

Design Configurations and Operating Parameters of Bio-electrochemically Enhanced Anaerobic Digestion

A. Shabib, M. Abdallah, A. Shanableh, and M. Sartaj

Abstract—Bio-electrochemical anaerobic digestion (AD) is one of the most recent advancement in anaerobic treatment processes. Microbial electrolysis cells (MECs) are used for bio-electrochemical treatment, where the supplied external power is used to enhance the performance of AD. Multiple studies have investigated the viability of MECs under various operating parameters and for different organic wastes. The present paper aims at reviewing the latest literature regarding bio-electrochemical enhanced AD through MECs. It was concluded that MEC reactors significantly enhance AD performance under different supplied voltages, temperatures, electrodes configuration, as well as other operating parameters. Based on the compiled literature, further comprehensive life cycle assessment of MECs is recommended prior to any full-scale implementation.

Index Terms—Anaerobic digestion, bio-electrochemical enhancement, microbial electrolysis cells, state-of-the-art review.

I. INTRODUCTION

The world population reached around 7.5 billion in 2017, and is projected to increase by another one billion before 2030 [1]. This population growth, associated with an increase in living standards and urbanization levels, comes with increasing hazards to the environment. For instance, wastewater generation has significantly increased due to the increasing water demand, as well as the escalating municipal solid waste (MSW) production. However, only 70, 38, and 28% of generated wastewater is treated in high, middle, and low-income countries, respectively [2]. Additionally, Around 75% of the generated waste is disposed in landfills and open dumps, from which 44% is composed of organic fractions leading to multiple intensified hazards [3]. Therefore, numerous technologies have been established to treat those types of wastes.

Anaerobic digestion (AD) is one of the most sustainable biochemical methods utilized to treat organic substrates, such as wastewater, sludge, livestock manure, and organic fractions of MSW (OFMSW). However, conventional AD processes have been commonly limited with low organic removals, low methane yield, and long retention time requirements [4]. Therefore, multiple advancements have been suggested to overcome those limitations, including

bio-electrochemical enhancement using microbial electrolysis cells (MECs). MECs have gained substantial interest due to its significant potential in enhancing the overall AD process. In fact, life cycle assessment has suggested that MECs could change the entire economics of AD processes and provide major environmental benefits [5].

The present paper aims at reviewing the latest literature regarding bio-electrochemical enhanced AD through MECs. The review compiles the different design configurations of MEC reactors, as well as the impact of multiple operating parameters on their performance. The aim of this review study is to contribute in future adaptation of MECs, as well as policy development for potential full-scale implementations.

II. ANAEROBIC DIGESTION

AD is a complex, multi-stage process, that occurs in an oxygen-free environment and commonly operated in mesophilic conditions, i.e., operating temperature between 35 and 37°C [6]. The AD process constitutes four phases, namely: hydrolysis, fermentation, acetogenesis, and methanogenesis [7]. Fig. 1 shows flow diagram of the AD process. AD is considered a promising alternative for the management of organic wastes and energy generation [8]. The process typically takes few weeks to obtain maximum energy yield, and the amount of waste is reduced by about 50-60% after digestion [9]. Additionally, the remaining 40-50% is converted to digestate which is either landfilled or utilized in agricultural activities as soil conditioner.

AD has been proven as a viable solution for the treatment of various industrial and municipal wastes with multiple advantages [6]. Typically, anaerobic treatment generally consumes little energy, as energy requirements are in the range of 0.18-0.36 MJ/m³ per treated substrate [7]. In addition, AD facilitates sludge dewatering, raw waste stabilization, and produces a relatively odor-free end-product. A study found that methane production from cow manure via AD had an optimum flow rate of 376.53 L-CH₄ per day, which could represent a valuable alternative energy source to fossil fuels [10]. It was also found that implementing AD in dairy farms could reduce the annual methane emissions in the United States by 7% [11]. Reference [12] showed that AD facilities would reduce greenhouse gas (GHG) emissions by around 98,500 Gg CO₂-eq. in selected Middle East and North Africa (MENA) countries.

A. Limitations

Despite the various potential benefits of AD systems, there are multiple limitations related to the process operation. For instance, AD is typically limited with long hydraulic

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A. Shabib, M. Abdallah, and A. Shanableh are with the Department of Civil and Environmental Engineering, University of Sharjah, Sharjah, United Arab Emirates (e-mail: ahmadgshabib@gmail.com, mabdallah@sharjah.ac.ae, shanableh@sharjah.ac.ae).

M. Sartaj is with the Department of Civil Engineering, University of Ottawa, Ontario, Canada (e-mail: msartaj@uOttawa.ca).

retention times (HRT) and low methane yield [4]. Additionally, the conventional anaerobic treatment is typically limited by organic removal at low organic loading rates (OLR) as higher rates lead to the accumulation of volatile fatty acids (VFAs), thus preventing optimum methane production [13]. Moreover, the AD of particular substrates, such as waste activated sludge (WAS), is limited by the complex organic degradation in the hydrolysis phase, thus leading to reduced methane production rate [14]. Additionally, dairy manure is best digested in mesophilic conditions (35–37°C), as a study showed that the biogas production at 20 and 28°C were measured as 70% and 87%, respectively, of the biogas produced at 35°C [15]. However, maintaining such temperature could be financially unfeasible, particularly for small-scaled AD plants.

B. Enhancements

Multiple enhancements have been developed in recent years to overcome the multiple limitations of conventional AD processes. For instance, various pre-treatments including mechanical, thermal, chemical, and biological intermediates could be used to enhance the limiting hydrolysis phase of AD [16]. Pre-treatment of substrates accelerates the solubilization and transformation of larger organic compounds into smaller biodegradable matter. Additionally, co-digestion of substrates with other organic wastes has multiple benefits compared to conventional AD [17]. Co-digestion balances the C/N ratio, increases the pH buffering capacity, decreases ammonia toxicity, and decreases VFAs accumulation. A study was conducted to compare the methane production of co-digesting manure with OFMSW compared to manure digestion alone, and concluded that co-digestion improved the specific methane production by 86% [18].

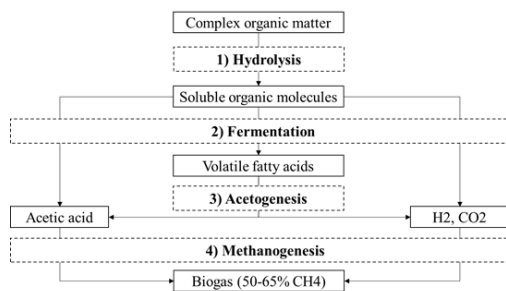
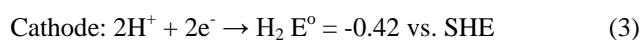
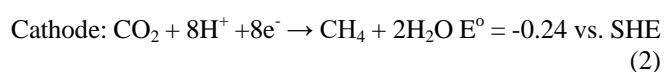
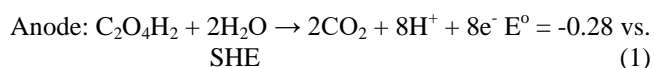


Fig. 1. Flow diagram of the anaerobic digestion process.

III. BIO-ELECTROCHEMICAL ANAEROBIC DIGESTION

The most recent advancement in anaerobic treatment is bio-electrochemical upgrading of AD through the use of MECs. Bio-electrochemical methane production via MECs is based on the supplementation of external energy in order to stimulate additional methane production compared to conventional AD [4]. The MEC technology is based on the utilization of microorganisms as catalysts that harvest electricity and enhance the anaerobic treatment through the redox reactions between organic and inorganic compounds [19]. Fig. 2 shows a simple configuration of MECs. MECs simply consist of a pair of electrodes (anode and cathode) with low voltage supplied externally. The inhabitant bacteria in MECs are exoelectrogens, which means that they release

electrons instead of hydrogen during the process [20]. This exoelectrogenic bacteria, accompanied with the supplied voltage, decompose acetic acid formulated due the accumulation of organic matter (VFAs) at the anode, which produces CO_2 , protons, and electrons. Following, direct methanogenesis occurs at the cathode surface, in which methanogenic archaea formulated on the electrode convert CO_2 , protons, and electrons into methane [21]. Additionally, voltage supplementation between the electrodes forces current generation, which produces H_2 at the cathode through the reduction of protons [20]. The presence of H_2 with CH_4 improves the combustion properties of biogas [22]. The following equations summarize the bio-electrochemical process inside an MEC [4].



where E° is the standard electrode potential, and *SHE* is the standard hydrogen electrode with known potential used as a reference electrode.

The performance efficiency of MECs is affected by multiple factors, including the supplied voltage, operating temperature, electrodes configuration, substrates treated, and other operating parameters.

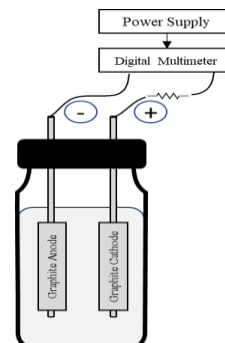


Fig. 2. Schematic of a simple MEC configuration.

A. Supplied Voltage

Supplying the appropriate magnitude of external voltage is critical to ensure optimum performance of MECs. A study was conducted to evaluate the performance of MECs compared to a control sample, i.e., no voltage supply, under different voltages [4]. The supplied voltages were 20, 40, 80, and 120 mV. Methane production was around 105.36 mL/g-chemical oxygen demand (COD) removed for the control sample. The optimum MEC performance was observed at an applied voltage of 40 mV with maximum CH_4 production of around 175.17 mL/g-COD removed. However, the methane yield was enhanced under all supplied voltages with around 111.03, 111.02, and 125.33 mL CH_4 /g-COD removed under 20, 80, and 120 mV, respectively. Another study evaluated the performance of MECs under a different set of supplied voltages, namely 0.5, 1.0, and 1.5 V [13]. The maximum biogas production was observed at applying 1.0 V

with an average 166.14 mL produced compared to 106.24 and 55.76 mL produced under 0.5 and 1.5 V, respectively. In addition, the soluble COD (S-COD) removal was around 80.2, 83.6, and 41% under 0.5, 1.0, and 1.5 V, respectively.

The lower performance under the supplementation of 0.5 and 1.5 V was related to the low potential drive and microbial inhibition effect beyond a threshold value, respectively.

TABLE I: COMPILED LITERATURE ON MECs PERFORMANCE IN TREATING DIFFERENT SUBSTRATES

Reference	Substrate characteristics				MEC performance	
	Substrate	pH	Total solids (TS)	Volatile solids (VS)	Chemical oxygen demand (COD)	Methane production
[4]	Wheat Straw	-*	97.87±0.72 %	75.60±0.77 %	-	105.36 mL/g-COD
[23]	Yard waste	7.5±0.1	91.2±0.4 %	82.45±0.3 %	-	287 mL/g-VS
[24]	Glucose	7.2±0.1	-	-	450 mg/L	10.2-21.7 mL/day**
[19]	Swine manure	-	15,611±1,998 mg/L	8,733±194 mg/L	19,621±131 mg/L	167 mL/g-COD
[25]	Sewage sludge	6.04±0.0	50,917±1,451 mg/L	32,458±473 mg/L	40,766±501 mg/L	322-432 mL/g-COD*
[26]	Pulp and paper mill sludge	6.53±0.5	26.25±0.4 %	18.88±0.75%	-	0.301 m ³ /kg-VS
[27]	Food waste	5.2±0.7	5.2±0.4 %	3.9±0.3%	-	12.1 L/day
[28]	Soybean oil refinery wastewater	9	-	-	40,000-60,000 mg/L	8-45 mL/g-COD**
[29]	Table olive brine processing wastewater	5.4	76,700 mg/L	10,200 mg/L	23,800 mg/L	109 mL/g-COD
[30]	Waste activated sludge	6.32±0.0 8	39,500-39,900 mg/L	29,000-29,300 mg/L	32,570-37,640	72.4 m ³ /m ³ of sludge

* The value was not reported in the study.

** The methane production ranges among different operating conditions

Moreover, reference [31] evaluated the performance of MEC under a broad set of applied voltages, specifically 0.6, 0.8, 1.3, 1.8, and 2.3 V. The S-COD and sludge volatile suspended solids removal rates were enhanced under all applied voltages by 2.6-27.6 and 17.1-51.3%, respectively, compared to the control sample. However, the optimum applied voltage was 1.8 V with increased methane production of around 79.3% compared to the control sample. The optimum performance under the 1.8 V was due to the prevention of water electrolysis under this voltage magnitude. The results of previous studies indicate the supplementation of external voltage to maximize the performance of anaerobic treatment is not straightforward as the optimum voltage supply varies based on other parameters. Therefore, the selection of voltage supply for optimized efficiency of MEC reactors require further analysis of other contributing parameters.

B. Temperature

In addition to the supplied voltages, varying the

temperature levels affect the performance of MECs. A study was conducted to assess the performance of MEC systems under three different temperatures, namely 25, 35, and 45°C, under a voltage supply of 0.7 V [19]. The total methane yield was around 0.53, 0.69, 1.44 L CH₄/g-volatile solids (VS) removed under 25, 35, and 45°C, respectively. It was concluded that the enhanced hydrogenotrophic methanogenesis, i.e., use of H₂ for CO₂ reduction to CH₄, appeared to be responsible for methane production under higher temperatures. Another study was conducted to evaluate the performance of MEC under ambient temperature for the digestion of sewage sludge under different applied voltages [32]. It was found that bio-electrochemical AD via MECs could still produce significant results, as the process was stable in term of pH, alkalinity, and VFAs conversion under an optimum voltage of 0.5 V. Additionally, the methane yield was around 350 mL/g-COD removed with a methane content of around 80.6% of the produced biogas.

C. Substrates

TABLE II: CHARACTERISTICS OF DIFFERENT ELECTRODES USED IN MECs THROUGHOUT THE LITERATURE

Reference	Electrodes characteristics	
	Materials	Dimensions and configuration
[4]	Graphite	<ul style="list-style-type: none"> 15.2 cm length 0.5 cm diameter 7.6 cm spacing edge to edge
[23]	Graphite	<ul style="list-style-type: none"> 10 cm length x 2.4 cm width x 0.5 cm thickness 0.4 cm apart 2 cm from the bottom
[13]	Non-catalyzed carbon brush	<ul style="list-style-type: none"> 2.5 cm depth 4 cm height
[19]	Graphite	<ul style="list-style-type: none"> 6 cm length x 6 cm width
[33]	Thermally activated carbon felt	<ul style="list-style-type: none"> 0.46 cm thickness 170 cm² surface area
[34]	Carbon felt	<ul style="list-style-type: none"> 15.2 cm length x 2.5 cm width x 2.54 cm thickness
[35]	Carbon felt cathode, graphite anode	<ul style="list-style-type: none"> Anode: 15 cm length x 0.25 cm diameter Cathode: 22 cm length x 6 cm width

MECs have showed significant enhancement in the performance of conventional anaerobic treatment of multiple

substrates. Table I summarizes the results of multiple studies evaluating the performance of MECs in treating various substrates. Based on these results, it is clear that the efficiency of MEC systems differs based on the substrate digested. This difference can be generally attributed to the varying characteristics of substrates, such as the pH, total solids (TS), VS, and COD. However, the direct relation between the chemical composition of substrates and the performance of MECs is yet to be identified.

D. Electrodes

The main architectural feature of MECs is the installation of electrodes to stimulate the anaerobic treatment through the transfer of electrons. Different electrode dimensions and materials could be used, such as graphite felt, graphite brushes, carbon cloth, and carbon paper [20]. Table II summarizes the different characteristics of electrodes used throughout the literature in conducting an MEC process. Those general electrode features do not impact the efficiency of MECs compared to the previously mentioned process parameters. Additionally, advanced modification of electrodes could significantly influence the performance of MECs. Reference [24] assessed the impact of modifying the cathodes on the performance of MECs under similar operating conditions. Two types of modification were tested, modification of cathodes using graphene (Gr)/polypyrrole (PPy) and MnO_2 nanoparticles (NPs)/ polypyrrole (PPy). It was found that both modifications enhanced the methane yield with around 22.8 and 39.0% for the Gr/PPy and NPs/PPy modifications, respectively, compared to using unmodified carbon cathodes. This improvement was attributed to the increased conductivity of the modified cathodes, which stimulates the metabolic activity of anaerobic treatment.

In addition to material modification, the positioning of electrodes could influence the performance of MECs. A study tested the impact of electrodes positioning in the top and bottom portions of the cells [36]. It was found MECs with electrodes arranged at the bottom had better performance with methane production of 304.5 mL/L/day compared to 154.6 mL/L/day for MECs with electrodes arranged at the top. Those findings were attributed to the higher inhibitions of methanogens and electrogens on the biofilms of electrodes when arranged at the bottom.

E. Operating Parameters

In addition to the main process parameters previously discussed, multiple operating parameters such as the HRT and OLR affect the performance of MECs. Reference [37] evaluated the performance of MEC in OFMSW digestion compared to a conventional AD reactor under different OLRs. The OLRs used were 3.0, 4.0, 6.0, 8.0, and 10.0 kg-COD/m³/day, all under similar temperature of 35°C and HRT of 20 days. In the conventional AD reactor, maximum methane production was reached at 4.0 kg-COD/m³/day, followed by sharp decrease due to VFAs accumulation as a result of increased hydrogen production. On the other hand, methane production increased throughout the different OLRs in the MEC reactor, with a maximum methane production of around 75.8 L/day obtained at an OLR of 10.0

kg-COD/m³/day. The significantly superior performance of MECs was attributed to the enhanced reduction of H^+ to H_2 , thus preventing VFA accumulation and pH decrease. However, another study assessed the performance of MEC in digesting glucose concentrations of 2, 4, 8, and 10 g/L, and found that the reactor performance decreased sharply at a concentration of 10 g/L due to VFA accumulation [38]. This shows that the recovery of MEC reactors from VFA accumulation under increased OLRs could be related to the characteristics of substrates, and possibly their chemical composition.

Reference [25] studied the impact of different HRT values on the performance of MECs under similar operating conditions. Two HRT values of 10 and 20 days were tested under an ambient temperature (25°C) and voltage supply of 0.3 V. It was found that the stability of the reactor increased with an HRT of 20 days, with COD and VS removals of 54.6 and 65%, respectively, compared to removals of 34.5 and 54.5% under a 10-day HRT, respectively. However, the methane yield was interestingly higher at an HRT of 10 days with a rate of 389 mL/g-COD removed compared to a methane yield of 322 mL/g-COD removed under a 20-day HRT.

IV. CONFIGURATIONS AND APPLICATIONS

Bio-electrochemical treatment through MECs is typically done through adjusting conventional AD cells by supplying external voltage and electrodes installation (Fig. 2). However, different configurations of MEC reactors were examined in multiple studies throughout the literature. A study was conducted to evaluate the performance of indirect voltage supply by having an auxiliary bio-electrochemical reactor (ABER) that replicates the MEC process and compared to direct voltage supplied through conventional MEC installation [39]. In both configurations, the process was conducted over five stages with increasing OLRs. In the ABER-based AD test, the AD reactor was operated independently during stages up to an OLR of 6 kg/m³/day, where methane production in the AD reactor started decreasing due to VFA accumulation. Following, the contents of the AD reactor were circulated to the ABER to restore stable methane production. The methane production was enhanced after the circulation and reached around 80 L/day at an OLR of 20 kg/m³/day, which is almost similar to the methane production reached by the conventional MEC reactor at the same OLR. Despite showing similar results, it was concluded that indirect voltage supply through an ABER was superior to conventional MEC installation in terms of economic efficiency and applicability.

Another study tested a different configuration of MECs by installing a rotating impeller anode inside the AD reactor [40]. The anode was installed by attaching six cross-type impellers on a stainless-steel axis and rotated at 15 rpm, while cylindrical cathode fabricated from the same material was attached to the inside of the reactor wall. The results showed that such configuration would still enhance the performance of anaerobic treatment compared to conventional AD reactor. For instance, the methane yield at an OLR of 6 kg-COD/m³/day was around 0.28 and 0.21 L/g-COD

removed for the MEC and AD reactors, respectively.

V. CONCLUSIONS AND RECOMMENDATIONS

This study aimed at reviewing the literature related to the utilization of MEC reactors for bio-electrochemically enhancing the performance of conventional AD. The compiled literature included detailed process description of MECs, influence of main process parameters, as well as the different design configurations and applications. Based on the results obtained from the reviewed studies, the performance of MEC reactors varied significantly throughout the literature based on multiple factors. Multiple studies evaluated the performance of MEC reactors for the treatment of various substrates. However, there is a clear lack of knowledge regarding the direct relationship between the effect of digested substrate and the performance of MECs. Therefore, it is recommended to further analyze the influence of the substrate chemical composition on the behavior of MEC reactors under different operating parameters. Additionally, comprehensive environmental and financial life cycle assessments of the applicability of MECs are required prior to any full-scale implementations.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All authors have significantly contributed in the present work. A. Shabib conducted the research and co-wrote the paper, M. Abdallah co-wrote the paper, A. Shanableh and M. Sartaj thoroughly revised and improved the paper, and all authors had approved the final version.

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A. Shabib is a research assistant in the Department of Civil and Environmental Engineering in the University of Sharjah, United Arab Emirates. He obtained his B.Sc. and M.Sc. degrees in civil and environmental engineering from the same university in 2018 and 2020, respectively.

During the last 5 years, he occupied multiple part- and full-time positions as a teaching and research assistant. His first publication came in 2018; "Abdallah, M., Shanableh, A., Shabib, A., and Adghim, M. (2018), Financial Feasibility of Waste to Energy Strategies in the United Arab Emirates, *Waste Management*, 82, 207-219". His research interests are mainly waste management, waste-to-energy, microbial electrolysis cell, climate change and hydrology, as well as sustainable transportation and pavement designs.

Eng. Shabib has published 7 journal and conference papers in 6 years of education (BSc and MSc). He has also worked on 2 projects with funded grants.



M. Abdallah is an assistant professor in the Department of Civil and Environmental Engineering in the University of Sharjah, United Arab Emirates. He obtained his B.Sc. in civil engineering in Ain Shams University, Egypt, 2004, his M.Sc. in environmental engineering in the same university, 2007, and his Ph.D. in environmental engineering in the University of Ottawa, Canada, 2011. He also received his P.Eng. license from Ontario, Canada in 2012.

During the last 15 years, he occupied multiple jobs, including a Wastewater Design Engineer (2006-2007) in EnviroCivic Consultant Office, Egypt, a

Water Design Engineer (2007) in Water & Environment Group (WEG), Kuwait, a Postdoctoral Fellow (2011-2013) in the Department of Civil and Environmental Engineering, University of Ottawa, Canada, a Research and Development Engineer (2014-2015) in Clearford Industries Inc., Canada, a Project Manager (2015-2016) in AECOM, United Arab Emirates. His research interests include solid waste management, waste-to-energy, advanced wastewater treatment, microbial fuel cell, and life cycle assessment.

Dr. Abdallah is the author or co-author of more than 25 research publications in peer-reviewed journals and conferences. He has received multiple recognitions, such as the University Faculty Incentive Award in Teaching (2018), the Steve Hart Award by the Air & Waste Management Association (2011), and the Ottawa Startup Award by Ontario Centers of Excellence & Ottawa Technology Transfer Network (2010).



A. Shanableh is a professor in Department of Civil and Environmental Engineering in the University of Sharjah, United Arab Emirates. He is also the director of the Research Institute of Sciences and Engineering (RISE) in the University of Sharjah. He received his B.Sc. degree in civil engineering, structural engineering specialization, from the University of Jordan, Amman, Jordan, in 1986, then received his M.Sc. degree in civil engineering, environmental engineering specialization, in University of Texas at Austin, United States, in 1988, then the Ph.D. degree in civil engineering, environmental engineering specialization, from University of Texas at Austin, United States, in 1990. He also received his professional registration as a CPEng from the Institution of Engineers, Australia, in 1995.

During the last 30 years, he occupied multiple academic positions, such as a Research Assistant (1989-1990) in the University of Texas at Austin, United States, Assistant Professor (1992) in the University of Jordan, Jordan, Lecturer (1994-1996) in Queensland University of Technology, Australia, Senior Lecturer (1996-2002) in Queensland University of Technology, Australia, then Associate Professor (2000-2007) in the University of Sharjah, United Arab Emirates. He has also occupied multiple administrative positions, such as the Department Chairman of the Central Research & Consultancy Department, Research Center, University of Sharjah (2001-2003), Department Chair of the Research Groups Department, Research Center, University of Sharjah (2003-2006), Acting Dean of the College of Engineering, University of Sharjah (2007/08 Summer), and as the Chairman of the Department of Civil & Environmental Engineering, University of Sharjah (1996-2010).

Prof. Shanableh is the editor of 8 published books, and is the author or co-author of 3 book chapters, more than 80 research publications in peer-reviewed journals, more than 115 conference publications, more than 20 conference abstracts, as well as more than 10 technical reports. Prof. Abdallah supervised 4 Ph.D. students and tens of M.Sc. students. He has also received multiple recognitions, including the Fulbright Scholar and receipt of a number of teaching, research and community service awards at the University of Sharjah and Queensland University of Technology.



M. Sartaj is a professor of the Civil Engineering Department, University of Ottawa. He obtained his Ph.D. in environmental engineering from University of Ottawa in 2001. After graduation he worked for 2 years in consulting industry, where he was Project Engineer for the development of the first Engineered Landfill for the Caribbean nation of St. Lucia. He was also a faculty member of Isfahan University of

Technology before joining University of Ottawa in 2011.

During the past 20 years, his research was directed towards developing sustainable solid waste management (SWM) technologies, with the main focus on Bioreactor Landfilling and biogas/renewable natural gas (NRG) production. Benefits of operating a landfill as a bioreactor include enhancement of the landfill gas (LFG) generation rates; reduction of environmental impacts, reduction of landfilling operation and post-closure activities and costs; abatement of greenhouse gas emissions. In addition, bioremediation of contaminated soils and application of adsorption and Ion-Exchange processes for reduction and removal of contaminants released by different industries and agricultural activities such ammonia, heavy metals, cyanide and nitrate and modeling their fate and transport in the environment are among his other research topics of interest.

Dr. Sartaj is the author or co-author of over 75 research publications in peer-reviewed journals and conferences, and one book chapter. He has supervised or co-supervised more than 35 graduate students. Dr. Sartaj has been an active participant and organizer of several national and international conferences.