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Assessment of the efficiency of phytofiltration systems with energy willow for reducing nitrate pollution in the Vereshchytsia River catchment

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ABSTRACT

This article investigates the efficiency of using energy willow (*Salix* spp.) as a component of phytofiltration systems for reducing nitrate concentrations in the Vereshchytsia River catchment. The relevance of the study is driven by the increasing diffuse nitrate contamination of surface waters in agricultural regions and the need to implement nature-based purification methods. Experimental studies were conducted under laboratory conditions using a model soil-plant filtration system. Model solutions contained nitrates at concentrations of 10, 25, and 50 mg/L. Nitrate concentrations in the water were determined by the photometric method before and after passing through the system. The results demonstrated that the presence of energy willow in the filtration substrate ensures a significant reduction in nitrate concentrations in the filtrate. The purification efficiency increased with longer contact time between the solution and the substrate, reaching 45÷60% after 24 hours. The obtained results confirm the potential of using energy willow in nature-based water purification systems for nitrate contamination reduction in the Vereshchytsia River catchment.

Keywords: energy willow, phytofiltration systems, nitrate pollution, water purification, biological nitrogen uptake.

INTRODUCTION

Nitrate contamination of surface waters remains one of the most pressing environmental problems in agricultural regions of Europe, particularly under conditions of intensive land use and developed drainage systems [1–3]. The main source of nitrate input into water bodies is diffuse runoff from arable lands, caused by the application of mineral nitrogen fertilizers, suboptimal timing of their application, and insufficient buffering capacity of agricultural landscapes [3–6, 27, 28]. As a result, elevated concentrations of NO_3^- accumulate in surface waters, leading to deterioration of water quality, eutrophication of water bodies, and creating potential risks for public water supply [29].

The problem of nitrate contamination is particularly acute in small and medium-sized catchments, where agricultural land use, drainage systems, and the limited self-purification capacity of watercourses coincide [7, 28]. The Vereshchytsia River catchment is one such system, characterized by a significant proportion of arable lands in the land use structure, the presence of a drainage network and ponds, as well as pronounced seasonal variability of the hydrological regime. Monitoring studies indicate elevated nitrate concentrations in water during spring floods and autumn rainfall periods, suggesting the dominance of diffuse pathways for nitrogen compound migration

[8]. Conventional engineering methods of water treatment are economically costly and inefficient for addressing the problem of diffuse pollution within catchments. In this context, modern environmental research is increasingly focused on nature-based solutions that rely on natural ecosystem self-regulation processes. One such approach involves the establishment of riparian phytofiltration strips composed of perennial grasses, shrubs, and moisture-loving vegetation capable of intercepting surface and drainage runoff and reducing nitrate inputs into water bodies [9].

At the same time, the efficiency of conventional grass buffer strips is often limited, as a significant portion of the absorbed nitrogen returns to the soil through mineralization of plant residues. In this regard, the use of energy willow (*Salix* spp.) as a structural component of phytofiltration systems represents a promising alternative. Owing to its high biomass productivity, well-developed root system, and adaptability to waterlogged conditions, energy willow is capable of intensively accumulating nitrogen compounds from soil and drainage waters. Regular harvesting of aboveground biomass ensures long-term nitrogen removal from the catchment ecosystem, which fundamentally enhances the environmental effectiveness of this approach [10, 11].

Given the above, the scientific substantiation and adaptation of the method for creating multilayered phytofiltration strips incorporating energy willow for specific catchment conditions is a relevant research task. The aim of this study is to develop and assess the efficiency of a nature-based method for reducing nitrate contamination of surface waters in the Vereshchytsia River catchment through the creation of phytofiltration strips composed of perennial grasses, shrubs, and moisture-loving vegetation, with emphasis on the use of energy willow as the key biofilter.

To achieve this aim, the study involves the analysis of spatiotemporal dynamics of nitrate contamination, substantiation of the phytofiltration strip structure, formalization of indicators for nitrate load reduction efficiency, and assessment of the potential for practical implementation of the proposed method.

Theoretical background and ecological mechanisms of phytopurification

The migration of nitrates in agricultural catchments is a complex, multifactorial process determined by the combination of natural conditions and anthropogenic impacts. Within agricultural landscapes, the main pathways for nitrogen compound entry into surface waters are surface runoff, subsurface infiltration flow, and drainage waters from land reclamation systems. Unlike ammonium forms, nitrates are characterized by high mobility in the soil environment, weak adsorption by soil colloids, and the ability to be rapidly transported with water flows, which leads to their accumulation in watercourses even under relatively moderate doses of mineral fertilizer application.

During periods of intense wetting, particularly during spring floods and prolonged rainfall, there is a sharp increase in diffuse nitrogen loading, as the soil system loses its buffering capacity and excess nitrates are leached beyond the plowed layer. Drained lands are particularly hazardous in this respect, as drainage channels significantly shorten the migration pathway of pollutants to water bodies, bypassing the natural zones of biogeochemical transformation.

Phytofiltration strips are considered one of the most effective nature-based tools for reducing nitrate contamination, as they restore the lost ecological function of riparian and floodplain ecosystems. Their action is based on the combination of several interrelated mechanisms. First, the vegetation cover reduces the velocity of surface runoff, promotes the settling of suspended particles, and increases water infiltration into the soil. Second, plant root systems ensure direct uptake of nitrates and ammonium forms of nitrogen from the soil solution, incorporating them into biological synthesis processes.

Biogeochemical processes of nitrogen transformation, primarily denitrification, play an important role in the functioning of phytofiltration strips. In the zone of contact between the soil and the root system, under conditions of elevated moisture and limited oxygen access, favorable conditions are created for the activity of denitrifying microorganisms, which reduce nitrates to gaseous forms of nitrogen. Thus, a portion of nitrogen compounds is not only retained but also irreversibly removed from the aquatic and soil environment [13, 14].

The efficiency of phytofiltration strips increases significantly when they have a multi-layered structure. Strips of perennial grasses provide a primary hydraulic barrier and soil stabilization, shrub vegetation enhances filtration properties and promotes organic matter accumulation, while moisture-loving plant species form zones with prolonged water retention and active anaerobic processes. The combination of these components allows covering different nitrate migration pathways and increasing the overall stability of the system to seasonal fluctuations of the hydrological regime [15].

However, conventional phytofiltration strips formed exclusively from grass or shrub vegetation have a limited potential for long-term nitrogen removal, as after the dieback of aboveground biomass, a significant portion of accumulated compounds returns to the soil through mineralization. In this regard, modern research pays particular attention to the integration of highly productive woody species capable of intensive accumulation of biogenic elements into the phytofilter structure.

Energy willow (*Salix* spp.) in this context is considered one of the most promising phytofiltration components. Its bioecological characteristics, including rapid growth, high transpiration capacity, and a well-developed root system, ensure effective uptake of nitrates from both surface and drainage waters. Moreover, the ability of willow to produce significant amounts of biomass under conditions of periodic flooding makes it suitable for use in riparian and reclaimed zones of catchments.

Thus, the theoretical basis for using phytofiltration strips incorporating energy willow is grounded in the combination of physical processes of runoff retention, biological uptake of nitrogen compounds, and biogeochemical mechanisms of their transformation. It is the integration of perennial grasses, shrubs, moisture-loving vegetation, and energy willow that creates conditions for comprehensive and long-term reduction of nitrate loading in agricultural catchments.

Rationale for using energy willow as the key phytofilter

Energy willow (*Salix* spp.) belongs to the group of fast-growing woody species widely used in short-rotation coppice systems and nature-based environmental technologies [21–23]. Its bioecological characteristics make this species particularly suitable for use in phytofiltration strips designed to reduce nitrate loading in catchments dominated by agricultural land use. Unlike conventional grass or shrub plantations, energy willow combines high biomass productivity with intensive uptake of biogenic elements and the ability to function over extended periods under conditions of periodic waterlogging.

One of the key advantages of energy willow is its well-developed and deep root system, which encompasses a significant volume of the soil profile and ensures effective interception of nitrates from surface, subsurface, and drainage runoff. The root system of willow is capable of penetrating into zones of active groundwater movement, which is particularly important for reclaimed territories where the main nitrogen load is transported through drainage channels. Owing to this, energy willow functions as a biological pump that removes dissolved nitrogen compounds before they reach surface water bodies [21, 22].

The high growth rates and large leaf surface area of energy willow result in an increased plant demand for nutrients, primarily nitrogen compounds. During the growing season, nitrates are actively incorporated into the metabolic processes of the plant and accumulated in the aboveground biomass. According to summarized research data, energy willow plantations are capable of accumulating 80 to 150 kg of nitrogen per hectare per year, depending on hydrological conditions, planting density, and plantation age [16, 17]. This indicator significantly exceeds the corresponding values for conventional grass phytofiltration strips, which justifies the inclusion of willow in the structure of nature-based purification systems.

A fundamental advantage of using energy willow is the possibility of long-term nitrogen removal from the catchment ecosystem through regular harvesting of aboveground biomass. When short-rotation coppice technology is applied (harvesting every 2÷4 years), the nitrogen compounds accumulated in plant tissues are physically removed from the phytofiltration system, preventing their return to the soil. Thus, unlike perennial grasses and shrubs, energy willow ensures not only temporary retention but also a stable reduction in the total amount of nitrogen compounds in the catchment [18, 21–23].

An additional factor enhancing the efficiency of energy willow in phytofiltration strips is its ability to create a specific microenvironment in the rhizosphere. Enhanced transpiration and the release of organic root exudates stimulate the development of microbial communities, particularly denitrifying bacteria. This creates conditions for the intensification of biogeochemical processes of nitrate transformation into gaseous forms of nitrogen, further reducing their concentration in soil and drainage waters [19].

Comparative analysis of phytofiltration systems indicates that the inclusion of energy willow in the multi-layered strip structure significantly enhances their environmental efficiency and resistance to seasonal fluctuations of the hydrological regime. During peak runoff periods, willow plantations are capable of receiving excess moisture and nutrients without losing functional stability, while during low-flow periods, they maintain active nitrogen uptake from deeper soil horizons.

In addition to the environmental effect, the use of energy willow in phytofiltration strips has important practical significance. The harvested biomass can be used as a renewable energy source or as feedstock for bioenergy installations, creating an additional socioeconomic incentive for the implementation of this method at the level of local communities and land users [23]. The combination of environmental protection function with the possibility of economic use of biomass increases the acceptability and long-term effectiveness of the proposed approach [20].

Thus, energy willow is regarded as a key structural and functional element of phytofiltration strips that ensures the integration of biological uptake, biogeochemical transformation, and physical removal of nitrogen compounds from the catchment ecosystem. Its use allows significantly enhancing the efficiency of nature-based measures for reducing nitrate contamination of surface waters and adapting them to conditions of intensive agricultural land use.

MATERIALS AND METHODS

The studies were conducted under laboratory conditions using model phytofiltration installations that simulate the process of nitrate-contaminated water passing through a soil-plant substrate with energy willow (*Salix* spp.) plantations. The aim of the experiment was to determine the ability of the root system of energy willow to absorb and transform nitrogen compounds under conditions of the Vereshchytsia River catchment.

For the experiments, a phytofiltration system model was used – laboratory columns (lysimeters) of cylindrical shape with a height of 80 cm and a diameter of 20 cm, made of inert material (plastic). A drainage outlet for filtrate collection was provided at the bottom of the columns (Figure 1).

The columns were filled with substrate layers simulating the natural soil profile of the Vereshchytsia River catchment:

- lower drainage layer — gravel (10 cm);
- middle layer — sandy loam soil (40 cm);
- upper layer — fertile soil (15 cm).

Energy willow cuttings 20–25 cm in length were planted in the upper part of the columns. After planting, the plants were grown in the laboratory for 6 weeks until a stable root system was established.

To ensure uniform experimental conditions, all installations were maintained at the same temperature (20–22 °C), lighting (12 hours of daylight), and substrate moisture.

To simulate nitrate contamination, model aqueous nitrate solutions prepared using potassium nitrate (KNO_3) were used. Nitrate concentrations in the model solutions were set at levels typical of agricultural landscapes [30]:

- 10 mg/L NO_3^- (low contamination);
- 25 mg/L NO_3^- (medium level);
- 50 mg/L NO_3^- (high level).

The initial nitrate concentration in each solution was determined before the start of the experiment.

Figure 1. Schematic diagram of the laboratory experimental setup

The model solution was applied to the upper part of the column in measured doses, simulating water infiltration through the soil-plant system. The volume of a single application was 500–1000 mL.

After passing through the substrate and the willow root system, the filtrate was collected through the drainage outlet at the bottom of the installation. Samples were collected at defined time intervals:

- 1 hour after solution application;
- 6 hours;
- 24 hours.

A minimum of three replicates were performed for each experimental variant. Nitrate concentrations in the input solution and filtrate were determined by the photometric method using a spectrophotometer. The method was based on the formation of a colored nitrate complex with reagents followed by measurement of optical density at the corresponding wavelength. To improve measurement accuracy, a calibration curve constructed from standard nitrate solutions was used. After the completion of the experimental series, a portion of the plants were removed from the columns to determine nitrogen content in the plant biomass.

Plant tissue samples were dried to constant mass at a temperature of 70 °C, after which total nitrogen was determined by the mineralization method followed by photometric analysis.

The efficiency of nitrate concentration reduction in water was determined using the formula:

$$E = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \quad (1)$$

where: C_{in} – the initial nitrate concentration in the model solution, mg/L; C_{out} – the nitrate concentration in the filtrate after passing through the column, mg/L; E – the purification efficiency, %.

The obtained results were subjected to statistical processing using descriptive statistics methods. To assess the relationship between nitrate concentration in water, duration of contact with the root system, and purification efficiency, correlation analysis was applied using the Spearman rank correlation coefficient.

RESULTS AND DISCUSSION

In the laboratory experiment, the ability of the model phytofiltration system using energy willow to absorb nitrates from aqueous solutions of various concentrations was investigated. The averaged results of the experimental studies are presented in Table 1.

Analysis of the results showed that the passage of the model solution through the soil-plant substrate with the willow root system led to a significant reduction in nitrate concentration in the filtrate.

After the solution passed through the column, a decrease in nitrate content was observed, the magnitude of which depended on both the initial concentration and the duration of water contact with the soil-plant system.

For the variant with an initial concentration of 10 mg/L NO_3^-, as early as 1 hour after infiltration, the filtrate concentration decreased on average to 7÷8 mg/L. After 6 hours, it was approximately 6 mg/L, and after 24 hours, it decreased to 4÷5 mg/L. Accordingly, the efficiency of nitrate concentration reduction in this variant ranged from 20÷30% at the initial stage to 50–60% with prolonged contact.

In the variant with a medium contamination level (25 mg/L NO_3^-), a similar trend was observed. One hour after solution application, the filtrate concentration decreased to approximately 19÷21 mg/L, corresponding to a purification efficiency of 15÷20%. After 6 hours, the concentration decreased to 15÷17 mg/L, and after 24 hours to 11÷13 mg/L. Thus, the overall efficiency of nitrate concentration reduction in this variant reached 45÷50%.

The most indicative results were obtained for the variant with a high nitrate concentration (50 mg/L NO_3^-). At the initial stage (1 hour), the filtrate concentration decreased to 40÷43 mg/L. After 6 hours, it was approximately 32÷35 mg/L, and after 24 hours - 24÷27 mg/L. Accordingly, the efficiency of nitrate concentration reduction varied from 15÷20% to 45÷48% depending on the duration of water contact with the substrate.

The obtained results indicate a clear dependence of purification efficiency on the duration of contact between the solution and the root system of plants and the soil substrate (Figure 2).

With increasing water residence time in the column, a gradual decrease in nitrate concentration was observed, indicating the combination of several mechanisms of their removal.

The first mechanism is physicochemical filtration and partial adsorption of nitrates by the soil substrate. Although the nitrate ion is characterized by high mobility in the soil environment,

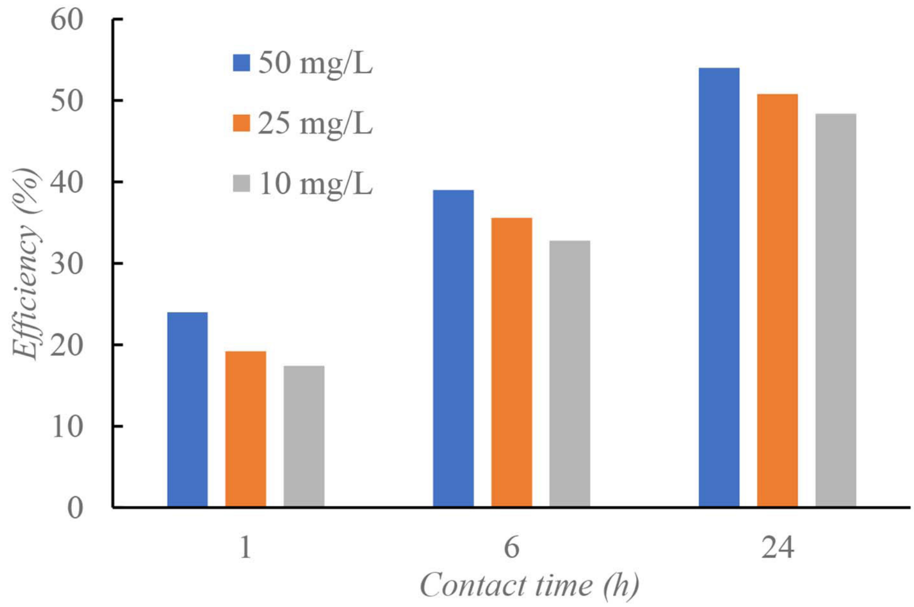

Figure 2. Dependence of nitrate removal efficiency on the contact time of the model solution with the soil-plant system and energy willow

a portion of it may be retained in micropores of the substrate or incorporated into microbiological transformation processes.

The second and more important mechanism is biological uptake of nitrates by the root system of energy willow. Active plant growth is accompanied by intensive nitrogen assimilation, which is used in the synthesis of amino acids, proteins, and other cellular components. Determination of total nitrogen content in the plant biomass of energy willow was performed to quantitatively confirm the mechanism of biological nitrate uptake and to assess the role of the plant component in the overall water purification process. Table 2 presents the results of experimental studies on total nitrogen content in the plant biomass of energy willow.

The amount of accumulated nitrogen was calculated using the formula:

$$N_{acc} = \frac{m \cdot C_N}{100} \quad (2)$$

where: m – the dry mass of the plant, g; C_N – the nitrogen content, %.

The obtained results showed that with increasing initial nitrate concentration, there is a statistically significant increase in nitrogen content in plant tissues from 1.45% to 2.12% of dry mass. The total amount of accumulated nitrogen increased almost 1.7-fold.

Correlation analysis established a strong positive relationship between initial nitrate concentration and accumulated nitrogen (r ≈ 0.91). Approximation of the data by the least squares method yielded a linear dependence of the amount of accumulated nitrogen on the initial nitrate concentration in water:

$$N_{acc} = 4.2 \cdot C_{\text{in}} + 225 \quad (3)$$

The coefficient of determination for this relationship is $R^2 \approx 0.83$. The obtained equation indicates that with increasing initial nitrate concentration, there is a proportional increase in nitrogen accumulation in plant tissues.

For a plantation area with a planting density ρ (plants/ha), the amount of nitrogen removed through the biological mechanism can be determined using the following equation:

$$N_{bio,ha} = \frac{(4{,}2 \cdot C_{\text{in}} + 225)\rho}{10^6} \quad (4)$$

where: $N_{bio,ha}$ – the amount of nitrogen removed biologically, kg/ha.

At a density of 15,000 plants/ha and a nitrate concentration of 25 mg/L, the amount of removed nitrogen $N_{bio,ha} \approx 80 \div 120$ kg N/ha per year, which is consistent with literature data [16, 17].

The accumulation of nitrogen in plant tissue confirms the importance of biological uptake as the leading purification mechanism alongside microbiological transformation. According to the calculations, the share of biological accumulation

Table 1. Reduction of nitrate concentrations in the model phytofiltration system with energy willow (M – mean value (n = 3), SD – standard deviation)

C_{in}, *mg/L*	Time, *h*	C_{out}, *mg/L (M ± SD)*	*Efficiency, % (M ± SD)*
10	1	7.6 ± 0.3	24.0 ± 3.0
10	6	6.1 ± 0.4	39.0 ± 4.0
10	24	4.6 ± 0.3	54.0 ± 3.0
25	1	20.2 ± 0.5	19.2 ± 2.5
25	6	16.1 ± 0.6	35.6 ± 2.8
25	24	12.3 ± 0.7	50.8 ± 3.0
50	1	41.3 ± 0.8	17.4 ± 2.0
50	6	33.6 ± 0.9	32.8 ± 2.4
50	24	25.8 ± 1.0	48.4 ± 2.5

Table 2. Total nitrogen content in plant biomass

C_{in}, mg/L	Plant dry mass, g	N content, %	Accumulated N, mg/plant
10	18.4 ± 1.2	1.45 ± 0.08	267 ± 22
25	19.6 ± 1.4	1.78 ± 0.10	349 ± 28
50	21.1 ± 1.6	2.12 ± 0.12	447 ± 35

is approximately 55÷65% of the total nitrate mass reduction in the system [18, 19].

The third important factor is the microbiological transformation of nitrogen in the rhizosphere. The root system of willow creates a specific microenvironment that stimulates the development of microorganisms capable of nitrification and denitrification processes. As a result, a portion of the nitrates may be converted to gaseous forms of nitrogen and removed from the system [25, 26].

Analysis of the obtained data also showed that the purification efficiency decreases in relative terms with increasing initial nitrate concentration in the solution (Figure 3).

This indicates the limited absorption capacity of plants and the soil substrate within a short contact time. At the same time, even under conditions of high concentrations (50 mg/L), the system ensured a reduction in nitrate content by nearly half, confirming the high potential of using energy willow in phytofiltration technologies.

Thus, the results of the laboratory experiment confirm the efficiency of using soil-plant systems with energy willow for reducing nitrate concentrations in water. It was established that under model experimental conditions, the water purification efficiency for nitrates averaged 40–60% and increased with longer contact time between the solution and the plant root system. The obtained results indicate the potential of applying phytofiltration systems with energy willow for the purification of drainage and surface waters in agricultural landscapes.

At the same time, for an objective assessment of the obtained results, it is advisable to consider them in the context of other approaches to reducing nitrate loading within catchments. In modern water quality management practice, both agronomic measures (optimization of fertilizer application rates, regulation of crop structure) and landscape-based nature-oriented solutions are

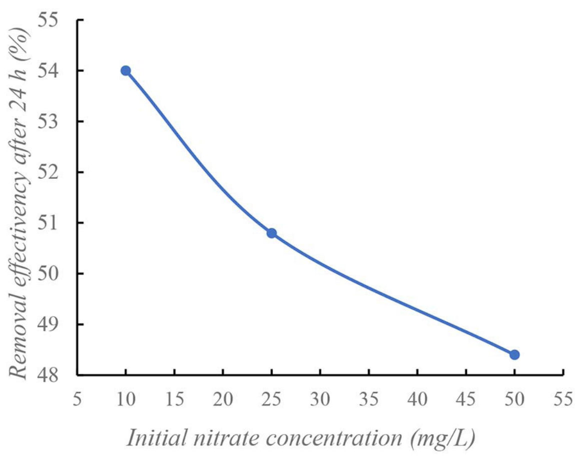

Figure 3. Dependence of nitrate removal efficiency on the initial NO_3^- concentration in the model solution (after 24 hours of contact)

employed, including riparian buffer strips, shelterbelts, floodplain restoration, and the creation of constructed wetland systems.

Studies on the effectiveness of riparian buffer strips demonstrate that, given sufficient width and a favorable hydrological regime, they can provide a substantial reduction in nitrate concentrations in surface and subsurface runoff [10, 17, 18, 24]. The main mechanisms involved are biological nitrogen uptake by plants and microbiological denitrification in the soil environment [12, 19, 20]. However, the effectiveness of such systems largely depends on the strip width, vegetation type, and water exchange intensity, and with insufficient contact time between water and the root zone, the reduction in nitrate concentration may be limited [10, 11, 24].

Floodplain restoration and the rehabilitation of natural hydromorphic ecosystems are also considered effective tools for enhancing denitrification processes and reducing nitrogen loading on river systems [25]. However, the implementation of such measures requires significant territorial resources and comprehensive management of the hydrological regime. In urban and transformed landscapes, an additional constraint is the disruption of the natural connectivity between groundwater and surface water, which affects the intensity of nitrogen transformations [26].

Agronomic approaches aimed at reducing nitrate leaching from arable lands are a necessary component of integrated water resource management [27, 28, 31, 32]. However, even under optimized fertilization conditions, it is difficult to completely prevent diffuse pollution, especially in regions with a high proportion of intensive agriculture.

Against this background, the use of energy willow as a component of phytofiltration strips offers a number of significant advantages. According to long-term studies of short-rotation willow coppice plantations, such stands are capable of reducing nitrate concentrations in groundwater through intensive nitrogen uptake and the development of a robust root system [21, 22, 33]. An additional advantage is the possibility of using the biomass as an energy resource, which enhances the economic attractiveness of the technology [23]. Unlike grass buffers, where a portion of the accumulated nitrogen returns to the soil after vegetation dieback, regular harvesting of willow biomass ensures long-term nitrogen removal from the catchment ecosystem. The experimental results obtained in this study (40–60% reduction in nitrate concentration depending on contact time) are consistent with literature data on the effectiveness of forest and shrub buffer systems [17, 21, 24, 34] and confirm that the key factor is the duration of hydraulic contact between water and the root zone. At the same time, the implementation of the method has a number of limitations. The purification efficiency is significantly dependent on hydrological conditions, particularly the duration of water contact with the root zone. Under conditions of intensive surface runoff or short water residence time in the filtration strip, the degree of nitrate concentration reduction may be lower. The effectiveness also varies depending on the initial contamination level and the seasonal dynamics of plant growth, which causes variability in performance indicators throughout the year. Furthermore, the implementation of phytofiltration strips requires the allocation of land areas and coordination with the existing land use structure, which may limit application in regions with a high intensity of agricultural development.

Thus, compared with engineered water treatment facilities, the proposed nature-based approach is less energy-intensive and more integrated into the landscape structure of the catchment; however, it requires comprehensive planning and consideration of spatiotemporal factors. It should be considered as a component of an integrated water quality management system that combines agronomic, landscape, and biological measures for the control of diffuse nitrate pollution.

To quantitatively assess the relationship between the initial nitrate concentration in the model solution (C_{in}), the duration of water contact with the soil-plant system (τ), and the purification efficiency (E), a correlation analysis was performed using the Spearman rank correlation coefficient (r_s). The choice of the non-parametric method was determined by the small sample size (n = 9) and the absence of grounds to assume a normal distribution of the studied variables.

The calculation results showed the presence of a very strong positive statistically significant relationship between the duration of solution contact with the root system and purification efficiency ($r_s = 0.95$; $p < 0.01$). This indicates a regular increase in the degree of nitrate removal with increasing water residence time in the phytofiltration system.

A moderate negative correlation was established between the initial nitrate concentration and purification efficiency ($r_s = -0.62$; $p \approx 0.08$), reflecting a tendency for the relative purification efficiency to decrease at high levels of initial contamination. This pattern is consistent with the limited absorption capacity of the plant and microbiological system.

To quantitatively describe the established trend, a generalized empirical mathematical model was constructed that approximates the effect of contact duration and initial concentration on purification efficiency:

$$E = a \cdot ln(\tau) - b \cdot C_{in} + c \quad (5)$$

where: E – the purification efficiency, %; τ – the contact duration, h; C_{in} – the initial nitrate concentration, mg/L; a, b, c – empirical model coefficients.

Based on the regression estimation for the experimental data, the following approximate equation was obtained:

$$E = 10.8 \cdot ln(\tau) - 0.27 \cdot C_{in} + 28.5 \quad (6)$$

The coefficient at the logarithm of time is positive ($a > 0$), which confirms the increasing nature of the relationship; however, the logarithmic form of the function reflects a gradual decrease in the rate of efficiency increase with increasing contact time. This is consistent with the biological nature of the process, as the intensity of nitrate uptake over time transitions to a saturation regime.

The negative coefficient at C_{in} ($b > 0$ in the negative term) characterizes the decrease in relative purification efficiency with increasing initial loading, which corresponds to the experimentally established trend.

The coefficient of determination of the model is $R^2 \approx 0.89$, which indicates a high level of agreement between calculated and experimental values and allows the model to be used for predictive assessment of phytofiltration system efficiency within the studied parameter range.

The obtained results confirm that the determining factor in the formation of purification efficiency is the duration of water contact with the root system, while the influence of initial concentration has a limiting character. The practical significance of the established mathematical relationship lies in the possibility of using it for the engineering substantiation of phytofiltration strip parameters, particularly for determining the minimum required hydraulic contact time and predicting the expected level of nitrate load reduction.

Practical aspects of implementation

The conducted laboratory studies showed that the use of energy willow is characterized by a high efficiency of nitrate absorption from the aquatic environment. The obtained results indicate significant potential for using energy willow as a biological filter for reducing diffuse nitrogen contamination of surface waters.

To transfer these results to field conditions, the hydrological parameters of surface runoff must be taken into account. The main indicator determining the effectiveness of the phytoprotective strip is the contact time of water with the plant root system τ_f (s), which depends on the strip width B (m) and the surface runoff velocity v (m/s). Then the actual contact time:

$$\tau_f = \frac{B}{v} \quad (7)$$

To create a field model of purification efficiency, we substitute Equation 7 into the base model (6) and after certain mathematical transformations, we obtain:

$$E = 10.8 \cdot [ln(B) - ln(3600v)] - 0.27 \cdot C_{in} + 28.5 \quad (8)$$

Analysis of Equation 8 showed that the purification efficiency increases with increasing strip width and decreases with increasing runoff velocity. From Equation 8, a relationship was derived that allows determining the minimum width of the phytofiltration strip to achieve a given purification efficiency:

$$B = 3600v \cdot exp\left(\frac{E+0.27 \cdot C_{in} - 28.5}{10.8}\right) \quad (9)$$

Using the obtained Equation 9, the phytofiltration strip width was calculated as a function of the initial nitrate concentration in water and surface runoff velocity to achieve a purification efficiency of 50%. The calculation results in graphical form are presented in Figure 4.

Analysis of the obtained relationships (Figure 4) shows that there is a direct functional relationship between the surface runoff velocity and the required width of the phytofiltration strip. With increasing water flow velocity, the minimum strip width required to ensure the specified level of purification increases. This is explained by the fact that at higher water flow velocities, the contact time with the soil-plant system decreases, and accordingly, the intensity of biological uptake and microbiological transformation of nitrates is reduced. Under such conditions, to compensate

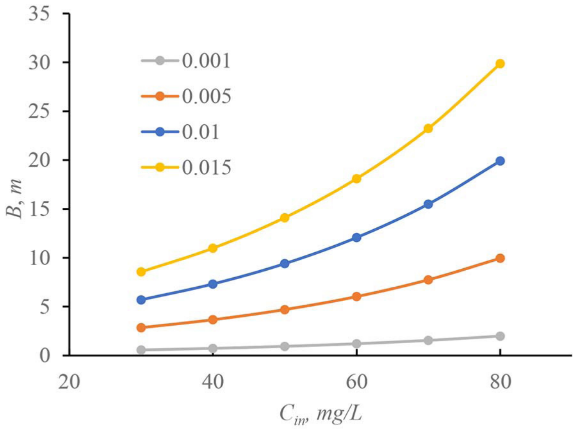

Figure 4. Dependence of the required width of the energy willow phytoprotective strip zone for achieving 50% nitrate removal efficiency at different surface runoff velocities *v* (m/s)

for the reduction in hydraulic contact time, the filtration path length must be increased, i.e., the width of the phytofiltration strip. According to the graph, at low surface runoff velocities (on the order of 0.001–0.005 m/s), typical of gently sloping areas of the agricultural landscape or areas with dense vegetation cover, a relatively small strip width of approximately 8÷10 m is sufficient. Under such conditions, the water moves slowly, ensuring adequate contact time with the plant root system and active nitrate uptake processes.

As the runoff velocity increases to values of approximately 0.01÷0.02 m/s, typical of areas with a steeper slope or sparser vegetation cover, the required phytofiltration strip width increases to 12÷15 m. This reflects the need to increase the biological filter area to maintain purification efficiency at the 50% level.

At even higher surface runoff velocities (above 0.02÷0.03 m/s), the graph demonstrates a sharper increase in the required strip width. In this case, the values may exceed 18÷20 m, which is associated with a substantial reduction in water residence time in the phytofiltration zone. This trend indicates that under conditions of intensive surface runoff, phytofiltration efficiency is significantly dependent on the spatial parameters of the buffer strip. The obtained relationship has important engineering and practical significance, as it allows using Equation 9 for preliminary calculation of the parameters of riparian phytofiltration strips in real agricultural landscapes. In particular, it provides the ability to determine the minimum required width of energy willow plantations considering the hydrological conditions of the territory and the projected surface runoff velocity [24].

Thus, the graph in Figure 4 confirms that the optimal width of the phytoprotective strip is a function of hydrodynamic conditions of surface runoff, and the efficiency of nitrate load reduction is largely determined by the duration of water contact with the soil-plant system. This justifies the feasibility of using the obtained mathematical model for designing nature-based purification systems for drainage and surface waters in agricultural catchments.

Considering the biological characteristics of energy willow and the research results, the design of a riparian phytoprotective strip was modeled, consisting of three main zones. The first zone is represented by grass vegetation with a width of 3÷5 m, whose primary function is to reduce surface runoff velocity and retain soil particles transported by the water flow. The second zone consists of energy willow plantations with a width of 8÷12 m, which play the main role in the process of nitrate nitrogen uptake and its accumulation in plant biomass. The third zone includes shrub and moisture-loving vegetation with a width of 3÷5 m, providing additional filtration of the water flow before it enters the water body. The proposed system ensures a gradual reduction in surface runoff velocity, retention of suspended particles, and biological uptake of nitrates by plants. With this strip configuration, the laboratory-established nitrate uptake efficiency can translate into field conditions as a reduction in nitrate nitrogen concentration in surface and drainage runoff by 35÷50%, depending on the intensity of water flow, soil type, and vegetation density [16–18]. A schematic model of the phytoprotective strip with energy willow is presented in Figure 5.

An important practical aspect is the agronomic management of phytofiltration strips during the initial stages of their formation. In the first years after establishment, it is necessary to ensure weed control, maintain optimal water regime, and protect young plants from mechanical damage. Subsequently, management is limited to periodic harvesting of energy willow biomass, which simultaneously serves to maintain the high environmental efficiency of the system.

An important element of the phytoprotective strip functioning is the regular removal of willow biomass, which ensures the actual export of accumulated nitrogen from the ecosystem. At an average energy willow productivity of 10÷15 tonnes of dry biomass per hectare per year, the total nitrogen removal can be 80÷150 kg *N*/ha per year,

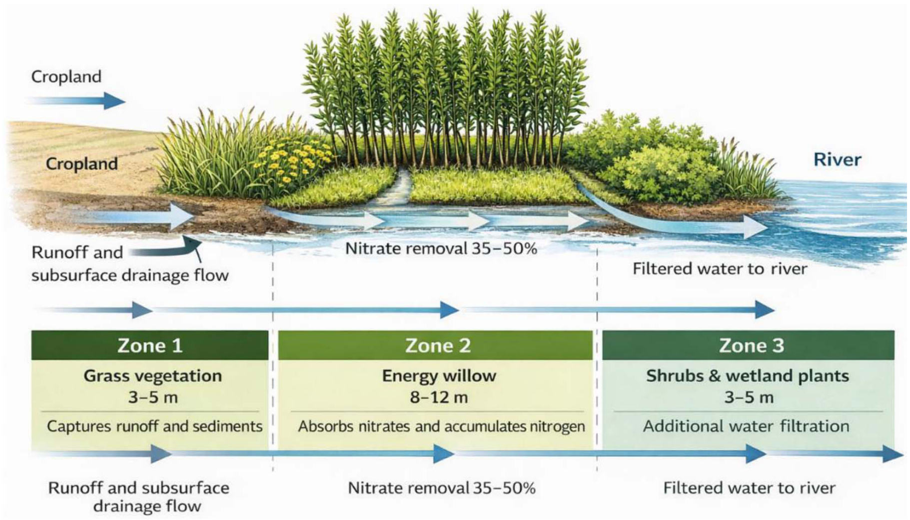

Figure 5. Conceptual model of a vegetative buffer strip with energy willow for nitrate removal from agricultural runoff

confirming the environmental feasibility of using such plantations to reduce diffuse contamination of water bodies.

The obtained energy willow biomass can be used as a renewable energy source, particularly for the production of thermal energy or biofuel, creating an additional economic incentive for land users and local communities. The combination of the environmental protection function with the possibility of economic utilization of biomass increases the level of acceptance of phytofiltration strips in agricultural land use practice.

From the perspective of water resource management, the implementation of phytofiltration strips with energy willow should be considered as a component of an integrated approach to reducing diffuse pollution. Their efficiency significantly increases when combined with the optimization of mineral fertilizer application systems, adherence to crop rotations, and the implementation of soil conservation technologies [27, 28]. Regulatory and institutional support also plays an important role, particularly the designation of riparian protective strips and the stimulation of environmentally oriented measures at the level of regional programs.

Thus, phytofiltration strips using energy willow represent a practically feasible, scalable, and adaptable measure for agricultural catchment conditions that combines environmental efficiency with socioeconomic viability. Their implementation allows not only reducing nitrate loading on water bodies but also enhancing the ecological resilience of agricultural landscapes in the long term.

CONCLUSIONS

The conducted studies confirmed the efficiency of using energy willow (*Salix* spp.) as a component of phytofiltration systems for reducing nitrate concentrations in water. Laboratory experiments, performed taking into account the conditions of the Vereshchytsia River catchment, showed that the passage of water through the soil-plant substrate with the willow root system provides a reduction in nitrate content by an average of 40–60%. It was established that the purification efficiency increases with increasing duration of water contact with the soil-plant system. The nitrate removal process has a complex character and is determined by the combination of physicochemical filtration, biological nitrogen uptake by plants, and microbiological transformation of nitrogen compounds in the rhizosphere. Based on the obtained results, the parameters of riparian phytofiltration strips were substantiated, with widths ranging from approximately 8 to 20 m depending on surface runoff velocities. The obtained results confirm the feasibility of applying phytofiltration strips with energy willow to reduce diffuse nitrate contamination in the Vereshchytsia River catchment.

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