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Review

Microbial Biosensors for Wastewater Monitoring: Mini-Review

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Abstract: Research on the use of microbial biosensors for monitoring wastewater contaminants is a topic that covers few publications compared to their applicability in other fields, such as biomedical research. For this reason, a systematic analysis of the topic was carried out, for which research-type articles were reviewed during the period 2012 to September 2022. For this, different search platforms were used, including PubMed, ScienceDirect, Springer Link, and Scopus, and through the use of search equations a relevant bibliography was located. After that, the research articles were selected based on exclusion criteria. As a result, it was found that, of the 126 articles, only 16 articles were strictly related to the topic, since there was a duplication of articles among the different databases. It was possible to demonstrate the usefulness of microorganisms as components of biosensors to monitor BOD, heavy metals, and inorganic contaminants in wastewater that also had a high sensitivity. Additionally, recombinant DNA techniques were shown to improve the performance of this type of biosensor and can finally be coupled to other emerging technologies, such as microbial fuel cells (MFCs). In conclusion, it was established that microbial biosensors have high acceptability and monitoring characteristics that make them a useful tool to detect low concentrations of pollutants in wastewater that can also provide results in real-time, thus generating forms of ecological safety and social responsibility in companies where wastewater is generated.

Keywords: microbial biosensors; monitoring; wastewater; wastewater monitoring

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1. Introduction

The current water demand exceeds the amount of fresh water on the planet due to rapid urbanization, accelerated growth of populations, industry, etc., which release contaminants that are distributed into aqueous systems [1–3]. These activities discharge a large number of harmful contaminants, which become part of the wastewater, where its composition and concentration of microorganisms, inorganic chemical products, and organic contaminants varies according to the origin of the pollutants [4]. The rapid growth of the world population endangers the water balance of ecosystems and generates a significant amount of wastewater [5]. The wastewater reaches the treatment plants (WWTP), where it is subjected to conventional mechanical and biological methods, however, the efficiency is not adequate to eliminate all of the contaminants before it is released back into the biotic and abiotic environments of the ecosystem [6,7]. For this reason, it is important to identify and monitor the constituents of these released waters since they vary over time and location, which is why new low-cost and real-time monitoring technologies are required. The ability to monitor pollutants in this way allows for the environmental impact to be minimized and the good ecological status of water bodies to be ensured [5,6]. For this reason, WWTPs play an important role in the purification of polluted waters and in monitoring how the treated waters leave the facility [8,9]. Given this, monitoring alternatives have emerged for the efficient detection of contaminants, such as biosensors.

Biosensors are devices that integrate a receiver and a transducer, through which biological or chemical reactions are measured when a signal proportional to the concentration of an analyte is generated [8,10,11]. The biological part of the biosensor can be microorganisms, antibodies, enzymes, DNA, etc., while the transducers can be electrochemical, colorimetric, optical, piezoelectric, acoustic, etc., to obtain a signal output [12,13]. Biosensors traditionally use a bioreceptor (bioelement), which is a biological molecule that binds to a transducer and generates a signal, and it is the bioreceptor that provides the specified sensitivity of the biosensor [14]. However, while having good specificity, they also have low detection limits, and research is being carried out to improve their sensitivity, such as the development of bioreceptor-free biosensors and the application of nanotechnology [14–16]. The increasing attention toward biosensors is due to their usefulness in different areas of science [17–21], in such a way that different specialized journals are dedicated to this subject [8]. Likewise, during the pandemic caused by the SARS-CoV-2 coronavirus in 2020, interest was aroused in using biosensors to detect the coronavirus in wastewater, as displayed in the Scopus database, where nine articles were published between 2020–2022 [22–30]. Another possible application that has gained interest is the use of biosensors for detecting minimum levels of contaminants in complex matrices such as wastewater [4].

Microbial biosensors detect a target substrate and evidence it by emitting a signal that can be quantified physiologically, electrically, or biochemically [31]. This type of biosensor has advantages in terms of low cost, unlike other methods. In addition, microorganisms can be large quantities produced in culture media, some can withstand wide ranges of pH and temperature [31], and, thanks to molecular techniques, microorganisms can be genetically manipulated via gene insertion to help determine the toxicity of heavy metals in water [32]. Bose et al. (2021) reported that microbial biosensors are more efficient and have a wider detection range compared to other conventional biosensors [32].

In this bibliographic review, the objectives are to analyze the number of publications related to the use of microbial biosensors in the monitoring of pollutants in wastewater, and which microbial biosensors have been used in the analysis of the quality of different types of wastewater. In addition, this revision has a practical justification because microbial biosensors would be very beneficial for companies since it would help them monitor their effluents more frequently and comply with the maximum permissible limits established in the regulations more economically and efficiently.

2. Materials and Methods

The literature review aims to analyze the types of microbial biosensors used to detect contaminants in wastewater, based on this, the keywords used to collect information from the different databases were defined as: "Microbial biosensor", "wastewater", "bacterial biosensor", quality monitoring", "microbial fuel cell", "MFC", "biosensor", "bacteria", and "yeast". With these keywords, the search equations were built to investigate articles in databases such as PubMed, ScienceDirect, Springer Link, and Scopus. In the systematic analysis related to the use of microbial biosensors to monitor contaminants in wastewater, a total of 1129 publications were obtained for the research article type, which was obtained through the search equations detailed in Table 1.

The inclusion criteria were that the articles be found in indexed journals, published between 2012 and September 2022, and that they contain the keywords that appear in Table 1. On the other hand, articles that refer to biosensors that use other bioelements coupled to the transducers, such as enzymes, antibodies or tissues, are used as exclusion criteria.

Table 1. Search equations used in the publication search.

Database	Search Equation
PubMed	"Microbial biosensor" AND "wastewater", "bacterial biosensor" AND "wastewater", "Biosensor" AND "yeast" AND "wastewater", "Biosensor" AND "bacterial" AND "wastewater", "Biosensor" AND "Yeast" AND "wastewater".
ScienceDirect	"Microbial biosensor" AND "wastewater" AND "quality monitoring", "bacterial biosensor" AND "wastewater" AND "monitoring", "Biosensor" AND "bacteria" AND "wastewater".
SpringerLink	"Microbial biosensors" AND "wastewater quality monitoring", "bacterial biosensors" AND "wastewater" AND "monitoring" AND ("microbial fuel cell" OR "MFC"), "Biosensor" AND "bacteria" AND "wastewater", "Biosensor" AND "Yeast" AND "wastewater".
Scopus	"Microbial biosensors" AND "wastewater", "Microbial biosensors" AND "wastewater" AND "monitoring", "bacterial biosensors" AND "wastewater AND "monitoring", "Biosensor" AND "bacteria" AND "wastewater", "Biosensor" AND "Yeast" AND "wastewater".

3. Results

Figure 1 shows that some databases had more articles related to the topic than others because some databases specialize in biomedical literature such as the PubMed platform [33,34]. A disadvantage of this database is that articles on biosensors mostly consider medical applications, which limits finding articles on biosensors with applicability in other fields, unlike the Web of Science and Scopus [35] databases. On the other hand, the ScienceDirect database provided the highest number of publications (n = 1129) found between 2012–September 2022, followed, in order, by SpringerLink (n =816), Scopus (n = 108), and PubMed (n = 41). The greater number of publications is possibly because non-specialized databases cover more multidisciplinary literature, with Scopus being one of the three most important sources in the last 15 years [36]. However, when the inclusion and exclusion criteria were applied, the number of publications was reduced (n = 45), and the number of publications related to the topic varied for each database. In another sense, the databases that had the most articles found were ScienceDirect and SpringerLink, which was possibly because the search engine of these databases has shown better precision compared to other databases (PubMed and Google Scholar) [37,38].

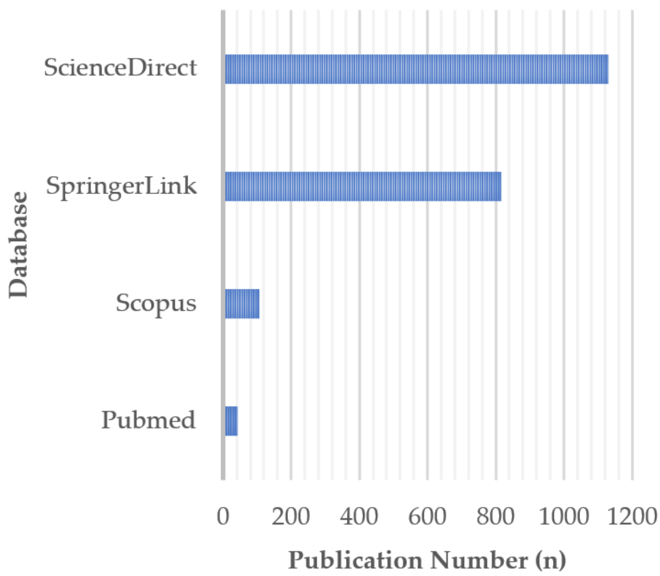

Figure 1. Publications in different databases between 2012–September 2022 (n = 2094).

Figure 2 shows a comparison between the graph obtained in this mini-review with the number of publications selected and related to the use of microbial biosensors in wastewater monitoring and the graph obtained in Scopus when using the search formula: "Biosensor" AND "Bacteria" AND "wastewater". Figure 2 was obtained after applying the inclusion and exclusion criteria, which show the same tendency to increase over the last 10 years (from 2012 to September 2022). This comparison was possible thanks to the fact that the Scopus database allows for bibliographic analysis. The similarity in the increase of research related to the topic also shows the importance that microbial biosensors have gained in the last decade in relation to their application in the monitoring of different pollutants present in different types of wastewater.

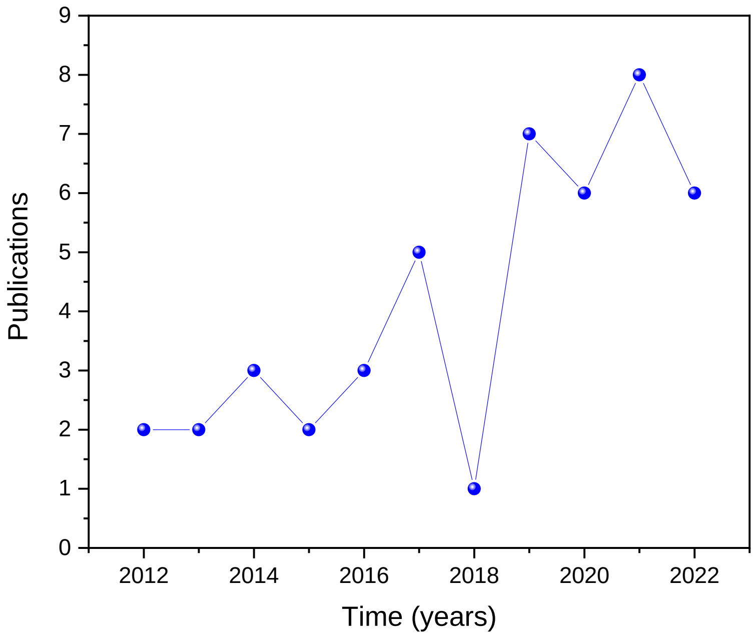

Figure 2. Comparison of graphs between the number of publications obtained in this mini-review and the Scopus database during the period 2012 to September 2022. Number of documents obtained in Scopus (n = 82), with the search formula: "Biosensor" AND "Bacteria" AND "wastewater".

The reduction in the total number of publications after applying the exclusion and inclusion criteria was due to the fact that during the analysis, duplicate publications were detected between the different databases. In addition, publications that were not specifically related to wastewater monitoring using microbial biosensors were excluded. The duplicity of publications was due to the fact that the databases share the following characteristics as search subcategories other bibliography search engines such as Medline, PubMed [38], and SpringerLink.

Figure 2 shows that, although in the last decade there has been an increasing trend in research, this has not been significant, as can be compared with the total number of articles related to the use of microbial biosensors from 1981 to 2017, where a total of 2323 publications were registered in the databases [39]. However, there was no exact data on the number of publications about wastewater monitoring using these microorganism-based devices. The monitoring of this type of water possibly began due to the concerns about transferring pathogens and contaminants that put human health at risk [23,28]. However, the use of microbial biosensors in wastewater monitoring continues to attract the attention of the scientific community due to the need for new monitoring alternatives capable of detecting minimum concentrations of pollutants in real-time and thus being able to guarantee public and environmental health [4,40]. Another problem that may have delayed research in this area of biomonitoring was the COVID-19 pandemic [41,42]. According to Riccaboni and Verginer (2022), subsidies from other areas unrelated to COVID-19 were displaced during the pandemic [43], while Gao et al. (2021) reported that the average number of hours dedicated to research decreased in the first year of the pandemic [44].

Table 2 details the microbial biosensors and their components, which have been used in research for the monitoring of contaminants in various types of wastewater between the period 2012 and September 2022. It is observed that more microbial biosensors of the electrochemical type have been developed, possibly because these are one of the most used due to their high detection precision [31]. Microbial biosensors can reduce the measurement time of some parameters, such as biochemical oxygen demand (BOD) and chemical oxygen demand (COD) [45]. The standard BOD technique usually uses a colorimeter kit, which is toxic and can take 5 days for BOD and a few hours for COD [45]. These parameters are important for measuring organic contamination in fresh water and wastewater [46–58]. COD represents the amount of oxygen required to oxidize organic matter by chemical means. Microbial biosensor systems have recently been deployed to monitor this parameter by microbial fuel cells (MFC) using wastewater from an oil refinery and a brewery as substrate, where COD shows a linear relationship with voltage output [59,60].

Table 2. Microbial biosensors tested in wastewater reported in articles during the period 2017–2022.

Target	Microorganisms	Transducer Type	Wastewater Type	Limit of Detection	Country	Ref.
BOD	*Pseudomonas aeruginosa*, *Bacillus cereus*, and *Streptomyces*	Electrochemical	food processing wastewater	-------	Vietnam	[46]
BOD	*Gluconobacter oxydans*	MFC	wastewater	2.6–58 mg O2/dm^3	Russia	[47]
BOD	biofilms on the anode surface	SCMFC	synthetic wastewater, distillery wastewater	-------	Thailand	[48]
BOD	*B. aquatica*, *C. testosteroni*, *P. putida* (DSM 1868), *V. paradoxus*, *C. pseudodiphteriticum*, *P. mirabilis*, *E. coli* y *B. subtilis*	Electrochemical	synthetic wastewaters	6 mg/L BOD	France	[49]
BOD	microorganism inmovilized. Bacteria: *Paracoccus yeei*, *Pseudomonas veronii*, and *Bacillus proteolyticus*. Yeast: *Ogataea angusta*, *Blastobotrys adeninivorans*, and *Debaryomyces hansenii*	Electrochemical	wastewater from municipal water-treatment	bacteria: 0.5 mg O2/dm^3 Yeast: 0.7 mg O2/dm^3	Russia	[50]
BOD	*Saccharomyces cerevisiae*	Electrochemical	wastewater	10–220 mg O2l−1	China	[51]
BOD	microbes of anode	MFC	domestic and brewery wastewaters	~ 20 mg BOD5 l−1	Hungary	[52]
BOD	*Paracoccus yeei* VKM B-3302	Electrochemical	municipal wastewater	0.05–5.0 mg/dm^3	Russia	[53]
BOD	bacterial strains (SPB1, SPB2, and SPB3)	MFC	urban wastewater	2 mg/dm^3	Russia	[54]
BOD	*Debaryomyces hansenii*	Electrochemical	wastewater from a city purification plant	25.2 mg O2/dm^3	Russia	[55]
BOD	*Microbacterium phyllosphaerae*	Electrochemical	dairy wastewater	5 mg L^{-1} of BOD7	Estonia	[56]
BOD	cells of *Bacillus subtilis* and *Paenibacillus* sp. immobilized in an agarose gel matrix.	Electrochemical	pulp and paper industry wastewater	5 mg/L of BOD7	Estonia	[57]
BOD	*Geobacter* sp.	Electrochemical	Synthetic waswater	174 mg/L	New Zealand	[58]

Table 2. *Cont.*

Target	Microorganisms	Transducer Type	Wastewater Type	Limit of Detection	Country	Ref.
COD	electrogenic bacteria on the anode surfaces	MFC	petroleum refinery wastewater	-------	China	[59]
COD	electrogenic bacteria on the anode surfaces	MFC and MEC (microbial electrolysis cell)	brewery wastewater		Canada	[60]
Cu^{2+} and $Cr_2O_7^{2-}$	*E. coli*	Electrochemical	industrial, dining, and laboratory wastewater	Cu^{2+}: 0.14 mg/L, $Cr_2O_7^{2-}$; 0.025 mg/L	China	[61]
Cu^{2+}	*non-pathogenic Escherichia coli BL21*	Optical	mining wastewater	1 µM	China	[62]
Zn^{2+}	*E. coli* BL21	MFC	wastewater	20–400 µM	China	[63]
Heavy metals (Cd, Cu, and Zn)	electrogenic bacteria on the anode surfaces	MFC	synthetic wastewaters	-------	China	[64]
Alkylbenzene sulfonate (LAS)	biofilms on the anode surface	MFC	wastewater	10–120 mg/L	Iran	[65]
Catechol	*E. coli* BL21-C23O	Electrochemical	wastewater	0.24 µM	China	[66]
Bisphenol A	mixed bacterial culture	Dual-chamber microbial fuel cell (MFC)	Wastewater	-------	Australia	[67]
Pharmaceuticals (omeprazole and lansoprazole)	recombinant *Arxula adeninivorans*	Electrochemical	wastewater samples from a zoo, chemical factory, mixed sample, hospital, and hotel	O: 95.01 µg/L: 83.65 µg/L	Germany	[68]
Cyclophosphamide and L-ascorbic Acid Residues	*Escherichia Coli* K-12/recA-gfpmut2	Optical	wastewater	CP: 3.5–0.35 µg/mL AA: 250 µg/mL	Poland	[69]
Environmental toxicity	Recombinant luminescent bacteria strains	Optical	wastewater		Tunisia	[70]
Perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS)	*P. aeruginosa* (PAO1), *P. aeruginosa* (1688) and *Burkholderia* FA1	Optical	industrial wastewater highly polluted sewage	10 ng/L–1000 ng/L	India	[71]
Formaldehyde	electroactive biofilm	Electrochemical	wastewater	-------	China	[72]
Heavy metals: As^{3+}, Cd^{2+}, Hg^{2+}, Pb^{2+}	acidophilic iron-oxidizing bacterium Strain Y10	Optical	industrial wastewater	-------	Taiwan	[73]
n-cyclohexyl-2-pyrrolidone	*E. coli* K12 MG1655	Electrochemical	wastewater	0.4 mg/L	Singapore	[74]
Sulfide	*E. coli* BL21 (expressing sulfide: quinone oxidoreductase (SQR))	Electrochemical	wastewater	2.55 µM	China	[75]
Sulfide	recombinant *E. coli* SQR	Electrochemical	wastewater	98.5 nM	China	[76]
Ag+, Hg+, Co2+, and Ni2+	Luminous *Vibrio* sp. 6HFE	Optical	industrial wastewater		Egypt	[77]
Pb2+	*E. coli* (inactivated)	Electrochemical	wastewater	0.13 µg/L	Algeria	[78]
toxic compounds (Cr (VI))	microbes of anode	Dual-chamber microbial fuel cell (MFC)	potato chips' processing wastewater	-------	Iraq	[79]
biodegradable organics	electrogenic bacteria on the anode surfaces	MFC	domestic wastewater treatment plant	≥ 5 mg COD l−1	Hungary	[80]

Table 2. *Cont.*

Target	Microorganisms	Transducer Type	Wastewater Type	Limit of Detection	Country	Ref.
Genotoxic compounds	*Vibrio aquamarinus* VKPM B-11245, *E. coli* MG1655 (pXen7), *E. coli* MG1655 (pRecA-lux), *E. coli* MG1655 (pSoxS-lux), *E. coli* MG1655 (pKatG-lux), *E. coli* MG1655 (pIbpA-lux), *E. coli* MG1655 (pIbpA-lux), *E. coli* MG1655 (GrpE-lux), *E. coli* MG1655 (pFabA-lux).	Optical	wastewater of two cities.	-------	Russia	[81]
Heavy metals	*Shewanella putrefaciens*	MFC	food industry wastewater	-------	Saudi Arabia	[82]
Chromium, iron, nitrate, and sodium acetate	electrogenic bacteria on the anode surfaces	A single chamber batch-mode cube microbial fuel cell (CMFC)	wastewater	-------	USA	[83]
Silver, zinc oxide and titanium dioxide nanoparticle	*Pseudomonas putida* BS566:luxCDABE	Optical	artificial wastewater	-------	Scotland	[84]
Cu2+	*Pseudomonas putida* whole-cell bioreporter	Optical	food industry wastewater	1–70 mg/L	China	[85]
Ammonium nitrogen	*Nitrosomonas* sp.	Optical	synthetic and industrial wastewaters	20 mg/L of NH+4−N	Estonia	[86]
Ammonium nitrogen	electrogenic bacteria in the anode chamber	dual-chamber microbial fuel cell (MFC)	synthetic municipal wastewater		China	[87]
Phenolic compounds	recombinant *E. coli*	Optical	hospital wastewater	10 μM	Republic of Korea	[88]
Toxic chemicals for control of the nitrification process of the wastewater	recombinant *E. coli* (*E. coli* pMosaico-*Pamo-gfp* and *Pamo-luxAB*)	Optical	mixture of industrial and municipal wastewater	*E. coli* pMosaico-*Pamo-gfp*: 1.0 μg/L *E. coli* *Pamo-luxAB:* 0.5 μg/L	Italy	[89]
p-nitrophenol	*Pseudomonas monteilii* LZU-3	aerobic anode microbial fuel cell	industrial wastewater	44 ± 4.5 mg L^{-1}	China	[90]

Table 2 shows that most microbial biosensors used the electrochemical transducer type, which has high sensitivity, low detection limits, and good selectivity [91]. Additionally, it was observed that electrochemical and optical microbial biosensors are useful in monitoring some environmental contaminants, such as inorganic compounds and heavy metals [46,49,61–64,73,77,82,84,85], which are very frequent in wastewater. Although optical biosensors indeed represent the most common type of biosensor with multiple applications in different fields [92], the bioluminescence and fluorescence measurement methods of this type of biosensor have focused the attention of researchers because they use complete bacterial cells, which provide advantages such as flexibility, resistance to electrical noise, low cost, and the ability to obtained results in real-time [93]. Likewise, the fluorescence-based method has high sensitivity, short-term detection, and easy operation [94]. This was corroborated in the review by Voon et al. (2022), which stated that whole-cell bioluminescent biosensors have high sensitivity and selectivity in environmental samples and are useful in hydrocarbon monitoring [95].

Another important aspect that stands out from Table 2 is the recent use of genetically manipulated microorganisms [62,69–71,73,75,81,85,86,88], which improves the biosensor's specification and sensitivity [95]. This is possible thanks to recombinant DNA technology that allows genes encoding transcriptional regulators to be integrated into biorecognition genes. Some of the most widely used genes are *lux/luc*, *lacZ*, and *gfp*, which code for the enzyme firefly/bacterial luciferase, β-galactosidase, and green fluorescent protein, respectively [78,96]. On the other hand, the microorganisms most used in biosensors for the monitoring of environmental contaminants are bacteria because they are easy to reproduce in cheap media, resistant to stress, detect specific signals, and also provide online analysis, in vivo, and dose-response. Of these bacteria, the *E. coli* species is the most widely used due to its easy handling [78]. In this way, this species can be used with the respective genes for the detection of environmental contaminants such as heavy metals and various inorganic contaminants [61–63,66,69,74–76,78,81,88] present in wastewater, as described and demonstrated in the analyzed articles. However, other bacterial species can also be used as components of biosensors with good detection limits, such as species of *Pseudomonas*, *Bacillus*, *Burkholderia*, *Vibrio*, etc. [97].

It can also be seen that emerging technologies such as microbial fuel cells (MFCs) have been used as electrochemical microbial sensors, and according to Table 2, they have been very useful in monitoring BOD [46–57] and other pollutants such as Zn^{2+} [63] and linear alkyl benzene sulfonate [65]. The latter is one of the most dangerous contaminants in wastewater and comes from the detergent industry, which is extremely important to detect early [65]. This utility as a microbial biosensor is possible due to its operation. Chu et al. (2021) [98] explained how these electrochemical devices function as biosensors, where the anode biofilms fulfill the role of component detection, monitoring toxic compounds by monitoring the extracellular transfer of electrons (ETE) by electroactive microorganisms and the anode. However, the cathode can also function as a biosensor, which is based on the electrochemical reduction of the analytes to be detected or through the inhibition of the oxygen reduction reaction. Likewise, the same author emphasized that through this type of biosensor, an early warning of the toxic compounds present in a body of water can be generated. Another novelty of these devices was presented by Emaminejad et al. (2022), who evaluated for the first time in the long term, the quantification of the sensitivity to variations in the organic load in a channel of primary effluents for 247 days, yielding encouraging results. However, it is also necessary to appreciate the environmental factors such as pH, the concentration of volatile fatty acids, and temperature that influenced the accuracy of the electrochemical biosensor [99].

The versatility of MFCs provides potential to monitor heavy metals in wastewater and, at the same time, generate bioelectricity, as shown in Zhang et al. (2022) [64] and Do et al. (2022) [100]. Likewise, Hui et al. (2022) highlighted the advantages of these electrochemical biosensors to detect toxic compounds in polluted water bodies since they are easy to operate, provide fast results in real-time [101], and can be built on small scales, which adds to their portability, making them very useful tools for in-situ tests. On the other hand, Tucci (2020), in his academic work, showed that electrochemical biosensors are useful for the detection of pollutants related to agriculture, such as herbicides, since for their detection there are classical analytical techniques (HPLC, GC-MS, etc.,), which are expensive and take a long time to issue results [102]. Although the low output potential and the scaling of MFCs indeed represent a challenge for electricity generation, that is different from its potential as a biosensor, of which it is a very practical monitoring system [103]. On the other hand, the sensitivity and specificity of these biosensors are lower than that of a subcomponent-based electrochemical biosensor (for example, an electrochemical enzyme biosensor) and an electrochemical sensor equipped with a chemically modified electrode, respectively. However, enzyme purification techniques make these other biosensors expensive and laborious, representing an economic disadvantage for researchers and companies [98].

Finally, the review shows that microbial biosensors are versatile in terms of their application in the environmental area, specifically in the monitoring of wastewater quality. This is possible because microbial biosensors can operate under different working conditions and are more sensitive to environmental signals than conventional sensors, as well as interacting not only with one but with multiple analytes [11]. However, Chu et al. (2021) stated that the main challenge remains the gap between the results of academic research and the implementation of these biosensors as marketable products, which is why future research is needed [98]. An important fact is the compatibility between MFCs and microbial biosensors since they allow for better monitoring of wastewater, which is a worrying environmental issue and needs these hybrid technologies to have early warnings for contaminants existing in the environment of these waters, to develop more effective treatment strategies [102]. In addition, it should be emphasized that this biomonitoring technology based on the use of microorganisms in conjunction with MFCs, makes up a sustainable technology for the environment, and allows for achieving the Sustainable Development Goal 7 (SDG 7) affordable and non-polluting energy, as referred by Fagunwa and Olanbiwoninu (2020) [104]. In this sense, biosensors are an even more promising technology in every way, due to the simplicity and reliability of detecting a large number of contaminants using miniaturized biological and chemical signals [105,106].

Finally, most of this research was carried out in Eastern countries where China and Russia stand out as major producers of articles oriented toward wastewater monitoring. It is striking that South American countries are not included in this list, and it is known that in Latin America, 70% of wastewater is discharged into water bodies (rivers, etc.) without any treatment, putting public and environmental health at risk [107,108]. Therefore, there is ample opportunity to develop research projects aimed at biomonitoring in these regions.

4. Conclusions

Microbial biosensors represent an economical alternative technology with good sensitivity and specificity and the ability to monitor contaminants in wastewater online, thus ensuring public and environmental health. This is important as, in many places, the type and concentration of pollutants that the treated effluents carry when they are released into the environment are not considered. In addition, the topic of microbial biosensors applied to wastewater monitoring is a topic of great interest in the field of biomonitoring. However, in the last five years (2012-September 2022), research has been affected by the COVID-19 pandemic; except for the year 2022 as it has not yet ended. On the other hand, microbial biosensors can be coupled with other technologies such as MFCs, thus enhancing their usefulness, which also allows for achieving the SDG 7 affordable and non-polluting energy. Finally, this review provides summarized information about the applicability and advantages of the use of microbial biosensors that can be directed to other research and also generate interest in their use in companies with environmental social responsibility.

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