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Review

Wastewater as a Renewable Energy Source—Utilisation of Microbial Fuel Cell Technology

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Abstract: An underappreciated source of renewable energy is wastewater, both municipal and industrial, with global production exceeding 900 km^3 a year. Wastewater is currently perceived as a waste that needs to be treated via energy-consuming processes. However, in the current environmental nexus, traditional wastewater treatment uses 1700–5100 TWh of energy on a global scale. The application of modern and innovative treatment techniques, such as microbial fuel cells (MFC), would allow the conversion of wastewater's chemical energy into electricity without external energy input. It has been demonstrated that the chemically bound energy in globally produced wastewater exceeds 2.5×10^4 TWh, which is sufficient to meet Europe's annual energy demand. The aim of this paper is to answer the following questions. How much energy is bound in municipal and industrial wastewaters? How much of that energy can be extracted? What benefits will result from alternative techniques of waste treatment? The main finding of this report is that currently achieved energy recovery efficiencies with the use of microbial fuel cells technology can save about 20% of the chemical energy bound in wastewater, which is 5000 TWh on a global scale. The recovery of energy from wastewater via MFC technology can reach as much as 15% of global energy demands.

Keywords: microbial fuel cell; wastewater; renewable energy; wastewater treatment; clean energy; industrial wastewater

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1. Introduction

Global energy consumption is continually rising, and in 2019, it exceeded 1.7×10^5 TWh (19 TW) [1]. The Intergovernmental Panel on Climate Change (IPCC) forecasts that energy demand will double by 2095 and reach 1200×10^{18} J/year [2], which is equal to 3.3×10^5 TWh/year. Unfortunately, approximately 84% of globally produced energy still comes from fossil fuels, which is the largest source of carbon dioxide (CO_2), as shown in Figure 1.

In the quest to reduce CO_2 emissions, wastewater needs attention. Currently, wastewater is perceived as a waste that must be treated with the use of energy-consuming processes; alternatively, the concept of the circular economy posits that a waste generated in one process becomes a valuable resource in another one [3]. In 2020, the global market for wastewater treatment was over 263 billion USD, and it is projected to reach almost 500 billion USD by 2028 [4]. The energy used for the conventional treatment of wastewater is 1–3% of global energy consumption, which is 1700–5100 TWh—an amount that is as high as the annual energy consumption of Germany and Spain combined [5,6]. Historically, wastewater is overlooked as a source of energy [7–9]. Wastewater contains considerable amounts of energy in the form of chemical and thermal energy, which is currently underutilised in conventional wastewater treatment. The chemical energy of wastewater accumulates in chemical compounds and may be extracted through the oxidation–reduction reactions of these substances. The amount of chemical energy in wastewater is usually called the chemical oxygen demand (COD), which represents the amount of oxygen that is needed to oxidise the organic matter present in wastewater [10]. It has been reported that municipal wastewater contains 9.3 times more energy than it requires for treatment, while the available energy is less, but still 4 times more than needed for its treatment [11,12]. The recovery of chemical energy from wastewater can be realised with the use of microorganisms, which can utilise organic matter from wastewater in their metabolic processes. A highly efficient method of organic contaminant removal from wastewater is anaerobic digestion (AD) [13]. Currently, the extraction of energy from wastewater with the use of microorganisms is realised on a practical scale via the AD process in which organic matter from wastewater is converted into biogas [14]. However, in the biogas produced via AD, in addition to energetically useful methane, CO_2 (which can reach 50%), NOx, SO_2 and CO are present too, which is why the AD process requires a separate co-generation plant [15,16]. Practically, it is limited to sludge treatment, and it requires post-treatment because its effluents have a high organic content [17]. Although various established water purification technologies have been commercialised and are widely used (i.e., distillation, membrane filtration and adsorption), they are not really sustainable due to their high energy consumption [18].

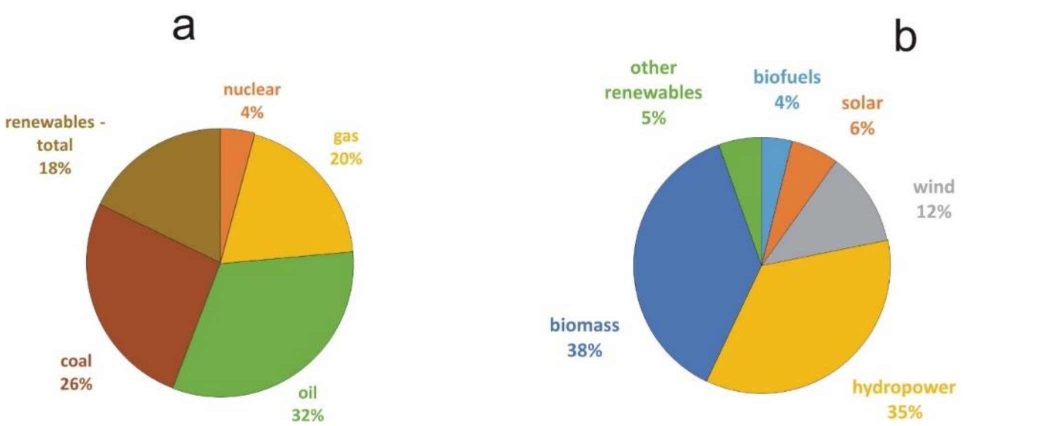

Figure 1. (**a**) Global production of energy in 2019 and (**b**) global production of energy from renewables in 2019 [1].

A more environmentally benign alternative to AD is microbial fuel cell (MFC) technology, which enables the direct production of energy from wastewater in the form of an electric current. The electricity produced in MFCs results from the flow of electrons released by bacteria during their metabolic processes [19–22]. An MFC electric current is produced due to electrogenic microorganisms oxidising organic substances from wastewater [23]. The current is generated without external energy input. Contrary to AD, which requires relatively high temperatures (> 30 °C), MFCs operate within a wide range of temperatures and COD loadings. Moreover, a stable power output is obtained in MFCs within a few days, whereas in AD it requires months. Electricity in MFCs is produced directly, whereas AD requires the conversion of methane into electricity with ca. 35% effciency [24]. However, MFC technology is currently restricted to the laboratory scale because it is considered incapable of producing an acceptable power density, which is a barrier to commercialisation. While most MFCs do not exceed the power production of 1 kW per 1 m^3 of wastewater [25], a new look at the energy balance of MFC technology, as presented in this work, indicates that MFCs can be used for wastewater treatment as a self-sufficient technology that allows for significant energy savings on a global scale.

In this article, an attempt to estimate the global production of industrial wastewater has been undertaken for the first time. The article was written in response to the lack of data on industrial wastewater and especially lack of studies describing the energy potential of wastewater—particularly industrial ones. The estimation was made on the basis of available data of water use and recovery as well as on the production volume by the biggest industrial sectors.

This study asks key questions. How much energy is bound in municipal and industrial wastewaters? How much of that energy can be extracted? What benefits will result from alternative techniques of waste treatment, such as microbial fuel cell technology?

2. How Much Municipal and Industrial Wastewater Is Produced Globally?

According to United Nations Educational, Scientific and Cultural Organization (2017), the total water withdrawal can be estimated at 3928 km^3 per year [26]. Globally, wastewater produced from municipal and industrial activity accounts for 24% of this amount, as illustrated in Figure 2. Municipal wastewater contains wastewater discharged from residences, institutions and public facilities and has a typical COD range of 300–900 mg/L. In 2019, the global production of municipal wastewater exceeded 305 $\times$ 10^9 m^3, and the two largest producers were the USA (over 60 $\times$ 10^9 m^3) and China (over 40 $\times$ 10^9 m^3) [27]. Municipal wastewater is usually treated with the use of activated sludge (AS)—the most common biological method of wastewater treatment—which utilises microorganisms for organic matter decomposition in aerobic conditions. The AS process requires intensive aeration, which makes 55–90% of the energy consumed in the treatment plant [28]. Typically, AS consumes 0.3–2.1 kWh/m^3 of energy, with higher values in small plants, but it usually does not exceed 1 kWh/m^3 [29–32]. Thus, we can estimate that municipal wastewater treatment on a global scale requires ca. 300 TWh of energy.

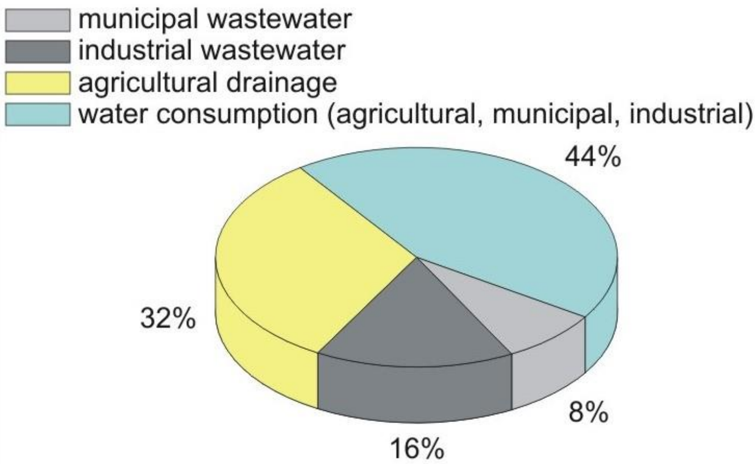

Figure 2. Global water use by sector [28].

Industrial wastewater includes effluents generated by various branches of industry at all stages of production and accompanying processes, including cooling or installation cleaning (Figure 3). According to the European Environmental Agency, industrial wastewater can be divided into two main categories: the manufacturing and energy supply industries [33]. Among manufacturing industry wastewater, there are effluents from the production of iron and steel, non-ferrous metals, non-metallic minerals, pulp and paper (P&P), chemicals, food and drink and other manufacturing activities. In the energy industry category, wastewater is generated in mining, the extraction of gas and oil, power plants and refineries. Based on AQUASTAT and the United Nations report (2017), industrial wastewater production in 2019 was ca. 630 $\times$ 10^9 m^3, which accounts for 16% of total global water withdrawal [26,34,35]. Similar to the case of municipal wastewater, two of the world's highest water consumers, which use 50% of global water for industrial purposes, are the USA (209.7 $\times$ 10^9 m^3) and China (133.5 $\times$ 10^9 m^3) [26]. Depending on the sector type, industrial wastewater is discharged or treated and re-used in place. For example, the Danish brewer Carlsberg claims to recycle 90% of the water used in its plants [36]. Conversely, in paint production, which uses up to 3.2 $\times$ 10^5 m^3 of water per day, only 4% of water is recycled [37]. Large-scale industries account for a significant proportion of the direct release of wastewater (e.g., the energy supply industry, which accounts for ca. 86%) [38]. According to a United Nations report, ca. 80% of wastewater globally is discharged without sufficient treatment [25]. Industrial wastewater is much more diversified in terms of its degree of pollution than municipal wastewater. The COD values of industrial wastewater are quite diverse between different sectors and within particular branches (Table 1). Obviously, a higher contamination level of industrial effluents requires more energy for treatment. A case study of dairy wastewater treatment with the use of AS showed that energy consumption was 0.9–1.2 kWh/m^3 when the COD of wastewater was 1900 mg/L, and it increased to 1.3–1.5 kWh/m^3 when the COD was 3700 mg/L [39]. Similar to municipal wastewater, AS is the technique of first choice for industrial effluents. However, AS often requires more advanced treatment methods when efficiency is unsatisfactory, especially for wastewaters with high COD loadings. The most efficient treatment techniques, such as membrane methods, need 1–6 kWh/m^3, which can obtain a COD removal efficiency >90% and reduce the production of sludge by as much as five-fold during treatment compared to AS [23,40]. In cases in which heavily polluted wastewater needs to be treated, the most effective electrochemical methods can consume as much as 153 kWh/m^3 [41].

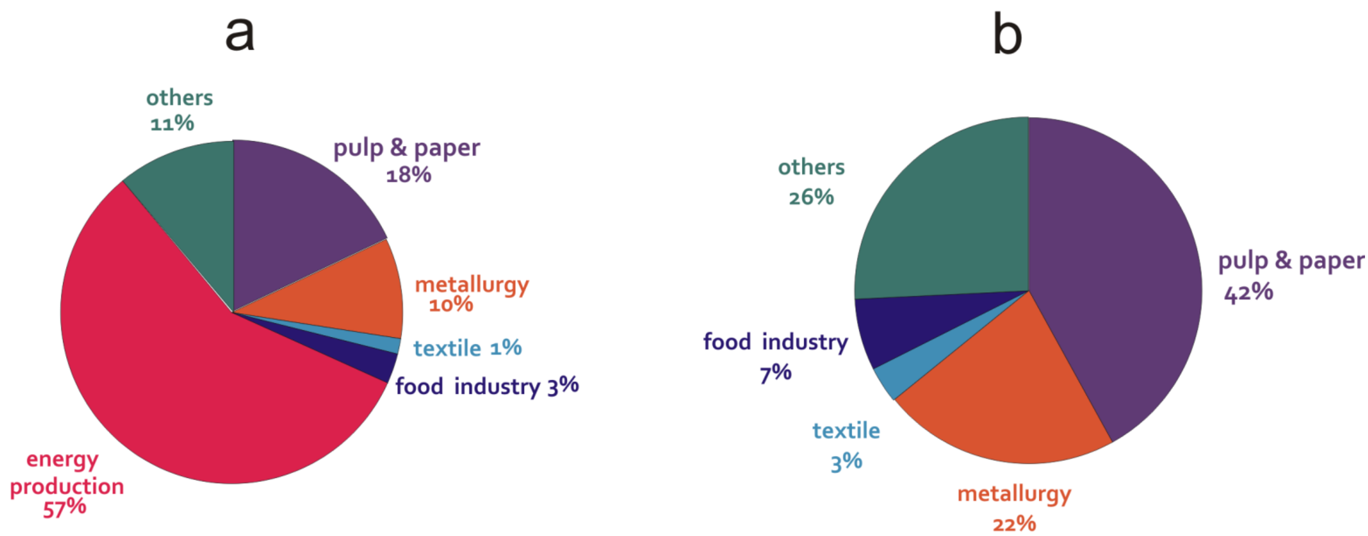

Figure 3. Global (**a**) industrial wastewater production and (**b**) manufacturing industry wastewater. The estimations are based on the statistical data of water use and production volume for various industrial sectors.

Table 1. Global municipal and industrial wastewater production for selected sectors.

Wastewater Type				Estimated Global Production in 10^9 m^3	COD [mg/L]	References
Municipal				305	300–600	[42]
Industrial	Energy sectors			392	395–45,000	[43–47]
	Manufacturing industry	Pulp and paper industry		123	480–115,000	[23]
		Food and beverage industry	Slaughtery	3.7	1140–16,000	[48,49]
			Dairy	2.5	500–100,000	[33,50]
			Wine, beer, beverages	5	1200–211,800	[51–56]
		Metallurgy		65	880–42,000	[57,58]
		Textile industry		10	150–30,000	[59]

The majority of wastewater produced by global industries comes from energy sec-tors, reaching 10% of global water withdrawal [60]. The energy production industry uses water for fuel extraction, processing, transport, cooling and gas purification in power plants. Oil production is estimated to generate 10 barrels of wastewater per each barrel of produced oil [61]. Based on global oil production in 2019, which was ca. 4.1×10^9 m^3, the amount of globally produced wastewater from oil production could reach 41×10^9 m^3 [62]. The energy industry's wastewater is polluted with chlorides, sulphates and heavy metals, such as Cr, As, Cd, Hg or Pb, which are recognised by the US Environmental Protection Agency and the American Lung Association as being responsible for cancer risks, heart attacks and asthma cases [60]. A wide spectrum of treatment techniques is used for energy industry effluents, from physical methods (e.g., coagulation, filtration and adsorption in the case of wastewater from gas desulphurisation in power plants) to membrane processes and electrochemical methods for petro-chemical wastewater, with energy demand reaching ca. 3–6 kWh per 1 m^3 of wastewater [63–66].

Among all industrial manufacturing sectors, the P&P industry is the biggest in-dustrial water consumer, requiring 5–200 m^3 of water per 1 tonne of product [23,67]. Based on global paper production in 2019, which was ca. 700×106 tonnes, and considering that the P&P industry is responsible for the generation of 42% of industrial wastewater, we estimate that the P&P sector can produce up to 123×10^9 m^3 of highly polluted wastewater annually [23,68]. The COD of P&P wastewater varies widely, spanning from hundreds of mg/L to hundreds of g/L, depending on the specific process by which it was generated, with the average value being a few g/L [23]. Most P&P treatment plants use biological aerobic methods, including aerated lagoons or AS [69]. Their application produces large amounts of waste sludge (0.4 kg of sludge per kg of organic substrate consumed) [61,70]. Alternative treatment methods used in the P&P industry that reduce sludge production and enhance COD removal efficiency (> 90%) include membrane processes or electrochemical methods. However, these still require a high energy input, from 1 to 6 kWh/kg COD in membrane processes to 20 to 35 kWh/kg COD in electrochemical methods [23].

After the P&P industry, the textile industry consumes the largest amount of water per 1 tonne of product (ca. 200 m^3/t), 90% of which ends up as wastewater [71]. In India, the third-largest textile exporter worldwide, the wastewater production of their textile industry is 640 mln m^3 a year, based on official statistics [72]. Considering only the top 10 textile-exporting countries, in 2019, global wastewater generation from the textile industry exceeded 10×10^9 m^3 [73]. The biggest problem with effluents from the textile industry is the use of dyes in the production process (ca. 280,000 tonnes of various dyes are discharged every year, causing serious environmental and health risks [64]). According to the World Bank, the textile industry may be responsible for as much as 20% of industrial water pollution [64,74,75]. Recent research has shown the toxic, carcinogenic and mutagenic activity of dyes used in the textile industry on biological organisms, which highlights the need for effective treatment of this type of waste [76–80]. Of the various treatments for textile effluents, the most economically beneficial are biological methods, in which microorganisms are utilised for the decomposition of dyes. However, membrane methods (membrane bioreactors and photocatalytic membrane bioreactors) are the most efficient, as they allow for COD and dye removal with an efficiency as high as 99% [59].

Metal production generates 26.5 m^3 of wastewater per 1 tonne of steel [81]. In metal-lurgy, water is used for flotation, sintering, cooking or steel making. Global steel production in 2019 was 1869 mln tonnes, and for non-ferrous metals, it was 1265 mln tonnes, which led to world wastewater production from metallurgy, being ca. 65×10^9 m^3 [82,83]. Due to the presence of cyanide in wastewater, AS has been found to be ineffective for metal-lurgy wastewater treatment [51]. In practical applications, a combination of two or more energy-consuming methods is usually used (e.g., membrane or electro-chemical methods, coagulation with microfiltration or advanced oxidation with H_2O_2 [57]).

The food processing industry, which is one of the most water-consuming sectors, produces diverse effluent pollution, depending on the production type (e.g., meat, dairy, alcohol, bakery or others, Table 1) [84]. The American food manufacturing sector has been identified as responsible for 20% of greenhouse emissions and 12% of water withdrawals [85]. For example, in the production of 1 tonne of poultry, 6–30 m^3 of water is used. Other examples are 1.5–10 m^3/t for pork and 2.5–40 m^3/t for beef [86]. Additionally, 98% of water consumed during meat processing is discharged as wastewater [87]. While the COD of the greatest wastewater producers in the food industry—meat processing and the dairy sector—usually do not exceed 5000 mg/L, there are technologies that generate effluents with an extremely high COD (e.g., rapeseed oil production: 3,000,000 mg/L; mayonnaise production: 1,820,000 mg/L; cream: 1,550,000 mg/L [88]). Global meat production in 2018 was 341 mln tonnes, generating 3.7×10^9 m^3 of wastewater [89]. Data from 2019 indicate that the annual amount of wastewater produced by the food and beverage industry in Europe was 3.7×10^9 m^3 [90]. Given that Europe accounts for about 19% of the global food market, the world wastewater production from the food and beverage industry may reach ca. 19.5×10^9 m^3 [91]. Depending on the wastewater composition and pollution degree, a wide spectrum of treatment techniques is applied, from co-treatment with municipal wastewater (e.g., for winery effluents) to sophisticated membrane, electrochemical and oxidation [88], enzymatic [92] or anaerobic [93] methods.

Other types of water-consuming industries are the chemical industry, building and construction, electronics and semiconductors, leather products and other engineering sectors. Among these, the chemical industry is extremely diversified and is the greatest consumer of water. In 2020, just in the EU the production of chemicals reached 270.8 mln tonnes [94]. In the chemical industry, water consumption may reach 20 m^3/m^3 (e.g., for methanol [95]) or 50–100 L of wastewater per 1 kg of produced substance, such as in the pharmaceutical sector, in which products are usually manufactured in multi-step processes and can involve as many as 30 steps [96,97]. In China alone, the pharma industry generates at least 1×10^9 m^3 of wastewater per year (incomplete data) [98]. For chemical industry wastewater treatment, depending on the effluent type, a combination of anaerobic and aerobic methods is used, and more often, membrane and chemical oxidation methods [99,100].

3. Recovery of Chemical Energy from Wastewater—Treatment with MFC Technology

Chemically bound energy in municipal wastewater is often expressed per mass of COD and is determined as 4.9 kWh/kg COD [101,102]. Additionally, the amount of thermal energy in wastewater is ca. 7 kWh/m^3, which can be recovered through heat pumps for heating or cooling processes in plants [103]. Considering global municipal wastewater production and its typical COD range, the amount of chemical energy in municipal wastewater varies between 448 TWh and 1345 TWh per year. Regarding industrial wastewater, chemical internal energy can be estimated based on the research by Heidrich et al., whose study used mixed municipal and industrial wastewater of COD 718 mgO_2/L and was estimated based on 7.97 kWh/kg COD [104]. However, given that the COD of industrial wastewater is typically on the order of a few g/L, we can assume that the value is heavily underestimated. It is known that the energy content of wastewater relies on its COD; however, there have been no investigations showing a direct relationship between these two parameters in high-strength wastewater to date [105]. Thus, the amount of chemical energy entrapped within industrial wastewater, when considering the estimations of Heidrich et al., global yearly production and assuming an average COD of 5000 mg/L for industrial effluents, can be estimated as ca. 2.5×10^4 TWh.

MFCs are currently perceived as a treatment technique (allowing for >90% COD removal) rather than a power production technology because the power produced is considered low, in the order of a few W/m^3 [24,106–109]. However, recent research has shown that power production efficiency in MFCs has increased remarkably in recent years; more often, it is close to the 1 kW/m^3 level in litre-scale reactors. Table 2 shows selected examples of the MFCs in which power productions are above 10 W/m^3. The highest power densities (>1 kW/m^3) are obtained in very small reactors as a result of reactor volume and electrode configuration optimisation, which are not yet reliable on a practical scale. Usually, power production in MFC is given in W/m^3 of reactor or in W/m^2 of electrode, but in such system there is a huge influence of reactor size and configuration on the power production amount. Increases in power densities obtained in MFCs have resulted in the description of their performance by a more objective and practically useful parameter—normalised energy recovery (NER), which gives the information about the energetic efficiency of MFCs without the influence of the reactor volume or electrode size. NER shows energy recovery on the basis of wastewater volume or COD and is expressed in kWh/m^3 of substrate or kWh/kg COD. Most MFCs produce energies lower than 1.5 kWh/m^3, which is 1 kWh/kg COD [110]. It is also generally accepted that MFCs need to produce power density in the order of 1 kW/m^3 to become a self-sufficient technology [25]. However, currently obtained power densities may be enough to achieve energy self-sufficiency because, in practice, MFCs consume only 0.076 kWh/kg COD during wastewater treatment, which is one order of magnitude less that of AS (0.3–0.6 kWh/kg COD) [25]. Many investigations conducted on synthetic and real wastewater showed that MFC technology, contrary to the AD process, may remain self-sufficient because the amount of energy produced during the treatment process meets the total energy needs required to operate the system [111–114]. The data collected in Table 3 show that even below 1 kW/m^3, MFCs have the potential to become energetically self-sufficient with a positive energy balance. Especially promising is the investigation conducted on real brewery wastewater in a 90-L reactor in which the net energy 0.034 kWh/m^3 was obtained, with the COD removal efficiency reaching almost 90% [115]. In addition, there is still space to enhance energy recovery in MFCs, and the most recent research on synthetic wastewater shows that energy production during treatment in MFCs may be in the order of 11.5 kWh/m^3 or even 22.5 kWh/m^3 [116–118].

Table 2. Power production in MFCs above the 10 W/m^3 limit.

Substrate	W/m^3	Reactor Volume	Reference
Anaerobic + aerobic sludge	258	360 mL	[119]
Anaerobic + aerobic sludge	280	360 mL	[120]
Sewage sludge	45	1 L	[121]
Domestic WW + textile WW	750	2 L	[122]
Oil palm mill effluent	18	4 L	[123]
Synthetic wastewater	11	20 L	[124]
Synthetic wastewater	890	10 L	[112]
Acetate	1550	2.5 mL	[125]
Acetate	2150	0.3 mL	[126]

WW—wastewater.

Table 3. Comparison of energy balances in real wastewater—conventional treatment methods vs. MFC technology.

Substrate	Conventional Wastewater Treatment				MFC Technology				References
	Treatment Type	Energy Consumption kWh/m^3	Energy Production kWh/m^3	Energy Balance kWh/m^3	Energy Consumption kWh/m^3	Energy Production kWh/m^3	Energy Balance kWh/m^3	Max. Power Density W/m^3	
Municipal wastewater	AS	0.52	0	−0.52	-	-	0.024	-	[127,128]
	AD	0.865	0.52	−0.345	0.141	0.205	0.064	-	[129,130]
					0.0147	0.0239	0.009	4.1	[131]
					-	0.08	-	11	[132]
					-	0.57	-	2.6	[133]

Table 3. *Cont.*

Substrate		Treatment Type	Conventional Wastewater Treatment Energy Consumption kWh/m³	Energy Production kWh/m³	Energy Balance kWh/m³	MFC Technology Energy Consumption kWh/m³	Energy Production kWh/m³	Energy Balance kWh/m³	Max. Power Density W/m³	References
Primary sludge						-	3.2	-	6.4	[134]
Industrial wastewater	Brewery	Electrochemi-cal methods	ca. 30	0	−30	0.027	0.097	0.034	-	[115,135]
Industrial wastewater	Brewery					-	0.35	-	3	[136]
Industrial wastewater	Fish processing	AS	0.5	0	−0.5	-	0.27	-	3.8	[137,138]
Industrial wastewater	Fish processing	Reverse osmosis	3.3	0	−3.3					[65]
Industrial wastewater	Distillery	Advanced oxidation processes	0.1–1.19	0	−(0.1 ÷ 1.19)	-	1.8	-	4.7	[132,139]
Industrial wastewater	Distillery	Electrooxida-tion processes	24-28	0	-(24 ÷ 28)					[140]

4. Conclusions

In the time of global energy shortages, searching for new renewable energy sources is an urgent need. In this article, we paid the attention to globally produced wastewater as an invaluable renewable energy source. On the basis of the most recent literature, the reports and databases of non-profit organizations as well as the reports of governmental institutions, we demonstrated the potential of energy recovery from various types of wastewater through MFC technology.

This is the first paper presenting the quantities of wastewaters available globally in conjunction with their energy content as well as identifying the unexploited reservoirs of clean energy. A great potential of wastewater-fed MFCs has been demonstrated as well as its three key advantages over the established approaches to wastewater treatments, which are: (1) no energy input requirement, (2) net energy produced during the treatment and (3) high organic contaminant removal efficiency.

If the self-sufficiency of wastewater treatment processes became technically possible due to the implementation of MFC technology on a practical scale, we could save the entire amount of energy spent on wastewater treatment, which currently, on a global scale, is ca. 5100 TWh. This value will constantly increase as a result of global water shortages and the need to meet stricter environmental standards, which will force the use of more efficient treatment techniques that consume less energy. Increases in power production in MFCs over the years have shown that there is still space to enhance the efficiency of energy recovery from wastewater and other organic substrates. Any net energy production in MFCs from wastewater will be an energetic gain. The considerations presented in this paper indicate that ca. 900 TWh can be produced in MFCs on a global scale only when their efficiency reaches 1 kWh/m^3 of wastewater. However, the total chemical energy bound in wastewater that can be recovered with the use of MFC technology is ca. 2.6×10^4 TWh, which is 15% of the current global energy demand. These values demonstrate the real potential of MFCs in the exploitation of wastewater as a new source of renewable energy and indicate an urgent need to intensify research efforts on the development of MFC technology, which may become a green route to the energy of the future.

Further research should focus on overcoming the existing issues, which are: (1) limited power output [141], difficult scaling-up [142], increasing the overall efficiency of MFCs via systematic development of new electrode materials [143,144], improved performance at ambient temperature [108] and microbial consortia of the enhanced electrogenic activity—i.e., increased electron transfer rates [145]. When the above-mentioned issues are successfully resolved, the world will gain a powerful source of clean, environmentally benign energy.

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Abbreviations

AD	anaerobic digestion
AS	activated sludge
COD	chemical oxygen demand
kWh	kilowatt-hour
L	litre
MFC	microbial fuel cell
mL	millilitre
P&P	pulp and paper
TWh	terawatt-hour
W	watt
WW	wastewater
NER	normalised energy recovery

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