Environmental Pollution

Bioelectrochemical Systems (BESs) for agro-food waste and wastewater treatment, and sustainable bioenergy-A review

--Manuscript Draft--

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Abstract:	Producing food by farming and subsequent food manufacturing are central to the world's food supply, accounting for more than half of all production. Production is, however, closely related to the creation of large amounts of organic wastes or byproducts (agro-food waste or wastewater) that negatively impact the environment and the climate. Global climate change mitigation is an urgent need that necessitates sustainable development. For that purpose, proper agro-food waste and wastewater management are essential, not only for waste reduction but also for resource optimization. To achieve sustainability in food production, biotechnology is considered as key factor since its continuous development and broad implementation will potentially benefit ecosystems by turning polluting waste into biodegradable materials; this will become more feasible and common as environmentally friendly industrial processes improve. Bioelectrochemical systems are a revitalized, promising biotechnology integrating microorganisms (or enzymes) with multifaceted applications. The technology can efficiently reduce waste and wastewater while recovering energy and chemicals, taking advantage of their biological elements' specific redox processes. In this review, a consolidated description of agro-food waste and wastewater and its remediation possibilities, using different bioelectrochemical-based systems is presented and discussed together with a critical view of the current and future potential applications.
Suggested Reviewers:	Dr. A. Naresh Kumar, Ph.D Postdoctoral Reseach Fellow, University of Maryland Center for Environmental Science nareshka@umd.edu He is expert in the field of bioelectrochemical systems for bioenery and biofuels. His expertise may help to improve manuscript quality.
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Response to Reviewers:	

Cover Letter

Prof. Su Shiung Lam, PhD (Cambridge)
Special Issue Editor
Environmental Pollution

Dear Prof. Su Shiung Lam,

I am re-submitting the revised version of the manuscript "Bioelectrochemical Systems (BESs) for agro-food waste and wastewater treatment and sustainable bioenergy - A review" Reference Number- ENVPOL-D-22-01324R5 by S.V. Ramanaiah, K. Chandrasekhar, Cristina M. Cordas and Irina Potoroko. All the authors of this revised manuscript mutually agree that it should be submitted to "Environmental Pollution" journal in Special Issue on "Agri-food Waste as Environmental Pollutant: Root Causes, Challenges and Solution (VSI: Food Product Pollut)".

We sincerely thank the careful reading of our manuscript and the valuable comments and suggestions. Based on those comments and suggestion, we carefully revised the written English to enhance the quality and to correct grammar and typo issues in the text already accepted by reviewers. We believe that this revised version is finally much more clear, readable and complete. Below, we answer the reviewer's questions, as requested. The revised manuscript will be uploaded with track changes for an easier visualization of the revisions.

I believe that we have addressed all the reviewer concerns and the revised manuscript is now suitable for publications in "Environmental Pollution" Journal in Special Issue on "Agri-food Waste as Environmental Pollutant:Root Causes, Challenges and Solution (VSI: Food Product Pollut)".

Thank you for your kind attention.

Yours sincerely,
Dr. S. V. Ramanaiah & Co-authors

Response to the Editor and Reviewers comments

Dear Editor,

Dear Reviewers,

We deeply appreciate all the time and effort that both the reviewers and the editor have spent reviewing our manuscript "Bioelectrochemical Systems (BESs) for agro-food waste and wastewater treatment, and sustainable bioenergy - A review" Manuscript No. ENVPOL-D-22-01324R5 by S.V. Ramanaiah, K. Chandrasekhar, Cristina M. Cordas, Irina Potoroko.

We sincerely thank the valuable comments and suggestions. In agreement with these last comments, we have revised the manuscript, including the remaining written English issues.

We believe that this revised version is now clear and suitable for publication. Below, please find the list of questions of the reviewer (grey text) followed by the authors' answers and subsequent revisions in the manuscript. We show the changes in the revised the manuscript marked in yellow.

Thank you.

Yours sincerely,
Ramanaiah S.V

Editor comments

Q1.When revising your manuscript, please consider all issues mentioned in the reviewer's comments carefully: please outline every change made in response to their comments and provide suitable rebuttals for any comments not addressed. Please note that your revised submission may need to be re-reviewed.

Dear editor, we thank you once again for your valuable suggestion. We have carefully revised the entire manuscript in agreement with the reviewer comments and suggestions. We hope that this new version can now be considerable as suitable for publication.

Comments (Reviewer #3)

Dear Reviewer, we thank you once again for your very careful reading and valuable comments and suggestions. We have carefully revised the manuscript according to your suggestions and comments. The changes are highlighted in yellow. Please see below.

Q1. Highlights: 2nd sentence - "BESs can be used…".

A1.Thank you very much for the careful revision. We have revised the 2nd sentence in Highlights as per the reviewer suggestion. Please see highlighted text.

Q2. Line 28: considered → considered as

A2. Thank you very much for the careful revision. It was corrected.

Q3. Line 45: remove "of cases"

A3. Thank you very much for the careful revision. Corrected.

Q4. Line 48: "way' - "ways"

A4. Thank you very much for careful revision. Corrected as requested.

Q5. Line 53: "the provided waste estimations" - "the waste estimations provided in Fig.1"

A5. Thank you very much for the valuable suggestions. Corrected, according to the suggestion.

Q6. Line 55: "state" - "stated

A6. Thank you very much for the revision. Corrected.

Q7. Line 82-86: "These systems…" the sentence is little bit confusing. The four functions of BES, bioelectricity generation, biohydrogen generation, value-added compounds production, and desalination, should be clearly denoted with relevant microbial systems.

A7. Thank you very much for the careful revision. We understand the reviewer's point, but in our opinion, giving concrete examples of microbial systems in this sentence will decrease the text readability. Throughout the manuscript text some typical examples and references are mentioned, for the different functions, to ensure that the reader get the more suitable information. We have revised the sentence in order to draw the reader attention for this point, without breaking the text fluidity. Please see highlighted text (lines 82 to 87).

Q8. Line 89: "considered" - "considered as"

A8. Thank you very much for the careful revision. It was corrected accordingly to the suggestion.

Q9. Line 95-86: remove ", among others."

A9. Thank you for the attention. It was removed.

Q10. Line 114: "research" - "researches"

A10. Thank you for the careful revision. It was corrected according the suggestion of the reviewer.

Q11. Line 162-163; Remove "The high value…the globe". It hurts readability of the text.…

A11. Thank you for the suggestion. The sentence was removed according to the reviewer suggestion.

Q12. Line 167-168: Remove "These regions… (Ganesh et al., 2010)"

A12. Thank you for the suggestion. The sentence was removed.

Q13.Line 236: Remove "to be"

A13. Thank you for the careful revision. It was corrected.

Q14.Line 241: "due to the" - "from"

A14. Thank you for the careful revision. It was revised according to the suggestion.
reviewer suggestion.

Q15. Line 243: remove "that are collected upon MFC opreration"

A15. Thank you for the careful revision. The sentence was removed at revised the Line 241 as per the reviewer suggestion.

Q16. Line 245: "that may be" - "can"

A16. Thank you for the careful revision. It was revised accordingly.

Q17. Line 253: "commercially used by scaling up devices" - "scaled up for commercial use"

A17. Thank you for the careful revision. The sentence was corrected.

Q18. Line 275: "cobioprocesses" - "co-bioprocesses"

A18. Thank you very much for careful revision. We have been revised the Line 273 as per the reviewer suggestion..

Q19. Line 323: "using" - "that utilizes"

A19. Thank you for the careful revision. It was corrected according to the suggestion.

Q20. Line 337-338: …into simple and low molecular weight molecules that can be easily degraded by several microbial populations,"

A20. Thank you for the careful revision. The sentence was revised.

Q21. Line 390: "that can be" - ","

A21. Thank you for the careful revision. It was revised.

Q22. Line 395-396: remove "in MESs to generate valuable biological products"

A22. Thank you for the suggestion. The sentence was changed accordingly.

Q23. Line 439: "plentiful in saltwater and/or seawater," - "deficient in freshwater sources,"

A23. Thank you for the careful revision. The entence was revised.

Q24. Line 442-445: "The desalination rate…" Not clear what the sentence meant to be. Rewrite.

A24. We acknowledge the reviewer for the comment. The sentence was rewritten to improve the clarity. Please see revised text (highlighted).

Q25. Line 529: "loss of interest for" - "limited advantage over"

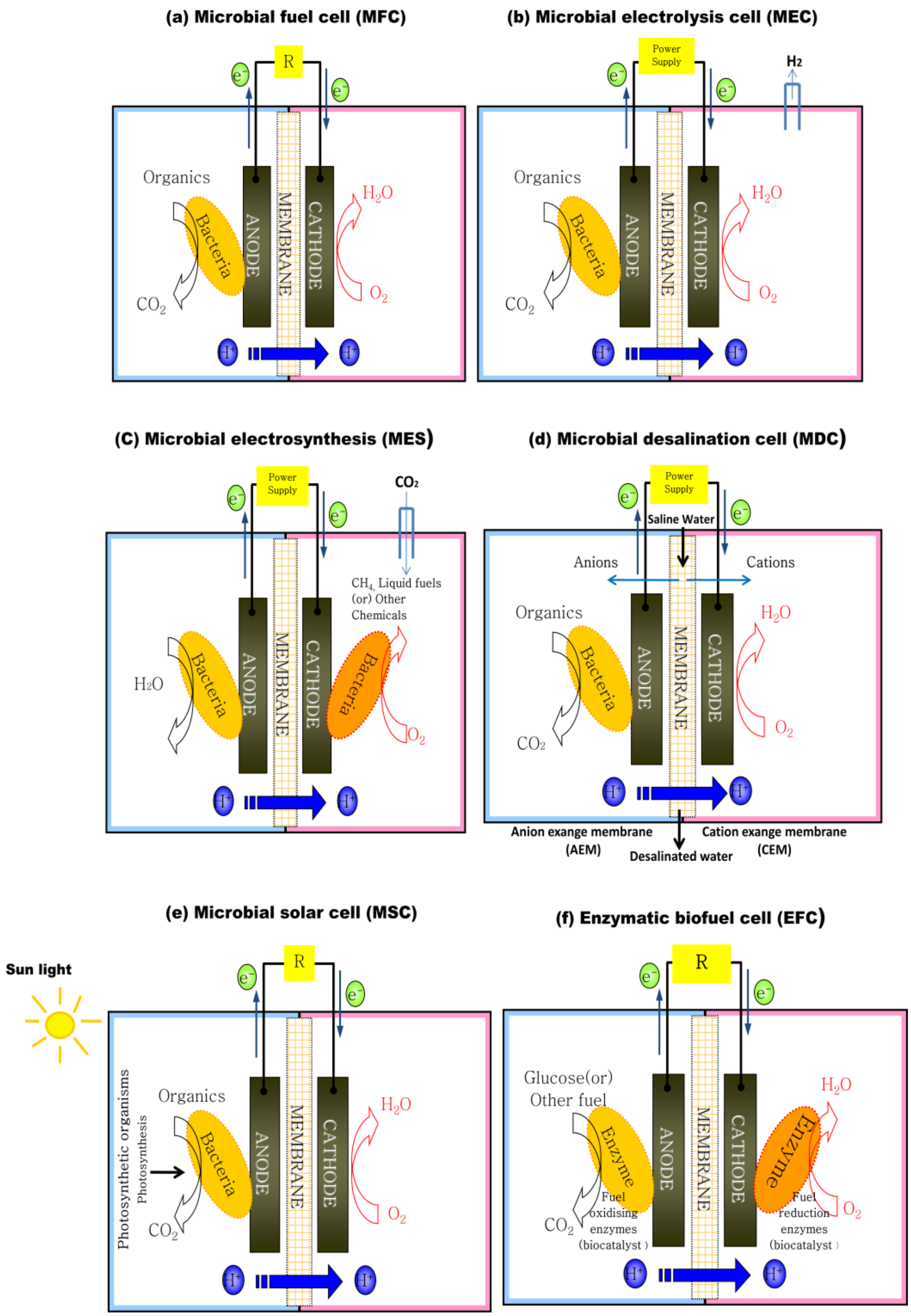
A25. Once again, we thank the reviewer for the careful revision. The sentence was revised.

Highlights

- Agro-food waste significantly contributes to worldwide pollution.
- Bioelectrochemical systems for agro-food waste treatment and energy production.
- Innovative applications for agro-food waste/wastewater treatment are discussed.
- Most promising current and future applications of BESs are critically discussed.

Graphical Abstract

BESs Applications for agro-food waste and wastewater treatment, and sustainable energy



Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author's Statement

S.V. Ramanaiah, Conceptualization, Methodology, Original draft preparation. K.Chandrasekhar, Writing-Reviewing a part of the paper. Cristina M. Cordas, Writing-Reviewing a part of the paper. Irina Potoroko, Writing-Reviewing a part of the paper. All authors read and approved the final manuscript.

Revised Manuscript

Bioelectrochemical Systems (BESs) for agro-food waste and wastewater treatment, and sustainable bioenergy-A review

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Highlights

- Agro-food waste significantly contributes to worldwide pollution.
- Bioelectrochemical systems for agro-food waste treatment and energy production.
- Innovative applications for agro-food waste/wastewater treatment are discussed.
- Most promising current and future applications of BESs are critically discussed.

Abstract

Producing food by farming and subsequent food manufacturing are central to the world's food supply, accounting for more than half of all production. Production is, however, closely related to the creation of large amounts of organic wastes or byproducts (agro-food waste or wastewater) that negatively impact the environment and the climate. Global climate change mitigation is an urgent need that necessitates sustainable development. For that purpose, proper agro-food waste and wastewater management are essential, not only for waste reduction but also for resource optimization. To achieve sustainability in food production, biotechnology is considered as key factor since its continuous development and broad implementation will potentially benefit ecosystems by turning polluting waste into biodegradable materials; this will become more feasible and common as environmentally friendly industrial processes improve. Bioelectrochemical systems are a revitalized, promising biotechnology integrating microorganisms (or enzymes) with multifaceted applications. The technology can efficiently reduce waste and wastewater while recovering energy and chemicals, taking advantage of their biological elements' specific redox processes. In this review, a consolidated description of agro-food waste and wastewater and its remediation possibilities, using different bioelectrochemical-based systems is presented and discussed together with a critical view of the current and future potential applications.

Keywords: Bioelectrochemical systems (BES), agro-food waste and wastewater, microbial fuel cell, microbial electrolysis cell, bioenergy, biohydrogen

1. Introduction

Food waste (FW) is generated throughout all phases of the food cycle, beginning with agriculture and progressing through industrial manufacture and processing, retail, and at-home consumption. For instance, in the EU, 42% of FW are generated in the household, with the remaining 58% in food manufacturing, distribution, and retailing industries (European Commission, 2012). Every year, worldwide, approximately 1.3 billion tons of food produced for human consumption are lost in some ways, costing the global economy approximately $940 billion, as estimated by the Food and Agriculture Organization (FAO) of the United Nations (FAO, 2014). According to predictions made by the World Bank, FW is increasing at an alarming rate (Fig.1). It is projected that by 2050, the extent of FW generated will be a critical problem (Hiç et al., 2016; Ching-Hsu et al., 2020). Although some countries have no available public food waste data, the waste estimations provided in Fig.1 are the most comprehensive global numbers currently available, despite some associated uncertainty (Lipinski et al., 2013; UNP, 2021). Gustavsson et al. (2011) stated that developed countries generate more food losses and waste (FLW) than developing countries. In addition, FLW has an extensive effect on the environment. Carbon footprint calculations indicate that wasted food is estimated to be approximately 3.6 gigatonnes. Regarding global warming, the contribution of FW discharges is almost as large (87%) as the proportion of world road transport emissions (FAO, 2015). According to a survey undertaken by the Russian Association of Electronic Communications (RAEC) and the TIAR Center consulting organization, more than 25 billion dollars' worth of food is wasted in Russia every year (The Moscow Times, 2019). Additionally, every year in the United States, over 61 million tons of food are lost (GMA, 2013). Dee (2013) claimed that Australia generates 4 million tons of FW annually. Other important waste food producers include South Korea, generating 6.24 million tons of FW per year (Hou, 2013); China, generating 92.4 million tons per year (Lin et al., 2011) and Japan, which created approximately 21 million tons of FW in 2010 (Kojima and Ishikawa, 2013). FW production in Europe is estimated to be 90 million tons per year (EC, 2013).

According to other studies, the United Kingdom (UK) has the highest FW production rate in Europe, with more than 14 million tons per year (from 2013 data) (Youngs et al., 1983;WRAP, 2013; Francesca et al., 2015; Thi et al., 2015). Furthermore, 24% of freshwater sources and 23% of the cropland used to produce food in 2011 were lost at some point (Kummu et al., 2012). In the context of eco-innovation, industrial ecology standards, such as the cradle-to-cradle and circular economic systems, are increasingly being regarded as primary principles, with the ultimate goal of achieving a "zero waste economy," necessitating efforts to valorize wastes into value-added products. Simultaneously, biotechnology is in constant development and has the potential to benefit ecosystems, transforming pollutants into biodegradable materials and improving manufacturing and discarding processes to become environmentally friendly. One of the most promising biotechnological solutions is bioelectrochemical systems (BESs) in multidimensional applications (Gul and Ahmad, 2019; Zheng et al., 2020; Ramanaiah et al., 2021a,b; Chandrasekhar et al., 2022a,b; Singh et al., 2022). BESs are bioengineering technologies that integrate microorganisms or other biobased catalysts, such as enzymes, with electrochemical techniques driven by redox reactions (Logan et al., 2019; Ramanaiah et al., 2021a). These systems can effectively minimize waste and treat wastewater while concurrently performing other functions, depending on the microbial systems (and type of BESs), as recovering bioelectricity through microbial fuel cells (MFCs), biohydrogen production using microbial electrolysis cells (MECs), to produce value-added compounds through microbial electrosynthesis systems (MESs) and desalinate salt water through microbial desalination cells (MDCs). These systems can also be coupled with other devices to use solar energy, e.g., microbial solar cells (MSCs), or specific enzyme catalysts, e.g., enzymatic fuel cells (EFCs), taking advantage of specific redox reactions. BESs are consistently considered as very promising biotechnology development. In BESs, at least two electrodes are used, the anode and the cathode, where the oxidation and reduction reactions occur, respectively, usually located in different compartments separated by a membrane, although membrane-less BESs have also been reported (Du et al., 2007). To improve treatment efficiency in terms of both contaminant removal and resource recovery, BESs may involve various types of membranes, such as ion exchange membranes, microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) membranes, reverse and forward osmosis membranes, and gas permeable membranes. These are adopted in waste and wastewater treatment systems and are able to eliminate suspended solids (SS), protozoa, bacteria, and even viruses (Millanar-Marfa et al., 2021). BESs can complement other biological treatment units, such as activated sludge reactors, generating 10 to 20% more energy. The low biomass yield is another advantageous factor, saving costs for sludge disposal, since BESs can achieve high levels of chemical oxygen demand (COD) (92%) and total suspended solids (>99.0%) removal (Pant et al., 2010; Ren et al., 2014). Processes involving membranes, however, have also caused some environmental concerns, with high operation costs and limited availability. From the science citation index expanded (SCIE) database, it is possible to attain an overview of research on BES technology and identify the main applications in the agro-food waste and wastewater field. The keyword analysis revealed that research on BESs can be separated into three aspects, namely, the different types of BES reactors, possible applications and methods to improve performance. MFCs are the most popular BES, and their use for direct electricity generation and simultaneous wastewater treatment is the most studied application. BES-related publications have significantly increased during the past 24 (1998-2022) years, and they are expected to continue to grow in the future. Articles were published in 197 journals in 25 subject categories. Bioresource Technology published the most articles in the BES field, followed by Fuel and Energy Abstracts and Renewable and Sustainable Energy Reviews. Although several studies have shown significant improvement in BES performance over the last 10-15 years (Carlo et al., 2017), researches and reviews on BESs associated with agro-food fields are extremely restricted (Ahmed et al., 2015). The increasing need for food, energy and water implies that innovative agricultural technologies are required to increase productivity while ensuring long-term sustainability. The present review article is based on a comprehensive literature survey on BES technology applications in agro-food loss and waste fields.

Fig.1

2. Generation of agro-food waste

Although food is a fundamental human need, vast portions of food are being wasted in all stages, from the beginning of production to final consumption. The designations when referring to items for human consumption that were lost, degraded, or contaminated are food loss (FL) and food waste (FW) (or both food loss and waste, FLW). FL is defined (by FAO) as any food suitable for human consumption that, due to availability, edibility, wholesomeness, or quality, is, in any way, excluded from being consumed. These classifications are used for after-food production or harvest, which ends when the food is placed in the custody of the last surviving consumer after harvest (FAO, 1981). The definition of FL given by Gustavsson et al. (2011) included the production period of a food supply chain (FSC) rather than only the harvesting and processing phases exclusively. Parfitt et al. (2010) defined FW as the FL that occurs at the marketing and ultimate eating levels and stated that its creation is linked to the behavior of stores and customers. These terminologies were created to describe material produced at the production and retail levels and at the consumption or home level, underlining the need for generally accepted and extended definitions (Williams et al., 2015). Everything from collection to ultimate disposal takes place in the FSC. FL, organic waste, and FW influence all steps of FSC, including manufacturing, distribution and consumption (Parfitt et al., 2010; Pfaltzgraff et al., 2013). In agriculture, in which farming generates waste byproducts that may be both organic waste (e.g., cornstalks, manure) and

FW or FL, an FSC is built, beginning with the agricultural stage. The food processing industry carries some degree of FL and FW through the global production process for several reasons, including damage during transportation and packing, storage faults and contamination. FL and FW are generated by the retail system and markets, primarily due to problems in conservation or handling, as well as a lack of cooling and cold storage (Parfitt et al., 2010). Excessive or unsuitable food purchases, inadequate storage circumstances, excessive processing, portioning, and heating are all factors that contribute to FW by the end user (Glanz and Schneider, 2009; Papargyropoulou et al., 2014). There is also a misunderstanding of the "best before" and "use by" dates (Glanz and Schneider, 2009; Papargyropoulou et al., 2014). In regard to the creation of FW on the household scale, there are a number of linked elements, including the sociodemographic features of the family, eating behavior and dietary forms (Glanz and Schneider, 2009) (Fig.2).

Fig.2

3. Generation of agro-food wastewater

The agro-food sector is one of the most significant pollution producers among various industrial activities. The produced effluents pose a hazard to the environment, requiring the implementation of a management plan appropriate for each situation (the dairy industry is a notable example). Throughout the world, environmental regulatory bodies enforce stringent rules for the disposal of wastewater from industrial facilities. It is estimated that 65-70% of natural pollution discharged into water bodies across the globe originates from agricultural and food product enterprises, which include distilleries, sugar factories, dairy farms, fruit canning, and food manufacturing facilities, as well as pulp and paper mills (Rajagopal, 2008; Rajinikanth et al., 2013).

Sweden's pulp and paper business is one of the country's most important sectors, which is also the case for several other nations (Badshah et al., 2012). The wine sector is one of the most important agricultural and food industries in the Mediterranean and in other production regions, such as Chile, Australia, the United States of America, South Africa and China. Massive quantities of wastewater are generated in the wine industry, the majority of which occurs during numerous cleaning operations, such as crushing and squeezing grapes and cleaning fermenters and vessels, along with several other devices and surfaces in the vineyard (Ganesh et al., 2010). Additionally, the olive oil industry has grown up in various Mediterranean countries (Meksi et al., 2012) and, notably, in the United Kingdom due to globalization. In terms of oils, Malaysia is currently the largest producer (39%) and exporter (44%) of palm oil worldwide (MPOC, 2013). POMEF (palm oil mill effluent) refers to a large amount of polluted wastewater that is produced as a consequence of the overproduction of palm oil. Another leftover effluent (from coffee) has emerged as a serious ecological disaster in coffee-producing countries such as Brazil, Vietnam, and Colombia, according to Fia et al. (2012), driving the necessity for low-cost solutions for handling these wastewaters.

The quantity of wastewater produced varies among countries. It was originally estimated that wine production in the United States, Argentina, Australia, Chile, South Africa, and New Zealand was 18.7, 15.5, 11.9, 10.6, 9.3, and 2.33 million hectoliters (H) in 2011, respectively, while the European Union produced 152 million H (France produced 50.2 million H, Italy produced 40.3 million H, and Spain produced 35.4 million H) in 2011. Over 1750 million metric tons of olive oil are produced worldwide each year, with the bulk of products originating from Italy, Greece, Spain, Tunisia, and Portugal (Veronafiere, 2013). Every year in the Mediterranean region, approximately 30 million cubic meters of oil mill waste (OMW) are generated during olive oil seasonal extraction (Un et al., 2008; Meksi et al., 2012).

Nieto et al. (2012) examined the viability of producing methane (CH_4) from agricultural FW (beverage, milled apple scraps, milk, yogurt waste, lipids, and oils from dairy industrial effluents and cow manure), and from this study, it is possible to estimate the corresponding waste reduction. The energy content of wastewater from dairy or sugar mill effluents is low, whereas wastewaters from wineries, olive mills and cheese have high energy density. This is particularly true in terms of organic matter, proteins, acids, aromatic compounds, widely accessible nutrients, and so on (Ganesh et al., 2010; Zhao et al., 2012; Rajinikanth et al., 2013). Table 1 depicts the characteristic features of agro-food industry wastewater, including complete solids (TS), total nitrogen (TN), total phosphorus (TP), and biological and chemical oxygen demand (BOD and COD) (Ganesh et al., 2010; Zhao et al., 2012; Rajinikanth et al., 2013).

Table 1

4. Bioelectrochemical systems in agro-food waste and wastewater

FW has a high concentration of biodegradable organic components and has the potential to be anaerobically digested to form biogas that can be used as renewable energy. Furthermore, FW exploitation as a source of bioenergy is expected to relieve some of the issues associated with waste treatment and power generation and help to solve the question around using vegetation for fuel and energy production. Treatment of FW using anaerobic techniques can significantly increase the efficacy of hydrogen and methane production for energy use (Kim and Kim, 2013; Thi et al., 2014). Many countries might benefit from the implementation of this energy conversion since it can provide a reliable source of electrical energy. Some earlier studies suggest that FW can be handled either by a two-step dark fermentation and photofermentation process for biohydrogen generation or by a three-stage process for biohydrogen and biomethane synthesis (Kim and Kim, 2013). The adoption of green technologies using agro-wastes for power generation and/or resource regeneration has increased, with BESs appearing to be the most suitable (Bajracharya et al., 2016; Simeng et al., 2018). BESs are energy-producing systems that use agricultural waste and wastewater for energy production or resource restoration (Chandrasekhar et al., 2021; Singh et al., 2022). These are hybrid-biosystems based on microbiology and electrochemistry that can generate bioelectricity or a range of value-added biochemicals through microorganism-catalyzed redox processes (Li et al., 2018; Simeng et al., 2018; Ramanaiah et al., 2021a). In electrochemical devices, electricity is generated due to spontaneous oxidation reactions, where electrons are collected at the anode and transferred through the circuit to the cathode where reduction processes occur. The overall process is present in all types of electrochemical devices, including electrochemical batteries. Alternatively, external power can be used to drive the flow of electrons toward the opposite direction, forcing the selected redox process for resource retrieval (Bajracharya et al., 2016; Simeng et al., 2018). The ability of BESs to use a diverse array of biodegradable organics as electron donors enables the efficient breakdown of various organics concurrently (Pant et al., 2012). To adapt to different systems (e.g., reactions, substrates, etc.), BESs often range significantly in terms of reactor design, size, substrates, bacterial populations, and other characteristics (Bajracharya et al., 2016; Simeng et al., 2018; Ramanaiah et al., 2021a).

Despite their many variations, MFCs, MECs, MESs, MDCs, MSCs and EFCs are the most frequent forms of BESs (Li et al., 2018; Simeng et al., 2018), schematically represented in Fig.3. Several advances have been made in the mechanistic understanding, component improvement and applications of these systems, including the development of household and industrial wastewater treatment (Song et al., 2015; ElIchi-Ribault et al., 2018). In comparison, BES applications in the agro-food industry have not received notable consideration. The next part of this review will discuss the most recent advancements of BES research on the applications associated with agro-food waste and wastewater.

Fig.3

4.1 Microbial fuel cell

MFCs, schematically represented in Fig. 3(a), are the most common BES explored in practical applications (Rachinski et al.,2010; Santoro et al.,2017). MFCs are a kind of bioelectrochemical system that uses microorganisms, usually bacteria, to generate electricity. When electrochemically active microorganisms are present on the anode (or anodic chamber), bioenergy is produced by directly generating bioelectricity from degradation of different compounds (Li and Chen, 2018; Ramanaiah et al., 2021a,b). Organic compounds are consumed by exoelectrogenic microorganisms producing extracellular electrons at the anode electrode (acting as electron donors). The formation of a gradient of potential results in the flow of electrons from the anode to the cathode over an external circuit and the electric current that can be used immediately or stored using batteries (Li et al., 2018). The progress of single-chamber MFCs (in opposition to the classic two-compartment MFCs) has increased the viability of this technology in terms of treating wastewater and producing energy in practice (Logan et al., 2015). According to several researchers (Jiang et al.,2011; Logan et al., 2015; Tota-Maharaj and Paul, 2015; Ramanaiah et al., 2021a,b), a considerable amount of electric power can be achieved using MFCs with waste streams such as household wastewater (Park et al., 2017), industrial waste (Pant et al., 2012), landfill percolate (Li and Chen, 2018), swine wastewater (Min et al., 2005), and others (Logan et al., 2015). On the other hand, MFCs that have been scaled up for commercial use have been limited by two primary factors: the cost of the electrodes and their relatively modest power.

Despite the limitations, MFCs have been widely investigated for their ability to deal with a range of difficult agro-food wastes (i.e., comprising organic/inorganic compounds that are not easily digested by microorganisms) and (or) wastewater while simultaneously producing sustainable electricity that may be used *in situ*, for instance, on farms (Angenent et al., 2004; Min et al., 2005; Kim et al., 2008; Fornero et al., 2010; Pant et al., 2010; Ramanaiah et al., 2021b). Electricity production varies according to the type and quality of feedstock and the type of employed MFC (Table 2). Using swine waste with 8320±190 mg/L soluble chemical oxygen demand (SCOD), Min et al. (2005) attained an extreme power density (PD) of 45 mW/m^2 with a double chamber MFC using an aqueous cathode and a higher PD of 261 mW/m^2 by using an air-cathode MFC. In a second study (Kim et al., 2008), the same kind of MFC (i.e., single-chamber MFC (SCMFC)) was used to treat less concentrated swine effluent (1820±83 mg SCOD/L), leading to a significantly lower PD of 205 mW/m^2. Additionally, lignocellulosic biomass, including maize stover and wheat straw, has been investigated as a possible feedstock for MFCs, showing positive prospects (Zuo et al., 2006; Zhang et al., 2009; Wang et al., 2009). Using raw corn stover and steam-exploded corn stover, Wang et al. (2009) attained a higher PD of 296 and 343 mW/m^2, respectively, while feeding SCMFCs. In addition, wastewater from agro-relevant sectors, for instance, rice mill effluents (Behera et al., 2010) and food-processing effluents (Oh and Logan, 2005), has also been recognized as a promising feedstock for efficient power production in MFCs. Despite continuous advances in the use of biomass waste and effluent as raw materials for MFCs, bioelectricity generation from these materials is frequently constrained by the occurrence of co-bioprocesses, including methane production and ammonification (Angenent et al., 2004; Min et al., 2005). Since the conversion of CO_2 to CH_4 in the cathode chamber costs electrons, the coulombic efficiency and power generation of MFCs are decreased (Rachinski et al., 2010). In addition, high concentrations of ammonia are toxic to the majority of the exoelectrogens that power MFCs (Logan, 2009). As a result, to maximize the amount of energy that can be recovered from agro-wastes and wastewater, upcoming efforts must be directed to reducing the devastating effects of methanogenesis and ammonification on MFCs. Plant microbial fuel cells (PMFCs) and MSCs (Timmers et al., 2010) have attracted the interest of researchers in recent years because of their ability to produce electrical energy from rhizodeposits (i.e., organic acids and organic compounds, among other things) released by plant roots (Hou, 2013). The anode of the MFC has been incorporated into plant-growing soil in certain MSC studies, allowing rhizodeposits from the plants and other compounds from the soil to be harvested and used for power production (de Schamphelaire et al., 2008; Kaku et al., 2008; Kouzuma et al.,2014). Based on estimations, the electricity produced by a PMFC has been calculated to be 21 GJ ha^{-1} $year^{-1}$ (equal to 67 mW/m^2) (Strik et al., 2008). On a laboratory scale, studies using rice rhizodeposits to gather energy have shown a significantly greater power generation rate of 300 mW/m^2 compared to previous findings (Timmers et al., 2013). For instance, it was possible to greatly increase the power generation of long-term PMFC with the use of *Spartina anglica* (Kouzuma et al., 2014) by changing the ion transport route inside the BES (Timmers et al., 2013). Improving the research is essential to understand the fundamental methods and realistic applications of PMFC. To optimize the design of the system elements and operation requirements, it is still necessary to develop mechanistic models (Strik et al., 2011).

Table 2

4.2 Microbial electrolysis cell

The MEC, the scheme of which is presented in Fig. 3(b), is derived from the MFC. MECs can generate hydrogen, methane, and (or) a variety of value-added compounds by using indirect energy and storage (Bajracharya et al., 2016, Lu and Ren, 2016). According to theory, MECs can produce valuable biochemical compounds, independent of the redox variations present on the electrodes. The thermodynamic limitations of specific redox processes can be overcome using external electric power to drive the electron flux in the desired direction. To optimize the efficiency, it is more favorable to keep the cathode in the anaerobic or anoxic state. Among the products that may be manufactured in MECs, H_2 is already established as having an important market value, with the benefit of being a green energy source, due to its rising market demand (Show et al., 2012). Increasing research interest has been directed toward MEC-mediated H_2

generation utilizing a wide range of carbon-rich wastewater as potential feedstock (Lee et al., 2010; Escapa et al., 2012; Heidrich et al., 2013; Dinesh et al., 2018) since the efficiency of these systems is noticeably higher than that of different BESs (Lu et al., 2016). Over the past few years, significant development has been made in MEC-based H_2 production. For example, H_2 yield (HY) has increased from ≤ 50% to nearly 100%, and H_2 production rates (HPR) have increased from less than 0.1 m^3H_2/m^3 reactor/day to as high as 50 m^3H_2/m^3 reactor/day (Lu et al., 2016).

Various types of agro-food wastewater, including dairy manure slurry (Cai et al., 2016), swine wastewater (Lu et al., 2010), and fermentation reactor effluent (Cai et al., 2016), have been used to generate biohydrogen in micro- and nanoscale energy conversion systems (Table 3). MECs have exhibited greater results in comparison to other H_2 production methods, such as anaerobic digestion (AD) and photobiological processes (Logan et al., 2008; Lu et al., 2016; Chandrasekhar et al., 2022a). The reason is their ability to circumvent thermodynamic restrictions. Although various substrates were used for the conversion, there was significant variation in the efficiency of MECs in terms of the HPR and the HY (Kadier et al., 2014). In contrast, AD that utilizes easily decomposable carbon-rich substrates, such as acetate and different fermentation byproducts, has the advantage of providing HPR (up to 50 m^3/m^3/day) and HY (more than 100%) (Lu et al., 2016) without significant variation. An increment in the applied external voltage in most MEC systems results in increased HPR and HY due to the increase in the electron flow toward the cathode. In contrast, a larger external voltage is typically associated with lower energy efficiency since it requires the use of additional energy input. It has been suggested to use an applied voltage window between 0.6 and 0.8 V to achieve a balance between hydrogen generation and energy efficiency (Logan et al., 2008). MEC systems also offer the advantage of being able to be operated with energy provided by conventional power sources and by renewable energy harvested from micro - and small - scale hydroelectric plants and other sustainable power sources, including MFCs (Harnisch and Schroder, 2010). Biogas digesters are fermentation facilities that are often used to reduce agricultural waste and recover valuable biogases such as Bio-H_2 and CH_4 (Li et al., 2018). The combination of MECs with AD has resulted in HPR and HY intensification (Lu et al., 2016).

The capacity of AD to degrade complex carbohydrates into simple and low molecular weight molecules that can be easily degraded by several microbial populations, is one of its primary advantages. It is possible to recirculate CO_2 generated during fermentation operations for pH buffering (Mohanakrishna et al.,2018; Chandrasekhar et al., 2022a). MECs may be designed to create high-purity hydrogen under a variety of operating settings using the substrates produced by fermentation (Lu et al., 2012). To date, the use of integrated systems has resulted in the greatest HPR of 189 m^3/m^3/day, according to Lo et al. (2009), approximately 4 times higher than the HPR achieved by using MECs alone. The incorporation of MECs finishes the breakdown of complex carbon-rich organic matter into CO_2, which fermentation operations cannot accomplish alone. Lignocellulosic substances, traditionally regarded as refractory agricultural wastes, such as maize stover, plant stems, sugar beet, plant leaves and corn stalk, have been successfully used in these integrated systems to produce hydrogen (Lalaurette et al., 2009; Chookaew et al., 2014; Dhar et al.,2015; Khan et al., 2018). Combining H_2 production by fermentation resulted in an average increase of 148% (ranging from 42 to 538%) and 225% (ranging from 2 to 400%) in the total production rate and yield, respectively (Lu et al.,2016). The ability to balance the fermentation rate and electrohydrogenesis is essential for improving the overall system performance. The balance may be accomplished using customized feeding methods and innovative step-by-step processes (Logan et al., 2008). Long-term research on MECs has already been carried out, but pilot-scale MECs are not known to be built, possibly reflecting financial apprehensions due to the high prices of the electrode materials and the need for an external power supply (Logan, 2010; Heidrich et al., 2014; Cotterill et al., 2017; Khan et al., 2018).

Table 3

4.3 Microbial electrosynthesis

MESs, shown in Fig. 3(c), may produce valuable biochemicals (e.g., ethanol, butyric acid, acetic acid and biodiesel) by the mediated reduction of carbon dioxide (and other compounds) at the biocathode (Sadhukhan et al., 2016). MESs may potentially produce value-added products depending on the biocatalysts, electron acceptors and redox mediators used (ElMekawy et al., 2016). The oxidation processes at the anode in MESs may also be used to generate fuels such as bioethanol and biofuel (Sadhukhan et al., 2016). It must be emphasized that MESs are related to MECs, wherein the applied energy supplies extra electrical potential, enabling reduction reactions at the cathode, such as the reduction of H^+ to H_2 (May et al., 2016). A variety of applications of MESs are possible, as demonstrated by the number of available produced compounds that include, but are not limited to, various biofuels (Das et al., 2018) and other commercially valuable compounds (Kumar et al., 2017), such as drug intermediates (MPOC, 2013). Considering the general substrates and potential selectivity, many researchers anticipate that MESs will become increasingly crucial in the future for biological energy production (Rabaey and Rozendal, 2010).

It is expected that MESs may also work with organic-rich agro-food wastes and wastewater (Sadhukhan et al., 2016). The consumption of CO_2 and H_2O allows MESs to transform agricultural and forestry waste (e.g., grass, leaves, wood, corn stalks, stover, immature cereal, etc.) into syngas (Kumar et al., 2017), biohydrogen (Harnisch and Urban, 2018), biomethane (Babanova et al., 2017), formate (Batlle-Vilanova et al., 2017), ethylene (Sadhukhan et al., 2016), methanol (Montpart et al., 2014), dimethyl ether (Shen et al., 2016), urea (Bajracharya et al., 2016), succinic acid (Zhao et al., 2016), and other products (May et al., 2016; Das et al., 2018).

CO_2 can also be converted to precursor molecules of polymers and carbonate compounds for use in the building industry through mineralization processes (Ng et al., 2013). MESs are capable of producing a wide range of valuable biological compounds, together with fuels, for example, ethanol and diesel, when suitable redox reactions are achieved at the electrodes at appropriate applied potentials (Kondaveeti and Min, 2015; Bajracharya et al., 2016). Sadhukhan and colleagues (2016) have provided a better understanding of the equations and Gibbs free energies of anode reactions (63 reactions), cathode reactions (72 reactions) and different metabolic pathways (9 pathways) in MESs. This knowledge may allow us to determine whether energy recovery from wastes or wastewater is practically viable and/or if it is thermodynamically spontaneous. Agricultural waste is an abundant raw material that can be transformed into sustainable organic feed for harvesting energy, particularly useful for micro- and small-scale companies. However, among agricultural biomasses, the presence of lignocelluloses makes the transformation process more complicated. Lignocelluloses are complex combinations of structural polysaccharides such as lignocellulosic biomass encased in lignin and resistant to microbial oxidation (ElMekawy et al., 2015). A way to overcome this problem is to perform the pretreatment of agricultural wastes prior to their use. By pretreatment processes, cellulose and hemicellulose may be recovered and processed to generate a wide range of commercial chemicals, including xylite, L-arabinose, furan resin, and nylon (Sadhukhan et al., 2016). Lignin may be used to make hardwood adhesives, epoxy resins, gasoline additives, binders, and carbon fiber, as well as drugs and scent precursors (Sadhukhan et al., 2016). The efficiency of substrate biodegradation is regulated by media enzymatic hydrolysis. The biological transformation of lignocellulose biomass naturally occurs in three stages: hydrolysis, acidogenesis, and methanogenesis (Li and Chen, 2018), with acetogenesis being the most compatible with bioelectrochemical processes and the most effective at optimizing the production of electrons at the anode. Using electrons provided by organics, CO_2 may be reduced, producing organic compounds of interest (e.g., formate). Metal recovery technologies (MECs and MESs) have evolved in the last few years to recover metals from contaminated sites, waste streams and wastewater in a less disruptive and more environmentally friendly manner (Bajracharya et al., 2016). According to Zhang et al. (2013), when compared to conventional metallic recovery technologies that rely on chemical precipitation, BES technologies can significantly improve efficiency while simultaneously decreasing costs associated with the setup, operation and maintenance (Shikha Dahiya et al., 2018). Moreover, BESs may be integrated into other agricultural and food handling processes in the industry for producing value-added goods by selective synthesis (Sadhukhan et al., 2016). Although highly promising, the technology is still in its early stages, and it is recognized as a potentially important platform to convert organic materials into biochemicals and fuels.

4.4 Microbial desalination cell

To minimize the energy demand frequently used in desalination methods (such as electrodialysis, reverse osmosis and mechanical vapor compression), Sevda et al. (2015) modified an MFC into an MDC (see scheme in Fig.3(d)). Amid the anode and cathode electrodes, a desalination chamber with cation and anion exchange membranes (CEM and AEM, respectively) is introduced, which serves as a barrier between the two electrodes. Cations and anions move through the CEM and AEM and into the cathode and anode electrodes, respectively, as a consequence of the potential difference between the electrodes (Al-Mamun et al.,2018). Due to these ion losses, the saltwater is desalinated. The electrical energy taken from the organics in the anode electrode may be utilized or stored. The use of acetate (synthetic substrate) as an electron donor and ferricyanide as an electron acceptor has been found to achieve a desalination effectiveness of 90% at a maximum PD of 31 W/m^3 (Sevda et al.,2015). Additionally, subsequent research has revealed that when household wastewater is employed as an electron donor and sparged air is used as an electron acceptor, a significant salinity decrease of 60% may be achieved (Luo et al.,2012). MDCs have gained significant popularity as a viable energy-efficient technology for addressing a wide range of critical problems, such as saltwater and brackish water desalination, biochemical manufacturing, groundwater and wastewater treatment, and remediation and energy conversion (Cao et al., 2009; Brastad and He, 2013; Saeed et al., 2015; Sevda et al., 2015).

Water consumption by agricultural operations is high, accounting for almost 70% of total global water use (Jaramillo and Destouni, 2015). A combination of persistent increase in the world population and global warming has added further harshness to the water shortage problem (Gosling and Arnell, 2016). Although desalination methods have been developed, which include reverse osmosis, thermal desalination, and electrodialysis, that were proven effective for providing freshwater to regions deficient in freshwater sources, these methods are energy intensive and, as such, considered unsustainable (Sevda et al., 2015). MDCs are particularly designed for low-cost desalination and are capable of overcoming the limitations of conventional techniques while providing additional financial, energy and ecological benefits (Al-Mamun et al., 2018). The current desalination rate achieved using MDCs alone is considered low (in particular taking in consideration the price), implying that most of these devices are used for desalination or predesalination of saltwater (with lower salinity) rather than seawater (Al-Mamun et al., 2018). The freshwater shortage has driven farmers in many desert locations to utilize brackish groundwater for irrigation, which can provide short-term relief from freshwater stress but, at the same time, can cause longstanding problems, such as the accumulation of ion species potentially harmful for vegetation, expanding the salinity of soils (Ping et al., 2015). Furthermore, due to the excessive osmotic potentials created by high soil salinity, a plant’s ability to absorb water might be hampered (Ping et al., 2015). Therefore, it is vital to maintain the salinity of irrigation water below 450 mg/L TDS to inflict the least amount of harm to soil properties and crop development

(Misaghi et al., 2017). Current MDCs are capable of desalinating brackish water to a level of 450 mg TDS/L, which is the industry norm. Jacobson et al. (2011) found that for an extensive desalination rate of 7.5 g TDS/L/day, a continually operating upflow MDC removed more than 99% NaCl from a salt solution with an excessive salt content of 30 g/L of water. Alternatively, Ping et al. (2015) studied the desalination of 3 distinct types of saltwater at an HRT of 0.8 days and discovered that salts and organic compounds were effectively removed from the water. The MDCs reduced the saltwater TDS levels in a 1.7-day trial to 100 mg/L, which was equivalent to nearby tap water (90 mg TDS) in terms of TDS reduction. Brackish water desalination and MDC single ionic strength were also studied as part of the same research to better understand the primary determinants and construct a prediction model to calculate salinity and single ion concentrations. Some studies found MDC desalination rate values of 9.12 g TDS/L/day using biocatholytes and 8.16 g TDS/L/day using buffer saline solution, which are within the acceptable range (Ebrahimi et al., 2018). For the desalination of synthetic wastewater, larger-scale MDCs holding 105 liters of water were tested, and a salt removal rate of 3.7 to 9.2 grams of TDS/liter per day was found (Strik et al., 2010; Zhang and He, 2015). Future research should aim to scale up MDCs for applications to obtain higher yields of freshwater. As an alternative, MDCs can also be incorporated into existing membrane-based reverse osmosis facilities, reducing energy consumption. This appears to be the most likely scenario in the future until larger efficiencies of MDCs are attained (ElMekawy et al., 2014).

4.5 Microbial solar cell

By integrating photosynthesis with exoelectrogens (Strik et al., 2011), *in situ* bioelectricity can be retrieved. These systems are MSCs (see scheme in Fig.3(e)) and are capable of recovering *in situ* electrical energy or value-added compounds. MSCs use photosynthetic organisms such as photoautotrophic microorganisms or higher plants to transform sunlight into chemical energy stored as organic matter, which is subsequently used to generate electricity by MFCs, as discussed earlier. The transfer of electrons from the anode to the cathode originating from organic matter generated by photosynthesis is the most important operation in an MSC. Rhizodeposition of a higher plant, dispersion of a phototrophic biofilm, and pumping for relocation from a photobioreactor are the three most common modes of transmission (Strik et al., 2011). Among the many forms of MSCs, those combined with residing higher plants (plant MFCs; PMFCs) have proven to be the most beneficial for power production, with outputs reaching 1000 GJ/ha^{-1}/year^{-1} (i.e., 3.2 W/m^2) (Strik et al., 2010; Strik et al., 2011; Mateo et al., 2014). The availability of rhizodeposits for anodic oxidation processes in PMFCs has been shown to directly correlate with the power generated by the devices (Bajracharya et al., 2016; Simeng et al., 2018). A significant difference from traditional solar cells is that MSCs produce a wide range of high-value-added compounds in addition to producing energy (Wang et al., 2014). MSCs are self-repairing systems with an extended lifespan, requiring less maintenance due to the constantly increasing population of microorganisms performing photosynthetic and electrochemical processes (Strik et al., 2011). MSCs are also called molecular synthetic cells because of their wide range of potential uses and ability to be well paired with systems working with renewable and environmentally acceptable energy sources or biosynthetic reactors (Cho et al., 2008).

The development and widespread use of wireless sensor network (WSN) technology solutions in agricultural operations has been ongoing since their creation, with the goal of increasing productivity and automation in precise agricultural operations (Pietrelli et al., 2014). WSN technologies are capable of collecting data on a regular basis as well as performing real-time manipulation of on-farm equipment. Agricultural monitoring equipment, such as remote sensors, is often power-driven by batteries or solar energy, according to Pietrelli et al. (2014) and Brunelli et al. (2018). However, changing batteries in remote areas is difficult and untenable, and employing solar energy sources may be insufficient, costly, and highly dependent on the weather (Brunelli et al., 2018). A long-term power supply for WSN devices can be achieved by BES methods that include MSCs and EFCs and have been intensively investigated, with capacitors being employed to store the generated energy (Desmaele et al., 2015; Bajracharya et al., 2016; Yang et al., 2016; Brunelli et al., 2018). A particular type of MFC, named sediment MFC (SMFC), is being used to supply power to wireless sensors and other structures such as miniature telemetry devices that transmit the information to distant receivers (Kiran and Gaur, 2013). It has been more than a decade since Shantaram et al. (2005) collaborated to create one of the earliest SMFCs, combining MFCs for attaining lesser-power and higher-efficiency electronic circuits. During its initial phases of development, this SMFC was able to produce a voltage of 2.1 V, suitable to power the majority of commercially available electronic circuits when paired with a DC-DC converter for voltage increase (Shantaram et al., 2005). A power management system can be used to store energy, in addition to delivering stable and sustainable power to biosensors, when associated with some SMFCs, which can only produce limited potentials and retrieve electric power intermittently (Donovan et al., 2008). It is primarily possible to combine BES technology with particular agricultural sensor systems. Therefore, different BESs can be used as power sources for a variety of wireless sensors aiming to collect data, such as weather information, irrigation management statistics, availability of plant nutrients and insecticides or pH and concentration of O_2 in the land (Sartori and Brunelli, 2016). BESs will become a hybrid-microbial electrochemical supplemental technology for WSN technologies in agriculture if the electrode performance and system efficiency are further improved.

4.6 Enzymatic fuel cell

In EFCs, electricity is produced by electrochemical cells, as illustrated in Figure 3f, which use specific oxidoreductase enzymes as catalysts to transform the accumulated energy in a carbon-rich waste substrate (matter) into useful electrical energy. The conversion is achieved by using anodic substrate degradation processes at the anode and reduction reactions at the cathode. At some point, selective enzymes were used as biocatalysts in the electrolyte suspension of EFCs (in bulk), but the generally poor efficiency and robustness (Beilke et al., 2009) of the system led to a limited advantage over the in bulk technique. The more recent development of methods for immobilizing and stabilizing enzymes on electrode surfaces (Rasmussen et al., 2016) led to a renewed interest. Several approaches for enzyme immobilization were attained, such as the utilization of cross-linking redox hydrogels or in a *sandwich* (among layers of compatible materials) and encapsulation methods (Neto et al.,2010; Carvalho et al.,2016). Biocatalysts derived from thermophilic microorganisms have also been extensively studied to improve EFC stability due to the recognized thermal stability of these microorganisms even at high operating temperatures (Campbell et al., 2012; Neto et al., 2013 Cosnier et al.,2016). Since their rapid development in recent years, EFCs have been employed in biosensors and portable devices (Neto et al., 2013; Pinyou et al., 2015; Song et al., 2015; Hou et al., 2017), in addition to implantable structures (Alcaraz et al., 2016; Cadet et al., 2016; El Ichi-Ribault et al., 2018). Additionally, the viability of EFCs for energy storage and conversion from a range of sources has been the subject of increased interest (Cosnier et al., 2016). The ease of operation, appropriateness and economic potential, together with environmental sustainability, led MFCs, MECs, MESs, MDCs, MSCs and EFCs to be among the most widely applied and investigated BESs. The details of valuables recovered by different BESs, with their respective advantages and drawbacks, are summarized in Table 4.

Table 4

5. Future prospective applications of BESs in agro-food substances and Challenges

Agro-food waste material is a considerable potential low-cost substrate for BES application, allowing for suitable management of wastes. Further research is still needed for the technology to be completely viable as a biorefinery using agro-food wastes. Many factors need to be taken into consideration, such as soil contamination, including acidification (Zheng et al., 2014), petroleum hydrocarbon contamination (mainly from on-farm trucks) (Lu et al., 2014), metal contamination (Fedje et al., 2015), and transgenic toxicants (Yuan et al., 2017), which may disturb the normal operation of BESs (e.g., side redox reactions, undesirable microorganism selection). To repurpose polluted soils for agrarian reasons, *in situ* bioremediation must be performed. BESs have been explored for remediating toxic pollutants in aqueous media, but their efficiency in soil bioremediation has been hampered by the low efficiency of mass transfer (for example, oxygen and hydrogen ions in soils) (Li et al., 2015). Several studies describe the use of BESs for soil bioremediation in cases that include both petroleum contamination and toxic metals in a process called bioelectrochemical remediation. In this process, inexhaustible electrodes are placed in the contamination sites to perform suitable redox reactions to degrade the pollutants. Membranes are also being utilized as long-term options for the treatment of wastewater from the agro-food industry; nevertheless, a number of challenges continue to impede their efficient processing and restrict their wider implementation. Membrane fouling will likely continue to be the most significant obstacle, and further studies are urgently required to find a solution. The major obstacles that membrane technology faces lie in productivity, product quality, and sociopolitical issues due to energy consumption and greenhouse gas emissions impacting climate change (Fane, 2011). In more specific terms, electrospun nanofiber membranes need to improve their mechanical properties and stability over long-term and upscaling operations.

In situ soil bioremediation through the use of BESs has the potential to become a low-cost solution in the near future since it increases the soil porosity and decreases the ohmic resistance.

Plants need moderate conditions to generate organic energy, such as ATP and NADPH. The Calvin–Benson cycle (Pereto et al., 1999) is a response cycle where energy and ions in the stroma are generated, enabling the conversion of CO_2 into carbohydrates using chemical reactions. In 2016, scientists at Wageningen University introduced the concept of manufacturing food using anaerobic biosynthesis, which makes use of wastes and energy to produce nutrients (Buisman, 2017). The power and electrons produced by BESs could be utilized to substitute ATP and NADPH released during the initial stage of photosynthesis, whereas nutrients retrieved from wastes could be used to enhance biomass growth. A closed-loop self-sustaining system that effectively utilizes the energy and nutrients acquired by circular channels may fulfill all of the goals in a short amount of time. The researchers named their technology "dark photosynthesis" to distinguish it from regular photosynthesis. It is their belief that it has the potential to be extensively employed in the near future to produce food in environments that are unfavorable for regular agriculture (Buisman, 2017). It has been estimated that an approximately 1 m^3 dark photosynthesis food reactor might produce enough food for three people, according to Strik et al. (2010). These studies show the viability of using BESs to sustainably and efficiently produce energy and food. Agro-wastes can be transformed into useful compounds, thus decreasing the current high prices of BESs. It is also possible to obtain construction materials (Madurwar et al., 2013) based on lignocellulose waste, such as cotton stalk, rice husk, grass, and vegetable materials. As described, the technology may be useful simultaneously for several agricultural activities and bring financial, ecological and social advantages. Additional benefits include the ability to pyrolyze agricultural biomass to produce biochar and to achieve an innovative soil adjustment for increasing nutrient and water retention in agricultural soils (Li et al., 2018). Given the high potential of biochar to be used as a relatively low-cost electrode material when compared with conventional electrodes, future research should concentrate on determining the suitability of additional specific biochar products for BES applications.

BESs can be used to fuel agricultural and sensing devices, including self-powered sensors that can be operated either *in situ* and/or online, depending on the requirements (Chouler and Lorenzo, 2015). It is possible to compare BESs to contemporary biosensors, which rely on anolyte oxidation to create external power. The signaling attained with BESs is proportional to the biochemical processes of the electrochemically active microbial population and, particularly, to bacterial biofilm formed on the electrode surface, acting as a sensor. When a disruption occurs, the metabolic processes change the amount of current produced in the circuit. The rate variation of electron production is converted into a signal that reflects the amount of disturbance (Chouler and Lorenzo, 2015). Nevertheless, it is necessary to increase the long-term durability of the output and to attain more stable baseline signals of the BES biosensors (Feng et al., 2013). Another technological challenge for these sensors is the establishment of prediction connections amid the sign responses and the quantities of different substrates or chemicals (Stein et al., 2010). The use of more precise mathematical models as a tool to aid our knowledge is necessary to achieve this objective. Furthermore, as with other BES applications, additional high-performance and less costly materials must be engineered.

Energy savings from the integration of agricultural FW management and utilization in biorefineries will be realized through reductions in raw material consumption, shipping, and manufacturing, together with the development of new models in the food, chemical, health care, and logistics industries. To conduct in-depth research on integrated processes and biorefineries, economic aspects, such as the viability of valorization at a huge scale, the economic evaluation of agricultural FW valorization routes, and the FW supply chain, must be taken into consideration. The ecological advantages of adopting FW would be a reduction in greenhouse gas emissions and their influence on climate change, a reduction in landfilling, a reduction in adverse environmental effects, the use of greener goods and the use of renewable energy.

6. Conclusions

BESs are a recently developed technology for water and wastewater treatment that is both energy-efficient and environmentally friendly. The progression of this technology toward practical applications in the treatment of different types of waste and wastewater has required a great deal of work. The use of BESs in the agro-food industry has not been thoroughly investigated. This assessment includes BES research in the agro-food industry and its prospective use. The combination or integration of BESs with agro-food systems can generate energy, recover resources, reduce waste and treat wastewater and simultaneously reduce the carbon footprint. To expand the application of bioelectrochemical systems, researchers have focused on the selection and optimization of electrode materials, the design of electrochemical devices and the screening of electrochemically active or inactive model microorganisms. The accurate management of fermentation and breakdown, electron routes, intracellular reducing power and energy metabolism in BESs has recently become an important focus of attention. The scope of potential applications for BESs might be expanded with a better understanding of the electron transfer mechanisms occurring via extracellular/intracellular pathways. BESs have more recently found widespread use in various fields, including desalination, nitrate removal, processing solid waste, and materials research. These applications are all related to electron transfer and energy transformation. Designing BESs as self-powered biosensors, producing biochar and using them in food production and *in situ* applications, including soil remediation, are feasible options. Agro- and food-driven BESs have been limited, even though they have significant potential to be applied to food safety, energy sustainability and freshwater accessibility. Long-term and mass-scale studies are still needed to evaluate the steadiness of the systems and the future paybacks of BES applications on farmsteads. However, in green and alternative energy generation, there is an exponential increase in bioelectrochemical technology research, indicating that extensive advances in this domain can be expected in the near future.

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Declarations

Author's contributions

S.V. Ramanaiah, Conceptualization, Methodology, Original draft preparation. K.Chandrasekhar, Writing-Reviewing a part of the paper. Cristina M. Cordas, Writing-Reviewing a part of the paper. Irina Potoroko, Writing-Reviewing a part of the paper. All authors read and approved the final manuscript .

Availability of data and materials

The datasets generated for this study are available on request to the corresponding author.

Ethics approval and consent to participate

Not applicable.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table Legend

Table 1 Characteristics of typical agro-food industrial wastewater

Table 2 Electric power generation in microbial fuel cells (MFCs) using different types of agro-food waste and wastewater

Table 3 Hydrogen production in microbial electrolysis cells (MECs) from different types of agro-food wastes and wastewater

Table 4 Advantages and disadvantages of different bioelectrochemical systems

Table 1 Characteristics of typical agro-food industrial wastewater

Industry	**COD MgL^{-1})**	**BOD (MgL^{-1})**	**TS (MgL^{-1})**	**TP (MgL^{-1})**	**TN (MgL^{-1})**	**References**
Dairy	1400-2500	800-1000	1100-1600	-	-	Gotmare et al., 2011
Cheese Dairy	23000-40000	-	100-3900	60-100	400-700	Rajinikanth et al., 2013
Food processing [a]	1000-8000	600-4000	-	3	50	Wei et al., 2011
Sugar-beet processing	6600	-	6100	27	10	Alkaya and Demirer, 2011
Palm oil mill	50	25	40	-	750	Rupani et al., 2010
Dairy	400-15200	650-6250	250-2750	-	10-90	Passeggi et al., 2009
Corn milling	4850	3000	650	125	174	Ersahin et al., 2013
Bakery’s yeast	6100	-	600	3	275	Ersahin et al., 2011
Potato chips	5000	100	5000	100	250	Senturk et al., 2010
Winery	18000-21000	-	150-200	40-60	310-410	Rajinikanth et al.,2013; Ganesh et al., 2010
Casava Starch	10,500	6300	830	90	525	Sun et al., 2012
Olive mill	130100	-	75500	-	460	Gonçalves et al., 2012
Swineslurry	4600 –5600	2000 -2100	4800 - 4900	10-170	750-770	González-Fernández

liquid fraction						et al., 2008; Yanga et al., 2015
Cow slurry liquid fraction	10350–15510	-	12000-19000	630-770	2080-2030	Møller et al., 2000; Rico, 2007
Brewery	1000-10000	1000-7000	100-1000	10-20	10-100	Hultberg and Bodin, 2017; Lemji and Eckstädt, 2015
Vegetable and fruit industry	4400-5900	400-1700	-	100-200	700-900	Lehto et al., 2014

Note: COD: Chemical Oxygen Demand; BOD: Biochemical Oxygen Demand; TS: Total Solids; TP: Total Phosphorus; TN: Total Nitrogen; [a] Contains flour, soybean, tomato, pepper and salts.

Table 2 Electric power generation in microbial fuel cells (MFCs) using different types of agro-food waste and wastewater

MFC Type	Feed stock	Power Generation (mW/m^2)	Original COD (mg/L)	COD Removal efficiency (%)	References
Single Chamber	Starchprocessing wastewater	239.4	4852	98	Lu et al., 2009
Single Chamber	Brewery wastewater	205	1600	98	Feng et al., 2008
Single Chamber	White wine lees wastewater	262	6400	90	Sciarria et al., 2015
Single Chamber	Beer brewery wastewater	205	2240	87	Feng et al., 2008
Single Chamber	Swine wastewater	261	8320	80	Carlo et al., 2017
Single Chamber	Food waste	162.4	-	72	Chandrasekhar et al., 2015
Single Chamber	Corn stover hydrolysate	867	1000	70	Zuo et al., 2006
Single Chamber	Swine wastewater	205	1820	69	Li et al., 2018
Single Chamber	Winery wastewater	317	2200	65	Cusick et al., 2010
Single Chamber	Canteen based food waste	5.13	1130	64.83	Goud et al., 2011
Single Chamber	Composite vegetables waste	57.38	2080	62.86	Venkata Mohan et al., 2010
Single Chamber (Up-flow tubular)	Animal carcass Wastewater	219	11180	50.66	Li et al., 2013
Single Chamber	Raw corn stover	296	1000	42	Song et al., 2015
Single Chamber	Steam-exploded Corn stove	343	1000	42	Song et al., 2015
Single Chamber	Steam-exploded Corn stover	371	1000	-	El Ichi-Ribault et al., 2018

Single Chamber	Cattle manure	36.6	1000	-	Lee et al., 2011
Single Chamber	Cow manure	349	-	-	Wang et al., 2014
Two Chamber	Cereal wastewater	81	595	95	Oh and Logan, 2005
Two Chamber	Cheese whey	1800	-	92.8	Kassongo et al., 2011
Two Chamber	Acidogenic food Waste leachate	432	1000	87	Li et al., 2013
Two Chamber	Chocolate	1.5	-	75	Patil et al., 2009
Two Chamber	Soy-based food	100	3107	71.4	Pant et al., 2016
Two Chamber (upflow)	Chocolaterie wastewater	98	-	70	Subha et al., 2019
Two Chamber	Dairy wastewater	123.5	-	64	Sekar et al., 2019
Two Chamber	Distillery wastewater	31.49	-	60.78	Deval et al., 2017
TwoChamber (Continuous up flow)	Retting wastewater (Coconut husk)	254	2690	32	Jayashree, 2015
Two Chamber	Palm oil mill effluent sludge	451.26	2680	3	Nor et al., 2015
Two Chamber	Wheat straw	123	2000	-	Rachinski et al., 2010

Two Chamber	Tomato industry pomace	132	-	-	Fogg et al., 2015
Two Chamber	Fermented apple juice	78	3501	-	Cercado-Quezada et al., 2010
Two Chamber	Yoghurt wastewater	54	8169	-	Cercado-Quezada et al., 2010
Two Chamber (Anoxic/oxic)	Saline sea food wastewater	162	-	-	You et al., 2010
Two Chamber	Wheat straw hydrolysate	148	-	-	Thygesen et al., 2011
Earthen Pot -MFC	Rice Mill Wastewater	2	2250	96.5	Behera et al., 2010
Membrane electrode assembly- MFC	Molasses wastewater	16.1	1500	95.6	Wu et al., 2017
Tubular- MFC	Chilled ready-meal Food production	3.34 -5.86	843-1161	67-84	Boghani et al., 2017

Table 3 Hydrogen production in microbial electrolysis cells (MECs) from different types of agro-food wastes and wastewater

MEC Type	Feed stock	H_2 Production Rate (m^3/m^3/day)	Original COD (mg/L)	COD Removal efficiency (%)	References
Single Chamber	Soybean oil Refinery	0.133±0.005	2900±100	95.8	Yu et al., 2017
Single Chamber	Potato wastewater	0.74	7700	79	Kiely et al., 2011
Single Chamber	Glycerol, starch and milk	0.0-0.94	-	74	Montpart et al., 2015
Single Chamber	Milk	0.086	1000	73.5	Montpart et al., 2015
Single Chamber	Leachate and Dairy wastewater	15	24000	73	Rani et al., 2020
Single Chamber	Fermentation effluent	2.11	3200	60	Lu et al., 2009
Single Chamber	Fermentation effluent	4.55	8840	51	Li et al., 2017
Single Chamber	Cornstalk waste	3.43	4000	48	Li et al., 2014
Single Chamber	Winery	0.17	2200	47	Cusick et al., 2010
Single Chamber	Swine wastewater	0.9-1.0	2000	29	Wagner et al., 2009
Single Chamber	Table olive oil brine processing	109±21N ml CH_4/g COD rem	-	29	Marone et al., 2016
Single Chamber	Molasses	2.27-10.72	2000	-	Wang et al., 2014

Two Chamber	Cheese whey: Diluted and Fermented	0.5	15.26	82	Moreno et al., 2015
Two Chamber	Wheat straw	0.61	400	74	Thygesen et al., 2011
Two Chamber	Sugar industry	4.38	4400	56.6	Jayabalan et al., 2020
Two Chamber	Switchgrass wastewater	4.3	2000	48	Lewis et al., 2015
Two Chamber	Animal urine	32.0	1360	46	Kuntke et al., 2014
Two Chamber	Swine	0.061	1298	45-52	Jia et al., 2010

Table 4 Advantages and disadvantages of different bioelectrochemical systems

BESs	**Valuable(s) recovered**	**Advantage**	**Disadvantage**	**Reference**
MFC	Bioelectricity	Converts waste and wastewater to energy, low treatment cost, nutrients recovery, low sludge yield	Expensive catalyst, less power production, moderate COD removal	Paucar and Sato, 2021; Do et al., 2020; Gul et al.,2021
MEC	Biohydrogen, methane, and (or) a variety of value-added biochemical compounds	Removal of complex organic and inorganic pollutants, and easily modifiable to produce required end product	External power supply requires, low valuable production rate	Bajracharya et al., 2016; Hua et al., 2019
MES	Valuable biochemicals like ethanol, acetate, butanol and biofuels, biomethane	Carbon sequestration, high-value and multi carbon organic compounds recovered from industrial applications, metal recovery, and wide variety of applications	External voltage supply requires, lower production rate of chemicals with longer carbon chains	Sadhukhan et al., 2016; Kong et al., 2020
MDC	Saltwater and brackish water desalination, bioelectricity	Desalination and simultaneous waste and wastewater	Increase in anolyte salinity decreases bacterial removal efficiency,	Sevda et al., 2015 Gujjala et al., 2021

		treatment, doesn't rely on external power supply unlike other concurrent desalination technology	membrane fouling, inorganic elements in wastewater adversely impacts the efficiency of MDC, and scaling	
MSC	Bioelectricity	Use sunlight, self-repairing systems, Waste and wastewater treatment, use of wireless sensor network (WSN) technology solutions in agricultural operations	Employing solar energy sources is inefficient, costly, and highly changeable depending on the weather	Strik et al., 2011; Bajracharya et al., 2016; Pietrelli et al., 2014
EFC	Bioelectricity	Employed to authority biosensors and portable devices, energy storage and conversion applications, waste and wastewater treatment	Loss of enzymes activity upon immobilization, cost of immobilization process, and mass transfer limitations.	Neto et al., 2013; Pinyou et al., 2015; Hou et al.,2017; Song et al., 2015

Figure captions

Fig.1. Global food waste distribution and forecast (Source: World Bank, 2016: Ching-Hsu et al., 2020).

Fig. 2. Overview of Food Supply Chain (FSC) in Food Loss (FL) and Food Waste (FW)

Fig.3. Different types of bioelectrochemical systems (BESs); (a) Microbial fuel cell (MFC), (b); Microbial electrolysis cell (MEC), (c); Microbial electrosynthesis (MES), (d) Microbial desalination cell (MDC), (e) Microbial solar cells (MSC), (f) Enzymatic biofuel cells (EFC)

Figures

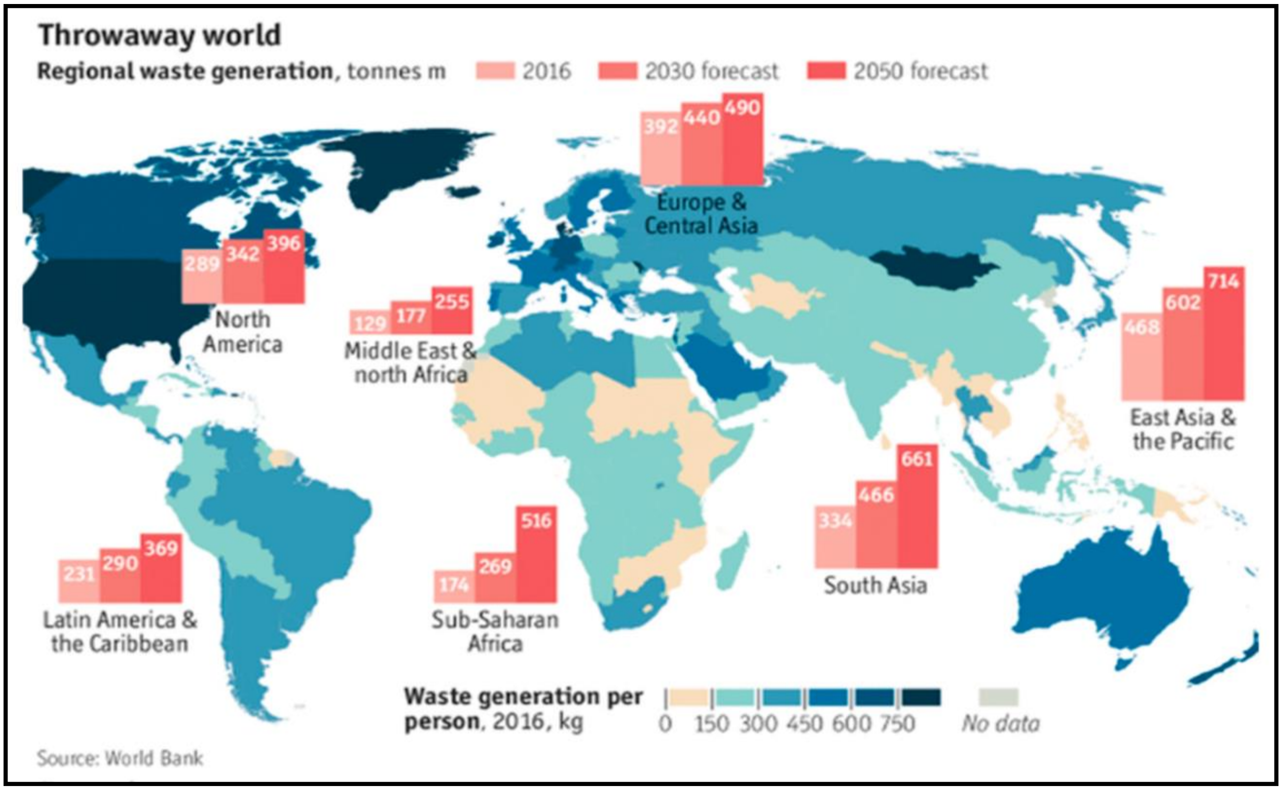

Fig.1

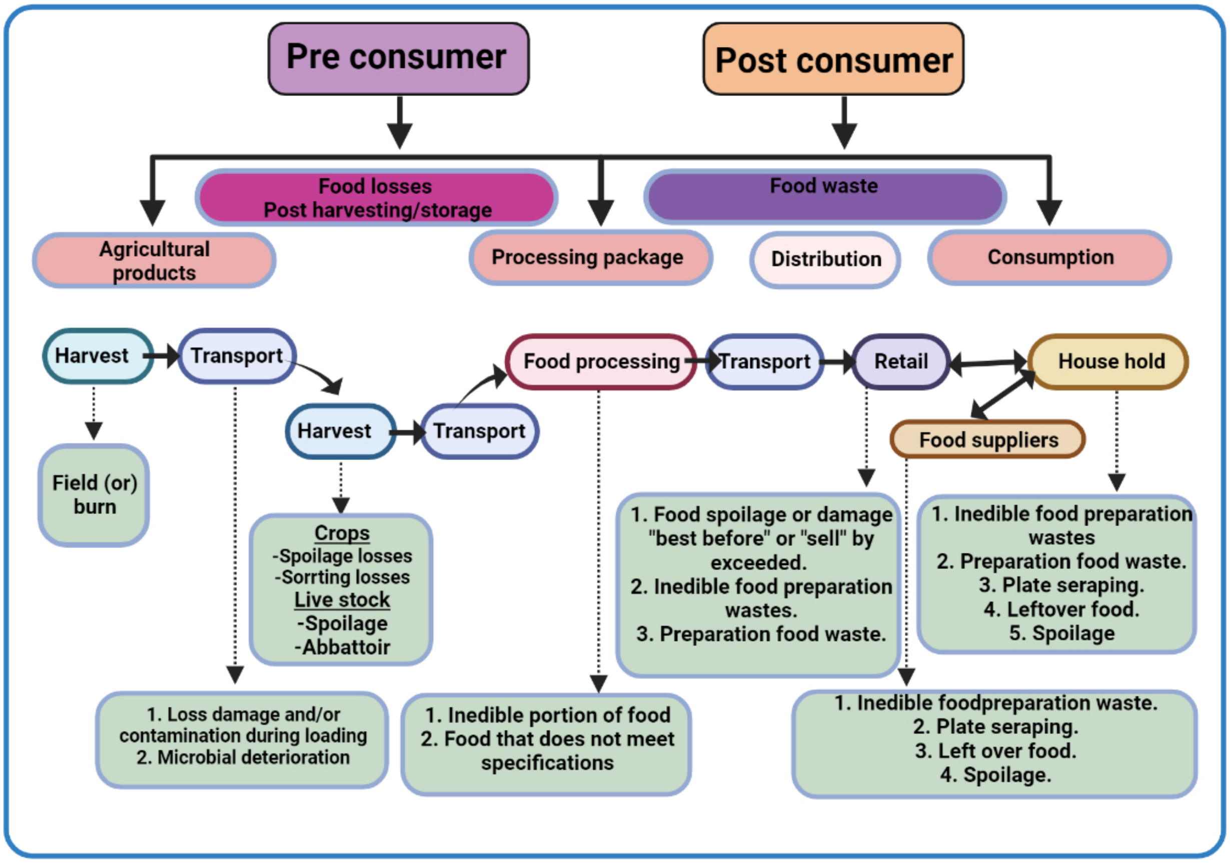
Pre consumer
Post consumer
Food losses
Post harvesting/storage
Food waste
Agricultural products
Processing package
Distribution
Consumption
Harvest
Transport
Field (or) burn
Harvest
Transport
Crops
-Spoilage losses
-Sorrting losses
Live stock
-Spoilage
-Abbattoir
Food processing
Transport
Retail
House hold
Food suppliers
1. Loss damage and/or contamination during loading
2. Microbial deterioration
1. Inedible portion of food
2. Food that does not meet specifications
1. Food spoilage or damage "best before" or "sell" by exceeded.
2. Inedible food preparation wastes.
3. Preparation food waste.
1. Inedible food preparation wastes
2. Preparation food waste.
3. Plate seraping.
4. Leftover food.
5. Spoilage
1. Inedible foodpreparation waste.
2. Plate seraping.
3. Left over food.
4. Spoilage.

Fig.2

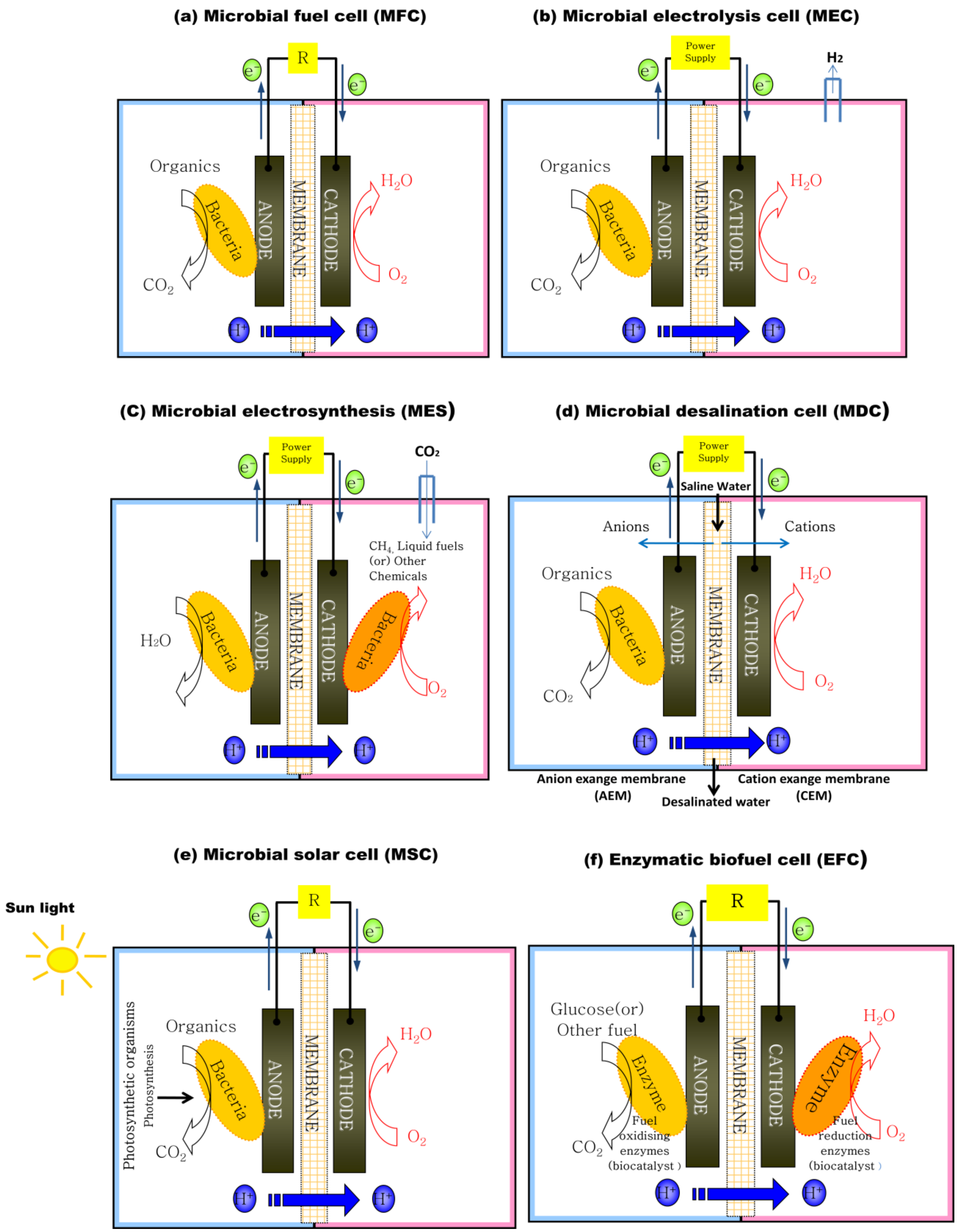
(a) Microbial fuel cell (MFC)
R
Organics
Bacteria
ANODE
MEMBRANE
CATHODE
H_2O
O_2
CO_2
(b) Microbial electrolysis cell (MEC)
Power Supply
H_2
(C) Microbial electrosynthesis (MES)
CO_2
CH_4, Liquid fuels (or) Other Chemicals
H_2O
(d) Microbial desalination cell (MDC)
Saline Water
Anions
Cations
Anion exange membrane (AEM)
Desalinated water
Cation exange membrane (CEM)
(e) Microbial solar cell (MSC)
Sun light
Photosynthetic organisms
Photosynthesis
(f) Enzymatic biofuel cell (EFC)
Glucose(or) Other fuel
Enzyme
Fuel oxidising enzymes (biocatalyst)
Fuel reduction enzymes (biocatalyst)

Fig.3

Revised Manuscript

Bioelectrochemical Systems (BESs) for agro-food waste and wastewater treatment, and sustainable bioenergy-A review

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Highlights

- Agro-food waste significantly contributes to worldwide pollution.
- Bioelectrochemical systems for agro-food waste treatment and energy production.
- Innovative applications for agro-food waste/wastewater treatment are discussed.
- Most promising current and future applications of BESs are critically discussed.

Abstract

Producing food by farming and subsequent food manufacturing are central to the world's food supply, accounting for more than half of all production. Production is, however, closely related to the creation of large amounts of organic wastes or byproducts (agro-food waste or wastewater) that negatively impact the environment and the climate. Global climate change mitigation is an urgent need that necessitates sustainable development. For that purpose, proper agro-food waste and wastewater management are essential, not only for waste reduction but also for resource optimization. To achieve sustainability in food production, biotechnology is considered as key factor since its continuous development and broad implementation will potentially benefit ecosystems by turning polluting waste into biodegradable materials; this will become more feasible and common as environmentally friendly industrial processes improve. Bioelectrochemical systems are a revitalized, promising biotechnology integrating microorganisms (or enzymes) with multifaceted applications. The technology can efficiently reduce waste and wastewater while recovering energy and chemicals, taking advantage of their biological elements' specific redox processes. In this review, a consolidated description of agro-food waste and wastewater and its remediation possibilities, using different bioelectrochemical-based systems is presented and discussed together with a critical view of the current and future potential applications.

Keywords: Bioelectrochemical systems (BES), agro-food waste and wastewater, microbial fuel cell, microbial electrolysis cell, bioenergy, biohydrogen

1. Introduction

Food waste (FW) is generated throughout all phases of the food cycle, beginning with agriculture and progressing through industrial manufacture and processing, retail, and at-home consumption. For instance, in the EU, 42% of FW are generated in the household, with the remaining 58% in food manufacturing, distribution, and retailing industries (European Commission, 2012). Every year, worldwide, approximately 1.3 billion tons of food produced for human consumption are lost in some ways, costing the global economy approximately $940 billion, as estimated by the Food and Agriculture Organization (FAO) of the United Nations (FAO, 2014). According to predictions made by the World Bank, FW is increasing at an alarming rate (Fig.1). It is projected that by 2050, the extent of FW generated will be a critical problem (Hiç et al., 2016; Ching-Hsu et al., 2020). Although some countries have no available public food waste data, the waste estimations provided in Fig.1 are the most comprehensive global numbers currently available, despite some associated uncertainty (Lipinski et al., 2013; UNP, 2021). Gustavsson et al. (2011) stated that developed countries generate more food losses and waste (FLW) than developing countries. In addition, FLW has an extensive effect on the environment. Carbon footprint calculations indicate that wasted food is estimated to be approximately 3.6 gigatonnes. Regarding global warming, the contribution of FW discharges is almost as large (87%) as the proportion of world road transport emissions (FAO, 2015). According to a survey undertaken by the Russian Association of Electronic Communications (RAEC) and the TIAR Center consulting organization, more than 25 billion dollars' worth of food is wasted in Russia every year (The Moscow Times, 2019). Additionally, every year in the United States, over 61 million tons of food are lost (GMA, 2013). Dee (2013) claimed that Australia generates 4 million tons of FW annually. Other important waste food producers include South Korea, generating 6.24 million tons of FW per year (Hou, 2013); China, generating 92.4 million tons per year (Lin et al., 2011) and Japan, which created approximately 21 million tons of FW in 2010 (Kojima and Ishikawa, 2013). FW production in Europe is estimated to be 90 million tons per year (EC, 2013).

According to other studies, the United Kingdom (UK) has the highest FW production rate in Europe, with more than 14 million tons per year (from 2013 data) (Youngs et al., 1983;WRAP, 2013; Francesca et al., 2015; Thi et al., 2015). Furthermore, 24% of freshwater sources and 23% of the cropland used to produce food in 2011 were lost at some point (Kummu et al., 2012). In the context of eco-innovation, industrial ecology standards, such as the cradle-to-cradle and circular economic systems, are increasingly being regarded as primary principles, with the ultimate goal of achieving a "zero waste economy," necessitating efforts to valorize wastes into value-added products. Simultaneously, biotechnology is in constant development and has the potential to benefit ecosystems, transforming pollutants into biodegradable materials and improving manufacturing and discarding processes to become environmentally friendly. One of the most promising biotechnological solutions is bioelectrochemical systems (BESs) in multidimensional applications (Gul and Ahmad, 2019; Zheng et al., 2020; Ramanaiah et al., 2021a,b; Chandrasekhar et al., 2022a,b; Singh et al., 2022). BESs are bioengineering technologies that integrate microorganisms or other biobased catalysts, such as enzymes, with electrochemical techniques driven by redox reactions (Logan et al., 2019; Ramanaiah et al., 2021a). These systems can effectively minimize waste and treat wastewater while concurrently performing other functions, depending on the microbial systems (and type of BESs), as recovering bioelectricity through microbial fuel cells (MFCs), biohydrogen production using microbial electrolysis cells (MECs), to produce value-added compounds through microbial electrosynthesis systems (MESs) and desalinate salt water through microbial desalination cells (MDCs). These systems can also be coupled with other devices to use solar energy, e.g., microbial solar cells (MSCs), or specific enzyme catalysts, e.g., enzymatic fuel cells (EFCs), taking advantage of specific redox reactions. BESs are consistently considered as very promising biotechnology development. In BESs, at least two electrodes are used, the anode and the cathode, where the oxidation and reduction reactions occur, respectively, usually located in different compartments separated by a membrane, although membrane-less BESs have also been reported (Du et al., 2007). To improve treatment efficiency in terms of both contaminant removal and resource recovery, BESs may involve various types of membranes, such as ion exchange membranes, microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) membranes, reverse and forward osmosis membranes, and gas permeable membranes. These are adopted in waste and wastewater treatment systems and are able to eliminate suspended solids (SS), protozoa, bacteria, and even viruses (Millanar-Marfa et al., 2021). BESs can complement other biological treatment units, such as activated sludge reactors, generating 10 to 20% more energy. The low biomass yield is another advantageous factor, saving costs for sludge disposal, since BESs can achieve high levels of chemical oxygen demand (COD) (92%) and total suspended solids (>99.0%) removal (Pant et al., 2010; Ren et al., 2014). Processes involving membranes, however, have also caused some environmental concerns, with high operation costs and limited availability. From the science citation index expanded (SCIE) database, it is possible to attain an overview of research on BES technology and identify the main applications in the agro-food waste and wastewater field. The keyword analysis revealed that research on BESs can be separated into three aspects, namely, the different types of BES reactors, possible applications and methods to improve performance. MFCs are the most popular BES, and their use for direct electricity generation and simultaneous wastewater treatment is the most studied application. BES-related publications have significantly increased during the past 24 (1998-2022) years, and they are expected to continue to grow in the future. Articles were published in 197 journals in 25 subject categories. Bioresource Technology published the most articles in the BES field, followed by Fuel and Energy Abstracts and Renewable and Sustainable Energy Reviews. Although several studies have shown significant improvement in BES performance over the last 10-15 years (Carlo et al., 2017), researches and reviews on BESs associated with agro-food fields are extremely restricted (Ahmed et al., 2015). The increasing need for food, energy and water implies that innovative agricultural technologies are required to increase productivity while ensuring long-term sustainability. The present review article is based on a comprehensive literature survey on BES technology applications in agro-food loss and waste fields.

Fig.1

2. Generation of agro-food waste

Although food is a fundamental human need, vast portions of food are being wasted in all stages, from the beginning of production to final consumption. The designations when referring to items for human consumption that were lost, degraded, or contaminated are food loss (FL) and food waste (FW) (or both food loss and waste, FLW). FL is defined (by FAO) as any food suitable for human consumption that, due to availability, edibility, wholesomeness, or quality, is, in any way, excluded from being consumed. These classifications are used for after-food production or harvest, which ends when the food is placed in the custody of the last surviving consumer after harvest (FAO, 1981). The definition of FL given by Gustavsson et al. (2011) included the production period of a food supply chain (FSC) rather than only the harvesting and processing phases exclusively. Parfitt et al. (2010) defined FW as the FL that occurs at the marketing and ultimate eating levels and stated that its creation is linked to the behavior of stores and customers. These terminologies were created to describe material produced at the production and retail levels and at the consumption or home level, underlining the need for generally accepted and extended definitions (Williams et al., 2015). Everything from collection to ultimate disposal takes place in the FSC. FL, organic waste, and FW influence all steps of FSC, including manufacturing, distribution and consumption (Parfitt et al., 2010; Pfaltzgraff et al., 2013). In agriculture, in which farming generates waste byproducts that may be both organic waste (e.g., cornstalks, manure) and

FW or FL, an FSC is built, beginning with the agricultural stage. The food processing industry carries some degree of FL and FW through the global production process for several reasons, including damage during transportation and packing, storage faults and contamination. FL and FW are generated by the retail system and markets, primarily due to problems in conservation or handling, as well as a lack of cooling and cold storage (Parfitt et al., 2010). Excessive or unsuitable food purchases, inadequate storage circumstances, excessive processing, portioning, and heating are all factors that contribute to FW by the end user (Glanz and Schneider, 2009; Papargyropoulou et al., 2014). There is also a misunderstanding of the "best before" and "use by" dates (Glanz and Schneider, 2009; Papargyropoulou et al., 2014). In regard to the creation of FW on the household scale, there are a number of linked elements, including the sociodemographic features of the family, eating behavior and dietary forms (Glanz and Schneider, 2009) (Fig.2).

Fig.2

3. Generation of agro-food wastewater

The agro-food sector is one of the most significant pollution producers among various industrial activities. The produced effluents pose a hazard to the environment, requiring the implementation of a management plan appropriate for each situation (the dairy industry is a notable example). Throughout the world, environmental regulatory bodies enforce stringent rules for the disposal of wastewater from industrial facilities. It is estimated that 65-70% of natural pollution discharged into water bodies across the globe originates from agricultural and food product enterprises, which include distilleries, sugar factories, dairy farms, fruit canning, and food manufacturing facilities, as well as pulp and paper mills (Rajagopal, 2008; Rajinikanth et al., 2013).

Sweden's pulp and paper business is one of the country's most important sectors, which is also the case for several other nations (Badshah et al., 2012). The wine sector is one of the most important agricultural and food industries in the Mediterranean and in other production regions, such as Chile, Australia, the United States of America, South Africa and China. Massive quantities of wastewater are generated in the wine industry, the majority of which occurs during numerous cleaning operations, such as crushing and squeezing grapes and cleaning fermenters and vessels, along with several other devices and surfaces in the vineyard (Ganesh et al., 2010). Additionally, the olive oil industry has grown up in various Mediterranean countries (Meksi et al., 2012) and, notably, in the United Kingdom due to globalization. In terms of oils, Malaysia is currently the largest producer (39%) and exporter (44%) of palm oil worldwide (MPOC, 2013). POMEF (palm oil mill effluent) refers to a large amount of polluted wastewater that is produced as a consequence of the overproduction of palm oil. Another leftover effluent (from coffee) has emerged as a serious ecological disaster in coffee-producing countries such as Brazil, Vietnam, and Colombia, according to Fia et al. (2012), driving the necessity for low-cost solutions for handling these wastewaters.

The quantity of wastewater produced varies among countries. It was originally estimated that wine production in the United States, Argentina, Australia, Chile, South Africa, and New Zealand was 18.7, 15.5, 11.9, 10.6, 9.3, and 2.33 million hectoliters (H) in 2011, respectively, while the European Union produced 152 million H (France produced 50.2 million H, Italy produced 40.3 million H, and Spain produced 35.4 million H) in 2011. Over 1750 million metric tons of olive oil are produced worldwide each year, with the bulk of products originating from Italy, Greece, Spain, Tunisia, and Portugal (Veronafiere, 2013). Every year in the Mediterranean region, approximately 30 million cubic meters of oil mill waste (OMW) are generated during olive oil seasonal extraction (Un et al., 2008; Meksi et al., 2012).

Nieto et al. (2012) examined the viability of producing methane (CH_4) from agricultural FW (beverage, milled apple scraps, milk, yogurt waste, lipids, and oils from dairy industrial effluents and cow manure), and from this study, it is possible to estimate the corresponding waste reduction. The energy content of wastewater from dairy or sugar mill effluents is low, whereas wastewaters from wineries, olive mills and cheese have high energy density. This is particularly true in terms of organic matter, proteins, acids, aromatic compounds, widely accessible nutrients, and so on (Ganesh et al., 2010; Zhao et al., 2012; Rajinikanth et al., 2013). Table 1 depicts the characteristic features of agro-food industry wastewater, including complete solids (TS), total nitrogen (TN), total phosphorus (TP), and biological and chemical oxygen demand (BOD and COD) (Ganesh et al., 2010; Zhao et al., 2012; Rajinikanth et al., 2013).

Table 1

4. Bioelectrochemical systems in agro-food waste and wastewater

FW has a high concentration of biodegradable organic components and has the potential to be anaerobically digested to form biogas that can be used as renewable energy. Furthermore, FW exploitation as a source of bioenergy is expected to relieve some of the issues associated with waste treatment and power generation and help to solve the question around using vegetation for fuel and energy production. Treatment of FW using anaerobic techniques can significantly increase the efficacy of hydrogen and methane production for energy use (Kim and Kim, 2013; Thi et al., 2014). Many countries might benefit from the implementation of this energy conversion since it can provide a reliable source of electrical energy. Some earlier studies suggest that FW can be handled either by a two-step dark fermentation and photofermentation process for biohydrogen generation or by a three-stage process for biohydrogen and biomethane synthesis (Kim and Kim, 2013). The adoption of green technologies using agro-wastes for power generation and/or resource regeneration has increased, with BESs appearing to be the most suitable (Bajracharya et al., 2016; Simeng et al., 2018). BESs are energy-producing systems that use agricultural waste and wastewater for energy production or resource restoration (Chandrasekhar et al., 2021; Singh et al., 2022). These are hybrid-biosystems based on microbiology and electrochemistry that can generate bioelectricity or a range of value-added biochemicals through microorganism-catalyzed redox processes (Li et al., 2018; Simeng et al., 2018; Ramanaiah et al., 2021a). In electrochemical devices, electricity is generated due to spontaneous oxidation reactions, where electrons are collected at the anode and transferred through the circuit to the cathode where reduction processes occur. The overall process is present in all types of electrochemical devices, including electrochemical batteries. Alternatively, external power can be used to drive the flow of electrons toward the opposite direction, forcing the selected redox process for resource retrieval (Bajracharya et al., 2016; Simeng et al., 2018). The ability of BESs to use a diverse array of biodegradable organics as electron donors enables the efficient breakdown of various organics concurrently (Pant et al., 2012). To adapt to different systems (e.g., reactions, substrates, etc.), BESs often range significantly in terms of reactor design, size, substrates, bacterial populations, and other characteristics (Bajracharya et al., 2016; Simeng et al., 2018; Ramanaiah et al., 2021a).

Despite their many variations, MFCs, MECs, MESs, MDCs, MSCs and EFCs are the most frequent forms of BESs (Li et al., 2018; Simeng et al., 2018), schematically represented in Fig.3. Several advances have been made in the mechanistic understanding, component improvement and applications of these systems, including the development of household and industrial wastewater treatment (Song et al., 2015; ElIchi-Ribault et al., 2018). In comparison, BES applications in the agro-food industry have not received notable consideration. The next part of this review will discuss the most recent advancements of BES research on the applications associated with agro-food waste and wastewater.

Fig.3

4.1 Microbial fuel cell

MFCs, schematically represented in Fig. 3(a), are the most common BES explored in practical applications (Rachinski et al.,2010; Santoro et al.,2017). MFCs are a kind of bioelectrochemical system that uses microorganisms, usually bacteria, to generate electricity. When electrochemically active microorganisms are present on the anode (or anodic chamber), bioenergy is produced by directly generating bioelectricity from degradation of different compounds (Li and Chen, 2018; Ramanaiah et al., 2021a,b). Organic compounds are consumed by exoelectrogenic microorganisms producing extracellular electrons at the anode electrode (acting as electron donors). The formation of a gradient of potential results in the flow of electrons from the anode to the cathode over an external circuit and the electric current that can be used immediately or stored using batteries (Li et al., 2018). The progress of single-chamber MFCs (in opposition to the classic two-compartment MFCs) has increased the viability of this technology in terms of treating wastewater and producing energy in practice (Logan et al., 2015). According to several researchers (Jiang et al.,2011; Logan et al., 2015; Tota-Maharaj and Paul, 2015; Ramanaiah et al., 2021a,b), a considerable amount of electric power can be achieved using MFCs with waste streams such as household wastewater (Park et al., 2017), industrial waste (Pant et al., 2012), landfill percolate (Li and Chen, 2018), swine wastewater (Min et al., 2005), and others (Logan et al., 2015). On the other hand, MFCs that have been scaled up for commercial use have been limited by two primary factors: the cost of the electrodes and their relatively modest power.

Despite the limitations, MFCs have been widely investigated for their ability to deal with a range of difficult agro-food wastes (i.e., comprising organic/inorganic compounds that are not easily digested by microorganisms) and (or) wastewater while simultaneously producing sustainable electricity that may be used *in situ*, for instance, on farms (Angenent et al., 2004; Min et al., 2005; Kim et al., 2008; Fornero et al., 2010; Pant et al., 2010; Ramanaiah et al., 2021b). Electricity production varies according to the type and quality of feedstock and the type of employed MFC (Table 2). Using swine waste with 8320±190 mg/L soluble chemical oxygen demand (SCOD), Min et al. (2005) attained an extreme power density (PD) of 45 mW/m^2 with a double chamber MFC using an aqueous cathode and a higher PD of 261 mW/m^2 by using an air-cathode MFC. In a second study (Kim et al., 2008), the same kind of MFC (i.e., single-chamber MFC (SCMFC)) was used to treat less concentrated swine effluent (1820±83 mg SCOD/L), leading to a significantly lower PD of 205 mW/m^2. Additionally, lignocellulosic biomass, including maize stover and wheat straw, has been investigated as a possible feedstock for MFCs, showing positive prospects (Zuo et al., 2006; Zhang et al., 2009; Wang et al., 2009). Using raw corn stover and steam-exploded corn stover, Wang et al. (2009) attained a higher PD of 296 and 343 mW/m^2, respectively, while feeding SCMFCs. In addition, wastewater from agro-relevant sectors, for instance, rice mill effluents (Behera et al., 2010) and food-processing effluents (Oh and Logan, 2005), has also been recognized as a promising feedstock for efficient power production in MFCs. Despite continuous advances in the use of biomass waste and effluent as raw materials for MFCs, bioelectricity generation from these materials is frequently constrained by the occurrence of co-bioprocesses, including methane production and ammonification (Angenent et al., 2004; Min et al., 2005). Since the conversion of CO_2 to CH_4 in the cathode chamber costs electrons, the coulombic efficiency and power generation of MFCs are decreased (Rachinski et al., 2010). In addition, high concentrations of ammonia are toxic to the majority of the exoelectrogens that power MFCs (Logan, 2009). As a result, to maximize the amount of energy that can be recovered from agro-wastes and wastewater, upcoming efforts must be directed to reducing the devastating effects of methanogenesis and ammonification on MFCs. Plant microbial fuel cells (PMFCs) and MSCs (Timmers et al., 2010) have attracted the interest of researchers in recent years because of their ability to produce electrical energy from rhizodeposits (i.e., organic acids and organic compounds, among other things) released by plant roots (Hou, 2013). The anode of the MFC has been incorporated into plant-growing soil in certain MSC studies, allowing rhizodeposits from the plants and other compounds from the soil to be harvested and used for power production (de Schamphelaire et al., 2008; Kaku et al., 2008; Kouzuma et al.,2014). Based on estimations, the electricity produced by a PMFC has been calculated to be 21 GJ ha^{-1} $year^{-1}$ (equal to 67 mW/m^2) (Strik et al., 2008). On a laboratory scale, studies using rice rhizodeposits to gather energy have shown a significantly greater power generation rate of 300 mW/m^2 compared to previous findings (Timmers et al., 2013). For instance, it was possible to greatly increase the power generation of long-term PMFC with the use of *Spartina anglica* (Kouzuma et al., 2014) by changing the ion transport route inside the BES (Timmers et al., 2013). Improving the research is essential to understand the fundamental methods and realistic applications of PMFC. To optimize the design of the system elements and operation requirements, it is still necessary to develop mechanistic models (Strik et al., 2011).

Table 2

4.2 Microbial electrolysis cell

The MEC, the scheme of which is presented in Fig. 3(b), is derived from the MFC. MECs can generate hydrogen, methane, and (or) a variety of value-added compounds by using indirect energy and storage (Bajracharya et al., 2016, Lu and Ren, 2016). According to theory, MECs can produce valuable biochemical compounds, independent of the redox variations present on the electrodes. The thermodynamic limitations of specific redox processes can be overcome using external electric power to drive the electron flux in the desired direction. To optimize the efficiency, it is more favorable to keep the cathode in the anaerobic or anoxic state. Among the products that may be manufactured in MECs, H_2 is already established as having an important market value, with the benefit of being a green energy source, due to its rising market demand (Show et al., 2012). Increasing research interest has been directed toward MEC-mediated H_2

generation utilizing a wide range of carbon-rich wastewater as potential feedstock (Lee et al., 2010; Escapa et al., 2012; Heidrich et al., 2013; Dinesh et al., 2018) since the efficiency of these systems is noticeably higher than that of different BESs (Lu et al., 2016). Over the past few years, significant development has been made in MEC-based H_2 production. For example, H_2 yield (HY) has increased from ≤ 50% to nearly 100%, and H_2 production rates (HPR) have increased from less than 0.1 m^3H_2/m^3 reactor/day to as high as 50 m^3H_2/m^3 reactor/day (Lu et al., 2016).

Various types of agro-food wastewater, including dairy manure slurry (Cai et al., 2016), swine wastewater (Lu et al., 2010), and fermentation reactor effluent (Cai et al., 2016), have been used to generate biohydrogen in micro- and nanoscale energy conversion systems (Table 3). MECs have exhibited greater results in comparison to other H_2 production methods, such as anaerobic digestion (AD) and photobiological processes (Logan et al., 2008; Lu et al., 2016; Chandrasekhar et al., 2022a). The reason is their ability to circumvent thermodynamic restrictions. Although various substrates were used for the conversion, there was significant variation in the efficiency of MECs in terms of the HPR and the HY (Kadier et al., 2014). In contrast, AD that utilizes easily decomposable carbon-rich substrates, such as acetate and different fermentation byproducts, has the advantage of providing HPR (up to 50 m^3/m^3/day) and HY (more than 100%) (Lu et al., 2016) without significant variation. An increment in the applied external voltage in most MEC systems results in increased HPR and HY due to the increase in the electron flow toward the cathode. In contrast, a larger external voltage is typically associated with lower energy efficiency since it requires the use of additional energy input. It has been suggested to use an applied voltage window between 0.6 and 0.8 V to achieve a balance between hydrogen generation and energy efficiency (Logan et al., 2008). MEC systems also offer the advantage of being able to be operated with energy provided by conventional power sources and by renewable energy harvested from micro - and small - scale hydroelectric plants and other sustainable power sources, including MFCs (Harnisch and Schroder, 2010). Biogas digesters are fermentation facilities that are often used to reduce agricultural waste and recover valuable biogases such as Bio-H_2 and CH_4 (Li et al., 2018). The combination of MECs with AD has resulted in HPR and HY intensification (Lu et al., 2016).

The capacity of AD to degrade complex carbohydrates into simple and low molecular weight molecules that can be easily degraded by several microbial populations, is one of its primary advantages. It is possible to recirculate CO_2 generated during fermentation operations for pH buffering (Mohanakrishna et al.,2018; Chandrasekhar et al., 2022a). MECs may be designed to create high-purity hydrogen under a variety of operating settings using the substrates produced by fermentation (Lu et al., 2012). To date, the use of integrated systems has resulted in the greatest HPR of 189 m^3/m^3/day, according to Lo et al. (2009), approximately 4 times higher than the HPR achieved by using MECs alone. The incorporation of MECs finishes the breakdown of complex carbon-rich organic matter into CO_2, which fermentation operations cannot accomplish alone. Lignocellulosic substances, traditionally regarded as refractory agricultural wastes, such as maize stover, plant stems, sugar beet, plant leaves and corn stalk, have been successfully used in these integrated systems to produce hydrogen (Lalaurette et al., 2009; Chookaew et al., 2014; Dhar et al.,2015; Khan et al., 2018). Combining H_2 production by fermentation resulted in an average increase of 148% (ranging from 42 to 538%) and 225% (ranging from 2 to 400%) in the total production rate and yield, respectively (Lu et al.,2016). The ability to balance the fermentation rate and electrohydrogenesis is essential for improving the overall system performance. The balance may be accomplished using customized feeding methods and innovative step-by-step processes (Logan et al., 2008). Long-term research on MECs has already been carried out, but pilot-scale MECs are not known to be built, possibly reflecting financial apprehensions due to the high prices of the electrode materials and the need for an external power supply (Logan, 2010; Heidrich et al., 2014; Cotterill et al., 2017; Khan et al., 2018).

Table 3

4.3 Microbial electrosynthesis

MESs, shown in Fig. 3(c), may produce valuable biochemicals (e.g., ethanol, butyric acid, acetic acid and biodiesel) by the mediated reduction of carbon dioxide (and other compounds) at the biocathode (Sadhukhan et al., 2016). MESs may potentially produce value-added products depending on the biocatalysts, electron acceptors and redox mediators used (ElMekawy et al., 2016). The oxidation processes at the anode in MESs may also be used to generate fuels such as bioethanol and biofuel (Sadhukhan et al., 2016). It must be emphasized that MESs are related to MECs, wherein the applied energy supplies extra electrical potential, enabling reduction reactions at the cathode, such as the reduction of H^+ to H_2 (May et al., 2016). A variety of applications of MESs are possible, as demonstrated by the number of available produced compounds that include, but are not limited to, various biofuels (Das et al., 2018) and other commercially valuable compounds (Kumar et al., 2017), such as drug intermediates (MPOC, 2013). Considering the general substrates and potential selectivity, many researchers anticipate that MESs will become increasingly crucial in the future for biological energy production (Rabaey and Rozendal, 2010).

It is expected that MESs may also work with organic-rich agro-food wastes and wastewater (Sadhukhan et al., 2016). The consumption of CO_2 and H_2O allows MESs to transform agricultural and forestry waste (e.g., grass, leaves, wood, corn stalks, stover, immature cereal, etc.) into syngas (Kumar et al., 2017), biohydrogen (Harnisch and Urban, 2018), biomethane (Babanova et al., 2017), formate (Batlle-Vilanova et al., 2017), ethylene (Sadhukhan et al., 2016), methanol (Montpart et al., 2014), dimethyl ether (Shen et al., 2016), urea (Bajracharya et al., 2016), succinic acid (Zhao et al., 2016), and other products (May et al., 2016; Das et al., 2018).

CO_2 can also be converted to precursor molecules of polymers and carbonate compounds for use in the building industry through mineralization processes (Ng et al., 2013). MESs are capable of producing a wide range of valuable biological compounds, together with fuels, for example, ethanol and diesel, when suitable redox reactions are achieved at the electrodes at appropriate applied potentials (Kondaveeti and Min, 2015; Bajracharya et al., 2016). Sadhukhan and colleagues (2016) have provided a better understanding of the equations and Gibbs free energies of anode reactions (63 reactions), cathode reactions (72 reactions) and different metabolic pathways (9 pathways) in MESs. This knowledge may allow us to determine whether energy recovery from wastes or wastewater is practically viable and/or if it is thermodynamically spontaneous. Agricultural waste is an abundant raw material that can be transformed into sustainable organic feed for harvesting energy, particularly useful for micro- and small-scale companies. However, among agricultural biomasses, the presence of lignocelluloses makes the transformation process more complicated. Lignocelluloses are complex combinations of structural polysaccharides such as lignocellulosic biomass encased in lignin and resistant to microbial oxidation (ElMekawy et al., 2015). A way to overcome this problem is to perform the pretreatment of agricultural wastes prior to their use. By pretreatment processes, cellulose and hemicellulose may be recovered and processed to generate a wide range of commercial chemicals, including xylite, L-arabinose, furan resin, and nylon (Sadhukhan et al., 2016). Lignin may be used to make hardwood adhesives, epoxy resins, gasoline additives, binders, and carbon fiber, as well as drugs and scent precursors (Sadhukhan et al., 2016). The efficiency of substrate biodegradation is regulated by media enzymatic hydrolysis. The biological transformation of lignocellulose biomass naturally occurs in three stages: hydrolysis, acidogenesis, and methanogenesis (Li and Chen, 2018), with acetogenesis being the most compatible with bioelectrochemical processes and the most effective at optimizing the production of electrons at the anode. Using electrons provided by organics, CO_2 may be reduced, producing organic compounds of interest (e.g., formate). Metal recovery technologies (MECs and MESs) have evolved in the last few years to recover metals from contaminated sites, waste streams and wastewater in a less disruptive and more environmentally friendly manner (Bajracharya et al., 2016). According to Zhang et al. (2013), when compared to conventional metallic recovery technologies that rely on chemical precipitation, BES technologies can significantly improve efficiency while simultaneously decreasing costs associated with the setup, operation and maintenance (Shikha Dahiya et al., 2018). Moreover, BESs may be integrated into other agricultural and food handling processes in the industry for producing value-added goods by selective synthesis (Sadhukhan et al., 2016). Although highly promising, the technology is still in its early stages, and it is recognized as a potentially important platform to convert organic materials into biochemicals and fuels.

4.4 Microbial desalination cell

To minimize the energy demand frequently used in desalination methods (such as electrodialysis, reverse osmosis and mechanical vapor compression), Sevda et al. (2015) modified an MFC into an MDC (see scheme in Fig.3(d)). Amid the anode and cathode electrodes, a desalination chamber with cation and anion exchange membranes (CEM and AEM, respectively) is introduced, which serves as a barrier between the two electrodes. Cations and anions move through the CEM and AEM and into the cathode and anode electrodes, respectively, as a consequence of the potential difference between the electrodes (Al-Mamun et al.,2018). Due to these ion losses, the saltwater is desalinated. The electrical energy taken from the organics in the anode electrode may be utilized or stored. The use of acetate (synthetic substrate) as an electron donor and ferricyanide as an electron acceptor has been found to achieve a desalination effectiveness of 90% at a maximum PD of 31 W/m^3 (Sevda et al.,2015). Additionally, subsequent research has revealed that when household wastewater is employed as an electron donor and sparged air is used as an electron acceptor, a significant salinity decrease of 60% may be achieved (Luo et al.,2012). MDCs have gained significant popularity as a viable energy-efficient technology for addressing a wide range of critical problems, such as saltwater and brackish water desalination, biochemical manufacturing, groundwater and wastewater treatment, and remediation and energy conversion (Cao et al., 2009; Brastad and He, 2013; Saeed et al., 2015; Sevda et al., 2015).

Water consumption by agricultural operations is high, accounting for almost 70% of total global water use (Jaramillo and Destouni, 2015). A combination of persistent increase in the world population and global warming has added further harshness to the water shortage problem (Gosling and Arnell, 2016). Although desalination methods have been developed, which include reverse osmosis, thermal desalination, and electrodialysis, that were proven effective for providing freshwater to regions deficient in freshwater sources, these methods are energy intensive and, as such, considered unsustainable (Sevda et al., 2015). MDCs are particularly designed for low-cost desalination and are capable of overcoming the limitations of conventional techniques while providing additional financial, energy and ecological benefits (Al-Mamun et al., 2018). The current desalination rate achieved using MDCs alone is considered low (in particular taking in consideration the price), implying that most of these devices are used for desalination or predesalination of saltwater (with lower salinity) rather than seawater (Al-Mamun et al., 2018). The freshwater shortage has driven farmers in many desert locations to utilize brackish groundwater for irrigation, which can provide short-term relief from freshwater stress but, at the same time, can cause longstanding problems, such as the accumulation of ion species potentially harmful for vegetation, expanding the salinity of soils (Ping et al., 2015). Furthermore, due to the excessive osmotic potentials created by high soil salinity, a plant’s ability to absorb water might be hampered (Ping et al., 2015). Therefore, it is vital to maintain the salinity of irrigation water below 450 mg/L TDS to inflict the least amount of harm to soil properties and crop development

(Misaghi et al., 2017). Current MDCs are capable of desalinating brackish water to a level of 450 mg TDS/L, which is the industry norm. Jacobson et al. (2011) found that for an extensive desalination rate of 7.5 g TDS/L/day, a continually operating upflow MDC removed more than 99% NaCl from a salt solution with an excessive salt content of 30 g/L of water. Alternatively, Ping et al. (2015) studied the desalination of 3 distinct types of saltwater at an HRT of 0.8 days and discovered that salts and organic compounds were effectively removed from the water. The MDCs reduced the saltwater TDS levels in a 1.7-day trial to 100 mg/L, which was equivalent to nearby tap water (90 mg TDS) in terms of TDS reduction. Brackish water desalination and MDC single ionic strength were also studied as part of the same research to better understand the primary determinants and construct a prediction model to calculate salinity and single ion concentrations. Some studies found MDC desalination rate values of 9.12 g TDS/L/day using biocatholytes and 8.16 g TDS/L/day using buffer saline solution, which are within the acceptable range (Ebrahimi et al., 2018). For the desalination of synthetic wastewater, larger-scale MDCs holding 105 liters of water were tested, and a salt removal rate of 3.7 to 9.2 grams of TDS/liter per day was found (Strik et al., 2010; Zhang and He, 2015). Future research should aim to scale up MDCs for applications to obtain higher yields of freshwater. As an alternative, MDCs can also be incorporated into existing membrane-based reverse osmosis facilities, reducing energy consumption. This appears to be the most likely scenario in the future until larger efficiencies of MDCs are attained (ElMekawy et al., 2014).

4.5 Microbial solar cell

By integrating photosynthesis with exoelectrogens (Strik et al., 2011), *in situ* bioelectricity can be retrieved. These systems are MSCs (see scheme in Fig.3(e)) and are capable of recovering *in situ* electrical energy or value-added compounds. MSCs use photosynthetic organisms such as photoautotrophic microorganisms or higher plants to transform sunlight into chemical energy stored as organic matter, which is subsequently used to generate electricity by MFCs, as discussed earlier. The transfer of electrons from the anode to the cathode originating from organic matter generated by photosynthesis is the most important operation in an MSC. Rhizodeposition of a higher plant, dispersion of a phototrophic biofilm, and pumping for relocation from a photobioreactor are the three most common modes of transmission (Strik et al., 2011). Among the many forms of MSCs, those combined with residing higher plants (plant MFCs; PMFCs) have proven to be the most beneficial for power production, with outputs reaching 1000 $GJ/ha^{-1}/year^{-1}$ (i.e., 3.2 W/m^2) (Strik et al., 2010; Strik et al., 2011; Mateo et al., 2014). The availability of rhizodeposits for anodic oxidation processes in PMFCs has been shown to directly correlate with the power generated by the devices (Bajracharya et al., 2016; Simeng et al., 2018). A significant difference from traditional solar cells is that MSCs produce a wide range of high-value-added compounds in addition to producing energy (Wang et al., 2014). MSCs are self-repairing systems with an extended lifespan, requiring less maintenance due to the constantly increasing population of microorganisms performing photosynthetic and electrochemical processes (Strik et al., 2011). MSCs are also called molecular synthetic cells because of their wide range of potential uses and ability to be well paired with systems working with renewable and environmentally acceptable energy sources or biosynthetic reactors (Cho et al., 2008).

The development and widespread use of wireless sensor network (WSN) technology solutions in agricultural operations has been ongoing since their creation, with the goal of increasing productivity and automation in precise agricultural operations (Pietrelli et al., 2014). WSN technologies are capable of collecting data on a regular basis as well as performing real-time manipulation of on-farm equipment. Agricultural monitoring equipment, such as remote sensors, is often power-driven by batteries or solar energy, according to Pietrelli et al. (2014) and Brunelli et al. (2018). However, changing batteries in remote areas is difficult and untenable, and employing solar energy sources may be insufficient, costly, and highly dependent on the weather (Brunelli et al., 2018). A long-term power supply for WSN devices can be achieved by BES methods that include MSCs and EFCs and have been intensively investigated, with capacitors being employed to store the generated energy (Desmaele et al., 2015; Bajracharya et al., 2016; Yang et al., 2016; Brunelli et al., 2018). A particular type of MFC, named sediment MFC (SMFC), is being used to supply power to wireless sensors and other structures such as miniature telemetry devices that transmit the information to distant receivers (Kiran and Gaur, 2013). It has been more than a decade since Shantaram et al. (2005) collaborated to create one of the earliest SMFCs, combining MFCs for attaining lesser-power and higher-efficiency electronic circuits. During its initial phases of development, this SMFC was able to produce a voltage of 2.1 V, suitable to power the majority of commercially available electronic circuits when paired with a DC-DC converter for voltage increase (Shantaram et al., 2005). A power management system can be used to store energy, in addition to delivering stable and sustainable power to biosensors, when associated with some SMFCs, which can only produce limited potentials and retrieve electric power intermittently (Donovan et al., 2008). It is primarily possible to combine BES technology with particular agricultural sensor systems. Therefore, different BESs can be used as power sources for a variety of wireless sensors aiming to collect data, such as weather information, irrigation management statistics, availability of plant nutrients and insecticides or pH and concentration of O_2 in the land (Sartori and Brunelli, 2016). BESs will become a hybrid-microbial electrochemical supplemental technology for WSN technologies in agriculture if the electrode performance and system efficiency are further improved.

4.6 Enzymatic fuel cell

In EFCs, electricity is produced by electrochemical cells, as illustrated in Figure 3f, which use specific oxidoreductase enzymes as catalysts to transform the accumulated energy in a carbon-rich waste substrate (matter) into useful electrical energy. The conversion is achieved by using anodic substrate degradation processes at the anode and reduction reactions at the cathode. At some point, selective enzymes were used as biocatalysts in the electrolyte suspension of EFCs (in bulk), but the generally poor efficiency and robustness (Beilke et al., 2009) of the system led to a limited advantage over the in bulk technique. The more recent development of methods for immobilizing and stabilizing enzymes on electrode surfaces (Rasmussen et al., 2016) led to a renewed interest. Several approaches for enzyme immobilization were attained, such as the utilization of cross-linking redox hydrogels or in a *sandwich* (among layers of compatible materials) and encapsulation methods (Neto et al.,2010; Carvalho et al.,2016). Biocatalysts derived from thermophilic microorganisms have also been extensively studied to improve EFC stability due to the recognized thermal stability of these microorganisms even at high operating temperatures (Campbell et al., 2012; Neto et al., 2013 Cosnier et al.,2016). Since their rapid development in recent years, EFCs have been employed in biosensors and portable devices (Neto et al., 2013; Pinyou et al., 2015; Song et al., 2015; Hou et al., 2017), in addition to implantable structures (Alcaraz et al., 2016; Cadet et al., 2016; El Ichi-Ribault et al., 2018). Additionally, the viability of EFCs for energy storage and conversion from a range of sources has been the subject of increased interest (Cosnier et al., 2016). The ease of operation, appropriateness and economic potential, together with environmental sustainability, led MFCs, MECs, MESs, MDCs, MSCs and EFCs to be among the most widely applied and investigated BESs. The details of valuables recovered by different BESs, with their respective advantages and drawbacks, are summarized in Table 4.

Table 4

5. Future prospective applications of BESs in agro-food substances and Challenges

Agro-food waste material is a considerable potential low-cost substrate for BES application, allowing for suitable management of wastes. Further research is still needed for the technology to be completely viable as a biorefinery using agro-food wastes. Many factors need to be taken into consideration, such as soil contamination, including acidification (Zheng et al., 2014), petroleum hydrocarbon contamination (mainly from on-farm trucks) (Lu et al., 2014), metal contamination (Fedje et al., 2015), and transgenic toxicants (Yuan et al., 2017), which may disturb the normal operation of BESs (e.g., side redox reactions, undesirable microorganism selection). To repurpose polluted soils for agrarian reasons, *in situ* bioremediation must be performed. BESs have been explored for remediating toxic pollutants in aqueous media, but their efficiency in soil bioremediation has been hampered by the low efficiency of mass transfer (for example, oxygen and hydrogen ions in soils) (Li et al., 2015). Several studies describe the use of BESs for soil bioremediation in cases that include both petroleum contamination and toxic metals in a process called bioelectrochemical remediation. In this process, inexhaustible electrodes are placed in the contamination sites to perform suitable redox reactions to degrade the pollutants. Membranes are also being utilized as long-term options for the treatment of wastewater from the agro-food industry; nevertheless, a number of challenges continue to impede their efficient processing and restrict their wider implementation. Membrane fouling will likely continue to be the most significant obstacle, and further studies are urgently required to find a solution. The major obstacles that membrane technology faces lie in productivity, product quality, and sociopolitical issues due to energy consumption and greenhouse gas emissions impacting climate change (Fane, 2011). In more specific terms, electrospun nanofiber membranes need to improve their mechanical properties and stability over long-term and upscaling operations.

In situ soil bioremediation through the use of BESs has the potential to become a low-cost solution in the near future since it increases the soil porosity and decreases the ohmic resistance.

Plants need moderate conditions to generate organic energy, such as ATP and NADPH. The Calvin–Benson cycle (Pereto et al., 1999) is a response cycle where energy and ions in the stroma are generated, enabling the conversion of CO_2 into carbohydrates using chemical reactions. In 2016, scientists at Wageningen University introduced the concept of manufacturing food using anaerobic biosynthesis, which makes use of wastes and energy to produce nutrients (Buisman, 2017). The power and electrons produced by BESs could be utilized to substitute ATP and NADPH released during the initial stage of photosynthesis, whereas nutrients retrieved from wastes could be used to enhance biomass growth. A closed-loop self-sustaining system that effectively utilizes the energy and nutrients acquired by circular channels may fulfill all of the goals in a short amount of time. The researchers named their technology "dark photosynthesis" to distinguish it from regular photosynthesis. It is their belief that it has the potential to be extensively employed in the near future to produce food in environments that are unfavorable for regular agriculture (Buisman, 2017). It has been estimated that an approximately 1 m^3 dark photosynthesis food reactor might produce enough food for three people, according to Strik et al. (2010). These studies show the viability of using BESs to sustainably and efficiently produce energy and food. Agro-wastes can be transformed into useful compounds, thus decreasing the current high prices of BESs. It is also possible to obtain construction materials (Madurwar et al., 2013) based on lignocellulose waste, such as cotton stalk, rice husk, grass, and vegetable materials. As described, the technology may be useful simultaneously for several agricultural activities and bring financial, ecological and social advantages. Additional benefits include the ability to pyrolyze agricultural biomass to produce biochar and to achieve an innovative soil adjustment for increasing nutrient and water retention in agricultural soils (Li et al., 2018). Given the high potential of biochar to be used as a relatively low-cost electrode material when compared with conventional electrodes, future research should concentrate on determining the suitability of additional specific biochar products for BES applications.

BESs can be used to fuel agricultural and sensing devices, including self-powered sensors that can be operated either *in situ* and/or online, depending on the requirements (Chouler and Lorenzo, 2015). It is possible to compare BESs to contemporary biosensors, which rely on anolyte oxidation to create external power. The signaling attained with BESs is proportional to the biochemical processes of the electrochemically active microbial population and, particularly, to bacterial biofilm formed on the electrode surface, acting as a sensor. When a disruption occurs, the metabolic processes change the amount of current produced in the circuit. The rate variation of electron production is converted into a signal that reflects the amount of disturbance (Chouler and Lorenzo, 2015). Nevertheless, it is necessary to increase the long-term durability of the output and to attain more stable baseline signals of the BES biosensors (Feng et al., 2013). Another technological challenge for these sensors is the establishment of prediction connections amid the sign responses and the quantities of different substrates or chemicals (Stein et al., 2010). The use of more precise mathematical models as a tool to aid our knowledge is necessary to achieve this objective. Furthermore, as with other BES applications, additional high-performance and less costly materials must be engineered.

Energy savings from the integration of agricultural FW management and utilization in biorefineries will be realized through reductions in raw material consumption, shipping, and manufacturing, together with the development of new models in the food, chemical, health care, and logistics industries. To conduct in-depth research on integrated processes and biorefineries, economic aspects, such as the viability of valorization at a huge scale, the economic evaluation of agricultural FW valorization routes, and the FW supply chain, must be taken into consideration. The ecological advantages of adopting FW would be a reduction in greenhouse gas emissions and their influence on climate change, a reduction in landfilling, a reduction in adverse environmental effects, the use of greener goods and the use of renewable energy.

6. Conclusions

BESs are a recently developed technology for water and wastewater treatment that is both energy-efficient and environmentally friendly. The progression of this technology toward practical applications in the treatment of different types of waste and wastewater has required a great deal of work. The use of BESs in the agro-food industry has not been thoroughly investigated. This assessment includes BES research in the agro-food industry and its prospective use. The combination or integration of BESs with agro-food systems can generate energy, recover resources, reduce waste and treat wastewater and simultaneously reduce the carbon footprint. To expand the application of bioelectrochemical systems, researchers have focused on the selection and optimization of electrode materials, the design of electrochemical devices and the screening of electrochemically active or inactive model microorganisms. The accurate management of fermentation and breakdown, electron routes, intracellular reducing power and energy metabolism in BESs has recently become an important focus of attention. The scope of potential applications for BESs might be expanded with a better understanding of the electron transfer mechanisms occurring via extracellular/intracellular pathways. BESs have more recently found widespread use in various fields, including desalination, nitrate removal, processing solid waste, and materials research. These applications are all related to electron transfer and energy transformation. Designing BESs as self-powered biosensors, producing biochar and using them in food production and *in situ* applications, including soil remediation, are feasible options. Agro- and food-driven BESs have been limited, even though they have significant potential to be applied to food safety, energy sustainability and freshwater accessibility. Long-term and mass-scale studies are still needed to evaluate the steadiness of the systems and the future paybacks of BES applications on farmsteads. However, in green and alternative energy generation, there is an exponential increase in bioelectrochemical technology research, indicating that extensive advances in this domain can be expected in the near future.

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Declarations

Author's contributions

S.V. Ramanaiah, Conceptualization, Methodology, Original draft preparation. K.Chandrasekhar, Writing-Reviewing a part of the paper. Cristina M. Cordas, Writing-Reviewing a part of the paper. Irina Potoroko, Writing-Reviewing a part of the paper. All authors read and approved the final manuscript .

Availability of data and materials

The datasets generated for this study are available on request to the corresponding author.

Ethics approval and consent to participate

Not applicable.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table Legend

Table 1 Characteristics of typical agro-food industrial wastewater

Table 2 Electric power generation in microbial fuel cells (MFCs) using different types of agro-food waste and wastewater

Table 3 Hydrogen production in microbial electrolysis cells (MECs) from different types of agro-food wastes and wastewater

Table 4 Advantages and disadvantages of different bioelectrochemical systems

Table 1 Characteristics of typical agro-food industrial wastewater

Industry	COD MgL^{-1})	BOD (MgL^{-1})	TS (MgL^{-1})	TP (MgL^{-1})	TN (MgL^{-1})	References
Dairy	1400-2500	800-1000	1100-1600	-	-	Gotmare et al., 2011
Cheese Dairy	23000-40000	-	100-3900	60-100	400-700	Rajinikanth et al., 2013
Food processing [a]	1000-8000	600-4000	-	3	50	Wei et al., 2011
Sugar-beet processing	6600	-	6100	27	10	Alkaya and Demirer, 2011
Palm oil mill	50	25	40	-	750	Rupani et al., 2010
Dairy	400-15200	650-6250	250-2750	-	10-90	Passeggi et al., 2009
Corn milling	4850	3000	650	125	174	Ersahin et al., 2013
Bakery's yeast	6100	-	600	3	275	Ersahin et al., 2011
Potato chips	5000	100	5000	100	250	Senturk et al., 2010
Winery	18000-21000	-	150-200	40-60	310-410	Rajinikanth et al.,2013; Ganesh et al., 2010
Casava Starch	10,500	6300	830	90	525	Sun et al., 2012
Olive mill	130100	-	75500	-	460	Gonçalves et al., 2012
Swineslurry	4600 –5600	2000 -2100	4800 - 4900	10-170	750-770	González-Fernández

liquid fraction						et al., 2008; Yanga et al., 2015
Cow slurry liquid fraction	10350–15510	-	12000-19000	630-770	2080-2030	Møller et al., 2000; Rico, 2007
Brewery	1000-10000	1000-7000	100-1000	10-20	10-100	Hultberg and Bodin, 2017; Lemji and Eckstädt, 2015
Vegetable and fruit industry	4400-5900	400-1700	-	100-200	700-900	Lehto et al., 2014

Note: COD: Chemical Oxygen Demand; BOD: Biochemical Oxygen Demand; TS: Total Solids; TP: Total Phosphorus; TN: Total Nitrogen; [a] Contains flour, soybean, tomato, pepper and salts.

Table 2 Electric power generation in microbial fuel cells (MFCs) using different types of agro-food waste and wastewater

MFC Type	Feed stock	Power Generation (mW/m^2)	Original COD (mg/L)	COD Removal efficiency (%)	References
Single Chamber	Starchprocessing wastewater	239.4	4852	98	Lu et al., 2009
Single Chamber	Brewery wastewater	205	1600	98	Feng et al., 2008
Single Chamber	White wine lees wastewater	262	6400	90	Sciarria et al., 2015
Single Chamber	Beer brewery wastewater	205	2240	87	Feng et al., 2008
Single Chamber	Swine wastewater	261	8320	80	Carlo et al., 2017
Single Chamber	Food waste	162.4	-	72	Chandrasekhar et al., 2015
Single Chamber	Corn stover hydrolysate	867	1000	70	Zuo et al., 2006
Single Chamber	Swine wastewater	205	1820	69	Li et al., 2018
Single Chamber	Winery wastewater	317	2200	65	Cusick et al., 2010
Single Chamber	Canteen based food waste	5.13	1130	64.83	Goud et al., 2011
Single Chamber	Composite vegetables waste	57.38	2080	62.86	Venkata Mohan et al., 2010
Single Chamber (Up-flow tubular)	Animal carcass Wastewater	219	11180	50.66	Li et al., 2013
Single Chamber	Raw corn stover	296	1000	42	Song et al., 2015
Single Chamber	Steam-exploded Corn stove	343	1000	42	Song et al., 2015
Single Chamber	Steam-exploded Corn stover	371	1000	-	El Ichi-Ribault et al., 2018

Single Chamber	Cattle manure	36.6	1000	-	Lee et al., 2011
Single Chamber	Cow manure	349	-	-	Wang et al., 2014
Two Chamber	Cereal wastewater	81	595	95	Oh and Logan, 2005
Two Chamber	Cheese whey	1800	-	92.8	Kassongo et al., 2011
Two Chamber	Acidogenic food Waste leachate	432	1000	87	Li et al., 2013
Two Chamber	Chocolate	1.5	-	75	Patil et al., 2009
Two Chamber	Soy-based food	100	3107	71.4	Pant et al., 2016
Two Chamber (upflow)	Chocolaterie wastewater	98	-	70	Subha et al., 2019
Two Chamber	Dairy wastewater	123.5	-	64	Sekar et al., 2019
Two Chamber	Distillery wastewater	31.49	-	60.78	Deval et al., 2017
TwoChamber (Continuous up flow)	Retting wastewater (Coconut husk)	254	2690	32	Jayashree, 2015
Two Chamber	Palm oil mill effluent sludge	451.26	2680	3	Nor et al., 2015
Two Chamber	Wheat straw	123	2000	-	Rachinski et al., 2010

Two Chamber	Tomato industry pomace	132	-	-	Fogg et al., 2015
Two Chamber	Fermented apple juice	78	3501	-	Cercado-Quezada et al., 2010
Two Chamber	Yoghurt wastewater	54	8169	-	Cercado-Quezada et al., 2010
Two Chamber (Anoxic/oxic)	Saline sea food wastewater	162	-	-	You et al., 2010
Two Chamber	Wheat straw hydrolysate	148	-	-	Thygesen et al., 2011
Earthen Pot -MFC	Rice Mill Wastewater	2	2250	96.5	Behera et al., 2010
Membrane electrode assembly- MFC	Molasses wastewater	16.1	1500	95.6	Wu et al., 2017
Tubular- MFC	Chilled ready-meal Food production	3.34 -5.86	843-1161	67-84	Boghani et al., 2017

Table 3 Hydrogen production in microbial electrolysis cells (MECs) from different types of agro-food wastes and wastewater

MEC Type	Feed stock	H_2 Production Rate (m^3/m^3/day)	Original COD (mg/L)	COD Removal efficiency (%)	References
Single Chamber	Soybean oil Refinery	0.133±0.005	2900±100	95.8	Yu et al., 2017
Single Chamber	Potato wastewater	0.74	7700	79	Kiely et al., 2011
Single Chamber	Glycerol, starch and milk	0.0-0.94	-	74	Montpart et al., 2015
Single Chamber	Milk	0.086	1000	73.5	Montpart et al., 2015
Single Chamber	Leachate and Dairy wastewater	15	24000	73	Rani et al., 2020
Single Chamber	Fermentation effluent	2.11	3200	60	Lu et al., 2009
Single Chamber	Fermentation effluent	4.55	8840	51	Li et al., 2017
Single Chamber	Cornstalk waste	3.43	4000	48	Li et al., 2014
Single Chamber	Winery	0.17	2200	47	Cusick et al., 2010
Single Chamber	Swine wastewater	0.9-1.0	2000	29	Wagner et al., 2009
Single Chamber	Table olive oil brine processing	109±21N ml CH_4/g COD rem	-	29	Marone et al., 2016
Single Chamber	Molasses	2.27-10.72	2000	-	Wang et al., 2014

Two Chamber	Cheese whey: Diluted and Fermented	0.5	15.26	82	Moreno et al., 2015
Two Chamber	Wheat straw	0.61	400	74	Thygesen et al., 2011
Two Chamber	Sugar industry	4.38	4400	56.6	Jayabalan et al., 2020
Two Chamber	Switchgrass wastewater	4.3	2000	48	Lewis et al., 2015
Two Chamber	Animal urine	32.0	1360	46	Kuntke et al., 2014
Two Chamber	Swine	0.061	1298	45-52	Jia et al., 2010

Table 4 Advantages and disadvantages of different bioelectrochemical systems

BESs	**Valuable(s) recovered**	**Advantage**	**Disadvantage**	**Reference**
MFC	Bioelectricity	Converts waste and wastewater to energy, low treatment cost, nutrients recovery, low sludge yield	Expensive catalyst, less power production, moderate COD removal	Paucar and Sato, 2021; Do et al., 2020; Gul et al.,2021
MEC	Biohydrogen, methane, and (or) a variety of value-added biochemical compounds	Removal of complex organic and inorganic pollutants, and easily modifiable to produce required end product	External power supply requires, low valuable production rate	Bajracharya et al., 2016; Hua et al., 2019
MES	Valuable biochemicals like ethanol, acetate, butanol and biofuels, biomethane	Carbon sequestration, high-value and multi carbon organic compounds recovered from industrial applications, metal recovery, and wide variety of applications	External voltage supply requires, lower production rate of chemicals with longer carbon chains	Sadhukhan et al., 2016; Kong et al., 2020
MDC	Saltwater and brackish water desalination, bioelectricity	Desalination and simultaneous waste and wastewater	Increase in anolyte salinity decreases bacterial removal efficiency,	Sevda et al., 2015 Gujjala et al., 2021

		treatment, doesn't rely on external power supply unlike other concurrent desalination technology	membrane fouling, inorganic elements in wastewater adversely impacts the efficiency of MDC, and scaling	
MSC	Bioelectricity	Use sunlight, self-repairing systems, Waste and wastewater treatment, use of wireless sensor network (WSN) technology solutions in agricultural operations	Employing solar energy sources is inefficient, costly, and highly changeable depending on the weather	Strik et al., 2011; Bajracharya et al., 2016; Pietrelli et al., 2014
EFC	Bioelectricity	Employed to authority biosensors and portable devices, energy storage and conversion applications, waste and wastewater treatment	Loss of enzymes activity upon immobilization, cost of immobilization process, and mass transfer limitations.	Neto et al., 2013; Pinyou et al., 2015; Hou et al.,2017; Song et al., 2015

Figure captions

Fig.1. Global food waste distribution and forecast (Source: World Bank, 2016: Ching-Hsu et al., 2020).

Fig. 2. Overview of Food Supply Chain (FSC) in Food Loss (FL) and Food Waste (FW)

Fig.3. Different types of bioelectrochemical systems (BESs); (a) Microbial fuel cell (MFC), (b); Microbial electrolysis cell (MEC), (c); Microbial electrosynthesis (MES), (d) Microbial desalination cell (MDC), (e) Microbial solar cells (MSC), (f) Enzymatic biofuel cells (EFC)

Figures

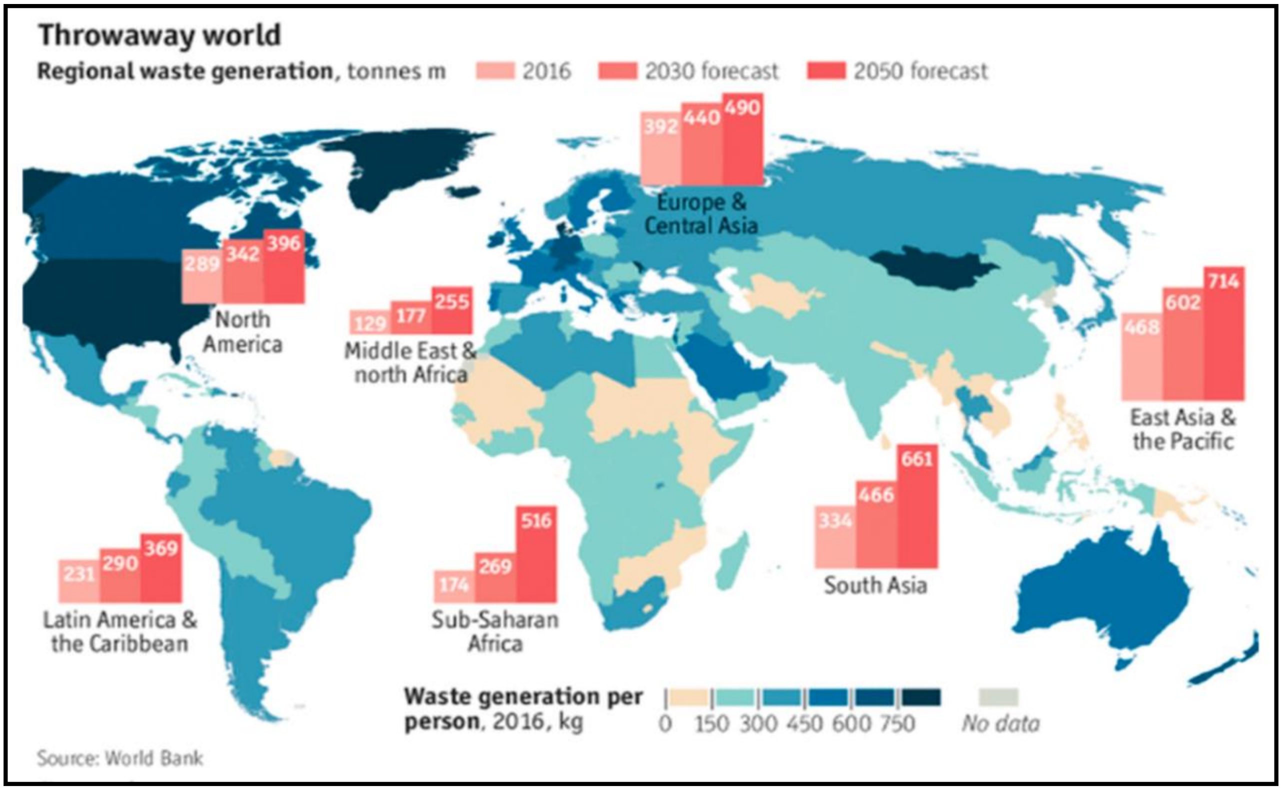

Fig.1

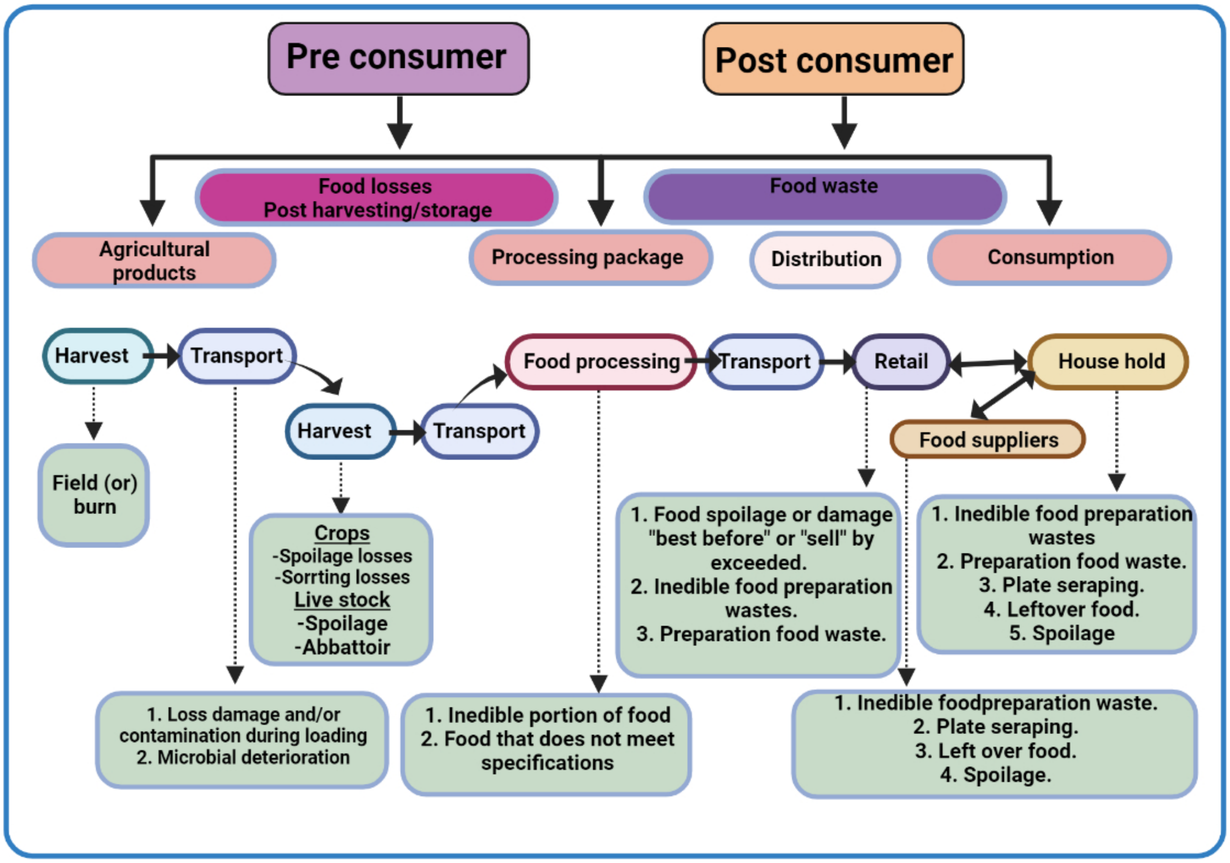
Pre consumer
Post consumer
Food losses
Post harvesting/storage
Food waste
Agricultural products
Processing package
Distribution
Consumption
Harvest
Transport
Field (or) burn
Harvest
Transport
Crops
-Spoilage losses
-Sorrting losses
Live stock
-Spoilage
-Abbattoir
Food processing
Transport
Retail
House hold
Food suppliers
1. Loss damage and/or contamination during loading
2. Microbial deterioration
1. Inedible portion of food
2. Food that does not meet specifications
1. Food spoilage or damage "best before" or "sell" by exceeded.
2. Inedible food preparation wastes.
3. Preparation food waste.
1. Inedible food preparation wastes
2. Preparation food waste.
3. Plate seraping.
4. Leftover food.
5. Spoilage
1. Inedible foodpreparation waste.
2. Plate seraping.
3. Left over food.
4. Spoilage.

Fig.2

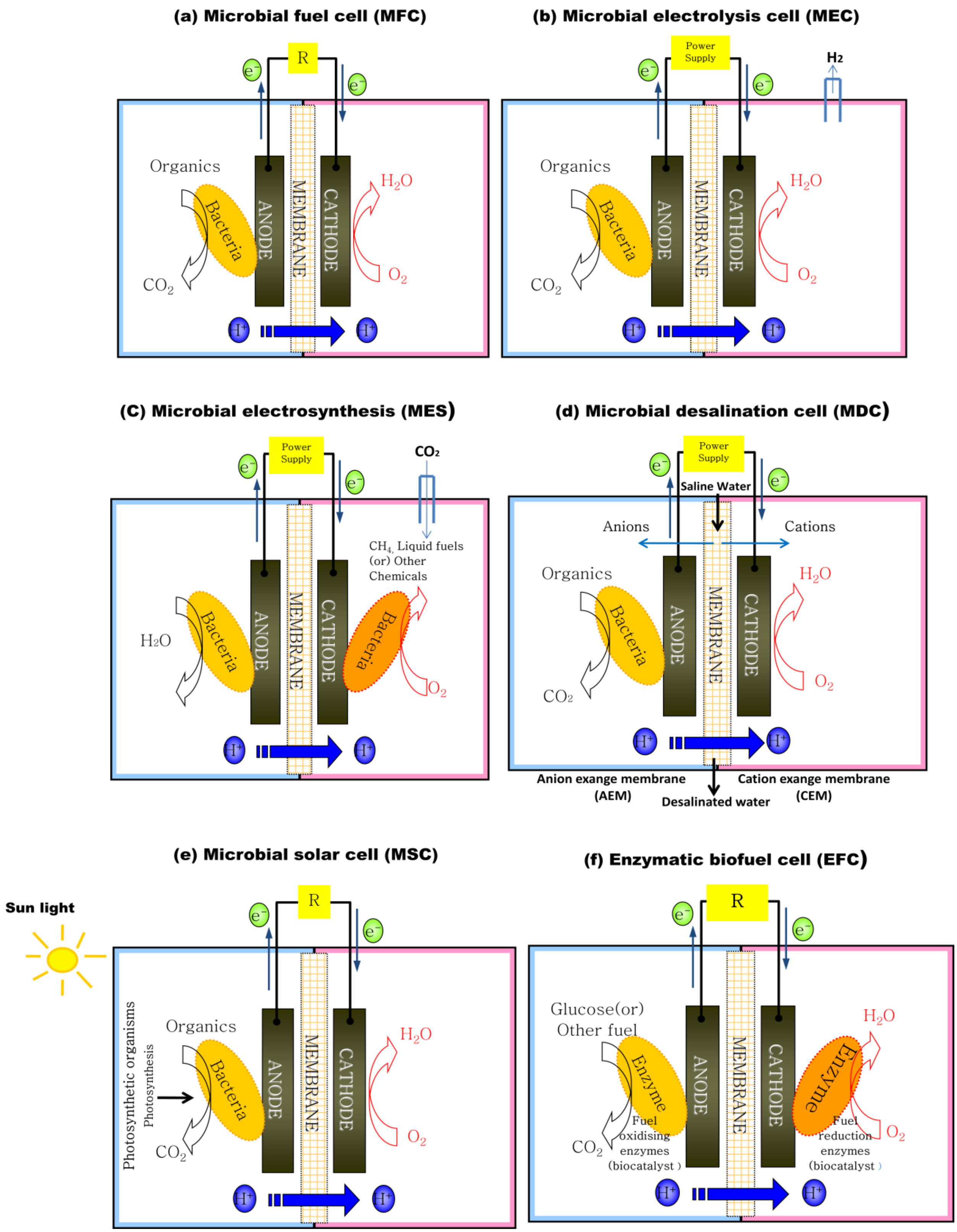
(a) Microbial fuel cell (MFC)
R
e⁻
Organics
Bacteria
ANODE
MEMBRANE
CATHODE
H_2O
O_2
CO_2
H^+
(b) Microbial electrolysis cell (MEC)
Power Supply
H_2
Organics
Bacteria
ANODE
MEMBRANE
CATHODE
H_2O
O_2
CO_2
(C) Microbial electrosynthesis (MES)
Power Supply
CO_2
CH_4, Liquid fuels (or) Other Chemicals
H_2O
Bacteria
ANODE
MEMBRANE
CATHODE
O_2
(d) Microbial desalination cell (MDC)
Power Supply
Saline Water
Anions
Cations
Organics
Bacteria
ANODE
MEMBRANE
CATHODE
H_2O
O_2
CO_2
Anion exange membrane (AEM)
Cation exange membrane (CEM)
Desalinated water
(e) Microbial solar cell (MSC)
Sun light
R
Photosynthetic organisms
Photosynthesis
Organics
Bacteria
ANODE
MEMBRANE
CATHODE
H_2O
O_2
CO_2
(f) Enzymatic biofuel cell (EFC)
R
Glucose(or) Other fuel
Enzyme
ANODE
MEMBRANE
CATHODE
H_2O
O_2
CO_2
Fuel oxidising enzymes (biocatalyst)
Fuel reduction enzymes (biocatalyst)

Fig.3