets

The reports available on the cost estimation of wastewater treatment are large. Wastewater treatment includes variation in operational methods and types of costs considered, hence cost comparison varies among different reports. In most studies, cost estimation of wastewater treatment is based on the quality parameters such as water quality of influent and effluent, pollutant elimination etc. Several other studies are based on only one of the parameters such as quantity of wastewater treated, operational cost, maintenance cost or energy cost of treatment. Sample data from 22 Spanish wastewater treatment plant were collected and their cost in five sets i) waste management; ii) reagents; iii) maintenance; iv) energy and v) staff were estimated (Molinos-Senante et al., 2010). This study estimated that 33.33% of total cost was spent on the staff, whereas 21% and 18% of total cost were spent on the maintenance and energy requirement respectively (Molinos-Senante et al., 2010). The green latrine of Ghana has a total construction cost of $3900 where less than $1000 for local raw material and $1200 for labor. It is expected that the expenditure of attaching an MFC module to a pre-constructed green latrine system will be 95% lesser (Castro, 2014). For fabrication and assembly of 1.5 m^3 capacity bioelectric toilet MFC (approximately 10-year lifespan) at IIT-Kharagpur $4386 was expended (Ashok, 2017) where construction of septic tank requires $ 1106. Bearing 10 years lifespan in mind, it may need only $1–$2 for the treatment of 1 kL of human waste (Ashok, 2017). It might be possible to reduce capital cost associated with bioelectric toilets with large scale production. Still, total operational cost of bioelectric toilets will be counterbalanced due to lesser maintenance with no additional staff requirement. Also, these toilets offer 80–85% COD removal efficiency along with energy recovery, water recycle and reuse feature for flushing, that will additionally benefit by way of preventing the groundwater contamination (Ashok, 2017).

3. Challenges and evaluation of bioelectric toilets

The performance of MFC hugely relies upon design, microbial inoculum, electrode material, feedstock characteristics, operating conditions, etc. (Asensio et al., 2017). Fig. 5 address major challenges occur during scale up of MFC technology and strategies to circumvent these challenges. Scaling up of systems is a multidisciplinary perspective associated with electrochemistry, materials science, chemical engineering, economics, biotechnology, and environmental engineering. Hence, the real-world application of MFC scale-up is limited (Gajda et al., 2018; Pandit et al., 2020). The bioelectric toilet setup incurs higher expenditure in construction. However, in such bioelectric toilets, water consumption is significantly less as it facilitates the reuse of treated water for flushing repeatedly (Ashok, 2017). Besides water-saving features, onsite bulb illumination with electricity generation makes it economical and user-friendly.

It has been speculated that such toilet systems will be common to use at public places in upcoming years (Ashok, 2017). MFC can be scaled up by enlarging the reactor or miniaturization with multiple units arranged together either in series or in parallel combinations (Greenman and Ieropoulos, 2017). However, power density reduces proportionately with the enlargement of the MFC reactor size (Greenman and Ieropoulos, 2017). Therefore, stack arrangement of multiple MFC units in series or parallel combination is an appropriate choice for scaling up and enhancing the power density significantly where total charge generated by MFC stacks can be stored in a power-managing system (Greenman and Ieropoulos, 2017). Despite all these issues, monitoring and evaluation of the results of MFC stacks is a tedious task while ensuring that no voltage reversal occurs in the stack (Kim et al., 2020; Kim and Chang, 2018). Voltage reversal in stacked MFCs results in a significant drop in power output. When MFCs stacks are arranged in series, connection voltage reversal occurs due to the nonspontaneous anodic overpotential. Mass diffusion limitations result in retarded anode reaction kinetics which is again responsible for anodic overpotential and ultimately causes voltage reversal (Osman et al., 2010). Recent MFC reports have made progress in design/architecture, electrode materials and cathode modification by different catalysts, affordable membrane fabrication (Palanisamy et al., 2019).

Cathode over potential minimization is still a challenging task even with efficient cathodic catalysts (Q. Wang et al., 2017; Ter Heijne et al., 2010). Though cathode modifications such as metal-doped catalysts have been reported previously, yet these alterations may not be form realistic approach for field application due to costly synthesis (Liu and Cheng, 2014; Oh et al., 2010). Nanoparticles created from transition metal alloy could be a great option to overcome the cost issue along with achieving high ORR, HER (Hydrogen evolution rate) and electrocatalytic activity (Das et al., 2020b). Das et al. (2020b) analysed Cu/Zn nanoparticles and observed excellent ORR, ensuring its utility as cathode catalyst in MFCs. Use of Cu/Zn nanoparticles improved the cathode performance where field-scale MFC showed 38% higher COD removal and lab scale exhibited 13% COD removal as compared to control field-scale and lab-scale MFCs (operated without Cu/Zn nanoparticles). Similarly, use of Cu/Zn nanoparticles achieved 4 times higher power density in lab scale MFC as compared to control lab scale MFC. Field scale MFC with Cu/Zn cathode catalyst achieve 64 times higher power density as compared to control field scale MFC (Das et al., 2020b). Thus, Cu/Zn is a worthy, easily affordable and widely available cathode catalyst for the field-scale application of MFC. Therefore, it is a milestone towards the effective commercialization of MFC technology. Expensive membranes could be replaceable with novel and affordable separator material having long-term durability, electrochemical properties and mechanical strength. Materials like clay, modified cement, and ceramic are somewhere close to an ideal and affordable separator material (Neethu et al., 2019; Khalili et al., 2017; Ghadge and Ghangrekar, 2015). Handling bulky wastewater flow and managing its uniform distribution to each MFC unit in the stack is a stimulating job for field applications (M. Lu et al., 2017; Ieropoulos et al., 2010). Considering the prolonged period of operation, it is crucial to manage membrane fouling by chemical and biological means while sustaining the stable performance of MFC (Ibrahim et al., 2020; Wang et al., 2018). Furthermore, unskilled labor for maintenance and operation of the

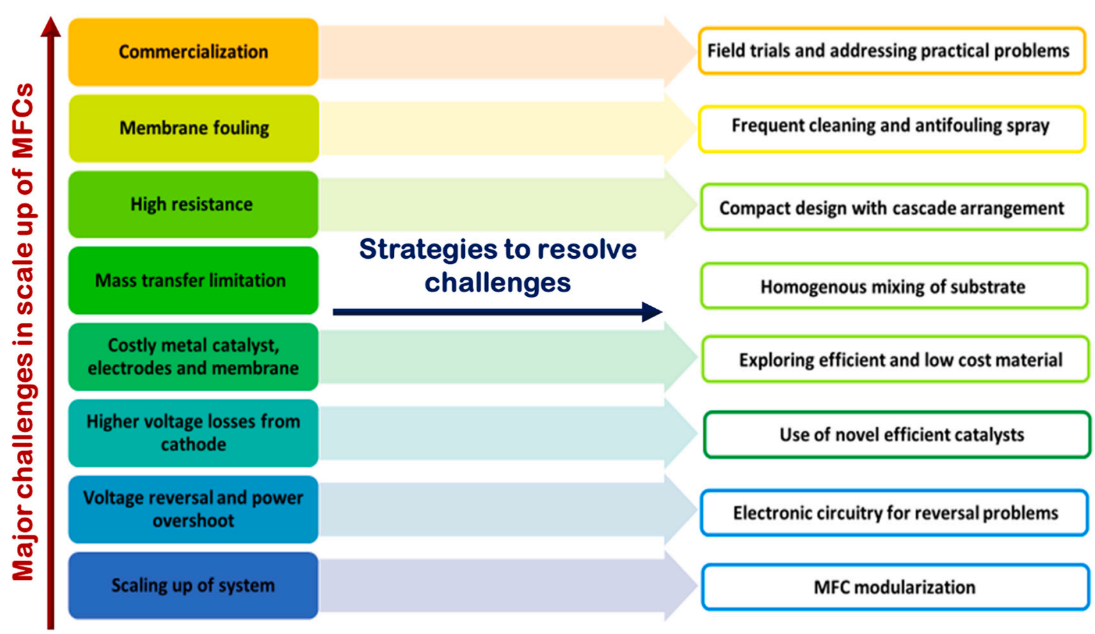

Fig. 5. Major challenges in scale up of MFC and strategies to circumvent.

reactor, leakage in the reactor, clogging of influent/effluent pipelines and substrate diffusion are few operational difficulties (Brunschweiger et al., 2020; Krieg et al., 2018; Choudhury et al., 2017). In most clay-based MFCs, biomass sludge development occurs inside the anodic chamber whereas washing out a surplus amount of anodic biofilm can cause clogging inside the effluent pipelines (Liu and Cheng, 2014). The growth of methanogens decreases MFCs power generation during an extended duration of operation (Jadhav et al., 2019; Rossi et al., 2019; Zhang et al., 2019;). An adequate environment-friendly approach is mandatory to suppress methanogenesis in MFC (Jadhav et al., 2019). The commercialization of MFC toilets is still in the trial due to lack of reproducibility of results and system stability issues. Several issues linked to the commercialization of MFC systems are its performance stability and reliability (Das et al., 2020a; Ghangrekar, 2019; Mathuriya, 2019; Mathuriya et al., 2018; Pant et al., 2011). While considering corporate or industrial interest towards MFC's commercialization, numerous start-up companies of USA such as Hy-SyEnce, IntAct Labs LLC, Lebone, Trophos Energy are established (Pant et al., 2011).

4. Future perspective

Human waste is a valuable feedstock, rich in organic compounds and macronutrient content (N, P, and K) for sustainable energy recovery (Simha et al., 2018; J. Lu et al., 2017; Yang et al., 2020). Over the past decade, many researchers reported the capability of urine-derived bioelectric fuel cell systems for power generation and valuable compost fertilizer by-products for agriculture. For a clean water system, utilization of pee powered MFC systems marked COD removal of >90% (Ieropoulos et al., 2016; Gao et al., 2018; Lu et al., 2019; Ozdemir et al., 2019), N and P recoveries of >50% (Zhou et al., 2015) and >90% (Zang et al., 2012), respectively. In spite of recent developments in using MFCs fed with urine, the major challenges are scale-up, real-world implementation and its commercialization (Das et al., 2020a; Ghangrekar, 2019; Mathuriya, 2019; Mathuriya et al., 2018; Pant et al., 2011). For the efficient solution to these challenges, both biological and electrochemical aspects are needed to be more improved. Therefore, to determine the exact capabilities of bioelectric toilets as a sustainable approach for resource recovery from human waste, additional research on the parameters limiting the biodegradation of organic matter is necessary. Extra attention should be made in the following areas: (i) the removal and simultaneous recovery of nutrients in urine (You et al., 2016), (ii) design strategies such as hydraulic retention time (HRT), anode over potentials and effective urine dilution to enhance coulombic efficiencies (Seelam et al., 2018; Mateo et al., 2019), (iii) genetic engineering strategies to develop efficient microbial strains with high extracellular electron transfer rates (Li et al., 2018; Zhao et al., 2020). The expertise of these parameters assists in enhancing the performance of the MFC and cuts the additional expenditure. The most influencing factor for successfully implementing such MFC toilets worldwide is the user's awareness of sanitation and energy recovery. Such sanitation facilities with effluent treatment, water reusability and hygienic conditions for protecting human health open new dimensions towards its field application and commercialization (Reddy et al., 2018).

5. Conclusion

Combining the MFC-based toilet to the user's typical sanitation practices is vital for implementing MFC as an energy recovery with sanitation. Trials of the bioelectric toilet (India), green latrine (Ghana), and pee-power urinal (UK) are the vital success indicators of the practical utility of MFC towards onsite sanitation. This review summarized the employment of the MFC into the septic tank to improve the treatment efficiency of toilet sanitation practices for providing an acceptable bioelectric toilet for commercialization. MFC technology would be applicable in the rural part of developing countries for energy recovery from human waste and improving current sanitation systems.

CRediT authorship contribution statement

Manisha Verma wrote the manuscript and prepared figures. Veer Singh and Manoj Kumar Verma added more technical facts to the manuscript, Jyoti Singh and Vishal Singh involved in data management, proof reading, and compilation of the manuscript. Dr. Vishal Mishra supervised the complete work and corresponding author of the manuscript.

Declaration of competing interest

The authors have declared no conflict of interest.

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