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Turbidity and color removal from river water with tree xylem as a natural filter

Doğal bir filtre olarak ağaç ksilemi ile nehir suyundan bulanıklık ve renk giderimi

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Abstract

This study evaluates the efficiency of xylem-based filters derived from five tree species—Pinus pinea, Populus nigra, Pinus brutia, Tilia tomentosa, and Quercus petraea—in removing turbidity and color from Bartın River water samples. Filtration experiments were conducted under varying pressure conditions (5 psi, 10 psi, and 15 psi) to assess the performance of each xylem filter based on flow rate, turbidity removal, and color reduction. The results highlighted that gymnosperm species, particularly Pinus pinea, exhibited high turbidity (up to 99.36%) and color removal efficiency (up to 95.58%) at lower pressures. Conversely, angiosperm species demonstrated higher flow rates but lower filtration efficiencies. Durability analysis of pit membranes revealed that high pressure could compromise their integrity, slightly reducing efficiency. These findings indicate that xylem-based filtration is a promising, cost-effective, and eco-friendly water purification method suitable for areas lacking advanced water treatment systems. Further optimization of pressure conditions and enhanced pit membrane durability are recommended to maximize efficiency and longevity.

Keywords: Xylem Filtration, Natural Water Purification, Sustainable Water Treatment, Eco-friendly Filtration, Wood-based Filtration, Plant Xylem

Öz

Bu çalışma, beş farklı ağaç türünden (Pinus pinea, Populus nigra, Pinus brutia, Tilia tomentosa ve Quercus petraea) elde edilen ksilem bazlı filtrelerin Bartın Nehri su örneklerinden bulanıklık ve renk giderimindeki etkinliğini değerlendirmektedir. Her bir ksilem filtresinin akış hızı, bulanıklık ve renk giderimi açısından performansını değerlendirmek için farklı basınç koşullarında (5 psi, 10 psi ve 15 psi) filtrasyon deneyleri gerçekleştirilmiştir. Sonuçlar, özellikle Pinus pinea olmak üzere gymnosperm türlerinin düşük basınçlarda bile yüksek bulanıklık (%99,36'ya kadar) ve renk giderim verimliliği (%95,58'e kadar) gösterdiğini ortaya koymuştur. Buna karşılık, angiosperm türleri daha yüksek akış hızları sergilemiş ancak daha düşük filtrasyon verimliliği göstermiştir. Pit membranlarının dayanıklılık analizi, yüksek basıncın zarların bütünlüğünü zayıflatabileceğini ve bunun da verimliliği bir miktar düşürebileceğini göstermiştir. Bu bulgular, ksilem bazlı filtrasyonun, gelişmiş su arıtma sistemlerine erişimi olmayan bölgeler için umut verici, düşük maliyetli ve çevre dostu bir su arıtma yöntemi olduğunu göstermektedir. Etkinliği ve dayanıklılığı en üst düzeye çıkarmak için basınç koşullarının daha fazla optimize edilmesi ve pit membran dayanıklılığının artırılması önerilmektedir.

Anahtar kelimeler: Ksilem Filtrasyon, Doğal Su Arıtma, Sürdürülebilir Su Arıtma, Çevre Dostu Filtrasyon, Ahşap Bazlı Filtrasyon, Bitki Ksilemi

1 Introduction

Water is the cornerstone of life on Earth and is indispensable for all living organisms. However, water resources are globally under serious threat due to rapid population growth, industrialization, urbanization, and environmental degradation. These threats manifest as a decrease in water quantity and a deterioration in water quality, particularly affecting surface water bodies [1]. The conservation and sustainable use of water resources have become increasingly important globally. In this context, improving the quality of surface water resources has become a priority in water management.

Today's water treatment methods do not always provide feasible solutions due to high costs and complex technological requirements [2]. While techniques such as reverse osmosis, activated carbon filtration, UV disinfection, coagulation, and sedimentation are widely used, most are based on high-cost and energy-intensive technologies [3]. Especially in developing countries and rural areas, these technologies are not always feasible options [4]. Therefore, research into more sustainable, low-cost, and accessible water treatment methods is gaining importance [5].

Using natural materials in water treatment has attracted attention due to their economical and environmentally friendly properties. Xylem is a vascular tissue that transports water from plant roots to leaves through fine tubular systems equipped with pit membranes that can filter contaminants [6], [7]-[9]. This natural filtration system within the xylem helps physically retain particulate pollutants while ensuring the safe transport of water.

This study uniquely investigates the differences in the real-world water treatment performance between gymnosperm and angiosperm tree species based on their xylem structures. While previous studies have generally been limited to specific laboratory conditions or a narrow range of tree species, this research provides a broader perspective by examining various tree species and testing the results on natural water sources [10]. Additionally, unlike previous studies that evaluate the effectiveness of xylem-based filters, this research compares the

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durability and filtration performance of pit membranes under different pressure levels [11].

There is an increasing body of literature on the potential of xylem-based filters in water treatment. Hacke et al. (2004) and Boutilier et al. (2014) demonstrated that the torus-margo pit membranes of gymnosperms play an influential role in water filtration under high pressure [12], [13]. Gymnosperms are distinguished by their specialized torus-margo pit membrane structures, which ensure the safe transport of water through the xylem and prevent the spread of air embolisms [14]. In contrast, angiosperms possess simpler pit membranes, which provide less resistance to water transport [15]. The role of these structures in water transport and filtration has been explored in various studies; however, most of these studies were conducted under specific laboratory conditions. Therefore, this study aims to provide a more comprehensive perspective by examining the impact of xylem structure differences between gymnosperm and angiosperm tree species on water filtration.

The primary objective of this study is to determine how different xylem structures perform in water treatment. This research, conducted on water samples taken from the Bartın River, compares the filtration capacities of gymnosperms (stone pine, Turkish pine) and angiosperms (black poplar, silver linden, sessile oak), which have two different types of xylem structures. The effectiveness of xylem-based filters in removing turbidity and color under different pressure conditions was investigated, and the potential of these filters as natural water treatment systems was assessed.

The findings of this study expand the existing knowledge by providing essential insights into how xylem-based filters can be used in water treatment. For example, this study tests the hypothesis that gymnosperms, with their torus-margo pit membrane structures, may be more effective than angiosperms in removing turbidity and color [10], [16]. However, due to the risk of damage to some pit membranes under high pressure, a slight decrease in turbidity and color removal efficiency was observed even in gymnosperms [17], [18]. These findings suggest that xylem-based filters can be successfully used in water treatment, but pressure control and optimization are critically important [19].

Given the differences between gymnosperms and angiosperms, studies on the efficiency of water transport and pressure resistance in both species provide important insights into plant physiology and ecology [20], [21]. Studies emphasize the critical role of pit membranes in water transport and their pressure resistance and indicate that membranes can be damaged by prolonged exposure to high pressures [22], [23].

The pore diameters of xylem structures, ranging between microfiltration and ultrafiltration (1-3 µm), and xylem vessel diameters (20-50 µm) indicate that these natural filters can be used in a wide range of water treatment applications [12], [13]. Gymnosperms typically withstand higher pressures better due to their more durable pit membrane structures. At the same time, angiosperms may exhibit lower performance under certain conditions due to their more simple and permeable structures [16]. Therefore, the performance of xylem-based filters in water treatment can vary depending on the tree species' xylem structure and the pressure applied.

This study approaches the applicability and effectiveness of xylem-based natural filters in water treatment from a broad perspective and demonstrates how different tree species perform in this process. The findings suggest that gymnosperm species such as stone pine can potentially develop low-cost and environmentally friendly water treatment systems. This study aims to make a significant contribution to the literature on the use of natural materials in water treatment and provide essential findings that will guide future research.

2 Materials and Methods

This study investigated the efficacy of xylem tissues from various tree species in purifying water. The research involved the use of five different tree species: stone pine (*Pinus pinea*), black poplar (*Populus nigra*), Turkish pine (*Pinus brutia*), silver linden (*Tilia tomentosa*), and sessile oak (*Quercus petraea*) (Table 1). The xylem tissue from each tree species was assessed through filtration tests using water samples from the Bartın River.

The collected branches were cut into 12 mm in diameter and length under laboratory conditions to optimize filtration capacity. These filter materials were sealed with epoxy resin, leaving one end open, to ensure that water passed exclusively through the xylem tissue. The epoxy resin was allowed to cure for 24 hours at 25°C, a critical step to prevent leakage during filtration. Every detail of the preparation process was meticulously carried out to ensure that the water would only pass through the xylem tissue during filtration.

As shown in Figure 1, the filtration tests were conducted using a modified dead-end filtration system. A constant air source pressured the filtration system. This system was optimized to measure the performance of xylem-based filters under constant pressures of 5, 10, and 15 psi. The xylem filters placed in the filtration module were tested individually at each pressure level. During filtration, a Hach/2100Q turbidimeter was used to measure turbidity in the filtrate, and a Hach DR3900 spectrophotometer was used for color measurements. During the tests, 20 mL of pure water was first filtered, followed by 75 mL of river water, and changes in the water's turbidity (NTU) and color (PtCo) parameters were recorded.

The water samples analyzed were retrieved from the Bartın River, with a turbidity measurement of 103 NTU and a color measurement of 44 PtCo prior to filtration. Each filtration assessment was conducted thrice at various pressure levels, and the findings were presented as mean values.

Table 1. Characteristics of the tree species used in the study

Feature	Silver Linden (*Tilia tomentosa*)	Sessile Oak (*Quercus petraea*)	Black Poplar (*Populus nigra*)	Turkish Pine (*Pinus brutia*)	Stone Pine (*Pinus pinea*)
Pit Membrane Diameter	1-3 µm	1-2 µm	1-3 µm	1-2 µm	1-2 µm
Xylem Vessel Diameter	20-50 µm	30-60 µm	20-50 µm	1-2 µm	30-50 µm
Reference	[24], [25]	[26], [27]	[28], [29]	[24], [30], [31]	[26], [27]

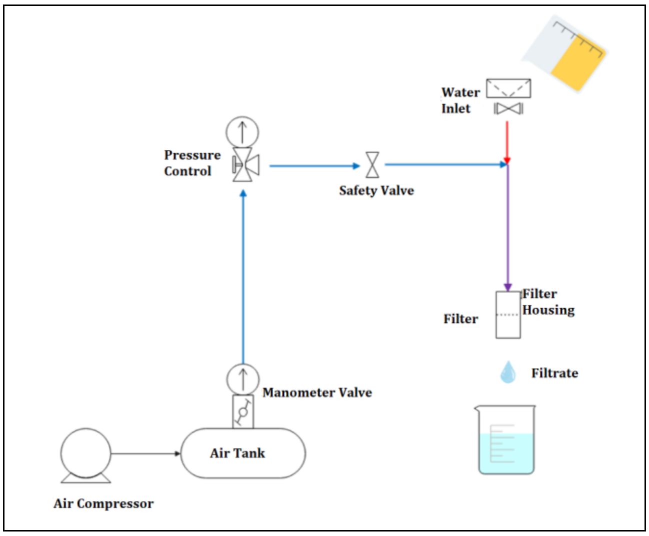

Figure 1. Schematic diagram of the filtration module and test system.

During each test, a 75 mL water sample was introduced into the filtration module, and any alterations in the turbidity (NTU) and color (PtCo) components in the filtrate were recorded. A modified dead-end filtration system was employed to evaluate the filtration efficiency. As shown in Figure 2, the filtration module was equipped with the prepared xylem filters and tested under operational conditions. This figure illustrates the setup of the filter within the module.

The water flow rate passing through the xylem tissue at each pressure level and the enhancements in water quality (turbidity and color removal) were subjected to comprehensive analysis. These evaluations are vital for comprehending the variances in efficiency discussed in the results section.

Figure 2. View of the filter placed in the filtration module under operation

3 Results

The efficiency of xylem structures from gymnosperm and angiosperm tree species in purifying water was assessed through filtration tests conducted on water samples from the Bartın River. The study phase examined each tree species' flow rate, turbidity removal, and color removal efficiencies under varying pressure conditions. The results unequivocally showcased the influence of tree species' xylem structures on water filtration (Table 2).

The unique torus-margo pit membrane structures of gymnosperms ensure efficient water transport under high pressure. This study found that stone pine (*Pinus pinea*) and Turkish pine (*Pinus brutia*) exhibit high turbidity and color removal efficiencies even under high-pressure conditions. Notably, stone pine achieved a remarkable 99.36% turbidity removal rate at five psi pressure and a 95.58% color removal rate, with the lowest flow rate recorded at 1.21 mL/min.

Table 2. Filtration performance of various tree species at different pressure levels

Sample	Pressure (psi)	Flow Rate (mL/min)	Turbidity Removal Efficiency (%)	Color Removal Efficiency (%)
Stone Pine (*Pinus pinea*)	5	1.21	99.36	95.58
	10	3.05	98.2	92.92
	15	5.23	97.04	90.26
Black Poplar (*Populus nigra*)	5	2.64	94.56	86.62
	10	7.54	90.62	82.15
	15	11.18	88.59	79.41
Turkish Pine (*Pinus brutia*)	5	1.635	98.86	94.92
	10	5.28	97.43	92.16
	15	7.92	96.17	90.02
Silver Linden (*Tilia tomentosa*)	5	1.5	97.5	90.5
	10	4.2	95.22	88.71
	15	6.8	93.48	86.25
Sessile Oak (*Quercus petraea*)	5	1.7	95.35	87.92
	10	5.24	92.76	84.58
	15	8.27	90.82	82.11

These results emphasize the potential of xylem structures in water purification and underscore the superior performance of gymnosperm species in this process, suggesting their viability as an effective filter material for water purification. Turkish pine, under 15 psi pressure, achieved a 94.56% turbidity removal rate and an 86.62% color removal rate, demonstrating significant success and reinforcing the effectiveness of gymnosperm species in water purification under high-pressure conditions.

Figure 3 shows the cake layer formation on the surface of the stone pine filter, which can negatively affect flow rate efficiency and necessitate regular maintenance of the filter. However, the formation of the cake layer can enhance filtration capability [32]. The formation of a cake layer on filtration surfaces, such as those observed in stone pine, can indeed have a dual effect. While the layer can negatively impact flow rate efficiency by increasing resistance, it can also enhance filtration by acting as an additional filter that captures finer particles. This phenomenon is well-documented in the literature, where studies have shown that the cake layer contributes to the overall filtration efficiency, especially in membrane and dead-end filtration systems [33].

Figure 3. Cake layer formation on the filter surface (stone pine)

On the other hand, angiosperms, due to their simpler pit membrane structures, exhibit lower resistance to water transport. The angiosperm species used in the study, such as black poplar (*Populus nigra*), silver linden (*Tilia tomentosa*), and sessile oak (*Quercus petraea*), generally provided higher flow rates compared to gymnosperms but showed lower turbidity and color removal efficiencies even under low-pressure conditions. For instance, under five psi pressure, black poplar achieved a turbidity removal rate of 94.56% and a color removal rate of 86.62%, with a flow rate of 2.64 mL/min. These results indicate the factors that limit the effectiveness of angiosperm xylem structures in water purification. Although silver linden achieved a noteworthy turbidity removal rate of 97.5% and a color removal rate of 90.5%, it was not as effective as gymnosperms. These findings demonstrate that the xylem structure of angiosperms performs less effectively in water purification than gymnosperms.

The impact of various pressure levels on the water purification capabilities of different tree species was meticulously analyzed. It was observed that while gymnosperms exhibited strong performance under high pressure, specific pit membranes were susceptible to damage. These damages could potentially affect filtration performance, resulting in a slight decrease in turbidity and color removal efficiency. However, species such as stone pine demonstrated effective water purification even under high pressure, with a remarkable color removal rate of 95.58%, showcasing the ability of gymnosperms to uphold efficient water purification under high-pressure conditions.

The comparison between angiosperm and gymnosperm species regarding water purification performance reveals interesting differences (Figures 4 and 5).

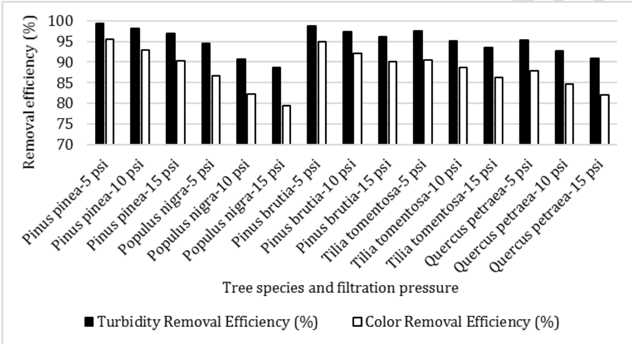

Figure 4. Turbidity and color removal efficiencies by tree species and pressure.

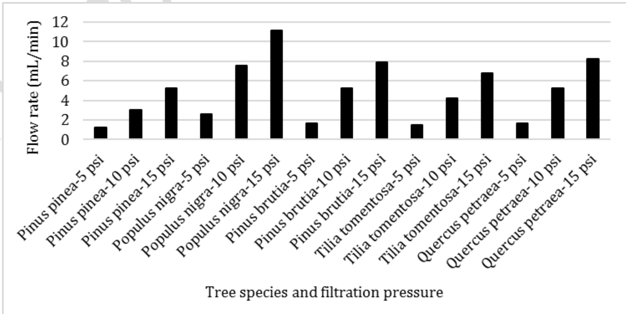

Figure 5. Filtrate flow rate by tree species and pressure

The pit membrane between the vessels of different angiosperm species and the tracheids of gymnosperm species is studied as an example (Figure 6) [34]. While black poplar, a type of angiosperm, achieved higher flow rates, its filtration efficiency notably decreased under high-pressure conditions. This indicates that angiosperms may be more susceptible to pressure, and the durability of their pit membrane structures could limit their water purification performance.

Figure 7 shows an example of SEM images of micro-explosion-treated and untreated poplar samples [35], highlighting the structural alterations that influence the filtration efficiency. In contrast, gymnosperms, mainly stone pine, demonstrated superior effectiveness in water purification, even under high-pressure conditions. This suggests that gymnosperms could serve as more effective natural filter materials for water purification, owing to their structural advantages [36] that ensure safe water filtration under high pressure. The studies concluded that bacteria can be retained by pit membranes under five psi pressure, but the permeability of viruses should be further investigated [37]. These findings underscore the potential of xylem-based filters for low-cost and environmentally friendly water treatment solutions, emphasizing further research to optimize gymnosperm and angiosperm species in water purification.

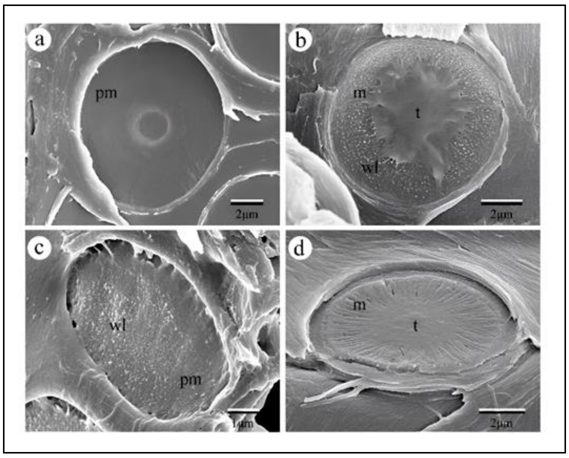

Figure 6. Representive SEM images of pit membrane in between vessels of different angiosperm species and tracheids of gymnosperm species. (a) The pit membrane from Catalpa bungei C. A. Mey. shows a very smooth surface with pit aperture visible through the pit membrane. (b) The pit membrane of Cedrus deodara (Roxb.) G. Don., showing scalloped torus margins and abundant warty layers inside the pit chamber. (c) The pit membrane from the Salix matsudana var. pseudo-matsudana, vessel shows a granular surface with many warty layers. (d) The pit membrane of Cephalotaxus sinensis, demonstrates extremely thick margo. Pm, pit membrane; m, margo; t. torus; wl. warty layer. Source: [34].

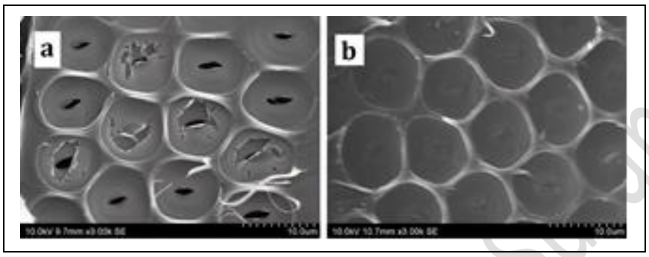

Figure 7. Representive SEM photographs of micro-explosion-treated (a) and untreated (b) poplar samples. Source: [35]

Turbidity-causing particles can vary in size over a wide range and are generally defined as microscopic particles between 0.1 µm and 100 µm. Soil erosion and sediments transported from riverbeds usually form larger particles in the 10-100 µm range, while microorganisms and organic matter are found as smaller particles in the 0.1-10 µm range [1]. The xylem filter successfully removed particles of different sizes in the river water used in this study. Depending on the tree species used, xylem pipes effectively removed particles above 20-30 µm (Figure 5), and pit membrane structures in xylem pipes removed particles above 1-3 µm. There are several studies on the biosorption of forest products and various plant materials [38], [39], [40], [41]. It is thought that during the filtration process with the xylem structures of the tree species used in this study, biosorption occurred during the contact of water with wood products, which contributed to the removal of color in the river water. A more detailed and multifaceted investigation of these processes is recommended.

Notably, it was evident that stone pine xylem filters displayed the lowest flow rate at five psi pressure while demonstrating the highest turbidity removal. Conversely, poplar xylem filters exhibited a higher flow rate but achieved lesser turbidity removal. These data shed light on the performance of each tree species' xylem structure in water purification.

The findings showcased the efficacy of xylem-based filters under diverse pressure conditions and the degree to which they could enhance water quality. This research underscores the potential of xylem tissues in water purification. It illustrates how these natural filtration techniques can aid in developing cost-effective and eco-friendly water treatment systems.

One of the notable characteristics of xylem-based filters is their biodegradable nature, which, although initially perceived as a limitation, can be considered an advantage in sustainable water treatment applications. Unlike synthetic or ceramic filtration membranes that contribute to long-term waste, xylem filters naturally decompose, reducing environmental burden and aligning with eco-friendly practices. This feature makes xylem-based filters highly suitable for temporary or emergency water purification systems, particularly in rural or underserved regions where access to advanced filtration technologies is limited. The natural degradation of xylem filters minimizes disposal concerns and facilitates easier integration into decentralized water treatment setups. While enhancing the durability of xylem filters through chemical treatments or coatings may extend their lifespan, their inherent biodegradability represents a significant step towards developing low-cost, renewable, and sustainable filtration solutions.

This study distinguishes itself by comparing xylem-based filters from five different tree species, addressing a gap in the literature where single-species or laboratory-focused studies dominate. By evaluating both gymnosperm and angiosperm species under varying pressure conditions with natural water samples, the research provides valuable insights into the relationship between xylem structure and filtration performance. This broader perspective enhances understanding of xylem-based filtration and supports future studies on optimizing and scaling this sustainable water treatment method.

4 Conclusions

The results highlight the potential of xylem vessels in trees for water filtration, effectively utilizing their permeability for physical separation processes. The study demonstrated that stone pine achieved the highest turbidity and color removal efficiencies, reaching 99.36% and 95.58%, respectively. Other species, including black poplar, Turkish pine, silver linden, and sessile oak, also exhibited notable removal rates. Filtration performance varied among species, emphasizing the importance of pressure control and optimization in enhancing xylem filter efficiency.

Despite having the lowest flow rate among the tested species, Stone pine successfully filtered 1.74 liters of water per day at five psi, meeting an individual's daily water needs. This finding reinforces the potential of xylem filters as a natural and sustainable solution for water purification, particularly in low-cost or emergency scenarios.

The study further suggests that xylem-based filtration systems could play a broader role in future water treatment strategies, offering an eco-friendly alternative to conventional methods. The observed efficiencies for turbidity and color removal were 95.58% and 99.36% for stone pine, 86.62% and 94.56% for black poplar and Turkish pine, 90.5% and 97.5% for silver linden, and 87.92% and 95.35% for sessile oak.

Differences in filtration performance are linked to the structural variations between gymnosperm and angiosperm xylem. The study noted that high positive pressures could damage pit membranes, slightly reducing filtration efficiency. As a result, optimizing pressure conditions remains critical for maximizing performance. However, stone pine consistently outperformed other species, underscoring its viability as a natural water filter.

In line with previous research, these findings highlight the potential for broader adoption of xylem-based purification systems. Future advancements, such as integrating xylem filtration with predictive technologies for turbidity monitoring [42], could further enhance their applicability and efficiency.

5 Author contribution statements

In the study, the Author contributed to the formation of the idea, design, literature review, evaluation of the results obtained, and examination of the results.

6 Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person / institution in the article prepared.

7 References

[1] Wetzel R.G. *Limnology: Lake and River Ecosystems*. Academic Press, 2001.

[2] Grzegorzek M, Wartalska K, Kaźmierczak B. “Review of water treatment methods with a focus on energy consumption”. *International Communications in Heat and Mass Transfer*, 143, 106022, 2023.

[3] Garg M, Rani R, Meena VK, Singh S. “Significance of 3D printing for a sustainable environment”. *Materials Today Sustainability*, 23, 100419, 2023.

[4] Shannon MA, Bohn PW, Elimelech M, Georgiadis JG, Marĩas BJ, Mayes AM. “Science and technology for water purification in the coming decades”. *Nature*, 452, 301–310, 2008.

[5] Peter-Varbanets M, Zurbrügg C, Swartz C, Pronk W. “Decentralized systems for potable water and the potential of membrane technology”. *Water Research*, 43(2), 245–265, 2009.

[6] Delelegn A, Sahile S, Husen A. “Water purification and antibacterial efficacy of *Moringa oleifera Lam*”. *Agriculture & Food Security*, 7(1), 1-10, 2018.

[7] Ramchander K, Hegde M, Antony AP, Wang L, Leith K, Smith A, Karnik R. “Engineering and characterization of gymnosperm sapwood toward enabling the design of water filtration devices”. *Nature Communications*, 12, 4098, 2021.

[8] Hashim A, Hashim NA, Junaidi MUM, Kamarudin D, Hussain MA. “Exploration of cassava plant xylem for water treatment: preparation, characterization and filtration capability”. *Water Science and Technology*, 86(4), 1055–1065, 2022.

[9] Holbrook NM, Ahrens ET, Burns MJ, Zwieniecki MA. “In vivo observation of cavitation and embolism repair using magnetic resonance imaging”. *Plant Physiology*, 126(1), 27–31, 2001.

[10] Pittermann J, Sperry JS, Wheeler JK, Hacke UG, Sikkema EH. “Mechanical reinforcement of tracheids compromises the hydraulic efficiency of conifer xylem”. *Plant, Cell & Environment*, 29(8), 1618–1628, 2006.

[11] Sperry JS, Hacke UG, Pittermann J. “Size and function in conifer tracheids and angiosperm vessels”. *American Journal of Botany*, 93(10), 1490–1500, 2006.

[12] Hacke UG, Sperry JS, Pittermann J. “Analysis of circular bordered pit function II. Gymnosperm tracheids with torus-margo pit membranes”. *American Journal of Botany*, 91(3), 386–400, 2004.

[13] Boutilier, M.S.H., Lee, J., Chambers, V., Venkatesh, V., Karnik, R.: “*Water filtration using plant xylem*”. PLoS One. 9, 1–11 , 2014.

[14] Tyree MT, Zimmermann MH. *Xylem Structure and the Ascent of Sap*. Springer, 2002.

[15] Domec JC, Gartner BL. “Cavitation and water storage capacity in bole xylem segments of mature and young Douglas-fir trees”. *Trees*, 15, 204–214, 2001.

[16] Choat B, Sack L, Holbrook NM. “Diversity of hydraulic traits in nine *Cordia* species growing in tropical forests with contrasting precipitation”. *New Phytologist*, 175(4), 686–698, 2007.

[17] Hacke UG, Sperry JS, Pockman WT, Davis SD, McCulloh KA. “Trends in wood density and structure are linked to prevention of xylem implosion by negative pressure”. *Oecologia*, 126(4), 457–461, 2001.

[18] Jansen S, Choat B, Pletsers A. “Morphological variation of intervessel pit membranes and implications to xylem function in angiosperms”. *American Journal of Botany*, 96(2), 409–419, 2009.

[19] Tyree MT, Sperry JS. “Vulnerability of xylem to cavitation and embolism”. *Annual Review of Plant Physiology and Plant Molecular Biology*, 40, 19–38, 1989.

[20] Dashti H, Tarmian A, Faezipour M, Hedjazi S, Shahverdi M. “Effect of pre-steaming on mass transfer properties of *Picea abies* L.”. *BioResources*, 7(2), 1907–1918, 2012.

[21] Gill RA, Ahmar S, Ali B, Saleem MH, Khan MU, Zhou W, Liu S. “The role of membrane transporters in plant growth and development, and abiotic stress tolerance”. *International Journal of Molecular Sciences*, 22(3), 2021.

[22] Jiao M, Yao Y, Chen C, Jiang B, Pastel G, Lin Z, Wu Q, Cui M, He S, Hu L. “Highly efficient water treatment via a wood-based and reusable filter”. *ACS Materials Letters*, 2(4), 430–437, 2020.

[23] Ooeda H, Terashima I, Taneda H. “Structures of bordered pits potentially contributing to isolation of a refilled vessel from negative xylem pressure in stems of *Morus australis* Poir.: Testing of the pit membrane osmosis and pit valve hypotheses”. *Plant and Cell Physiology*, 58(2), 354–364, 2017.

[24] Jansen S, Choat B, Pletsers A. “Morphological variation of intervessel pit membranes and implications to xylem function in angiosperms”. *American Journal of Botany*, 96(2), 409–419, 2009.

[25] Liu J, Wang Y, Wang T, Zhang X, Du D, Zhu X, Guo W, Zhang Y. “The xylem functional traits of eight subtropical tree species is closely related to the intervessel pits ultrastructure”. *Trees - Structure and Function*, 38, 13–26, 2024.

[26] Robert EMR, Mencuccini M, Martínez-Vilalta J. “The Anatomy and Functioning of the Xylem in Oaks”. In: Gil-Pelegrín E, Peguero-Pina JJ, Sancho-Knapik D (eds). *Oaks Physiological Ecology. Exploring the Functional Diversity of Genus Quercus L.* Springer, 2017, pp. 261–276.

[27] Cochard H, Bréda N, Granier A, Aussenac G. “Vulnerability to air embolism of three European oak species (*Quercus petraea* (Matt) Liebl, *Q. pubescens* Willd, *Q. robur* L.)”. *Annales des Sciences Forestières*, 49(3), 225–233, 1992.

[28] Hajek P, Leuschner C, Hertel D, Delzon S, Schuldt B. "Trade-offs between xylem hydraulic properties, wood anatomy and yield in *Populus*". *Tree Physiology*, 34(7), 744–756, 2014.
[29] Marron N, Ceulemans R. "Genetic variation of leaf traits related to productivity in a *Populus deltoides* × *Populus nigra* family". *Canadian Journal of Forest Research*, 36(2), 390–400, 2006.
[30] Schulte PJ, Hacke UG. "Solid mechanics of the torus–margo in conifer intertracheid bordered pits". *New Phytologist*, 229(3), 1431–1439, 2021.
[31] Held M, Ganthaler A, Lintunen A, Oberhuber W, Mayr S. "Tracheid and pit dimensions hardly vary in the xylem of *Pinus sylvestris* under contrasting growing conditions". *Frontiers in Plant Science*, 12, 2021.
[32] Delikanlı NE, Harman BI, Yiğit NO, Sardohan Köseoğlu T, Kitiş M, Köseoğlu H. "Separation of Cu^{2+} from membrane concentrate by SiO_2/3-Aminopropyltriethoxysilane-coated ceramic membrane". *International Journal of Environmental Science and Technology*, 18, 2021.
[33] Parlar İ, Jarma YA, Pek TO, Kabay N, Kitiş M, Yiğit NO, Yüksel M. "Effect of antiscalant usage and air diffuser perforation diameter on filtration performance of submerged flat sheet MBR for treatment of high salinity and scaling propensity wastewater". *Water*, 15(3), 2023.
[34] Li S, Wang J, Yin Y, Li X, Deng L, Jiang X, Chen Z, Li Y. "Investigating effects of bordered pit membrane morphology and properties on plant xylem hydraulic functions-A case study from 3D reconstruction and microflow modelling of pit membranes in angiosperm xylem". *Plant Methods*, 16, 2020.
[35] Ma Q, Zhao Z, Xu M, Yi S, Wang T. "The pit membrane changes of micro-explosion-pretreated poplar". *Wood Science and Technology*, 50, 1089–1099, 2016.
[36] Xia P, Gu J, Song W, Xie L, Wu Y, Zhang H, Li Q. "Contact mechanics between torus and pit border for developing air-seeding seal in aspirated bordered pits". *Forests*, 14(2), 2023.
[37] Boutilier, M.S.H., Lee, J., Chambers, V., Venkatesh, V., Karnik, R.: "*Water filtration using plant xylem*". PLoS One. 9, 1–11 , 2014.
[38] Delikanlı NE, Fil BA, Ucun Özel H, Gemici BT, Barış Özel H. "Biosorption of a crystal violet using *Equisetum telmateia* Ehrh.". *Iranian Journal of Chemistry and Chemical Engineering*, 43(1), 659–669, 2024.
[39] Gemici BT, Özel HU, Özel HB. "Adsorption property and mechanism of forest wastes based natural adsorbent for removal of dye from aqueous media". *Biomass Conversion and Biorefinery*, 2022.
[40] Delikanlı NE, Fil BA, Özel HU, Gemici BT, Özel HB. "Removal of crystal violet dye with an innovative biosorbent (*Equisetum ramosissimum* Desf.)". *Environmental Engineering and Management Journal*, 23(4), 587–598, 2024.
[41] Acar FN, Malkoç E. "Sulu ortamdan odun tozları kullanılarak nitritin adsorpsiyonu". *Mühendislik Bilimleri Dergisi*, 8(3), 381–385, 2002.
[42] Hrnjica B, Danandeh Mehr A, Behrem S, Ağıralioğlu N. "Genetic programming for turbidity prediction: hourly and monthly scenarios". *Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi*, 25(8), 992–997, 2019.