

Review

Microwave Irradiation in Technologies of Wastewater and Wastewater Sludge Treatment: A Review

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Abstract: Every year, the human impact on the world's water sources becomes more pronounced. One of the triggers to this increase is the use of ineffective wastewater and sludge treatment systems. Recently, the number of studies of microwave processing in handling liquid municipal and industrial waste has increased. This paper discusses heat treatment, change in properties, decomposition of substances, removal of metals, demulsification, pyrolysis, biogas processing, disinfection, and other topics. The findings of European, Chinese, Russian, and other authors are summarised and presented in this review. In addition, the most notable Russian patents for microwave installations/devices and reactors suitable for a wide variety of applications are discussed. In this article, the authors look at microwave wastewater and sludge treatment from the perspective of practical application in various fields of human economic activity.

Keywords: microwave irradiation (MW); wastewater (WW); wastewater/sewage sludge (WWS); treatment technology; MW installations/devices/reactors



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1. Introduction

The size of global urban water consumption can be estimated based on the total population of Earth living in urban environments, which is more than 3.4 billion people, and the average water consumption per human of 499 m³ per year [1]. While accurate data on the amount of wastewater (WW) generated around the world is not available, using a calculated method based on the standard of water use and the percentage of irreversible losses (roughly 30–35 per cent) can help us assume that more than 1100 billion m³ of wastewater and 0.1–0.05% of that amount—wastewater sludge (WWS)—is treated and disposed of annually in urbanised settlements. Solving high-quality WW and WWS treatment issues leads to a decrease in the anthropogenic impact on water and land resources. New methods and technologies, such as electromagnetic microwave irradiation (MW), may help make a breakthrough in this field.

Microwave radiation is electromagnetic ultrahigh-frequency radiation, including decimeter, centimetre, and millimetre ranges of radio waves with a frequency of 0.3 GHz to 300 GHz, corresponding to a wavelength from 1 m to 1 mm [2,3]. High-intensity microwaves are commonly used for contactless heating of objects, including stoves for cooking food, metallurgical industry heat treatment installations, and medical devices for treating veins. People actively involve microwaves of a particular range (frequency from 1 to 100 GHz) in radiolocation. MW reactors are increasingly adopted to neutralise various solid and liquid wastes produced by people and industrial enterprises [4–6].

Microwave irradiation is confidently entering the wastewater (WW) and sludge (WWS) treatment technology in the twenty-first century, primarily as an alternative to conditional heating [4]. MW is a well-known heating and drying process used both for domestic and industrial purposes.

This method has several advantages over conventional electric heating, including non-contact heating, instant and rapid process with a high degree of uniformity, and precise

heating, which induces dipolar oscillations and ionic conductivity in the medium [7,8]. In 2011, researchers conducted a comprehensive study of the existing state of MW technology for WW treatment [9]. According to this report, using MW to decompose contaminants has numerous advantages. For example, selectivity and reaction rate increase while reaction time, activation energy, equipment size, and waste parameters decrease.

These benefits are primarily due to the thermal and nonthermal effects of microwave irradiation. Many transformations with a beneficial impact on the structure and properties of water occur in the aquatic environment under the thermal influence of MW: increased dissolution of substances, coagulation and demulsification of pollution, activation of various chemical reactions (including oxidation of organic matter), and degradation of toxins; the disinfecting effect of MW is well known [10].

While the “thermal” effect of MW is well established and well understood for many environments, the “nonthermal” remains controversial [11,12]. Some researchers [13] believe that this type of physical impact can excite reactant molecules to higher vibrational and rotational energy levels, causing a weakening of the chemical bonds of polar molecules of substances. Thus, under the influence of MW, it comes out in the intensification of substance degradation. Various reviews and research articles have been published on specific issues using microwaves in WW and WWS treatment technologies. Table 1 shows the main directions of research in modern science on this topic.

Table 1. Key research directions on the use of MW in WW and WWS processing technologies.

Section	Direction of MW Research	WW	WWS	[Ref./No]
Section 3.1	Heating and thermal treatment	+	+	[3,9–27]
Section 3.2	Properties change	+	+	[28–42]
Section 3.3	Decontamination	+	+	[14,26,28,42–56]
Section 3.4	Decomposition of organic substances	+	-	[9,13,22,57–81]
Section 3.5	Demulsification	+	-	[82–90]
Section 3.6	Extraction of heavy metals	+	+	[6,14,24,91,92]
Section 3.7	Generation of biogas	-	+	[93–106]
Section 3.8	Pyrolysis of sewage sludge	-	+	[107–109]
Section 3.9	Sorbent modification	+	-	[73,110–119]
Section 3.10	Devices for WW and WWS MW processing	+	+	[120–128]

This article provides an overview of microwave radiation used in WW and WWS treatment systems, and additional information. The experience of Russian scientists is included in the presented summary knowledge and world accomplishments, which consider MW from the standpoint of promising practical applications in economic and industrial human activities.

2. Materials and Methods

Searching for materials, the keywords “microwaves”, “microwave irradiation”, “wastewater”, “wastewater/sewage sludge”, and “MW installations, devices or reactors” were used to scan for thematic papers and patents in Web of Science, Scopus, Google Scholar, ELIBRARY.RU, and other outlets, without regard to publication date.

More than 120 publications related to wastewater and its sediments treatment by microwave radiation were selected to solve practical engineering and technological problems. Most of the considered articles were written in English (99 pieces) and just several in Russian (29 pieces). The search results were initially analysed regarding their abstract, followed by a thorough evaluation of their context when specific criteria were met. The information provided was collected between September 2020 and May 2021. Table 2 contains a summary of the sources used in the article.

Table 2. Statistics of the sources used.

Paper's Category	Number	[Ref./No]	Country *
Magazine Site	1	[1]	Russia
Reviews	28	[2–4,7–9,13,14,16,17,21,43,51,57–59,73,76,90,91,93–95,98,107,108,112,119]	Australia, Taiwan, Japan, China, India, The Netherlands, Russia, Austria, UK, Malaysia, and Serbia
Research papers	86	[5,6,10–12,15,18–20,22–42,44–47,52–56,60–72,74,75,77–89,92,96,97,99–106,109–111,113–116,119]	Egypt, Russia, India, Austria, China, Japan, Italy, USA, UK, Malaysia, Afghanistan, The Netherlands, Hungary, Australia, Japan, Poland, Turkey, South Africa, Slovenia, Sweden, Canada, Korea, Denmark, Spain
Patents	13	[48–50,117,120–128]	USA, and Russia

* The countries where the studies took place are presented in order of mention.

3. Results

3.1. Heating and Thermal Treatment

MW has become increasingly common as a thermal method for treating wastewater and sediments in recent years, owing to its rapid and selective heating [9–15]. The thermal effect of MW [16] describes how ultrahigh-frequency energy can be consumed by microwave absorbers and dissipated as thermal energy. For many environments, including water solutions, microwave heating with dielectric losses is typical [13].

Water is a positive-charged molecule (or dipole) with a negative-charged opposite end. Dipolar polarization occurs due to intermolecular inertia, responsible for most of the microwave heating observed in liquids. The rapid change in the electric field of microwave radiation causes a rotation of dipoles. At the same time, the rate at which the dipole rotates (reverses) cannot accurately correlate to the rate at which the electric field shifts direction. It induces “internal friction” between water molecules, which leads to direct and very uniform heating of the reaction mixture. However, reflections and refractions at local boundaries between phases lead to the appearance of so-called “hot spots” and the effect of “overheating”, which has been extensively discussed by researchers [15,17–21].

Figure 1 presents the schematic diagram of microwave action [3,17], illustrating the advantages and scope of application of microwave processing. Microwave heating penetrates the liquid and creates the rapidly changing field: dipoles (water molecules) continuously react attempting to align in the field, which generates heat; heat is uniformly distributed throughout the water.

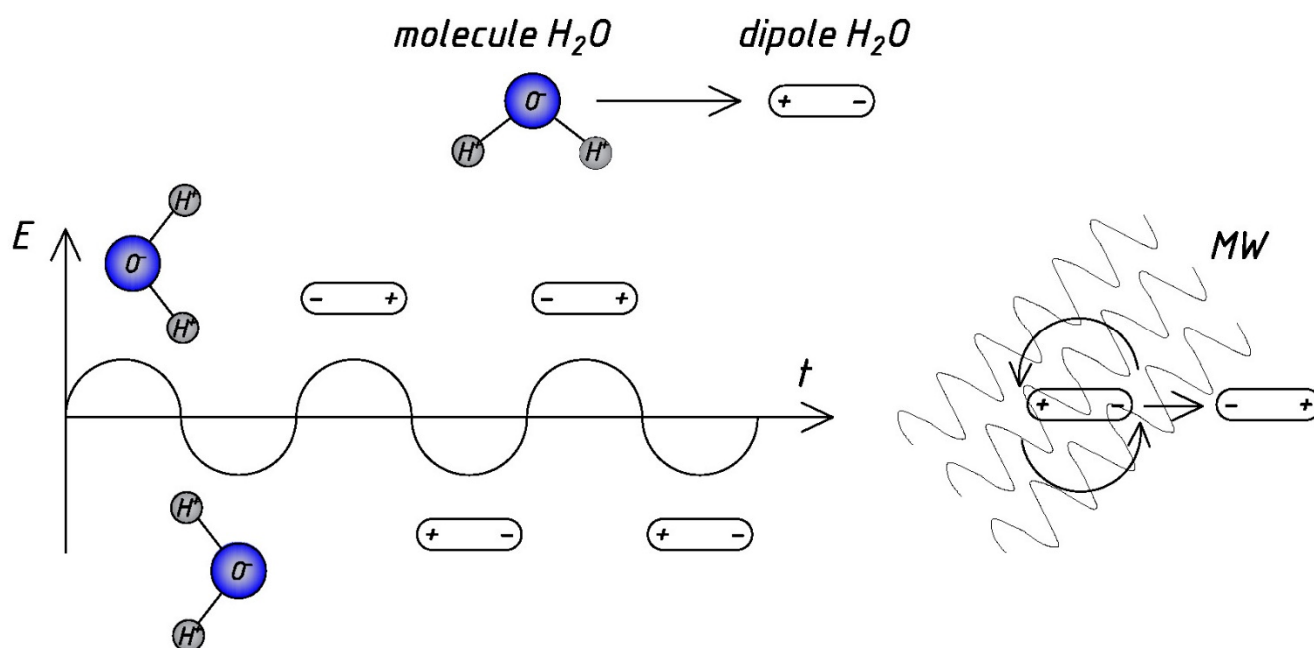


Figure 1. The scheme of mechanism of the MW water heating.

Under the influence of MW, several parameters such as strength, frequency, duration, treatment temperature, and sample volumes [9,14,22–27] can influence the efficiency of pollutant decomposition and mineralisation of wastewater and sediments. It is confirmed in the materials [25–27], which use the Netherlands, Kenya, China, and other countries as examples of MW-heating of faecal sludge (Figure 2).

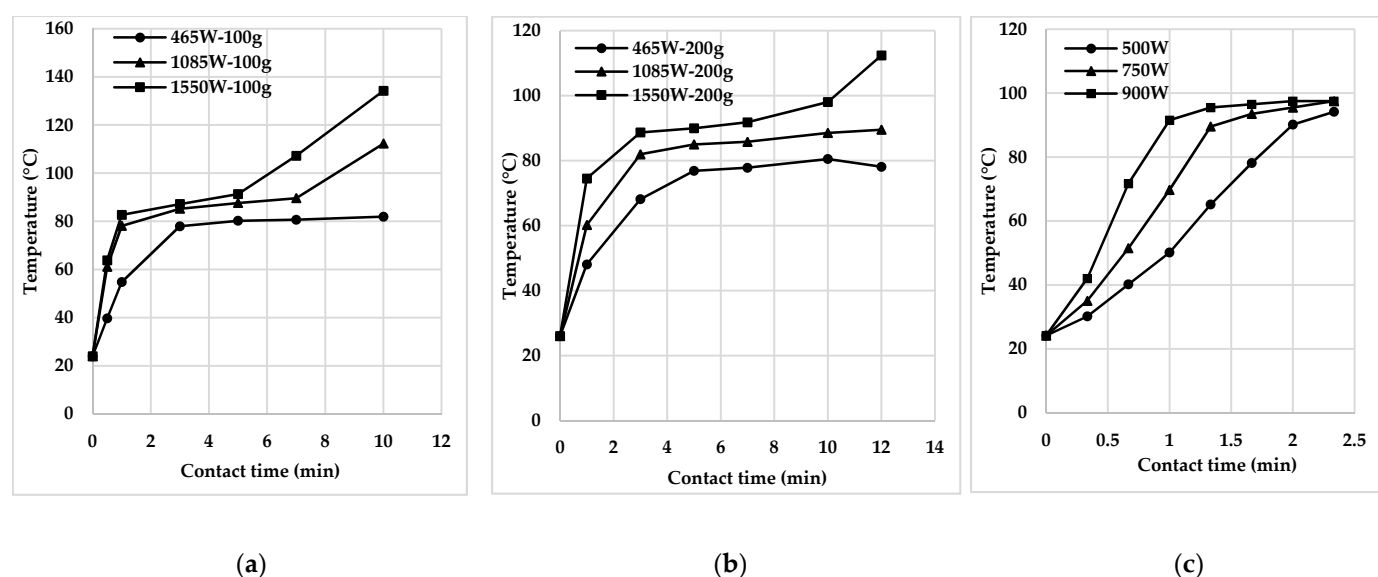


Figure 2. Dependence of temperature on the time of MW-heating of: (a) faecal sludge in Kenya, 100 g sample [27]; (b) faecal sludge in Kenya, 200 g sample [27]; and (c) active sludge in China Reprinted with permission from ref. [25].

As a rule, the efficiency of the MW system tends to rise with the increase of power and time of microwave irradiation [22]. It is due to the release of extra heat, contributing to the rapid movement of water molecules. In addition, increased time and power of irradiation amplify the decomposition of various contaminants in the water environment [9].

In some cases, the efficiency of the MW system is reduced at very high temperatures by evaporating water and increased viscosity of the substance by overheating. Thus, it is necessary to determine the optimal power and reaction temperature for decomposing a particular target pollutant [9,14,17–21].

It should be noted that the technological and economic efficiency of MW heating for the water environment is currently actively explored by contrasting it to other methods of heating and processing [14,23,24]. The Department of Water Supply and Sanitation (Industrial University of Tyumen, Russia) laboratory has carried out several experiments related to the MW-heating of wastewater sludge [14,24]. Firstly, a comparison is made between microwave and electric heating. The distinctive feature of microwave heating is its thermal effect, which is volumetric and does not involve thermal diffusion from the surface into the material, as conventional heating does, which explains its high thermostet reaction rates. According to observations, ultrahigh-frequency irradiation of liquid sewage sludge has a rapid thermal effect: samples of sludge with a 50–300 mL volume started to boil within one to two minutes (Figure 3) [14].

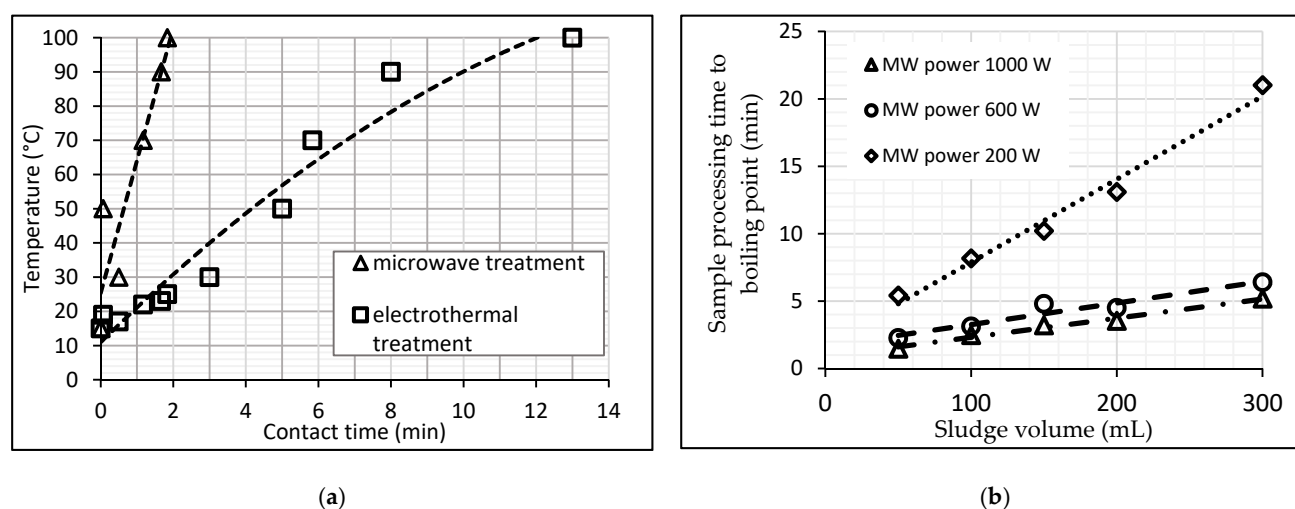


Figure 3. (a) Comparison of two methods of WWS-heating. (b) Boiling time dependence of the WWS on the sample volume at a constant power MW.

Figure 3a compares the heating curves of sewage sludge (mixture of the raw sludge and activated sludge) in two different ways, with the rate of heating the sludge to a given temperature using microwaves being four to six times faster than the usual heating on an electric stove. In addition, in the process of microwave irradiation, an improvement in the sedimentation and compaction of WWS was obtained by 13–15% compared to traditional convective heating to the same temperature [14].

Secondly, the maximum time for MW treatment of WWS samples to reach boiling point [24] was determined experimentally. Figure 3b illustrates dependency $t = f(V)$ at constant power MW based on the experience data. Obviously, the higher the microwave processing power, the faster the sludge samples reach the boiling point. At MW 200 W, the heating rate of sewage sludge is 3.7–4.0 times lower than at MW 1000 W and 3–2.8 times lower than at MW 600 W. Heating sludge with a power of 1000 W is 1.2 times more effective than heating with 600 W. Rapid and voluminous MW-heating of wastewater and sediments entails other positive effects discussed below.

3.2. Properties Change

3.2.1. Wastewater

Almost all researchers usually note changes in individual physical and chemical properties of wastewater and sludge under MW influence. The scope of the study includes such properties of water as temperature, viscosity, pH, electrical conductivity, and surface tension. There is a change in some quality indicators of water. However, some results are not widely confirmed, for example, the change in the structure of water under the influence of electromagnetic radiation.

In the studies presented, water samples from 100 to 300 mL were subjected to MW irradiation in MW furnaces of various powers from 30 W to 900 W and frequency $f = 2.45$ GHz during periods from thirty seconds to ten minutes. In some cases, experiments were carried out on pure water [28–32] and required testing on wastewater. Table 3 provides examples of changes in water or wastewater physicochemical properties under the influence of MW, as measured in batch laboratory studies.

Table 3. Changes in the physical and chemical properties of water/wastewater under the influence of MW.

Properties	Mechanism, Reason	Power MW	Duration MW	Description of Results	[Ref./No]
Structure	Water molecules' excitation and mobility	300 W	10 min	More mobile, less ordered water structure and corrugated water clusters	[28,29]
Surface tension	Decrease in viscosity and increase in water molecules' activity	30–600 W	10–120 s	Water surface tension rapidly decreased at about 20–30%	[30–32]
pH	Extraction of carbon dioxide	300 W 800 W	10 min 5–8 min	pH: from 4.81 to 4.91 pH: from 6.04 to 7.33	[33,34]
Electrical conductivity	Increase in water molecules' activity	300 W	10 min	Electrical conductivity of water samples increased by 7.8%	[33]
Nanobubbles formation	Surface tension change	30–100 W 100–500 W	60 s 10 s	Nanobubbles size: 200–2500 nm 400–4000 nm	[32]
Coagulation of suspended solids	MW treatment, reagent addition and sedimentation	396 W	2 min	Particles' growth process, high deposition rate	[25,35]
Change in quality indicators of WW	Decomposition of substances	800 W	5–10 min	Decrease in WW pollution (Table 4)	[14,34]

According to earlier studies [24,25], published back in the 1980s and 1990s, the structure of water after treatment with electromagnetic radiation changes: it becomes more mobile, less ordered, and expanded water clusters can be transformed into a corrugated structure. However, there has been no confirmation of these conclusions or further study on the wastewater samples in recent publications found.

According to the observations, during the microwave irradiation process, the water surface tension rapidly decreased along with the temperature growth. Once the microwave irradiation was turned off, the temperature quickly recovered, as expected. However, the surface tension remained significantly below the initial value for an extended period. The minimal surface tension depended on the MW power. Moreover, the repeated procedure can additionally reduce the surface tension. For example, a water sample irradiated for 120 s at a power of 600 W had the surface tension decreased from 75 to 55, and this effect persisted for one hour. There is a change to the alkaline side due to the release of carbon dioxide. Surface tension experiments were carried out in the laboratory on specifically constructed equipment [30,31].

The pH change is proportional to the MW treatment's power and time: the greater the power and duration, the more significant the pH change. Due to a rise in the water molecules' mobility, the electrical conductivity of water samples increased by 7.8%, from 0.9 to 0.97 (uS/cm). An improvement in the solubility of substances in water was also observed [30]. The nanobubbles formation was observed during the MW heating of the samples. It can be explained by a change in the surface tension [32].

The coagulation of suspended substances in wastewater under the influence of microwave irradiation is intensified during short-term treatment (one to two minutes). In order to analyse the wastewater of a metallurgical enterprise, after the treatment of blast furnace gases, polyaluminum chloride and phosphoric acid solutions were applied to water samples as catalysts for the coagulation of suspended substances. As a result, the concentration of suspended substances with preliminary microwave irradiation of the samples was 10–15% lower. In addition, it occurs that pretreatment with MW intensifies the reduction of turbidity and water hardness in the process of reagent coagulation [31].

Some authors also noted changes in wastewater quality indicators. Experiments in [14], for example, showed that the quality of sewage under the influence of MW electromagnetic irradiation improved. Table 4 illustrates the shift in wastewater criteria following microwave treatment. Results have been derived from batch experiments.

Table 4. Water indexes change after MW treatment [14].

Wastewater Indexes	Inlet Concentration before MW, mg/L	Outlet Concentration after MW, mg/L	Description of Results
Suspended matters	940	850	The concentration decreases from 940 to 450 mg/L (after first stage) and then increases to 850 mg/L (after second stage). Efficient is 9.5%
Chemical oxygen demand (COD)	1240	490	Efficient is 60.5%
Biological oxygen demand (BOD)	430	250	The concentration decreases from 430 to 250 mg/L (after first stage) and then increases to 280 mg/L (after second stage). Efficient is 35%
Ammonium-ion	200	150	Efficient is 25%
Nitrate-ion	0	3.8	The concentration increases by reason of the destruction of organic matters and transformation ammonium nitrogen into nitrate-ion
Phosphate-ion	29	19	Efficient is 34.5%
Sulfates	14	2	Efficient is 85.7%
Chlorides	4.8	2.8	Efficient is 41.7%
pH	6.04	7.33	The environment became more neutral

3.2.2. Wastewater Sludge

Microwave WWS treatment is mainly concerned with liquid municipal waste. There are quite a lot of studies on changing the properties of activated sludge; to a lesser extent, there are studies on a mixture of raw sediments and activated sludge, as well as studies on raw sediment separately. Few publications on the study of the properties of dehydrated sediments are available. Temperature and viscosity, moisture yield, compaction intensity, and mineralisation are all features that usually put into the analysis. It is worth mentioning that certain properties of WWS (compaction/deposition rate, resistivity, capillary suction time, and others) change for the better until the turning point (characterised by the power and duration of irradiation), after which they irreversibly deteriorate due to the high rate of water evaporation.

Many observers note a high level of disinfection of all WWS types (Section 3.3). Less attention is paid to the release of metals into the supernatant water, increasing stability, reducing rotting, and changing the structure of wastewater sediments. Table 5 shows variations in the physical and chemical properties of WWS under the influence of MW (frequency $f = 2.45$ GHz); the results have been derived from batch experiments.

Table 5. Changes in the physical and chemical properties of WWS under the influence of MW.

WWS Properties	WWS Form, Processing Method	MW Power	Duration MW	Description of Results	[Ref./No]
Structure change	Activated sludge; a mixture of activated sludge and raw sediment	450–900 W	1–10 min	Sediment's structure changes: the flakes firstly expand than collapse	[25,34,36]
Temperature	Activated sludge; a mixture of activated sludge and raw sediment	300–900 W	1–10 min	Rise in temperature and rapid boiling at 100 °C	[25,34,36]
Resistivity (fluidity)	Mixed sediments	800 W	3–4 min	Decrease in viscosity and resistivity by 5 times	[25,34,36,37]
	Raw sediment, mixed sediments	550 W	6 min	A decrease of 73–84% from the original value for raw sediment and a mixture of sediments	[38]
Humidity	Activated sludge, raw sediment, and mixed sediments	450–800 W	1–8 min	Humidity decreases by 2–3%	[34,36]
Moisture output	Mixture of sediments; activated sludge with the addition of an acid solution and heating to 100 °C	600–900 W	1–5 min	The time of capillary absorption of the sediment mixture is reduced by 1.2–1.3 times; when the pH changes to 2.0–2.4 of the activated sludge, a reduction of 4 times is achieved	[25,34,36,37,39]
	Raw sediment, mixed sediment, fermented sediment	500–600 W	1–1.5 min	The minimum capillary suction time is achieved only in the first 1–2 min of treatment to a temperature of 60–80 °C, then it begins to increase	[38,40,41]

Table 5. Cont.

WWS Properties	WWS Form, Processing Method	MW Power	Duration MW	Description of Results	[Ref./No]
Compaction (sedimentation)	Activated sludge	900 W 750 W	60 s 80 s	The settling velocity increases (the settling time is 24 h)	[25,34,36,37]
Mineralisation	A mixture of raw sediment and activated sludge; activated sludge	800 W	8 min	Increase in the ash content of the wastewater sludge mixture by 6.1%; intensification of solubilisation of organic matter	[31–34]
Dry matter content in the cake *	Dehydrated municipal sediment	550 W	0.5–4 min	In the raw sediment, the dry matter content increases by 8%; in the mixture and in the fermented—by 2%.	[38]
Cake * humidity	Dehydrated municipal sediment	400 W	2 min	May achieve 28%	[38]
Decontamination	Raw sediment, mixed sediments	800–900 W	1–8 min	Reducing the content of pathogenic microorganisms by 99%	[14,26,27,31,33,34,37,42,52]

* cake—dehydrated WWS.

Some publications [25,34,36] provide evidence of changes in the structure of wastewater sediments under the influence of MW irradiation. Microwave processing of activated sludge has a tipping point: up to a certain length at a constant strength, the flakes firstly expand (for example, at 900 W for the first one to two minutes), then the more extended process (over two minutes) destroys them [25]. At the same time, the structure becomes more homogeneous and dispersed [36].

A change in the spatial configuration of samples of a sediment mixture after MW heating to a temperature of 75 °C [34,36] was observed during a microbiological analysis using an electron microscope Micromed 2 (3–20). Figure 4 provides a view of a mixture of raw sediment and activated sludge in a ratio of 1:2, increased by 40 times.

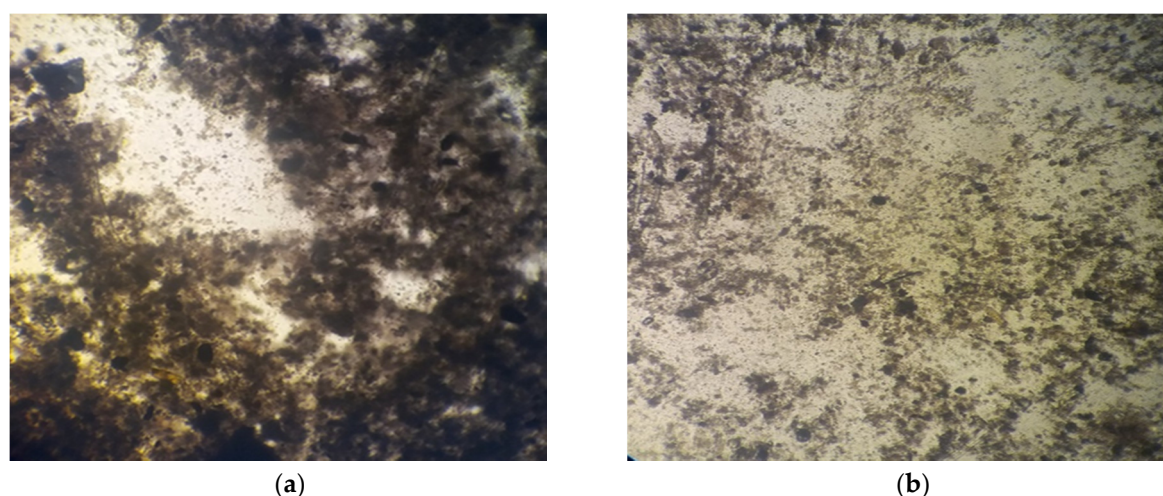


Figure 4. Structure of the initial mixture of primary sediments and activated sludge (a) and after MW treatment (b).

The initial structure of the sediment flakes (Figure 4a) is uneven, coarse-dispersed, with separate large conglomerates, saturated with protozoan bacteria. The species composition of the sample of the initial sediment mixture is as follows: filamentous bacteria, small benthic shell amoebas, free-floating infusoria, aspidiscs, and rotifers. There are no visible shell deformations. When analyzing images of samples of a mixture of primary raw sediment and activated sludge under a microscope before and after microwave treatment, when the heating temperature reaches 75 °C (Figure 4b), significant changes in the spatial structure of the samples under study are visually determined. For example, the structure of the treated sediment becomes finely dispersed and more uniform, and individual large silt conglomerates disintegrate. In addition, when analysing the external state of bacteria, there are visible deformations of their shells: arcella have a distorted shape, and the shells of rotifers are crumpled [34]. During MW treatment of any sewage sludge, there is a rapid increase in the temperature of the samples (in one to five minutes, samples with a volume of 100–300 mL at a power of 900 to 450 W reach 100 °C) as a result of the thermal effect of microwaves (see Section 3.1).

In the process of heating the sediments, there is a decrease in viscosity and resistivity of filtration. This decrease is observed when the evaporation of moisture is not so great until the critical moment. After microwave heating, the effect of reduced resistivity retains. Analysis of a series of experiments showed that MW treatment of sewage sludge during four minutes at a power of 800 W significantly reduces the specific resistance of filtration: the initial sludge average value of resistance is 37.15×10^{-10} cm/g with an allow for an error of no more than 10%, after microwave treatment it is 6.93×10^{-10} cm/g [34,36]. Under the further remained heating, the viscosity and resistivity can rise due to excessive evaporation after a turning point at a certain power and length of MW-treatment, which are calculated separately for each form of WWS [25]. It was verified in publication [37], where for wet sludge and a mixture of sludge were obtained the best resistivity results of a 73–84% reduction from the initial value after 180 s per minute at a processing power of 550 W. In the MW-treated fermented sediment, the maximal effect of reducing the resistivity reached only 18% [38].

The moisture-yielding properties of WWS play a vital role in the efficiency and duration of dewatering and volume reduction. The capillary suction period is the essential feature of moisture loss. In the experiments, when wastewater sludge was microwave irradiated for five minutes at a power of 0.8 kW, capillary suction time was reduced by approximately 1.2 times relative to untreated WWS [39–41]. This is explained by the fact that part of the bound water passes into the free state and evaporates during the MW treatment. However, due to a prolonged process over eight minutes, the capillary suction time increases by 2.4 times on average since significant moisture evaporation occurs and the sediment becomes viscous [34].

The moisture release of sludge can be intensified by reducing the pH to 2.5 at $T = 100$ °C: the capillary suction time (CST) is reduced from 37.7 s to 9.2 s (approximately four times), and the content of bound water is reduced from 1.96 ± 0.19 g/g to 0.88 ± 0.24 g/g of dry residue [37].

Domestic wastewater sludge has a humidity of 93–99.8% and is at the initial stage almost a highly concentrated water suspension, saturated with organic substances and bacterial contaminants. All WWS treatment methods aim to minimise its volume and achieve the required conditioned state for further disposal. The decrease in volume achieved by reducing the moisture content of the sediment to 50–70% is possible when compacting, dewatering in natural conditions on open silt sites, and mechanical dewatering on special equipment. Compacting usually takes from five to twenty hours, with the moisture content of the sludge reduced by 10–15%. Better results of humidity decrease to 50–70% can be achieved by dewatering in natural conditions, though this process takes from one to six months. The mechanical method's cycle duration is up to only one hour. The pace of the processes mentioned above depend on the sediment's ability to give off chemically un-

bound moisture. The moisture yield, in turn, directly relates to the quality of composition of the sediment and the transition of water from colloids to the free state [37].

The optimal time for MW treatment of activated sludge is 60 s at 900 W power and 80 s at 750 W [25]. At this point, the peak deposition rate is reached. With the increase of microwave processing time, the deposition/compaction rate will again decrease.

There is an experience of long-term MW processing of WWS from 30 to 240 min at a power of 3.4 kW. In this case, it is possible to reduce the volume of sediment by 60% due to intensive evaporation [41].

In all forms of WWS, there is a decrease in organic matter content. Several mechanisms mediate this response:

(1) Solubilisation occurs at certain microwave irradiation capacities (up to 900 W) and short phase durations (up to 140 s). Organic matter is released into the soluble phase during this process [25]. At the same time, COD levels in the sediment rise slightly as a result of microwave irradiation's ability to dissolve silt flocules. As a result, organic substances are hydrolysed into simpler forms, which are easily oxidised by microorganisms [37].

(2) When the sediments are exposed to MW radiation, the oxygen molecules in the sediments become stimulated or excited and they participate directly in the oxidative reactions of organic matter. Various oxidising agents can be added to speed up this process (see Section 3.4).

The ash content of WWS increases as a result of the mineralisation process (by 6–7% for a mixture of wastewater sludge under 8 min of MW irradiation time and power of 800 W) and the stability of WWS, faecal odour, and rotting of wastewater sludge during long-term storage decreases significantly [34].

3.3. Decontamination (Disinfection)

In the last century, the biophysical impact of the MW field on the viability and other properties of bacteria was discovered [43,44]. The sterilising efficiency of the MW field produced by the GZ–10A generator when irradiated for 10 min, for example, was used to assess the biological effect of microwaves on microorganisms [45]. The bacteria's viability was determined by the number of colonies developed within two days on the breeding ground. As a result, researchers discovered a bactericidal effect of pulsed and continuous microwaves on *Escherichia coli* and *staphylococcus* cultures.

Experiments on the influence of centimetre waves on the growth of *Escherichia coli* M–17 in a continuous mode (frequency 10.6 GHz, PPM = 0.1–5.5 MW/cm²) are presented in the paper [46]. According to the material results, microwave radiation has a harmful effect on *escherichia coli* (n = 10) at a power of 130 W for five minutes [47]. Water heating and disinfection systems were invented and patented in the 1970s and 1980s [48,49].

The modern use of MW for wastewater disinfection is based on earlier studies [50,51]. Less often it is mentioned that sewage sludge is also disinfected during microwave irradiation [14,26,27,31,33,34,37,42,52]. Water disinfection usually occurs at a power of MW from 300 W and higher (frequency 2.45 GHz) when heated from 45 to 100 °C. Therefore, the processing time depends on the sample volume and the MW heating power. This knowledge is very relevant concerning the further disposal of such liquid municipal waste. For example, faecal sludge formed in public toilets was treated using a laboratory microwave installation (MW) [26,27].

Total bacterial inactivation was achieved in 30–240 min after sewage sludge treatment in a special MW reactor [42]. According to findings in [52], high-level disinfection for enterococci and salmonella is possible to achieve in 9.5 min at MW energy consumption of 580 W·s/g and temperature 72 °C. In some studies [53,54], microwave irradiation proved to effectively reduce the bacterial content of sewage sludge prior to anaerobic digestion. In addition, a high degree of removal of faecal coliforms in the sediment is recorded in [55] (the content of 2.66 logs or less).

Similarly, researchers [56] confirmed that a single pretreatment with microwaves resulted in a 50% reduction of bacteria *C. Perfringens*. Furthermore, according to the

article [14], the microwave treatment of a mixture of sewage sludge can achieve 99% decontamination from all pathogenic bacteria subject to control.

The MW technology can be further investigated for potential expansion as a rapid treatment alternative for faecal effluents and sediments in emergencies [26,27], such as a pandemic.

3.4. Decomposition of Organic Substances

Organic pollution of natural and wastewater is a source of concern for scientists and environmentalists worldwide, as these contaminants have a detrimental impact on the natural environment, human life, and health. Approximately 3000 different organic contaminants have been identified [57,58] and classified into three groups: (1) organic substances of natural origin, (2) synthetic organic pollutants, and (3) chemicals reformed in water as a result of its purification. Many organic pollutants of the second and third groups are toxins and carcinogens [59]. Therefore, the international community is looking for creative, highly efficient advanced oxidative water treatment technologies that involve various pollutant exposure processes to address this problem.

In order to increase the performance of WW treatment from different contaminants and minimise reaction time, microwave exposure should be combined with oxidising agents OX (MW + OX), adsorbents activated carbon AC (MW + OX + AC), catalysts carbon C (MW + OX + C), and advanced oxidation processes with the addition of UV irradiation such as photo-Fenton (MW + OX + C + UV), direct photolysis using an electrodeless discharge lamp EDL (MW+OX+EDL), and photocatalysis using TiO₂ photocatalyst (MW + OX + UV + TiO₂) [60–72].

The review data were summarised reasonably well in the papers [9,73]. Other studies of the efficacy of MW oxidation of organic compounds under various treatment conditions are seen in Table 6 [22,61–72].

The addition of microwaves to oxidising agents accelerates the oxidation of organic compounds due to dipolar polarisation. For each pollutant, the form of oxidising agents, necessary doses, and reaction conditions (including temperature, strength, and treatment period MW) are calculated separately [64,66]. Microwave capacity ranges from 300 W to 900 W, temperature ranges from 20 °C to 130 °C, and processing time ranges from three minutes to one hour, depending on sample volume. Thus, the pollutant characteristics and their resistance to temperature and chemical factors affect the variance of parameter values.

Various catalysts, such as ferromagnetic metal, transition metal oxides, various types of activated carbons, and others, are applied to the water to increase the MW oxidation of organic compounds. The catalysts can be added to the water in two different ways: a suspension accompanied by sedimentation or a fixed filter plate. At the same time, the removal efficiency for a wide range of organic pollutants is about 85–100% [9].

A promising technology for the degradation of organic pollutants, even from the stage of mineralisation, is considered to be catalytic oxidation by moist air (CWAO) under conditions of high temperature (180–315 °C) and pressure (2–25 MPa), with the addition of catalysts [9]. The photo-Fenton process is based on the use of the Fenton reagent, that is, a mixture of Fe²⁺ salt (catalyst) and hydrogen peroxide (oxidiser) in combination with ultraviolet irradiation (UV). The study [9] provides research on the decomposition and mineralisation of different organic pollutants and reveals that compared to Fenton and photo-Fenton processes without MW, the decomposition rate of various pollutants increases by at least 50 times.

Table 6. The efficiency of MW oxidation of organic substances in WW.

Type of an Organic Substance	Sample Volume	Concentration	Oxidizing Agent, Catalyst, pH	MW Power	MW Duration, Temperature	Effect	[Ref./No]
Sample was only MW-treated							
Ammonia (laboratory installation)	100 mL	0.5–12 g/L	Air 1 L/min pH = 11	750 W	3 min 80 °C	D * 98.4–96.1%	[63]
Ammonia (pilot plant)	28,000 mL	2.4–11 g/L	Air 30 L/min pH = 11.6–12	4.8 kW	60 min 80–100 °C	D * 80%	[63]
With an addition of the oxidizer: MW + OX							
Naphthalene Disulfonic Acid	10 mL	1.0 mmol/L	H ₂ O ₂	300 W	20 min 30 min 80 °C	D * 90% M ** 50%	[64]
Dimethoate (phosphoric compound)	No Data	0.1 mmol/L	K ₂ S ₂ O ₈ pH = 6.8	750 W	4 min 100 °C	D * 100%	[22]
Perfluorooctanic acid	50 mL	0.25 mmol/L	Na ₂ S ₂ O ₈	800 W	240 min 60–130 °C	D * 99.3% M ** 74.3%	[66]
The photo-Fenton process: MW + OX + C + UV							
Polyacrylamide (PAA)	No Data	150 mg/L	H ₂ O ₂ /AC pH = 3	70 W 490 W	6 min	D * 20% D * 80%	[61]
Pesticides (dimethoate, triazophos, malathion)	1000 mL	6.11–31.65 mg/L	H ₂ O ₂ Fe ²⁺ ; pH = 5	80 W	120 min 25 °C	M ** 72.1%	[62]
Direct photolysis: MW + OX + EDL							
Phenol	50 mL	200 mg/L	H ₂ O ₂	1000 W	9 min 30 min 50 °C	D * 90% M ** 95%	[67]
Atrazine	50 mL	50 mg/L	pH = 6.3	900 W	30 min 30 °C	D * 100%	[68]
Photocatalysis: MW + OX + UV + TiO ₂							
Methylene Blue (aromatic compound)	50 mL	100 mg/L	TiO ₂ load pH = 7	900 W	15 min 100 °C	D * 96% M ** 50%	[69]
2,4–D chlorophenoxyacetic herbicide	10 mL	0.04 mmol/L	TiO ₂ load pH = 4.9	700 W	20 min 200 °C	D * 100%	[70]
Bisphenol A (Endocrine disruptor)	30 mL	0.1 mM	TiO ₂ load pH = 6.7	1500 W	90 min 150 °C	M ** 100%	[71]
Phenol	50 mL	10 mg/L	TiO ₂ /AC	900 W	30 min 1000 °C	D * 87%	[72]
Atrazine	50 mL	20 mg/L	TiO ₂ nanotubes pH = 8.1	900 W	5 min 20 min	D * 100% M ** 98.5%	[72]

D *—destruction efficiency; M **—mineralisation efficiency.

Electrodeless discharge lamp (EDL) use eliminates the issue of electrode destruction in a conventional mercury-based UV lamp. EDL consists of a glass tube—a plasma chamber filled under reduced pressure with argon and excitable matter (Hg, HgI₂, Cd, I₂, KI, P, Se, and S) and generating UV radiation under the action of MW (direct photolysis–MWDP). Together with microwaves and oxidising agents, MWDP is considered the most effective by many authors [9,67,68,74,75].

Microwave photocatalysis emerged to speed up and deepen organic carbon oxidation and mineralisation reactions, preventing secondary corrosion and iron-containing sediment production. The TiO₂ semiconductor photocatalyst is commonly used in this method in grains, nanoporous films, and nanotubes. In addition, the TiO₂ composite catalyst supported on activated carbon TiO₂/AC shows good results [9].

The authors [9,13,65,76] consider the most critical factors influencing the efficiency of decomposition and mineralisation of organic pollutants based on comprehensive experimental experience with microwaves for the removal of organic pollutants: microwave power (W), irradiation time (min), and exposure temperature (°C).

In complex treatment, the optimum dosages of oxidising agents and catalysts, pH values, and air supply parameters to the device must be determined. In addition to the influencing factors mentioned above, the light intensity and amount of oxygen in the solution are applied to photocatalysis and microwave photolysis reactions [70]. Thus, each specific organic contamination must determine the optimal values of these parameters of microwave exposure, depending on the required efficiency of destruction and mineralisation.

One urgent task of applying innovative oxidation methods is to optimise energy consumption, particularly when using microwaves. Hence, according to the authors [9], the least energy-intensive methods are MW+K and MW+UV+TiO₂; the most energy-intensive is water treatment using only microwaves [60]. On the other hand, MW radiation in the pulsed mode significantly saves energy [9,60].

The prospect of using MW in wastewater treatment is more justified in the presence of challenging organic substances that are not biodegradable.

Microwave irradiation has several practical uses, including the oxidation of synthetic dyes in the wastewater of industrial establishments in the textile, leather, cosmetic, food, paper, pharmaceutical, and other industries. In the presence of oxidants and catalysts, a 65–100% reduction in dye concentration can be achieved in 1.5–210 min at MW power of 150–900 W [73–75,77–80].

There is confirmation of successful MW oxidation of naphthenic acid, typical for industrial wastewater of oil-producing enterprises [81]. MW can be used for complex oxidation of wastewater containing ammonia [63], phosphorous compounds [65], phenols [9,62], pesticides [61], PAA [62], medical preparations [9], and other elements.

3.5. Demulsification

In many recently published papers on the subject of demulsification, we find information on MW destruction of two types of emulsions: (1) oil-in-water and (2) water-in-oil [82,83]. In the first type, oil-in-water, the dispersive environment is water, and oil is a dispersed phase, fragmented in water in the form of individual droplets (direct emulsions). In the second type, water-in-oil, water is a dispersed phase in the form of individual droplets in the oil, a dispersive environment (reverse emulsions).

Highly concentrated oil-containing or petroleum-containing industrial WW from oil-producing and oil-refining enterprises falls into the first category, oil-in-water. Emulsion wastewater is also generated in the metallurgical and machine-building industries, including the processing of metals [84,85]. Used oil emulsions, water-based oil sludge, and other liquid waste containing more oils or petroleum products fall into the second category, water-in-oil [23,81,86–90].

The basic features and results of several laboratory studies on microwave intensification of the method of demulsification of industrial WW and WWS are described in Table 7.

Table 7. Parameters and outcomes of several laboratory experiments on demulsification under the influence of MW.

Emulsion Type	Water Content	Catalyst (C)	MW Power and Frequency	MW Duration	Results	[Ref./No]
Waste water, sludge and oil-in-water emulsions: sample + C + MW+ 60 min settling						
Waste emulsions of the metallurgical industry	No Data	NaOH (6 M) HCl (0.12–0.6 M)	230–930 W 2.45 GHz	1–4 min	65–90%	[84]
Waste oil water emulsions after metalworking	99%	Sea water 20%	700 W 2.45 GHz	40 s	92–93.2%	[85]
Slurries, emulsions, and liquid waste of the water-in-oil type: sample + C/none + MW + 50–70 min settling						
Crude oil	20 (60)%	none	700 W 2.45 GHz	42 s	Efficiency 1/td 0.085 (0.04)	[82]
Crude oil	40–60%	Sodium Acetate 0.2 M	360–450 W 2.45 GHz	2–3 min	93–100%	[23,86]
Crude oil	50 (20)%	none	900 W 2.45 GHz	1–3.5 min 2–4.5 min	85% 75%	[87]
Low-temperature separation of emulsions						
Oil Sludge	40%	none	100 W 10 GHz	2–3 min	Visual destruction of oil globules	[90]
Oil/petroleum- emulsions	30%	none	45 W 0.5 GHz	10 s	Visual enlargement of water droplets in oil	[83]

The zeta potential at the interface decreases when MW is applied, and the viscosity of oils/oils decreases due to rapid heating, which is the reason for the accelerated separation of emulsions [86]. In addition, the presence of catalysts (alkalis, acids, salts, and other substances) accelerates the demulsification process, while the presence of anionic surfactants slows down the emulsion separation process [23,84–86]. The primary physical characteristics of MW heating were calculated after a thorough study of the heating effects of oil/oil–water emulsions associated with microwave resonance. It was found that the average power consumption decreases with a fall of the oil content in the oil-in-water emulsion and increases with a rise in the percentage of water in the water-in-oil emulsion [89].

Many authors emphasise that microwave irradiation is a relatively fast and, in general, cost-effective method for separating oil or petroleum products from wastewater [84,85,89]. Additionally, MW–demulsification of water-in-oil emulsions, common in slurries, is more effective and faster than traditional convective heating [23,82].

However, there are also some concerns. In the microwave treatment of oil sludge, the separation of the emulsion phases occurs mainly due to rapid heating, which requires sufficiently powerful MW generators [90]. In this instance, hydrocarbons are burned to form combustion products (gases), which is a significant drawback when choosing the MW method. It is also necessary to select the optimal MW power and processing time in each case [88].

Low-temperature microwave separation of oil emulsions has been studied and theoretically supported [83,90]. For example, the visible coalescence of oil droplets in the emulsion is observed at low power MW (up to 45 W) with a period of only ten seconds [83]. In another scenario, oil globules were destroyed during the experimental MW processing of oil sludge samples with a power of only 2 W to 100 W for two to three minutes. According to one hypothesis, low-temperature emulsion separation occurs under some conditions due to the rupture of chemical bonds under the influence of an electromagnetic field, i.e., the “non-thermal effect” of microwaves [90].

In the future, it is necessary to conduct a study on the MW effective demulsification of oil containing WW from gas stations, service stations, and surface wastewater from highways.

3.6. Extraction of Heavy Metals

Metal ions are one of the most toxic and difficult to remove forms of WW and WWS contamination. Chemically bound elements are one of the causes. It will be easier to remove these pollutants from wastewater and sediments if they decompose quickly in water. One of the obstacles to using this waste as agro-fertilisers is heavy metal ions in the sediments.

Experimental microwave treatment of WW and WWS samples to decompose the substance and improve the efficiency of laboratory analysis of the components was stated in a critical review published in 1998 [91]. Microwave radiation in the presence of reagents increases the accuracy of atomic absorption spectrometry and cathodic stripping voltammetry measurements of metal ion concentrations (Hg, Cd, Cr, Cu, Ni, Pb, Zn, Bi, Sn, and others). This effect is explained by the decomposition of compounds with metals in liquid substances under the action of MW.

The possibilities of microwave preparation of wastewater samples for determining metal concentrations in real wastewater samples using atomic absorption and atomic emission spectrometry with inductively coupled plasma were shown in the article [92], which reflected this subject. Furthermore, microwave sample preparation was compared to conventional WW thermal mineralisation. The best results were obtained under conditions of acid treatment for aluminum (the determined ion concentration after microwave heating increased by 1.56 times compared to treatment in a thermal mineraliser), cadmium (by 2.58 times), and iron (by 1.22 times). With an installed power of 1000 W to 2000 W, processing time in a domestic MW oven ranged from one to five minutes.

However, there are not enough recent scientific publications that indicate the possibility of using microwaves to facilitate the extraction of metal ions from WW and WWS. The articles [6,14] refer to changes in the properties of sewage sludge and the MW intensification of the release of metal ions into decanted water (Table 8). Results have been derived from batch experiments.

Table 8. The metal ions output into decanted water [6].

Indicators	Content of Metal Ions in Decanted Water, mg/L		Increase in Concentration of Metals in Water
	without MW Treatment	Following MW Processing	
Arsenic	<0.002	0.004 ± 0.002	2 times
Nickel	0.011 ± 0.003	0.020 ± 0.006	1.8 times
Mercury	0.013 ± 0.008	0.017 ± 0.010	1.3 times
Lead	0.002 ± 0.001	0.002 ± 0.001	Not observed
Chrome (6 ⁺)	0.114 ± 0.0052	0.218 ± 0.100	1.9 times

The yield of specific metal ions into decanted water (supernatant water) increases approximately 1.2–2 times after microwave treatment from five to ten minutes and subsequent compaction of a mixture of domestic WWS (raw sediment and activated sludge).

Other studies have also observed that the yield of heavy metal ions from WWS to water increases from 4 to 15%, especially lead, zinc, and chromium [24].

This property can be used in the technological schemes of wastewater treatment plant (WWTP) as a pretreatment to intensify the further release of heavy metal ions from wastewater and its sediments.

3.7. Biogas Processing

European and Asian experience in managing liquid municipal waste gives preference to the anaerobic treatment of wastewater and sediments to produce biogas. The maximum number of biogas plants operate in China—approximately fifteen million, and India—about ten million. The construction of biogas plants is actively developing in Europe, especially in Germany, with more than 9000 stations. Only 7% of the biogas produced by these enterprises goes to the gas pipelines. The rest is used for the manufacturer's needs. In the future, 10–20% of the natural gas used in the country can be replaced with biogas [93–95].

The biogas market is growing much more slowly in countries with natural gas resources. For example, only about 200 biogas plants operate on agricultural waste in the United States [95]. In Russia, the production of biogas is implemented in only a few WWTP [96].

Today, the anaerobic treatment of wastewater and sediments to produce biogas guarantees fuel and energy savings. However, there are problems related to the quality of the treated material, the provision of conditions for the stability of the biodegradation of organic matter, and the explosion hazard of biogas production [97,98].

Microwaving is a novel thermal pretreatment process for sludges that improves digestion efficiency and, under certain conditions, can intensify the gas output by 15–32% due to the solubilisation and hydrolysis of organic substances [99–105]. Previous studies have shown that MW pretreatment is more effective for sludge with a high concentration of solid particles [101,102]. It is also proved that in the thermophilic fermentation mode, the yield of biogas from the MW-treated sediment is higher than in the mesophilic mode [99]. The results of modern studies based on [99,106] are presented in Table 9.

Table 9. Intensification of the biogas output during the MW treatment of WWS.

Sediment	MW Power and Frequency	Temperature	Sample Processing Conditions	Description of Results	[Ref./No]
Domestic wastewater sludge mixture, ratio 48:52	1250 W 2.45 GHz	96 °C	500 mL samples heated in a home MW furnace to the boiling point, then subjected to anaerobic digestion in laboratory reactors for 5–18 days; biogas output recorded.	With thermophilic fermentation, the gas output increased by 17–26%.	[99]
Dehydrated WWS	1200 W 2.45 GHz	80–160 °C	Samples heated and kept at a set temperature for 1 min, then cooled for 25 min. Heating speed 7.5 °C/min. Further, the samples were subjected to anaerobic digestion in laboratory reactors for 5–20 days; biogas output was recorded.	Maximal biogas output: At 160 °C- on the fifth day of the fermentation process. At 120 °C on the tenth day.	[105]
Sludge mixture	300–600 W 2.45 GHz	- no data	Microwave pre-treatments were carried out in a semi-pilot MW unit in which the flow rate varied in the range of 5–60 L/h. Next, anaerobic digestion of the nitrogen-treated sludge mixture was carried out at a temperature of 37 degrees.	The biogas production improved by 174–210% (depending on the MW power and irradiated energy)	[106]

3.8. Pyrolysis of Wastewater Sludge

Pyrolysis is currently considered to be the most promising WWS disposal technology. The benefit of this approach is that it produces transportation-friendly fuel that can also be used to generate thermal and electrical energy. It also enables biomass to be converted into combustible gas, coal, liquid synthetic fuel, and chemical raw materials. Moreover, the waste from the process can be turned into an environmentally friendly granular glazed product for road building and the construction supply industry [107–109].

Pyrolysis, also known as dry distillation, is the thermal treatment of sewage sludge or other carbon-containing waste by high-temperature (450–800 °C) or low-temperature (200–400 °C) heating without air access. As a result of such process, about 50% of solid residues (coal, charred coal, and pyrocarbon), about 20–32% of liquid products similar in quality to crude oil (tar or primary tar-bio-oil), and 12–15% of a combination of gaseous products (biogas) are obtained. Pyrocarbon and bio-oil are the most valuable pyrolysis products. In the 1980s, more than 300 pilot plants for pyrolysis of precipitation, including those that mixed solid waste and industrial waste, were built in the United States, Germany, Italy, and Japan. However, owing to economic infeasibility and technical flaws, many of them were eventually shut down [107].

Microwave pyrolysis is a promising method for the thermochemical conversion of dehydrated sewage sludge into usable energy products, including bio-carbon, bio-oil, and biogas. However, there are not many publications on this subject. The article [107] provides an overview of the latest research on traditional and microwave pyrolysis heating. It compares alternate approaches, examines pyrolysis products, and discusses the pros and cons of using microwaves for pyrolysis of WWS. The structure of the residues, MW parameters, laboratory conditions, and catalyst forms all influence the efficiency and properties of microwave pyrolysis products.

When microwaving just the raw sample of sludge, it only dries. However, adding a small amount of a microwave absorber to the sample (such as the char produced during pyrolysis) leads to pyrolysis rather than drying [109].

3.9. Modification of Sorbents

Assuring sorption products for wastewater treatment should have high sorption properties and be non-toxic, regenerable, easily disposed of, low-cost; and an affordable raw material base. Natural materials' major weakness as sorbents is their poorly expressed sorption potential, which is also affected by their increased hydrophilicity. Reducing water absorption and increasing sorption activity can be achieved by various modifications [110].

Some inorganic sorption products, such as clays, natural zeolites, and active coals, have been shown to have increased basic surface area, porosity, and availability of functional groups after MW treatment. Microwave exposure may otherwise result in a degradation in the properties of coals due to the decrease in permeability [111]. Microwave radiation seems to accelerate many chemical reactions by dozens of times, promotes rapid volumetric heating of liquid and solid samples, and wholly and quickly removes moisture [112], which is vital in sorbents' production.

The best findings for MW treatment of sorbents based on natural materials used for wastewater treatment (frequency $f = 2.45$ GHz) can be found in Table 10.

Table 10. Results of MW processing of sorbents based on natural materials.

Sorbent	Sorbent Preparation Process	MW Power	Duration	Temperature	Description of Results	[Ref./No]
Peat	MW heat	60–600 W	60 min	No data	Oil capacity 2.5–2.73 g/g. With increasing power, the adsorption of iodine increases by 1.2–1.4 times (from 115 to 150 mg/g), and for methylene blue it decreases by 2 times (from 55 to 28 mg/g)	[113]
Peat	MW heat	900 W	12 min	450 °C	Iodine adsorption activity increased from 11.4% to 19.1%	[114]
Brown coal	MW heat	900 W	22.5 min	315 °C	Iodine adsorption activity increased from 18.0% to 34.9%	[114]
Montmorillonite	MW heat	800 W	4 min	154 °C	Water vapor adsorption increased from 0.67 to 3.66 mmol/g	[115]
Pine sawdust	Grinding, drying and MW heat	600 W	2 min	40 °C	Increase in the sorption capacity for petroleum products by 3.7–4 times for initial concentrations of less than 5 mg/L and by 1.2 times for initial concentrations of 16–35 mg/L	[110]
Rice husk	Combustion in the MW furnace	No data	288 h 384 h	500 °C 800 °C	Removal of petroleum products: 78% 98%	[116]

Intensified combined process of dye adsorption and decomposition is experienced using a hybrid catalyst rGO-TiO₂. The thermal mechanism of action on materials, especially carbon-based, is studied in the article [80]. This process consists of local MW heating of the area close to the catalyst's surface, which leads to the accumulation of heat on it, i.e., the creation of "hot spots" on the exterior, allowing processing speed to be increased.

A newly developed method for sorbent regeneration [117] is carried out in a resonant container with the addition of MW, which is only used to break the intermolecular bonds between the sorbent and the sorbate and does not result in thermal heating of the substances.

Several authors prove [73,118,119] that the microwave effect on sorption materials allows one to achieve an increase in their sorption activity and specific surface area, to reduce water absorption due to a uniform and rapid effect on the material, which reduces the time and simplifies the processing method and, accordingly, reduces material costs.

Still, there are the following main limitations of the use of microwave irradiation in sorbent preparation technologies: an increase in energy costs; the absence of industrial-scale magnetrons; and, due to the limited depth of penetration of microwaves into the material of solid sorbents, small volumes are subject to processing [116].

However, the introduction of microwave processing will provide environmentally friendly methods for the preparation of sorbing materials for wastewater treatment; efficient and economical intensification of the processes of sorption of pollutants; and minimal negative impact on the environment due to the reduction of reagents used at the stages of modification, regeneration, and activation of sorbents.

3.10. Devices for MW-Processing of WW and WWS

One of the problems with the widespread scaling of MW wastewater and sludge treatment is the lack of unified high-performance industrial reactors on the market that are adapted for municipal needs. MW plants (installations/devices/reactors) for liquid waste treatment are experimental equipment designed to handle small volumes.

Many scientists conduct experiments in home microwave ovens or reactors based on them or in modular laboratory systems [8,14,36,90,108,110].

The data obtained from a patent search in the Russian database for MW installations/devices intended or possible for the treatment of wastewater and its sediments are presented below (Table 11).

Table 11. MW installations/devices intended (or possible for use) for wastewater and sediments treatment (Russia).

Device/Installation	Application Domain: Treatment of		Type of Action		Parameters: Power N, Frequency f, Throughput Q, Temperature T	Patent Number, (Year)	MW Process Setting	[Ref./No]
	WW	WWS	1 *	2 *				
Sewage treatment installation	+	-	-	+	No Data	RU 116 851 (2012)	Combined UV and MW water disinfection	[120]
Industrial and domestic sewage handling equipment	-	+	+	-	T 430–1000 °C f 2.5 GHz	RU 2 552 259 (2015)	Decomposition of waste under the combined influence of thermal and electromagnetic fields without oxygen access	[121]
Waste incineration chamber	-	+	+	-	T 1200–1400 °C	RU 2 573 137 (2016)	Heating of the disposed waste to the combustion temperature	[122]
Sewage sludge MW treatment plant	-	+	-	+	N 5440 W Q 1.37 t/h	RU 2 582 415 (2016)	Disinfection of industrial, domestic, and agricultural sewage sludge	[123]
Wastewater and sediments MW treatment and decontamination device	+	+	-	+	N 2000 W f 2.45 GHz Q 0.1 m ³ /h T 50–85 °C	RU 2 693 783 (2019)	MW pretreatment of sediments prior to anaerobic fermentation	[124]
Anaerobic processing plant for liquid organic waste	-	+	+	-	T 60–70 °C	RU 2 687 415 (2019)	MW pretreatment of WWS prior to anaerobic fermentation	[125]
Electromagnetic phase separation system for oil–water emulsion	-	+	-	+	f 2.45 GHz	RU 2 710 181 (2019)	Destruction of oil–water emulsions (sludge from oil fields and oil refineries)	[126]
Wastewater treatment by irradiation with ultra-high-frequency waves and ultraviolet light plant	+	-	-	+	No Data	RU 193 171 U1 (2019)	Combined UV and MW wastewater disinfection	[127]
MW mobile technological complex treatment of acid mine water	+	-	+	-	N 1000 W f 1.38 GHz Q 150 m ³ /h	RU 2 739 259 (2020)	MW is used to transfer ionic and molecular components to the condensed phase and remove them from the treated water	[128]

* 1—serving type, 2—flow-through type.

4. Conclusions and Considerations for Future Research

Currently, the search for effective and economical methods for wastewater and its sediments treatment continues. As the gathered review showed, there is much more research on microwave radiation to manage wastewater and sediments. Microwave treatment of such liquid municipal and industrial waste is of interest primarily because of the rapid heating and improvement of the properties of the treated materials, which reduce the time of their stay in the facilities and increase the productivity and the efficiency of the equipment. Moreover, microwaves' decontaminating effect opens up a world of possibilities for using this process in the context of a pandemic.

Table 12 summarises the opportunities for practical implementation of MW in WW and WWS treatment technologies in different areas of human economic and industrial activities.

Table 12. The opportunities for practical implementation of MW in wastewater and sludge treatment technologies.

No	Practical Application Field	Promising Areas of Practical Application of MW in Wastewater and Wastewater Sludge Treatment Technologies
1.	Municipal local services	Wastewater treatment of all types (reduction of organic matter concentration, improvement of coagulation processes, and decomposition of chemicals), wastewater sludge treatment (reduction of volumes and organic matter content), an increase of biogas production during wastewater sludge fermentation on an urban spit, disinfection of all forms of wastewater and wastewater sludge, and intensification of pyrolysis and production of secondary raw materials
2.	Production of drinking water	Water disinfection. Treatment of water sludge in order to reduce the volume, reducing the organic component
3.	Agricultural industry	Improvement of biogas output in the fermentation of manure, sewage sludge, and other liquid industrial waste; decontamination of all types of wastewater and sediments; and decomposition of pesticides in surface wastewater
4.	Medical institutions, pharmaceutical industry	Disinfection of all types of wastewater and waste; decomposition of medicines in wastewater and sediments
5.	Metallurgical industry and machine-building	Industrial wastewater coagulation, extraction of metals from wastewater and sediments
6.	Oil and petroleum industry	Demulsification of oil-water emulsions and oil-containing industrial wastewater, decomposition and reduction of oil sludge volumes
7.	Dairy industry	Organic matter oxidation in industrial wastewater, sludge treatment to reduce volumes and organic matter, and decontamination of all types of wastewater and sludge
8.	Chemical industry	New substances synthesis; chemical decomposition in industrial wastewater and sediments
9.	Textile industry	Dye decomposition in industrial wastewater, improving the coagulation of contaminants; decontamination of all types of wastewater and sludge
10.	Recycling and disposal of industrial waste	Decomposition of chemical, organic, and radioactive substances; reduction of liquid waste; and decontamination
11.	Sorbent manufacture	Modification, regeneration, and activation of phyto-sorbents for sewage purification

Nevertheless, along with the broad prospects for the global practical relevance of microwaves in wastewater and wastewater sludge treatment, the main problems remain the lack of universal technologies and industrial equipment, small volumes, and high energy consumption. At the same time, almost all studies do not go beyond the laboratories and

usually relate to specific environments (water and sludge samples) and require verification and confirmation for a wide scale.

The lack of high-performance, high-efficiency, and energy-saving industrial MW reactors designed to treat liquid municipal and industrial waste is a concern. The future universal reactor must operate in the flow mode, be able to automatically change the MW parameters depending on the quality of the initial flow, and have reliable human protection from residual microwave irradiation during the process.

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