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ORIGINAL RESEARCH ARTICLE

Wastewater treatment using recycled automobile tires

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Abstract: This study explores a promising phytoremediation method for wastewater treatment using various filtering material types, including used automobile tires and construction waste. Developing an affordable, eco-friendly solution to minimize the release of untreated wastewater into natural water sources by utilizing industrial byproducts and waste materials is a critical challenge. This research focuses on the scientific understanding of implementing phytoremediation facilities that utilize construction debris and discarded automobile tires as filtering media for wastewater treatment. The proposed filter materials (waste tires and construction waste) demonstrated the following treatment effectiveness: ammonium – 40%; nitrates, nitrites, chemical oxygen demand (COD), and suspended solids – 70%; organic pollutants by COD and biological oxygen demand – 70% and 28.5%, respectively; chlorides – 20%; sulfates – 23%; total iron – 99%; surfactants – 28%; and overall disinfection efficiency of nearly 99%. These results confirm the effectiveness of the proposed filtering media in enhancing wastewater treatment through phytoremediation.

Keywords: Environmental hazard; Waste; Automobile tires; Utilization; Wastewater; Treatment facility; Purification processes

1. Introduction

One of the world's key environmental problems is the issue of car tire recycling. With the development of the automotive industry, the problem of recycling used tires is constantly growing. As the number of cars increases, so does the number of tires that need to be recycled. More than 1.5 million tons of car tires are used annually in the United States and more than 2 million tons in the European Union (EU).[1] Given the sharp increase in the number of cars in Ukraine – 202 cars per 1,000 inhabitants, totaling about 10 million units – there is an urgent issue of warehousing, storage, transportation, and processing of tens of millions of car tires annually.[2]

The storage of rubber waste is associated with the very long decomposition period of rubber under natural conditions. Worn tires are practically not subjected to natural degradation, and, as a result, require large space for storage and disposal. In landfills, tires can accumulate methane and other gases; they are flammable, posing risks of emergencies, fires, and pollution. When one ton of tires is burned, about 270 kg of soot and 450 kg of toxic substances are released into the atmosphere. Tire dump fires can last for weeks, poisoning the surrounding area within a radius of 10 km.

Despite the emergence of new environmentally friendly methods of recycling tire waste, the problem of environmental pollution due to the storage of used car tires in landfills becomes more acute each year.[3]

This research proposes an environmentally and cost-effective method of wastewater treatment for small settlements using used car tires and construction waste as a filter nozzle, which will improve the state of aquatic ecosystems and increase waste disposal.

Surface water pollution and waste management are major environmental issues in many countries around the world. An evaluation of environmental risks related to the degradation of surface waters in Ukraine has revealed that the waterways within the Siversky Donets River basin are in the most critical state.[4] An analysis of the quality of water resources in the Kharkiv region (Ukraine) indicated that, in many aspects, they fail to comply with international and national standards.[5] In one study,[6] the discharge of wastewater into the Udy River was analyzed over the period from 1992 to 2016. The investigation into how natural and anthropogenic factors influence the ecological condition of the Udy River demonstrated that wastewater discharge, with a correlation coefficient of 0.75, represents a major contributor to surface water pollution. In addition, a multifactor correlation-regression analysis identified the natural and anthropogenic factors exerting the greatest influence on the hydrochemical characteristics of the Oskil River. The results of the research showed that the quality of water bodies is most affected by wastewater discharges and rising air temperatures, which indicates the need to reduce the load from industrial facilities and utilities.[6]

The problem of surface water pollution caused by discharges of untreated wastewater in small towns without sewerage networks is extremely acute and may lead to emergencies due to the epidemiological risk of increasing infectious diseases through recreational water use.

2. Materials and methods

2.1. Method background

The determination of the possibility of using phytoremediation facilities with the addition of used automobile tires as filtering nozzles for wastewater treatment has become the main focus and scientific novelty of this study.

The main objective of this research was to explore the potential of using phytoremediation systems with waste automobile tires as filtering materials for wastewater treatment.

The purpose of this study was to reduce the pollution of aquatic ecosystems by introducing phytoremediation technology for wastewater treatment using construction waste and used car tires as filter nozzles.

To achieve this goal, the following tasks were set:

(i) To analyze modern methods for the utilization of used car tires
(ii) To evaluate phytoremediation-based methods of wastewater treatment
(iii) To improve the wastewater treatment method through the use of construction waste and used car tires.

The technological process of wastewater treatment at such facilities occurs in two stages. First, mechanical and primary wastewater treatment takes place in septic tanks, where suspended solids are removed by sedimentation. The next stage involves an underground filter trench system, which may be gravel- or tunnel-based. The primary function of this trench is to create conditions for the development of a significant number of microorganisms throughout its volume. A biofilm – a mucus coating formed by specific microorganisms derived from wastewater – develops on the trench's filter material and participates in the biological treatment process.

Sewage, clarified and pre-treated in the settling tanks through the drip biofilter, enters the area of the underground filter in portions. The natural soil acts as a carrier for the immobilization of microflora. Given that the filter unit (composed of used car tires, basalt crumb, and gravel) is a porous material, a biofilm begins to form during the first 2 – 3 weeks of operation. Intensive mass transfer and the presence of oxygen in the water support the active development of microflora on the filter material, ensuring the completion of the deep biological purification process.

From the filtering trenches, treated water can either be discharged into the artificial groundwater recharge system (AGRS) or undergo further treatment at the facilities using phytoremediation technology, mainly involving shrub plantings on the surface (Figure 1).

Such structures are located around reservoirs, intercepting pollutant flows. These are either neutralized by natural biochemical processes in the dams and trenches or transferred to the underground streams, where natural soil purification processes of contaminated water continue (Figure 1).

Most often, filter trenches are integrated with elements of AGRS. Their main purpose in this context is to divert purified water into aquifers through infiltration. A key function of the AGRS system is its barrier role – during short-term inflows of contaminated water, the AGRS system can prevent groundwater pollution. Water exiting the AGRS is typically of high quality, with almost complete retention of suspended solids and microorganisms, complete decomposition of pathogenic microorganisms, and overall improvement of other properties of water. Groundwater treated by AGRS systems usually meets hygienic standards for drinking water. In the AGRS system, the water temperature also stabilizes, aligning with natural groundwater temperatures.

The biochemical oxidation of pre-treated wastewater in the biofilter occurs in two phases as it seeps through the filter media: first, carbon and hydrogen are oxidized to produce carbon dioxide and water; then nitrogen is oxidized, initially forming nitrogen salts, and eventually nitrates (nitrification).

Figure 1. Filter trench in the zone of interception of polluted surface runoff

For each site, a treatment scheme was selected according to the construction conditions, terrain, and wastewater flow.

Settling tanks remain on the surface of the earth, and the area above the filter trenches can be used for landscaping (Figure 2).

Experimental studies of filtration and wastewater treatment processes were conducted under laboratory conditions using filtering phytoremediation facilities with specialized filtering nozzles.

As filtering materials, automobile tires with a directional tread pattern were used. The tire size used was 205/55 R16, where the profile width is 205 mm, the profile height is 55% of the width, and the inner diameter is 16 inches. The outer diameter for this size is approximately 630 mm, and the tire carcass is made of steel cord or polyester threads, ensuring strength and shape stability under high loads. The rubber compound consists of synthetic rubber with silica additives, allowing effective performance within a temperature range of −20°C – 40°C, as commonly used in summer or all-season tires. The tread depth initially measures 7 – 9 mm, with a minimum allowable depth of 1.6 mm.

The average lifespan of the tires used is 4 – 6 years or 40,000 – 60,000 km of mileage. Factors affecting tire quality include driving style, road conditions, and temperature variations.

Laboratory studies were conducted to evaluate the toxicity of tires in water-saturated soil. The data gathered indicate that tire samples containing rubber materials and metallic cords were not toxic to microorganisms.

Figure 2. Sewage treatment plants for individual houses using non-traditional materials operating in Ukraine (Tatarbunary Town Museum). (A-D) Stages of filter trench construction: (A) Arrangement of a septic tank; (B) Construction of a filter trench using available space; (C) Laying waste tires and geotextiles to prevent clogging; (D) Development of a recreational area on top of the filter trench.

Chemical and biological analyses were performed using standard methodologies.

The experiment lasted 6 months (from March 1 to August 31, 2024) under laboratory conditions, using a setup measuring 1 m × 0.5 m × 0.8 m, with a wastewater flow rate of 20 dm^3/day. The water first passed through a filtering layer of rubber granules (particle size 2 – 10 mm), which captured mechanical pollutants and adsorbed organic contaminants. It then reached the plant roots, which absorbed biogenic substances and facilitated biological treatment.

The filtrate analysis was performed on the day of sampling, with three replicates used to determine parameters such as suspended solids concentration, nitrates, phosphates, ammonium, chemical oxygen demand (COD), and biological oxygen demand (BOD_5).

2.2. Analysis of methods based on literature

2.2.1. Modern methods of used tire utilization

The rapid growth of the automotive industry, coupled with improvements in living standards, has resulted in a substantial increase in the production of car tires, which require proper disposal once they reach the end of their lifecycle.

Torosian and Chernyaev[7] investigated the environmental risks associated with car tires during their usage, assessing the extent of dust pollution and its effects on human health. They proposed a schematic for an international environmental safety control system designed to regulate tire usage. This system includes a procedural algorithm aimed at reducing risks associated with improper or disorganized tire disposal.

Shaker and Mohammed[8] presented various methods for recycling automotive waste – such as oils, tires, and glass – and discussed the economic feasibility of disposal and the potential of applying recycling processes in the city of Divaniya to reduce the amount and volume of waste.

Waste from car tires belongs to the category of waste subjected to industrial recycling. Thermal decomposition of polymer waste is one of the promising options for tire processing; however, it remains relatively expensive. In addition to incineration for energy purposes, tire waste can be mechanically processed – for example, by shredding – and used in road construction. While increasing fragmentation significantly improves functionality, it also raises operational costs, making the process less cost-effective. Of the total waste, 2 – 2.5 million tons of used tires were reprocessed in the EU, of which only 23% were reused. The remaining used car tires are not disposed of due to a lack of cost-effective disposal methods, which poses a significant environmental problem. Globally, efforts are underway to find solutions efficient solutions for tire utilization and to extend their safe operating lifespan. The most frequently discussed approaches in the literature for reducing the volume of used tire waste include: utilizing tires as fuel through energy recovery; shredding and repurposing the material for various applications; and modifying tire designs to enhance durability and prolong usability, such as through retreading or altering their chemical composition.[1]

Dębska *et al.*[9] documented the results of tests on epoxy solutions in which sand was replaced with granules made from used tires in amounts of 0, 20, 40, 60, 80, and 100% by volume. As the proportion of tire waste increased, the composite's strength parameters decreased. Nevertheless, the resulting material showed low water absorption and a low thermal conductivity coefficient. Using ADINA software, a numerical simulation of temperature distribution was conducted on a section of a building structure containing the modified rubber solution. The simulation results confirmed the composite's practical applicability due to its excellent thermal insulation properties.[9]

The use of rubber crumbs to modify road bitumen represents an environmentally sustainable solution for rubber waste management.[10] Enhancing the stability of rubber crumb-modified road asphalt mixtures is a critical environmental strategy for the future. Plewa[10] presented the findings of fatigue resistance tests conducted on asphalt concrete with asphalt rubber binders. The results demonstrated that mineral-rubber-asphalt mixtures exhibited improved functional properties compared to conventional mineral-asphalt mixtures.

Chen *et al.*[11] stated that used car tires have emerged as one of the fastest-growing types of solid waste in China. The paper examined the current recycling potential of pyrolysis, which is regarded as a promising technology for processing used tires. In addition, Chen *et al*. propose a novel pyrolysis method designed to overcome the limitations of existing tire recycling technologies and mitigate the growing tire waste crisis.

Pyrolysis is currently a modern technology used to recover fuel and soot from used tires. However, the detailed mechanisms of degradation and kinetics of tire pyrolysis remain under-researched. Shahi *et al.*[12] investigated the pyrolysis of the tread, sidewall, and inner liner of used light vehicle tires using thermogravimetric analysis. The degradation profiles of these tire components were predicted using different kinetic models.

In a study by Kuznetsov *et al*.,[13] the high potential for utilizing tires unsuitable for further use through pyrolysis and combustion of thermal decomposition products in coal-water fuel mixtures is demonstrated. It was found that adding pyrolysis products of liquid rubber to the structure of coal-water suspension leads to a significant acceleration of ignition processes. Based on experimental results, a new mathematical model was developed to describe the ignition process of highly inhomogeneous, multicomponent fuels.

In Vambol *et al.*'s research,[14] the authors used numerical simulations to demonstrate the feasibility of utilizing waste tires at high temperatures, followed by the methanation of fuel gases and the separation of multicomponent hydrocarbon mixtures to produce liquefied methane.

Nie *et al*.[15] highlight that hydrothermal gasification is a promising approach for recycling used tires. The hydrothermal gasification of spent tires was assessed through chemical equilibrium analysis combined with the response surface methodology. The study considered various parameters, including the subcritical temperature range (250 – 300°C), transition temperature range (350 – 400°C), supercritical temperature range (550 – 600°C), supercritical pressure (22.5 – 30.5 MPa), and raw material concentration (5 – 20 wt%). This investigation provides foundational data for the hydrothermal treatment of used tires. Meanwhile, Subatkevičienė *et al.*[16] proposed the use of car tire waste as sorbents for treating industrial wastewater containing petroleum products. Production of sorbents from shredded used tires reduces waste and protects water bodies from harmful pollutants. Experimental findings showed a cleaning efficiency ranging from 91.51% to 95.21%.

In a study by Sivaraman *et al*.,[17] a method for recycling used tires as an adsorbent to sequester hexavalent chromium from a simulated wastewater system is described. Leather and electroplating industry effluents often contain high concentrations of chromium, which is a toxic and mutagenic contaminant. The spent tire samples were activated with orthophosphoric acid and used for adsorption studies. The proposed method of using spent tire particles as adsorbents in the treatment of contaminated hexavalent chromium water provides valuable guidance for further research in the areas of dynamic adsorption and wastewater treatment.

The analysis of modern methods for the disposal of used car tires underscores the relevance and necessity of continued scientific research aimed at waste reduction and environmental protection.

2.2.2. Phytoremediation methods for wastewater treatment

Phytoremediation is an efficient and cost-effective biotechnology for the purification of water, soil, and air. It is based on the ability of plants and associated decomposer microorganisms to remove toxic substances from the environment or convert them into safe compounds.

Numerous studies by Ukrainian and international researchers have focused on the purifying properties of higher aquatic plants (HAP). These plants not only absorb dissolved substances from water but also serve as substrates for the growth of various microorganisms. These microorganisms contribute to the neutralization of a significant portion of pollutants discharged into natural water bodies through surface runoff, thereby enhancing the quality of aquatic ecosystems.[18,19]

Among the wide variety of macrophytes, the most commonly used species for wastewater treatment include common reed (*Phragmites australis* [Cav.] Trin ex Stend.), narrow-leaved cattail (*Typha angustifolia* L.), broad-leaved cattail (*Typha latifolia* L.), and lake bulrush (*Scirpus lacustris* L.), along with several other species. According to researchers, up to 450 kg of nitrogen, 180 kg of phosphorus, 220 kg of potassium, and 330 kg of chloride can be removed per hectare of reeds during the growing season.[19,20]

Air-water macrophytes (such as reeds, cattails, and others) enhance the gas regime of wetlands and waterlogged soils. In the oxygen-rich environment surrounding their fine roots, rhizosphere microorganisms proliferate in large numbers. These microorganisms play a key role in the aerobic decomposition of organic matter accumulated in silt deposits, facilitating the conversion of substances into more bioavailable forms such as nutrition. As a result, HAP stimulates self-purification processes and promotes air circulation within bottom sediments.[18] Research conducted by specialists at the Ukrainian Research Institute of Environmental Problems on the purification capacity of HAP led to the development of a method for using these plants in treatment systems such as Constructed Wetlands.[21] To date, more than 60 wastewater treatment projects in Ukraine have been designed based on this methodology.

Constructed Wetlands have been successfully implemented for the treatment of domestic wastewater in countries like the Netherlands, Japan, and China, as well as for the purification of contaminated surface runoff in Norway, Australia, and other nations, including Ukraine.[22]

In Ukraine, Constructed Wetlands treatment systems are referred to as bioengineered treatment plants (BTP). The operating principle of these systems is based on harnessing natural self-purification processes that occur within the filter layer, which serves as a substrate for the development of biogeocenoses of HAP. Table 1 provides an overview of the main purification systems that utilize phytoremediation.[23]

At present, several types of BTP have been developed, each with various treatment conditions and types of bioplateaus. Systems incorporating HAP are effectively employed for the additional purification of wastewater following traditional treatment methods. Bioplateau systems not only water-air HAP (such as reeds, cattails, bulrushes, and sedges) but also various types of submerged vegetation, including redwood, watercress, hornwort, and others.

The design characteristics and technological differences in the construction and operation of treatment facilities using HAP, similar to Constructed

Table 1. Comparative characteristics of purification systems using phytoremediation

Treatment system	Location	Application	Water movement	Treatment efficiency	Disadvantages
Botanical sites	Shallow water bodies	Primary and additional treatment of domestic and industrial wastewater	Horizontal (through HAP thickets)	Organic substances: Up to 97%; heavy metals: Up to 90%	(i) Efficiency depends on the season of the year (ii) Limited contact time between wastewater with HAP
Phytofiltration devices	Alluvial underwater ridges near rivers	Biomelioration of natural waters	Horizontal	Not specified	(i) Insignificant contact time between wastewater and HAP (ii) Possible leakage of treated water
Bio stands with HAP landings	Reservoirs with planted HAP	Primary and additional treatment of domestic wastewater	Horizontal (in water column)	N: 10 – 80%, chemical oxygen demand: Up to 90%; suspended solids: Up to 98%; petroleum products: Up to 60%; disinfection: up to 90%	(i) Low productivity (ii) Requires large areas of land (iii) Presence of stagnant zones (iv) Risk of recontamination
Artificial natural wetlands	Wetlands with artificial or natural embankments	Primary and additional treatment of domestic wastewater	Horizontal (through HAP thickets)	NH_4^{2-}: 30 – 60%; NO_3^-: 0 – 20%; biological oxygen demand (BOD_5): 50 – 70%	(i) Low controllability of cleaning processes (ii) Efficiency depends on the season of the year
Bioplato	Canals, rivers, lowlands, or upper ponds	Primary and additional treatment of domestic wastewater	Horizontal (through HAP thickets)	Ammonium nitrogen: 30 – 60%; NO_3^-: 10 – 20%; BOD: 50 – 70%; disinfection: up to 90%	(i) Requires large areas of land (ii) Efficiency depends on the season of the year

Abbreviations: HAP: Higher aquatic plants; N: Nitrogen; NH_4^{2-}: Ammonium; NO_3^-: Nitrates.

Wetlands, have led to a variety of terminological definitions. These include terms such as botanical sites (or hydrobotanical sites), filter ponds, biological ponds with HAP, filtration devices, artificial wetlands (or artificial swamps), bioplateaus, and bioengineering facilities for water quality regulation. A common feature across all these systems is the presence of biocenoses of HAP, which directly or indirectly influence the biological processes involved in water quality transformation (purification) and the engineering characteristics of the structures (e.g., specific structural elements, operational parameters).

Typically, in such systems, water passes through thickets of HAP or bog vegetation, partially through a soil layer, and is then removed from the site through drainage. The primary operational parameters of artificial wetlands include the filtration path length (ranging from 100 to 1,500 m) and the water flow velocity (requiring 6 – 10 days for passage). The effectiveness of these systems is evidenced by reductions in the concentrations of ammonium nitrogen (by 30 – 60%), nitrates (by 10 – 20%), and BOD_5 by 50 – 70%.[24]

To fully understand the potential of HAP, further research is needed to identify the most suitable phytoremediation technologies for treating contaminated wastewater.

To assess the efficiency of surface wastewater treatment after fires using the phytoremediation method, experimental studies were conducted using a model setup. The modeling of phytoremediation and infiltration processes was carried out in the laboratory of the Department of Labor Protection and Technogenic and Ecological Safety at the National University of Civil Defense of Ukraine.

Experimental results demonstrated the high effectiveness of using reeds and filter nozzles made from defibrated polyethylene terephthalate (PET) containers for stormwater treatment. The treatment efficiency reached 98.0% for suspended solids, 92.0% for BOD_5, 80.0% for petroleum products, and 90.0% for COD.[25]

2.2.3. Wastewater treatment method with used car tires

The problem of untreated wastewater remains particularly acute in small settlements lacking centralized sewerage networks. In many cases, insufficient attention has been given to wastewater treatment in these areas. Although aeration tanks, biofilters, or settling tanks were sometimes installed, issues related to their proper operation and ongoing maintenance were often left unaddressed. Some settlements still lack sewage treatment facilities altogether, even when a centralized water supply exists but no drainage system is in place.

At present, in numerous villages and even small towns, the volume of wastewater generated and the limited financial resources available for the operation of treatment facilities, such as funding for technical staff, electricity costs, and routine maintenance, have significantly decreased. As a result, most treatment facilities in such communities are either non-functional or used merely as reservoirs for wastewater storage before uncontrolled discharge into the environment.

This situation with water purification arises from two challenges: First, the unsuitability of existing (conventional) treatment technologies for small-scale applications, and second, the high cost of operating such systems. For example, aeration tanks, commonly used as treatment plants, require constant artificial support to maintain biodegradation processes. This includes aeration, the addition of microorganisms, electricity consumption, regular monitoring, and skilled maintenance. In addition, the operation of aeration tanks is affected by fluctuations in the flow rate and chemical composition of the water supplied for treatment. The maintenance of such structures is manageable for large cities with significant volumes of wastewater. However, in villages, wastewater volumes are typically low, and there are often no funds allocated for the operation of treatment facilities.

Typically, in small settlements, the consumption of wastewater ranges from 15 to 30 m3/day (in villages, the water supply usually serves several two- or three-story buildings, a school, or a hospital). In such conditions, the most promising solution is the creation of autonomous sewerage systems in the villages. However, establishing a closed drainage cycle requires an effective method for treating small volumes of wastewater. Among the various treatment options available for small volumes of wastewater, the market offers different types of bioprocessors. These systems are generally expensive to construct and operate, requiring the installation of prefabricated units, ongoing maintenance, and continuous servicing by the manufacturer. Unfortunately, the use of BTP is not always appropriate due to a number of limiting factors, such as terrain features, availability of free space, and other site-specific constraints. BTP is cost-effective primarily when wetlands are available or when they can use existing infrastructure from previous treatment facilities.

Recently, as an alternative to sewage treatment plants in settlements with small amounts of wastewater, the installation of autonomous sewage treatment plants employing phytotechnologies for individual houses and residential areas has become increasingly widespread. These modern small-scale treatment plants include components such as sand and gravel filters, filtration fields, and, where necessary, AGRS. They are adapted to provide complete wastewater treatment of small volumes of wastewater in the absence of centralized sewerage networks.

The following treatment facilities typically consist of three units (Figure 3): The first is a two-section septic tank (zone A); the second includes sludge wells (zone B); and the third is the core biological treatment unit – underground filter trenches (zone C). The number and length of these trenches are calculated based on the volume and quality of wastewater, topography, and soil properties. If needed, the facility may also include a phytotechnology unit.

At present, there are several options for such treatment plants, which differ in the design of filter trenches. Grytsenko *et al*.[26] proposed the use of filter trenches for surface wastewater treatment, with the filter layer made of basalt crumb, where pollutants are adsorbed. The treated wastewater is then filtered through a sand layer into the lower strata. This application is particularly suitable for areas where the water supply depends on underground storage and where the groundwater level is critically high. In another study,[27] the method of surface wastewater treatment was further improved by utilizing PET granules and polyurethane foam granules as the filter layer. The application of PET waste packaging for treating stormwater and meltwater not only helps to reduce the anthropogenic influence on the environment but also increases the utilization of plastic waste.

To treat wastewater from small settlements or individual houses, we propose the use of drainage tunnels incorporating secondary materials (used car tires, basalt crumbs, gravel, etc.).

A large number of used tires are generated annually at enterprises across the country, providing an opportunity for their reuse, particularly as a building material for strengthening drainage canals and constructing facilities of this type.

Modern tires are complex structures composed of layers reinforced with metal or textile cords and tread. Only high-quality and environmentally friendly rubber compounds are used for the production of car tires, including natural rubber, synthetic rubber, carbon black, and lubricant. Rubber compounds make up over 80% of the total weight of a tire, while the remaining 20% consists of various reinforcing materials.

Toxicity tests of tires in wet soil were performed in the laboratory. The data obtained showed that tire samples containing rubber materials and metal cords were not toxic to microorganisms. Tire waste is classified as hazard class IV, that is, non-toxic, which supports its further secondary use in underground filter trenches.

3. Results and discussion

This experiment on wastewater treatment using phytoremediation facilities with filtering media (based on used automobile tires and construction materials) demonstrated high efficiency in removing various pollutants. Specifically, after 6 months of research, the treatment efficiency was as follows: total iron removal – 99% (the best result among hydrochemical indicators); suspended solids, COD, nitrates, and nitrites – 70% removal efficiency; other parameters showed varying degrees of treatment, ranging from 50% to 99%, with an overall disinfection efficiency of 99% (Table 2).

These results confirm the effectiveness of the proposed method, particularly in the removal of organic pollutants, biogenic substances, and toxic components.

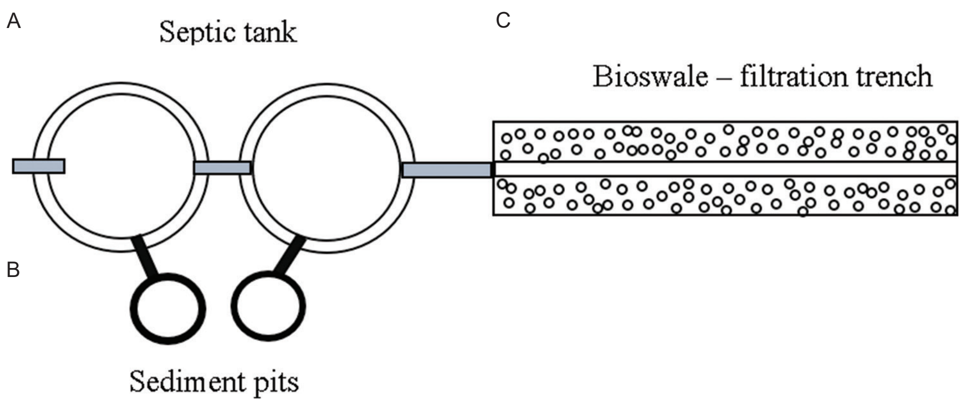

Figure 3. (A-C) Schematic of an autonomous treatment plant for individual houses and residential areas

Table 2. Efficiency of wastewater treatment by phytoremediation using used car tires

Ingredient name	Before treatment	After treatment	Treatment efficiency, %
Suspended substances, mg/dm^3	150	45	70
pH	8	Not determined	-
COD, mg O_2/dm^3	156	50	70
BOD_5, mg O_2/dm^3	70	50	28.5
Ammonium nitrogen, mg/dm^3	30	18	40
Nitrite, mg/dm^3	0.06	0.02	67
Nitrates, mg/dm^3	33.6	10	70.2
Chlorides, mg/dm^3	226.2	181	20
Sulfates, mg/dm^3	150	115	23
Iron, mg/dm^3	1.8	0,16	99
Surfactants, mg/dm^3	2.5	1,8	28
Total microbial amount, CFU/mL	8.8×10^5	1.0×10^3	99

Abbreviations: Abbreviations: BOD_5: Biological oxygen demand; CFU: Colony-forming units; COD: Chemical oxygen demand; O_2: Oxygen.

The efficiency of wastewater treatment is presented in Table 2.

It is important to highlight the role of filtering nozzles (2 – 10 mm) made from recycled automobile tires, which proved effective in the mechanical treatment of capturing suspended particles and adsorbing organic compounds. Rubber granules derived from tires possess a high adsorption capacity due to their porous structure, enabling them to efficiently retain petroleum products and heavy metals. Moreover, the use of construction materials (such as gravel or sand) in combination with rubber granules provided an additional filtration effect, further improving overall treatment quality.

Phytoremediation, with the usage of aquatic plants – common reed (*P. australis* [Cav.] Trin ex Stend.), narrow-leaf cattail (*T. angustifolia* L.), broadleaf cattail (*T. latifolia* L.), lake bulrush (*S. lacustris* L.), and other species – has proved their effectiveness with the removal of biogenic substances (nitrogen compounds) and organic pollutants. The plants actively absorbed nutrients from the water, while their root systems created favorable conditions for microorganism growth, facilitating the decomposition of organic compounds.

A remarkable result was the disinfection rate of 99%, demonstrating the combined effectiveness of filtration and biological plant activity in reducing the concentration of pathogenic microorganisms. However, it should be noted that treatment efficiency for certain components – such as ammonium nitrogen (40%), chloride ions (20%), sulfates (23%), and surfactants (28%) – remained relatively low. This may be attributed to the limited sorption capacity of the materials used in the filtering nozzles, as well as the high initial concentration of these substances in the incoming wastewater. To improve these results, the addition of supplementary sorbents, such as activated carbon or specialized mineral additives, could be considered.

The experiment also confirmed that the combination of phytoremediation and filtering media is a cost-effective and environmentally friendly technology. The use of waste automobile tires not only helps address the issue of waste disposal but also enables resource reuse, aligning with the principles of sustainable development. Moreover, this method can be easily adapted for local treatment facilities in small communities or industrial sites where access to large-scale treatment systems is limited. Overall, the experimental results demonstrate that the combined use of phytoremediation and filtering nozzles is a promising approach in the field of wastewater treatment.

It is worth mentioning that the implementation of autonomous treatment plants with elements of phytotechnology for small settlements is gaining popularity.

The introduction of autonomous treatment facilities, such as filter trenches, offers several advantages:

(i) No odors
(ii) No large land areas need to be allocated
(iii) No large sanitary protection zones are required
(iv) The possibility of creating separate treatment sections for individual buildings
(v) Independence from fluctuations in the volume and quality of wastewater.

For small cities, villages, or individual houses, a combination of several structures was used, each performing a specific function and contributing to improved water purification efficiency.

As the project did not include buildings, heating systems, water supply infrastructure, electrical equipment, or accommodation for service and laboratory staff, the overall development cost was lower compared to traditional treatment facilities with similar initial characteristics.

Such systems are specifically advantageous when sewage treatment plants are needed for individual users in rural areas or when the facility operates only seasonally, such as during the holiday period. During temporary surges in wastewater volume, additional phytotechnology treatment blocks can be employed to handle the overflow. In essence, such structures can be adapted to different living conditions and scenarios involving small volumes of wastewater. Facilities such as children's camps, sanatoriums, holiday homes, and recreational centers, which typically operate for up to 6 months a year, can effectively address their wastewater treatment needs using such phytotechnology-based systems.

4. Conclusion

Tire recycling is a critically important process for protecting both the environment and human health. The decomposition of tires takes about 100 years, as they are almost non-biodegradable.

The environmental and social harm caused by tire disposal in landfills, including the usage of large areas for unorganized (unauthorized) dumping and the risk of air pollution, highlights the urgent need for sustainable methods of reusing waste tires.

An analysis of the current waste management system in Ukraine has revealed significant shortcomings. Therefore, the use of waste car tires as a filter layer in wastewater treatment systems can simultaneously enhance the efficiency of industrial waste disposal and contribute to the protection of water bodies from contaminants.

The wastewater treatment efficiency of phytoremediation models with the filtering nozzles (made from used automobile tires and construction materials) was as follows: 40% for ammonium; 70% for nitrates, nitrites, COD, and suspended solids; 28.5% for BOD_5; 20% for chlorides; 23% for sulfates; 99% for total iron; 28% for surfactants, and 99% for overall disinfection. These results confirm the effectiveness of using this type of filtering media in wastewater treatment applications.

The economic benefits of the proposed method include several key factors: The simplicity of phytoremediation systems, the absence of complex engineering devices for controlling water levels or flow, the elimination of chemical or reagent use, and a reduced need for highly qualified personnel.

The environmental benefits are equally significant. Such systems can replicate natural riverine areas, using aquatic plants commonly found in floodplains. The development or expansion of such areas can intercept and treat wastewater before it enters rivers, without disrupting the natural conditions of the region. This approach effectively removes suspended solids, organic matter (including petroleum products), and pathogenic microorganisms, while also reducing overall water mineralization.

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Conflict of interest

The authors declare no conflicts of interest.

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Availability of data

Data are openly available in a public repository that issues datasets with and without DOIs.

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