ISBN: 978-628-96613-1-6. ISSN: 2414-6390. Digital Object Identifier: https://dx.doi.org/10.18687/LACCEI2025.1.1.1164

Evaluation of the Electricity Generation Potential from Plant Biomass through Microbial Fuel Cells

Abraham Nicolás Fernández-Mendoza[1]; Jorgelina Pasqualino[2]; Claudia Díaz-Mendoza[3]; Edisson Chavarro-Mesa[4]; Rosa Acevedo-Barrios[5]

[1]Programa de Ingeniería Ambiental, Universidad Tecnológica de Bolívar, Colombia, *abrafer03@hotmail.com*

[2,3]Grupo de Investigación en Sistemas Ambientales e Hidráulicos (GISAH), Escuela de Ingeniería Arquitectura & Diseño, Universidad Tecnológica de Bolívar, Colombia, *jpasqualino@utb.edu.co*, *cdiaz@utb.edu.co*

[4,5]Grupo de Estudios Químicos y Biológicos, Dirección de Ciencias Básicas, Universidad Tecnológica de Bolívar, Colombia, *echavarro@utb.edu.co*, *racevedo@utb.edu.co*

Abstract– ***Great amounts of vegetable waste are generated globally every year, which must be treated or, even, exploited to avoid environmental issues and improve resource use efficiency. This review analysis how to transform vegetable waste into glucose by means of acid hydrolysis and use the produced sugar as carbon source on Microbial Fuel Cells (MFCs) for energy generation. The research includes 18 papers that describe the hydrolyzation of 7 kinds of biomass into glucose, and 19 papers that study the electrical generation on glucose-fed MFCs. The highest power per glucose and glucose yield estimated were 5052 mW/g of glucose and 538 g of glucose/kg (of potato peal), respectively; corresponding to a biomass power of 2.8 kW/kg of potato peal. When sugarcane bagasse is analyzed, the highest glucose yield was 181.9 g/kg of bagasse, corresponding to a biomass power of 0.9 kW/kg of bagasse. Although MFCs are not a fully developed alternative to energy production yet, these results show its applicability.***

Keywords-- ***Biomass Energy, Acid Hydrolysis, Glucose, Microbial Fuel Cell.***

I. Introduction

Agricultural waste is produced in large quantities around the world, so it is necessary to manage it to avoid environmental and health problems. Given its energy potential for electricity generation, its use is proposed through Microbial Fuel Cell (MFC), a bioelectrochemical device with which both clean water and electrical energy can be produced [1], [2], [3], [4], [5]. MFCs have potential as environmentally friendly solutions to manage organic waste in an efficient way [4]. Some plant wastes used to produce electricity through MFC include sugarcane waste, banana peel waste, olive, pal oil, and corncob [6], [4], [7], [8].

Plant waste requires pretreatment to be able to take advantage of its energy potential through MFC. One of the most used pretreatment methods is the transformation into glucose, the most used carbon source in MFCs [9], [10]. Glucose can be extracted from the lignocellulosic fraction of plant residues by acid hydrolysis but can also be achieved with enzymatic hydrolysis [11], [12], [13], [14].

This review aims to evaluate the electrical generation capacity of plant waste by combining acid hydrolysis and MFC technologies. Emphasizing sugarcane bagasse as plant residues, studies that used acid hydrolysis to obtain glucose, and those that used this sugar as a substrate for MFCs, were evaluated.

II. Methodology

Databases of indexed journals were used in the review, taking a 20 years range as the period of interest, and including all relevant knowledge produced internationally. As a criterion, it was established that the publications consulted had to be original articles in which the authors determined their conclusions experimentally.

The experimental process variables that were compared included: pretreatment, catalyst type, catalyst concentration, hydrolysis time and temperature, and substrate concentration.

In the same way, the electrical generation of MFCs fed with glucose was studied, exposing the cell assembly factors that affect production: cell shape, concentration of the carbon source, surface area of the anode and the separator membrane.

The estimate of the energy produced per unit of raw material (P_{rm}) was calculated by multiplying the amount of glucose produced per unit of raw material (G_{rm}) with the power generated by glucose (P_g).

III. Results and Discussion

The estimation of the main variables was carried out by analyzing a total of 37 publications, whose authors determined their results experimentally. The databases consulted were Sciencedirect, Scopus, Springer, PubMed, Collection of Czechoslovak Chemical Communications, ACS Publications and American Society for Microbiology. The keywords used were: Biomass, Energy, Glucose, Acid Hydrolysis, and Microbial Fuel Cells.

For the specific case of glucose production from biomass, 18 reports developed in 11 different countries were analyzed: Brazil (1), China (1), Spain (3), India (1), Northern Ireland (1). , Malaysia (1), Mexico (5), Nigeria (1), Sweden (1), South Africa (1), and Thailand (2); with Mexico being the most frequent geographical origin. Regarding the review on electricity generation with MFCs, the most effective configurations described within the 19 reports analyzed used only 4 types of cells.

A. Analysis of Glucose Production from Plant Residues Using Acid Hydrolysis

Acid hydrolysis has been widely used to convert lignocellulosic matter into fermentable sugars. Acid catalysts (concentrated or diluted) can decompose the polymers present in lignocellulosic biomass to glucose, xylose and arabinose monomers [15], [16]. The main factors that affect process performance are retention time, temperature, type of catalyst and concentration [6], [17], [18]. The publications whose purpose was to obtain fermentable sugars from plant biomass using acid hydrolysis are compiled in Table 1.

TABLE I
METHODS COMPARISON OF VEGETABLE WASTE HYDROLYSIS INTO GLUCOSE

Material	Pre-Treatment	S_{rm} (mm)	Catalyst type	Ca (%w/w)	t_h (min)	T (°C)	R	C_{rm} (%w/w)	G (g/L)	G_{rm} (g/kg)	Source
SCB	D + C	< 0.5	H_3PO_4	6	300	100	1:8	12.5	1.6	12.8	[19]
COC	W + D + C + CTA	< 0.4	H_2SO_4	5	300	90	1:10	10	-	14.62	[6]
OPR	D + C	0.425 – 0.6	H_2SO_4	4.9	300	90	1:20	5	-	131	[20]
POP	D + C	1	H_3PO_4	10	4	135	-	5	-	538	[21]
FIW	C	2.2 – 10	H_2SO_4	1	3	209	-	-	-	183	[22]
SCB	D + C	< 0.5	HCl	6	122	107.1	1:10	10	6.04	60.4	[23]
SCB	D + C	< 0.5	H_2SO_4	6	180	128	1:10	10	8.86	88.6	[24]
SCB	D + C	< 0.5	HNO_3	6	9,3	122	1:10	10	2.87	28.7	[25]
COC	C + AH	-	H_2SO_4	2	492	135	1:8	12.5	2.6	20.8	[26]
SCL	D + C	< 1	HCl	5	150	100	-	40	14.57	36.4	[18]
SCB	D + C	< 0.5	H_3PO_4	6	300	122	1:8	12.5	3.2	25.6	[16]
SCB	C + 2CD	0.45 – 0.9	H_2SO_4	1.25	120	121	1:10	10	9.3	93	[27]
SCB	D + C + LE	< 5	HCl	5	120	120	1:15	6.7	5.47	82	[17]
SCB	LE + CE + CTN	-	H_2SO_4	2	10	155	1:8	12.5	22.74	181.9	[28]
SCB	B + C + W + D	2.2 -10	HCl	2.5	30	140	1:10	10	5.84	58.4	[29]
SCB	D	-	H_2SO_4	0.34	15	180	-	8	-	40.7	[30]
OPFB	D + C	< 1	H_2SO_4	6	90	120	1:8	12.5	4.1	32.8	[31]
OPR	D + C	0.425 – 0.6	H_2SO_4	4.9	270	90	1:20	5	6.5	130	[32]

The variables included in Table 1 are symbolized as follows: (S_{rm}) for the size of the raw material fraction, (C_{rm}) for its concentration, (C_a) for the acid catalyst concentration, (t_h) for the hydrolysis retention time, (T) for the treatment Temperature, (R) for the substrate to media ratio, (G) for the glucose concentration achieved, and (G_{rm}) for the estimated performance. The substrates are identified with acronyms as follows: sugar cane bagasse (SCB), olive pruning remains (OPR), potato peel (POP), fir wood (FIW), corn cob (COC), sugarcane leaves (SCL), oil palm fruit bunch (OPFB).

Finally, the pre-treatments are identified with acronyms as follows: breaking into pieces (B), washing (W), drying (D), crushing (C), chemical treatment in autoclave (CTA), autohydrolysis (AH), 2 cycles DAH process (2CD), lignin extraction (LE), cellulose extraction (CE), and chemical treatment with NaOH (CTN).

The highest estimated yield obtained was 538 g/kg using potato peel as substrate and H_3PO_4 as catalyst (Fig. 1), followed by the 183 g/kg achieved with fir wood, and the 181.9 g/kg with sugarcane bagasse, both using H_2SO_4 as catalyst (Fig. 2). The highest yield achieved using HCl was 82 g/kg with sugarcane bagasse (Fig. 3).

The performance achieved with each substrate compared is represented in Fig.4, where most of the studies used sugarcane as raw material, although potato peel reported better yields. Although H_3PO_4 provided the highest glucose production, this was one of the least used catalysts, while H_2SO_4 and HCl were more frequent (Fig. 5).

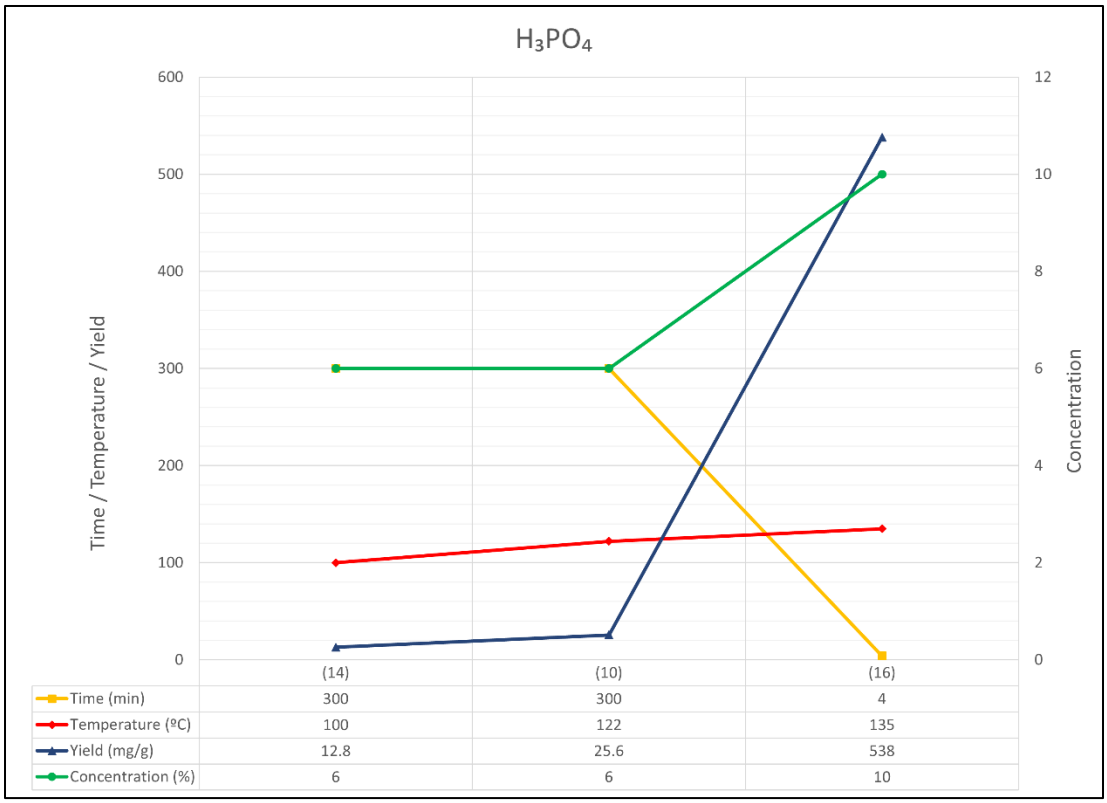

Fig. 1 Yields achieved using H_3PO_4 as catalyst

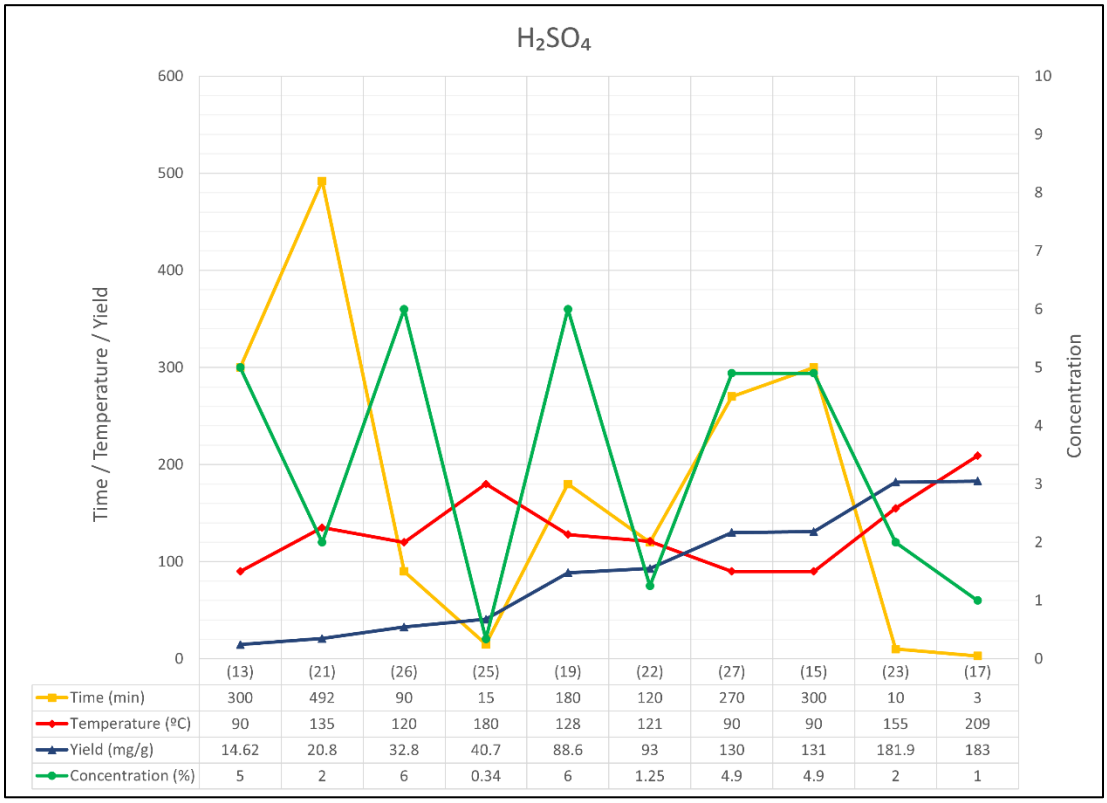

Fig. 2 Yields achieved using H_2SO_4 as catalyst.

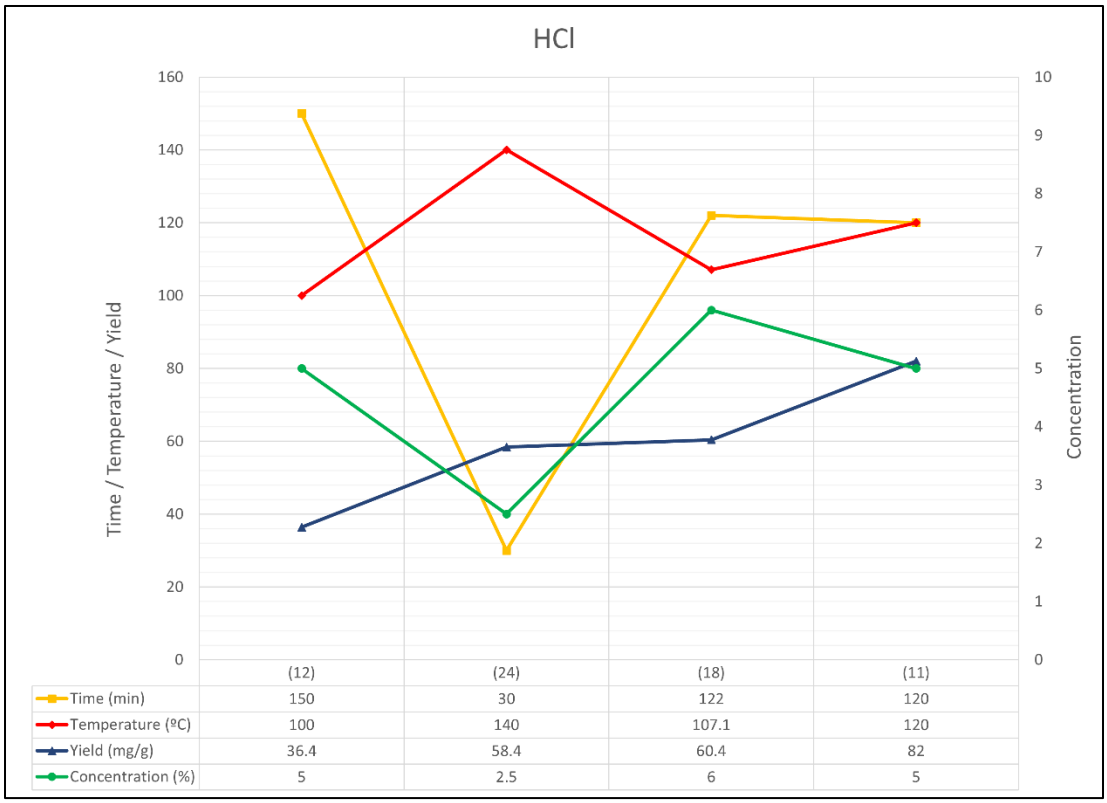

Fig. 3 Yields achieved using HCl as catalyst.

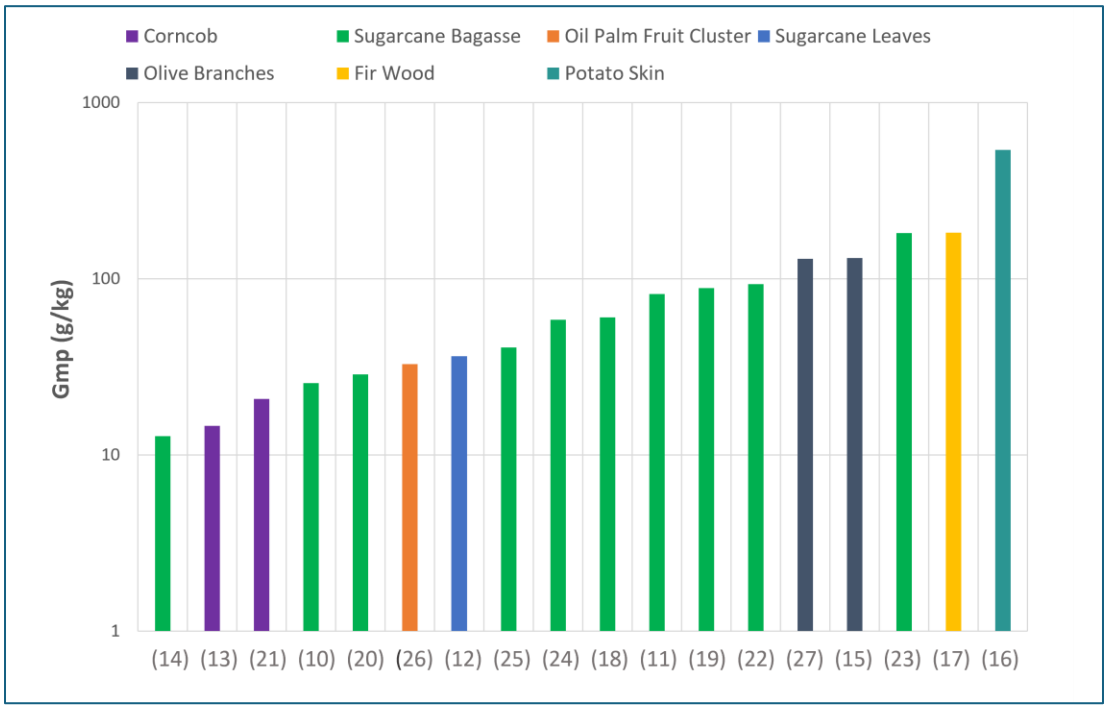

Fig. 4 Type of substrate as performance factor in glucose extraction. The horizontal axis shows the corresponding references.

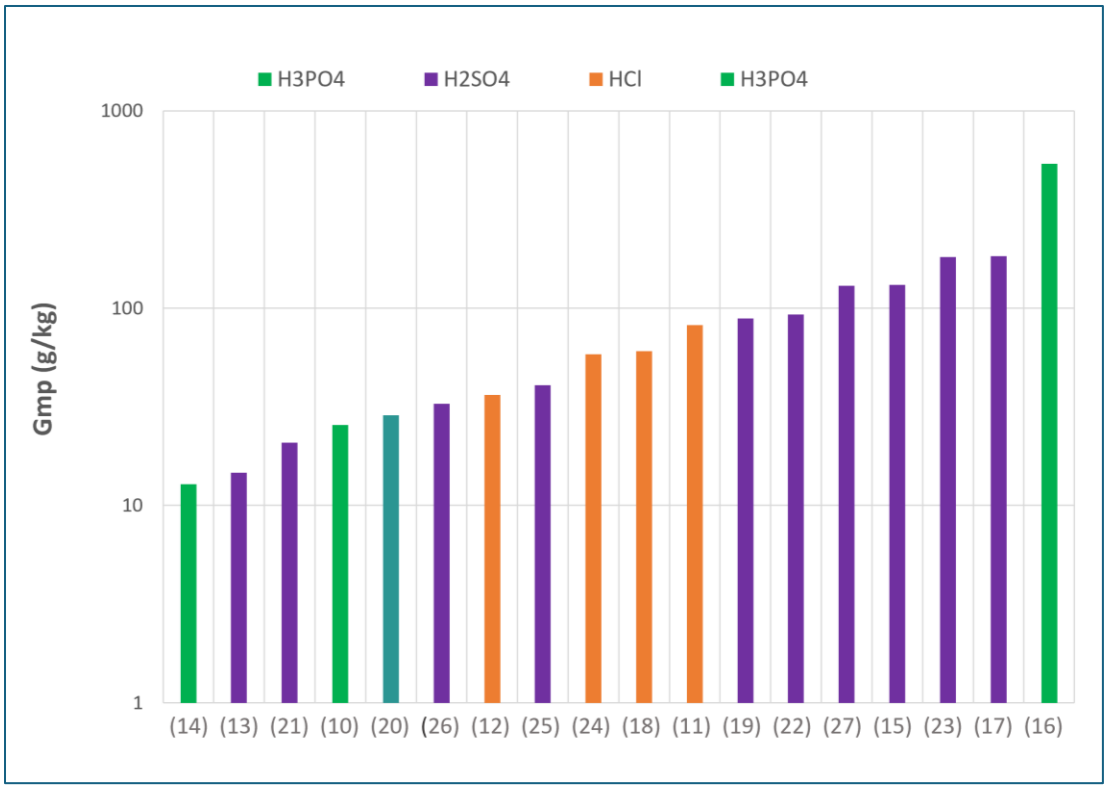

Fig. 5 Type of catalyst as performance factor in glucose extraction. The horizontal axis shows the corresponding references.

Moreover, it was observed that the concentration of the substrate affects the glucose yield in inverse proportion. The lower the C_{rm} used in hydrolysis, the better the results obtained for sugar extraction [33].

B. Energy generation using glucose as a carbon source in MFC

Since MFCs can be used both to treat wastewater and to generate electrical energy, the combination of these two aspects provides this technology with great potential. Different substances, such as acetate, butyric acid, brewery wastewater, and glucose, can be used as a carbon source to produce electricity with MFCs [7], [34], [35], [36].

The MFC process conditions parameters are summarized in Table 2. The variables compared include the cell type, anode material, membrane type, membrane surface area (A_m), glucose concentration (C_g), anode surface area (A_{an}), working volume (V_t) and the power density achieved at the reported conditions (D_p). The estimated power per amount of glucose (P_g) was calculated as in (1), considering the capacity of the assembly, in its corresponding conditions, to generate power.

$$P_g = \frac{A_{an} \cdot D_p}{V_t \cdot C_g} \qquad (1)$$

Different approaches of MFCs can be summarized into four main types of cell assemblies [37]: Four Batch-Type (FBT), Two Chamber H-Shaped (TCH), Single Chamber (SCR), and Single Chamber Air-Cathode (SCA) which are schematized in Fig. 6.

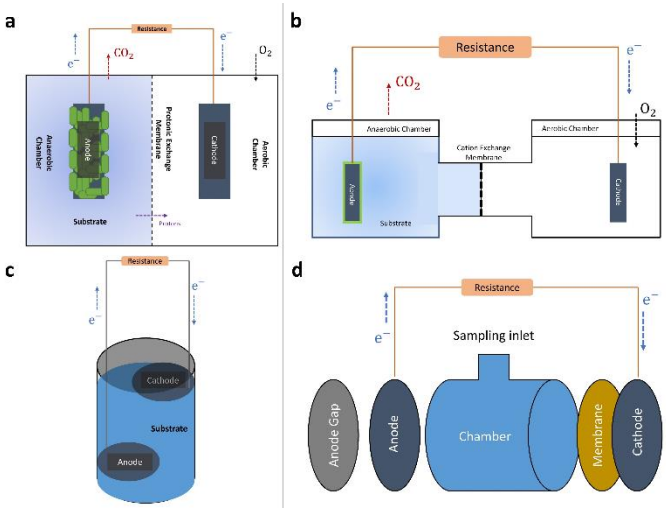

Fig. 6 Schemes of different MFC configurations. a) Four batch-type [9]; b) Two Chamber H-shaped [38]; c) Single Chamber [39]; d) Single Chamber Air Cathode [40]. Note: Images are representations based on the respective reference.

The highest P_g estimated were 5052.7 mW/g and 4367.2 mW/g, both using SCA cell type, with exposed cathode and

without cation exchange membrane. FBT is the second cell in performance, SCA and TCH being the most used types (Fig. 7).

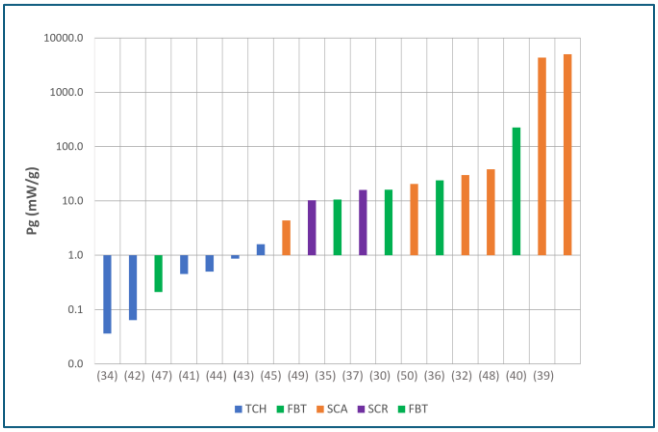

Fig. 7 Power obtained according to the type of assembly. The horizontal axis shows the corresponding references.

Although most of the studies analyzed used submerged cathodes, the results show that cathode air exposure contributes to better performance (Fig. 8). On the other hand, the absence of a cationic or proton exchange membrane was typical of the assemblies with the highest performance (Fig. 9).

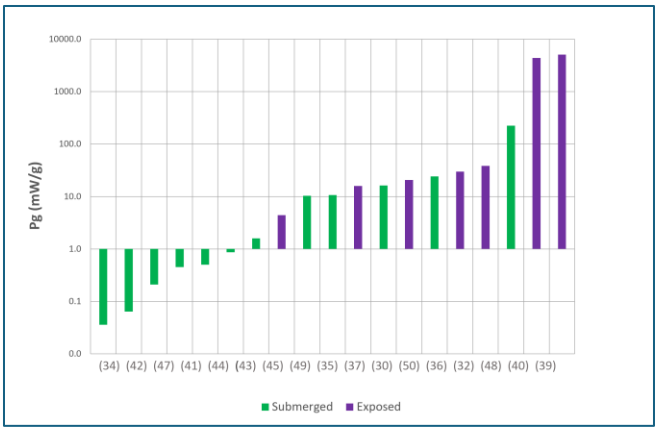

Fig. 8 Power obtained according to the type of cathode. The horizontal axis shows the corresponding references.

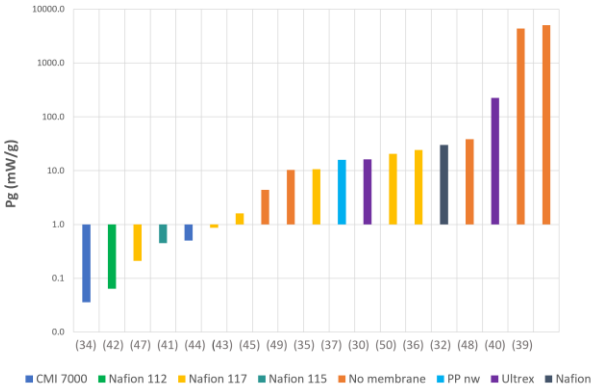

Fig. 9 Power obtained according to the type of membrane. The horizontal axis shows the corresponding references.

TABLE 2
CELL CONFIGURATION COMPARISON FOR MFCS USING GLUCOSE AS CARBON SOURCE

Cell Type	Anode Material	Cathode type	Membrane	A_m (cm^2)	C_g (g/L)	V_t (L)	A_{an} (m^2)	D_p (mW/m^2)	P_g (mW/g)	Source
FBT	Smooth graphite	Submerged	Ultrex - EM	-	2	0.04	0.005	3600	225	[41]
SCR	Graphite felt	Exposed	PP nw	12	0.51	0.225	0.0012	1519	15.9	[42]
SCA	Carbon textile	Exposed	Without membrane	-	0.5	0.028	0.0007	766	38.3	[43]
SCA	Toray carbon paper	Exposed	Nafion 117	7	0.6	0.028	0.0007	494	20.6	[40]
SCA	Graphite fiber	Exposed	Without membrane	-	1	0.3	1.06	1236	4367.2	[35]
FBT	Carbon textile covered in felt	Submerged	Nafion 117	-	0.5	0.5	-	5300	10.6	[41]
SCR	Graphite felt fibers	Submerged	Without membrane	-	1	0.5	0.0113	456.8	10.3	[39]
TCH	Carbon textile	Submerged	Nafion 115	25	3	0.3	0.003	136	0.45	[44]
TCH	Graphite bars	Submerged	CMI 7000	64	1	1.9	0.0022	31	0.036	[38]
TCH	Graphite felt	Submerged	Nafion 112	3.79	5	0.6	0.00384	50.41	0.064	[45]
TCH	Toray carbon paper	Submerged	Nafion 117	3.53	1	0.25	0.0042	52	0.87	[46]
TCH	Graphite bars	Submerged	CMI 7000	12.6	0.384	0.3	0.006	9.8	0.5	[47]
TCH	Carbon paper	Submerged	Nafion 117	3.5	0.2	0.25	0.002	40.3	1.6	[8]
SCA	Carbon fiber	Exposed	Without membrane	-	1	0.3	1.06	1430	5052.7	[48]
FBT	Graphite felt	Submerged	Nafion 117	25	0.09	0.18	0.0025	156	24.1	[36]
FBT	Graphite felt	Submerged	Nafion 117	-	2	0.1715	0.01064	7.07	0.21	[49]
SCA	Carbon textile	Exposed	Nafion	7	1.2	0.012	0.0002	2160	30	[50]
SCA	Toray carbon paper	Exposed	Without membrane	-	0.9	0.02	0.00049	161	4.4	[51]
FBT	Graphite	Submerged	Ultrex	80	1	0.24	0.0009	4310	16.16	[52]

The highest yields were obtained with glucose concentration between 0.5 and 2 g/L, which agrees with literature [41], where the optimal concentration range has been reported from 0.5 to 4 g/L, since higher values may derive in a cell that does not function properly, giving way to long adaptive periods and low power values.

The surface area of the anode has been reported to considerably influence the power density values, probably due to the reaction rate, meaning that a higher area contributes to a higher reaction rate and, therefore, higher power density values [42].

C. Power generation potential with acid hydrolysis and MFC combination

To evaluate the capacity for electricity generation from agricultural waste, the yield results obtained from the acid hydrolysis were combined with those of the MFC technologies. The power generated per unit of raw material (P_{rm})(mW/kg) was calculated as the product of the glucose extracted per unit of substrate (G_{rm}) and the power generated per unit of glucose (P_g). The P_{rm} reflects the conversion capacity of the substrate to energy via the combination of the best conditions for the acid hydrolysis configurations and the best configuration of the MFC assembly. The ten combinations that provide the highest P_{rm} yields are presented in Fig. 10.

The approaches that produce the highest values of P_{rm} are the combination of Lenihan et al. [21] and Logan et al. [49], and the combination of Lenihan et al. [21] and Xing et al. [35]. Both use potato peel as the carbon source for the acid hydrolysis stage with H_3PO_4 as catalyst, the SC cell type with carbon fiber anode, exposed cathode and no membrane. The first combination presents the lowest power density and reaches 2.8 kW/kg, while the second one reaches 2.4 kW/kg. These results demonstrate that the integration of acid hydrolysis efficiency with MFC performance provides a useful metric to assess the energy potential of various agricultural wastes. The comparison of different agricultural wastes, combined with the analysis of pretreatment and cell configuration, highlights the importance of both substrate selection and MFC configuration in maximizing energy output.

From the 10 combinations compared in Fig. 10, four of them use olive pruning as carbon source, while sugarcane bagasse, for wood and potato peel are used in two combinations each. Thus, olive pruning, sugarcane bagasse, and fir wood also showed promising results, suggesting the adaptability of this approach to diverse biomass sources.

Overall, the findings demonstrate that optimizing both hydrolysis and MFC design is key to improving biomass-to-electricity conversion.

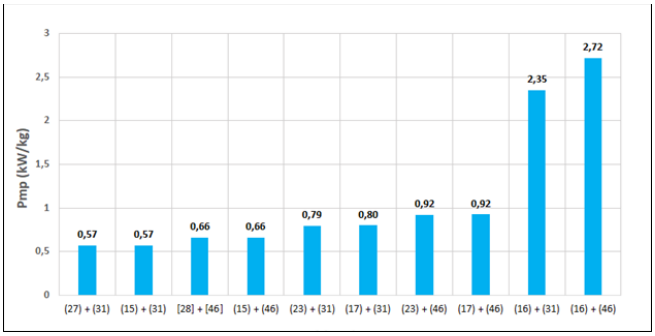

Fig. 10 Comparison of the 10 highest P_{rm} yields. The references involved in each combination are specified on the horizontal axis.

IV. Conclusions

Residual biomass has the potential to be transformed into energy by MFCs, particularly due to the ease with which its cellulosic and hemicellulosic components can be hydrolyzed into glucose. Among the substrates that have potential to produce the highest power yields are potato peels, sugarcane bagasse, fir wood and olive pruning. Hydrolyzation of potato peels produced the highest glucose yield with 538 g of glucose/kg carbon source. For the specific case of sugarcane bagasse, the highest of the 10 estimated yields for this biomass was 181.9 g/kg. These biomass sources are most commonly found in countries such as Brazil, China, Mexico, and Thailand.

On the other hand, the highest estimated power density was 5052.7 mW/g glucose. The MFC assembly with the highest yields is SCA type, using a glucose concentration of 1 g/L, a cathode exposed to air and without separating membrane. Using this approach, a power density of 2.8 kW/kg of carbon source was estimated for potato skin and 0.9 kW/kg for sugarcane bagasse.

These findings highlight the potential of agricultural residues, especially sugar-rich materials like sugarcane bagasse, in advancing renewable energy technologies. Taking into account that sugarcane bagasse is not the only residue from sugarcane processing activities, another promising raw material is the combination of bagasse with sugarcane stems, which contain a high concentration of fermentable sugars.

Additional to their contribution to clean energy alternatives, the use of agro-industrial waste in MFCs supports waste valorization and circular economy initiatives. This approach not only reduces environmental impacts of both energy production and waste management, but also provides a way for sustainable development in rural and agricultural regions, since it transforms low-value residues into a source of electricity. Future work should explore large-scale implementation, optimization of microbial consortia, and integration of MFCs into existing waste management systems to fully realize their potential as decentralized energy solutions.

ACKNOWLEDGMENT

The authors would like to thank Universidad Tecnológica de Bolívar for the support given under this project, as well as the Luis Enrique Borja Barón Library for the technical and bibliographic support procured during the making of this article.

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