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AGRO-PROCESSING INDUSTRY: ADVANCED TECHNOLOGIES FOR MEAT INDUSTRY WASTEWATER TREATMENT: A REVIEW

AGRO-PRERAĐIVAČKA INDUSTRIJA: NAPREDNE TEHNOLOGIJE ZA PREČIŠĆAVANJE OTPADNIH VODA MESNE INDUSTRIJE: PREGLEDNI RAD

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Abstract: *Wastewater from the meat industry contains high concentrations of organic matter. The composition of these wastewaters depends on the type of meat being processed, the frequency of slaughtering, the size of the plant, and the disinfectants used to maintain hygiene. In order to achieve satisfactory wastewater quality and reduce environmental pollution, the agroindustry applies and develops different technologies for wastewater treatment. This review paper provides a literature overview of some of the most commonly used methods in wastewater treatment within the meat industry.*

Key words: *agro-industry, wastewater, meat industry, purification*

Apstrakt: *Otpadne vode mesne industrije sadrže visoke koncentracije organskih materija. Sastav ovih otpadnih voda zavisi od vrste mesa koje se obrađuje, učestalosti klanja, veličine pogona i dezinficijenasa u cilju održavanja higijene. Da bi se postigao zadovoljavajući kvalitet otpadne vode i smanjilo zagađenje životne sredine, agroindustrija primenjuje i razvija različite tehnologije u tretmanima otpadnih voda. Ovaj pregledni rad daje literaturni pregled nekih najčešće korišćenih metoda u tretmanima otpadnih voda u industriji mesa.*

Ključne reči: *agroindustrija, otpadne vode, industrija mesa, prečišćavanje*

1. INTRODUCTION

The main factor contributing to environmental pollution, both in developing and developed countries, is the rapid development of the agro-processing industry. This issue is particularly pronounced in developing countries, where approximately 90% of wastewater is directly discharged from industrial plants without prior treatment [1]. The swift growth of the agro-processing industry, coupled with the rapid advancement of technology, has resulted in the generation of large amounts of industrial and communal wastewater flowing into canals, lakes, or rivers, ultimately reaching groundwater. The primary challenge lies in the insufficiently rapid development of wastewater purification techniques in relation to the agro-industry's swift growth, leading to significant pollution of both surface and underground waters. Statistical data concerning the treatment of wastewater in Serbia, particularly in the meat industry, as well as in all other branches of agro-industry, is concerning [2]. According to 2019 statistics, a total of 119 million m^3 of wastewater from

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various industries was discharged in Serbia. Of this, 47% originates from the processing industry sector alone, with only 5%-8% of the wastewater being treated. The meat industry alone utilizes about 25% of the total water compared to other food and beverage processing industries [3] (Table 1). In Europe, Belgrade stands out as the only capital city without a wastewater treatment plant [4]. Currently, a global combined approach to wastewater management is being implemented. The member states of the EU, Norway, and the European Commission have collaboratively developed a joint strategy to support the implementation of Directive [5], establishing a framework for Community action in the field of water (Framework Directive on Water - Framework Directive 2000/60/EC). This strategy includes the control of emissions and the establishment of environmental quality standards [5].

Table 1. Water use in processing industries

Food industry - processing	Water use (%)
Meat	25
Milk	13
Drinks	12
Fruit	10
Vegetables	9
Oils	8

This Directive regulates the collection and treatment of urban wastewater and water from certain industries [6]. The most significant environmental challenge arises from agro-industrial wastewater, characterized by a high content of organic substances such as total nitrogen, total phosphorus, phenols, total salts, solids, sulfides, heavy metals, chemical oxygen consumption and biochemical oxygen consumption [7].

The growing concern for environmental protection has led to the introduction of strict legal environmental regulations and the adjustment of emission limit values defining the quality of discharged wastewater (effluent standards). Among various types of agro-industries, the meat and meat products industry are identified as one of the three major polluters of the environment, alongside the milk processing industry and the beverage industry [8].

In 2004, the US Environmental Protection Agency (US EPA) identified wastewater from meat industry slaughterhouses as one of the most harmful types for the environment. This wastewater poses a significant environmental challenge due to its high content of suspended organic solids and concentrated nutrients, including animal blood, fatty tissue residues, hair, animal skin residues, and slaughterhouse disinfectants [9]. Meat industry wastewater contains aerobic and anaerobic bacteria, both pathogenic and non-pathogenic [10]. These substances are the primary contributors to unpleasant odors in wastewater.

To mitigate environmental pollution resulting from the discharge of wastewater from slaughterhouses and other meat industry plants, new anaerobic wastewater treatment technologies, such as anaerobic digestion, are being developed. Environmentally friendly anaerobic biotechnologies offer superior treatment options compared to conventional aerobic technologies, given their cost-effectiveness and economic benefits [11].

2. DIFFERENT TECHNOLOGIES IN THE TREATMENT OF WASTEWATER OF THE MEAT PROCESSING INDUSTRY

The technology applied in the treatment of industrial wastewater primarily depends on the observed characteristics of the wastewater. Purifying wastewater from the meat industry is highly complex due to the presence of proteins, fibers, lipids, blood, intestinal mucus from the slaughter process, various microorganisms, and detergents and disinfectants left behind during the washing of slaughterhouses and facilities [12, 13]. Wastewater quality control helps prevent eutrophication and the pollution of surface and underground waters with heavy metals and toxic compounds, thereby minimizing their presence in the food chain [14].

Factors influencing the selection of the most efficient, suitable, and cost-effective technology in wastewater treatment include the composition and amount of wastewater, plant capacity, and financial considerations. It has been demonstrated that the best results are achieved with combined processes tailored to individual plants and their wastewater. Before any wastewater treatment, mechanical wastewater treatment is performed initially, involving the removal of large and solid components and particles from the wastewater generated during meat processing [13].

The removal of remaining particles, such as finely suspended particles of fat and oil, is carried out through sedimentation or floating, using various methods like dissolved air flotation, ecocoagulation and flocculation, electrocoagulation, phytoremediation, membrane processes, and anaerobic and aerobic biological treatment [15].

2.1. Aerobic and Anaerobic Processes in Wastewater Treatment

Various aerobic and anaerobic biological processes are employed to eliminate organic substances in wastewater, including nitrogen (via nitrification and denitrification), organic fractions of sludge, and the decomposition of excess microflora biomass from the biological wastewater treatment process (secondary sludge). Aerobic oxidation generates substantial amounts of free energy (ΔG_0) and oxidation products with low energy content. The advantage of aerobic oxidation lies in its high purification efficiency and rapid purification. In contrast, the anaerobic oxidation process produces oxidation products with high energy content, but it has the drawbacks of slower purification and a weaker purifying effect [15].

2.2. Aerobic Processes

Aerobic wastewater treatment processes are divided into techniques with suspended microflora and techniques with an immobilized layer, i.e., microflora immobilized on a suitable inert carrier. Aerobic processes with suspended microflora can include purification processes with activated sludge in bioaeration basins or aerobically aerated lagoons and lakes. The biologically active mass of aerobic microflora is called activated sludge, which is suspended in wastewater in the form of flocs. These flocs contain living microorganisms, dead cells of microorganisms, as well as various organic and inorganic substances left over from wastewater. The most important and abundant microorganisms in activated sludge are bacteria (gram-negative bacteria of the genus *Pseudomonas*, *Zooglea*, *Flavobacterium*, *Mycobacterium*, and nitrifying bacteria *Nitrosomonas* and *Nitrobacter*), protozoa, and fungi [16].

2.3. Anaerobic Digestion (AD)

Anaerobic wastewater treatment processes are employed to treat highly polluted, mostly industrial wastewater. The process itself is based on biochemical reactions with the presence of bacterial microflora, which convert organic matter into a mixture of gases, the main components of which are methane and carbon dioxide. This process takes place without the presence of oxygen in a reducing environment and within a certain pH interval.

Currently, the most advanced anaerobic wastewater treatment technology is anaerobic digestion, also known as the activated sludge process [17]. Anaerobic digestion is a process in which microorganisms break down biodegradables (organic matter) under anaerobic conditions and transform them into CO_2 and CH_4 as end products. This type of wastewater treatment (AD), with a combination of the activities of various microorganisms, has found application in biogas production plants and is widely used as a source of renewable energy.

Biogas, which contains CH_4, CO_2 and various trace gases, has a dual application: direct use as fuel or further processing to produce biomethane - a substitute for natural gas. Important parameters that affect the formation of biogas during anaerobic digestion are temperature, pH value, increased concentration of fatty acids, and increased concentration of ammonia (which leads to the inhibition of the decomposition process). As technology advances, an increasing number of EU countries use anaerobic digestion as a source of renewable energy (such as Great Britain, Germany, Denmark) [12].

Digestion, or the formation of methane in anaerobic digestion, is divided into four phases: hydrolysis [18], acidogenesis [19], acetogenesis [20], and methanogenesis [21].

Hydrolysis, as the first phase of anaerobic digestion, occurs under the action of enzymes that break down complex organic substances (carbohydrates, proteins, and fats) into simple organic compounds (sugars, fatty acids, and amino acids). These compounds formed by enzymatic hydrolysis are a source of energy for the present microorganisms [18].

Acidogenesis is the stage in which bacteria, through anaerobic digestion, further break down hydrolysis products into volatile fatty acids with NH_3, CO_2, and H_2S as by-products [19].

The third phase, acetogenesis, is the phase in which microorganisms convert the products of acidogenesis into acetate and carbon dioxide. For this purpose, various microorganisms such as *Sintrophus*, *Clostridium*, and *Sintrobacter* bacteria are used, carrying out the process of acetogenesis [20].

The fourth and final phase, methanogenesis, is the key phase of anaerobic digestion. In strict anaerobic conditions, with the help of methanogenic bacteria, the products of all previous phases are converted into CH_4, CO_2, and H_2O [21]. The process of methanogenesis can be illustrated as follows:

$$CH_3COOH \rightarrow CH_4 + CO_2$$

$$CO_2 + 4H_2O \rightarrow CH_4 + 2H_2O$$

Methane and carbon dioxide constitute the largest mass fraction of biogas [22]. The critical factor in methanogenesis is the pH value, which must be in the range of 6.5 to 8 [21]. Any organic material that remains unprocessed by microorganisms during anaerobic digestion, along with the remains of deceased microorganisms, is termed digestate [23]. This digestate serves as a high-quality fertilizer used in agricultural production.

2.4. Anaerobic Filters (AF)

The Anaerobic Filter, illustrated in Figure 1, is one of the earliest and simplest types of filters used in anaerobic digestion. It comprises a tall biological reactor filled with an inert medium where biomass grows. The biomass retains and binds solid particles to the supporting stationary material, allowing sludge to settle. Microorganisms reproduce either on the medium or within its interstices. Wastewater purification is achieved by passing water through the filter, either from top to bottom or vice versa [24].

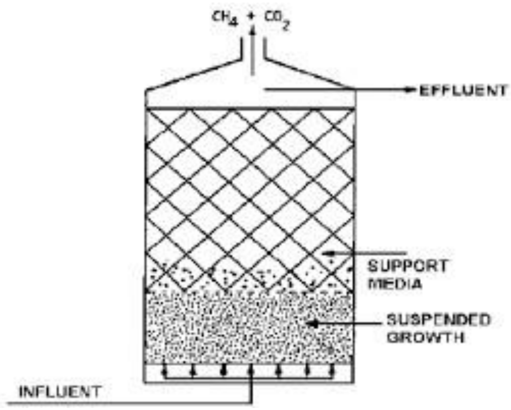

Figure 1. Anaerobic Filter

2.5. Anaerobic Contact Processes

The anaerobic contact process ensures the longest retention time of matter, directly influencing the higher energy yield in anaerobic biogas production technology with a high yield rate [25]. An advantage of this technology is that microorganisms are retained and do not need to be added afterward. During the digestion process, organic matter is separated and concentrated in separate bioreactors with the return of the introduced matter.

This way, more degradable waste is converted into biogas, and a large part of the anaerobic bacteria remains preserved. There are two types of contact reactors: complete mixing reactors or continuous organic flow reactors. Anaerobic contact is widely used because the process ensures the longest retention time of matter, directly contributing to a higher energy yield. This technology stands out as one of the most cost-effective methods for biogas production [25].

2.6. Covered Anaerobic Lagoons

Covered anaerobic lagoons are large lakes widely used in the treatment of wastewater in the meat industry, as well as other types of industrial wastewater [26]. Wastewater from the slaughterhouse is piped to the lagoon, where sludge is deposited as the lower semi-solid layer, and a liquid upper layer forms above. This upper layer, preventing the passage of oxygen, enables anaerobic digestion and decomposition of organic matter in wastewater (Figure 2) [27].

The loading volumes of anaerobic lagoons, at 0.056-0.104 kg volatile solids (VS)/m^3/day, are relatively low compared to temperature-controlled anaerobic digesters [27]. The amount of biogas produced from the surface of anaerobic lagoons did not prove to be profitable, so it was not intensively studied [28].

The advantages of these anaerobic lagoons are low costs, simple construction, and a low level of technology. They belong to systems with a low rate of biogas yield. Disadvantages include durability issues, the occupation of large areas, and the accumulation of a large amount of sludge due to poor mixing.

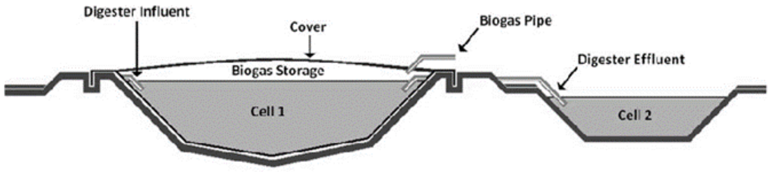

Figure 2. Covered Anaerobic Lagoon

2.7. Anaerobic Fermenters

For the large-scale production of biogas through anaerobic digestion, productive contact between bacteria and the substrate is necessary, primarily achieved by mixing the contents of the fermenter. Closed fermenters with thorough mixing are utilized in this type of anaerobic digestion (Figure 3) [29].

If the contents in the fermenter are not properly homogenized during the mixing process, over time, the separation of content and the formation of layers with different densities can occur. Due to the difference in density, most bacteria are retained in the lower sludge layer, while the substances needing decomposition are retained in the upper layer. This reduces the contact zone between the two layers, making anaerobic digestion challenging. Additionally, solids may float to the surface, creating a floating layer that hinders the release of biogas [30].

It is crucial that mixing is conducted at an intensity that provides the best conditions for anaerobic digestion. This is typically achieved in anaerobic fermenters with complete mixing using slow-moving rotary agitators, stirring the mixture in the reactor at well-defined time intervals [30,31].

The advantages of these anaerobic fermenters include their high technological level, the ability to receive and decompose various types of solid organic particles, and substantial biogas production. The disadvantage lies in the low mobility of the solid mass and the need for constant mixing [31]. Biological processes can also be combined with membrane processes, as is often done in the purification of wastewater from slaughterhouses in the meat industry. This combination of anaerobic processes and microfiltration removes over 95% of COD from wastewater [32], while the combination of aerobic processes and reverse osmosis removes 85.8% of COD [33].

Figure 3. Anaerobic Fermenter

2.8. Chemical Oxygen Demand (COD)

Chemical Oxygen Demand, or COD, quantifies the water's ability to utilize oxygen during the breakdown of organic matter in the water. In simpler terms, it represents the quantity of oxygen required to oxidize the organic substances present in a given water sample. COD analysis serves as an indirect measure of pollutants, specifically organics, within a water sample. This parameter holds significance in water quality analysis as it aids in mitigating risks to both humans and the environment [34].

Monitoring COD is a valuable method for assessing the efficiency of water treatment plants. Untreated or partially treated water discharge often contains effluent organics that can compete with downstream organisms for oxygen. This oxygen demand can potentially harm or inhibit life downstream of the discharge area. Therefore, accurate information about water quality, such as COD, plays a crucial role in minimizing the likelihood of pollutants causing environmental damage [35].

Why is Chemical Oxygen Demand important?
In modern societies with a high demand for water, there is a simultaneous production of various pollutants and environmental challenges. These issues pose serious health and biodiversity threats if left untreated, overwhelming natural recovery processes. Alongside products from the decomposition of natural substances, there is an accumulation of potentially harmful additives such as pesticides, effluents, and garbage, which contaminate drinking water supplies with their toxic or hormonal effects. These contaminants may also deplete oxygen levels in water resources [36].

High organic contamination in water discharged into tributaries and streams can result in several impacts, including toxicity of organic compounds affecting plants and wildlife, a reduction in dissolved oxygen leading to eutrophication, and adverse effects on fish populations. To prevent potential health hazards and protect species, it is essential to thoroughly assess water source quality before consumption or commercial use, with COD testing playing a pivotal role in this process. COD serves various purposes, including determining concentrations of oxidizable pollutants in wastewater, evaluating the effectiveness of wastewater treatment solutions, assessing the impact of wastewater disposal on the environment, and acting as an index for overall water quality. COD measures the oxygen required to break down organic substances that act as pollutants in water. A higher COD indicates elevated levels of oxidizable material in a sample, leading to reduced dissolved oxygen levels. In such cases, the environmental impact can be detrimental to higher aquatic lifeforms. Therefore, the goal of wastewater treatment is to minimize COD levels in water [37].

3. ADVANCED OXIDATION PROCESS TECHNOLOGY (AOP)/BIOTREATMENT TECHNOLOGY

Advanced oxidation technologies encompass processes that utilize powerful oxidizing agents to efficiently oxidize a broad range of organic compounds present in wastewater and gases. Various industrial applications of advanced oxidation process technologies (AOP) have been developed, including those for removing pesticides from drinking water and eliminating formaldehyde and phenol from industrial wastewater [38].

The development of such AOP applications is driven by increasingly stringent regulations, water resource pollution from agricultural and industrial activities, and the need for industries to meet wastewater discharge standards. These advanced wastewater treatment technologies possess the capability to adapt their microbiological and enzymatic composition to degrade all biological substances present in wastewater, such as starch, glycerol, hemicellulose, polyvinyl alcohols, and other substances [39].

Biological treatments effectively remove pollutants that are easily biodegradable. However, non-biodegradable components like waxes, oils, paraffin wax, and melamine resins pass through biological purification treatments unchanged. To address this, a combination of chemical oxidation and biological degradation is employed [40]. Advanced oxidation systems are designed to treat all types of contaminated water and wastewater.

4. CONCLUSION

The environmental impact of wastewater from the meat industry is highly detrimental, given its specific composition and the substantial presence of harmful organic substances. While various technologies and methods can be employed for treatment, anaerobic digestion, specifically through anaerobic reactors, has emerged as the most efficient system. This process yields biogas as a by-product, serving as a renewable energy source and an alternative to fossil fuels. Anaerobic digestion not only eliminates pathogenic organisms but also addresses unpleasant odors, enhancing the quality of recycled organic manure. Ongoing improvements in anaerobic digestion processes are crucial, as advancements in wastewater treatment technologies contribute to the reduction of greenhouse gas emissions

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