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IMPREGNATED WILLOW WOOD CHIPS (*SALIX VIMINALIS* L.): A NOVEL SOIL AMENDMENT FOR ENHANCING SOIL QUALITY

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ABSTRACT

This study introduces a novel method of treating willow chips (*Salix viminalis* L.) by impregnating them with a solution of conventional mineral fertilizers. Modified willow wood chips have the potential to utilize as an innovative soil amendment and offer benefits for agriculture, horticulture and forestry to improve soil water retention capacity, soil fertility and structure. Experimental results indicate the feasibility of developing a product with nitrogen (N) levels from a minimum of 2%, phosphorus (P) levels exceeding 0.5%, potassium (K) levels exceeding 1.5%, and an organic matter content over 90% of the dry weight.

KEYWORDS:Willow wood, impregnated wood chips, wood modification; soil amendment.

INTRODUCTION

Wood has been utilized for centuries as a versatile and renewable material across multiple sectors (Rowell 2012; Siciliano et al. 2023). Wood stands out as a remarkable renewable resource, offering a low carbon footprint and minimal embodied energy (Falk 2009).The wood modification sector has evolved significantly, with a growing focus on enhancing wood's physical, chemical, and biological properties. Traditional wood treatments including

thermal modification, chemical impregnation, and biological treatments improveits durability, dimensional stability, or resistance to biodegradation (Sandberg et al. 2017).

In this study, we propose a novel impregnated wood chips with a mineral fertilizers' solution, with the potential to utilize the modified wood as an innovative soil amendment.

To select an appropriate wood matrix for investigation, tree species with high absorption capacities were required. It has been confirmed in our previous research that willow wood chips (*Salix viminialis* L.) exhibit higher absorption capacity compared to oak, birch, pine, and beech (Spisak et al. 2020).

The structure of willow chips is composed of bark, periderm, a thin layer of phloem, and a larger layer of xylem. The xylem and phloem are integral parts of the vascular transporting system in plants, responsible for the movement of water, nutrients, and organic compounds (Hejnowicz 1973,1980). This vascular structure creates numerous empty spaces within the chips, potentially enhancing their ability to absorb and retain water and nutrients (Spisak et al. 2020). The bark of willow contains 8.3% tannins and glycosides. Moreover, the bark contains substantial amounts of salicylic acid derivatives, which are best known for their role in orchestrating plant immune responses (Spoeland Dong 2024). The focus on willow wood chips (*Salix viminialis L.*) was further supported by its resistance to pathogen colonization (Pei et al. 2003, 2004), making them an appealing choice for various applications, including agriculture, horticulture and potentially forestry. However, these wood chips can be earlier invaded by fungi and insects. Willow fungi were investigated by Mathiassen (1989) and Chlebicki (2002). Small diameter of willow twigs enables growth only small and early pathogens adapted to cellulose degradation: willow scab *Venturia saliciperda* willow cancer *Cryptodiaporthes*alicina, willow witches' broom *Taphrina sp*., *Diaportheeres, Valsellasalicis* (Grzywacz 1990), *Diatrype bullata* (Chlebicki 2005), *Dendrotelegriseocana, Dendrotelesalicicola* (Karasiński 2011). Schmidt (1990) presented more important pests *of Arthropoda* such as willow gall mites, stem borers and insects inducing galls. Wood chips from *Salix viminalis* L. are considered to be slow decomposers, as their tissues are rich in lignin, suberin, tannins, and other decomposition-resistant, natural compounds (Antoniadou et al. 2021). Incorporating willow chips, material rich in salicylic acids (Spoeland Dong 2024) into the soil, has a potential to enhance plant growth. According to Hayat et al. (2010) and Yalpani et al. (1994) and Senaratina et al. (2000) salicylic acid acts as a potent plant growth regulator capable of effectively modulating various growth responses in plants.

The aim of this study was to investigate an effect of impregnation of *Salix viminalis L.*wood chips with a solution of conventional mineral fertilizers, including aqueous urea nitrate, soluble potassium sulphate, and a multi-ingredient NPK fertilizer. We hypothesized that willow chips, due to their structural characteristics, have the capacity to absorb nutrients from a solution of mineral fertilizers during the impregnation process. Specifically, the study aimed to evaluate the chemical and physical properties of the impregnated willow wood chips including their nutrient and organic matter content as well as pH.

MATERIAL AND METHODS

Willow wood chips(*Salix viminalis* L.)

Three years old willow twigs were obtained from a commercial plantation in the Opole Voivodeship, Poland. Two fractions of willow chips were investigated. Fraction 1 consists of mechanically cut willow twigs, with chips ranging in length from 2.0 to 6.0 cm and diameters between 0.5 and 2.0 cm. The twigs were cut into cylindrical shapes (Fig. 1a). The bulk density of this fraction was measured to be 0.26 g/cm³. This larger particle size likely results in slower decomposition due to reduced surface area for microbial activity. The second fraction represents finely ground willow chips designed to promote faster decomposition. Willow twigs were ground into much smaller particles. The bulk density of this finer fraction was 0.22 g/cm³, slightly lower than that of the cylindrical stick form, due to the increased porosity and reduced particle size. The smaller particle size increases the surface area available for microbial and chemical interactions (Fig. 1b).Willow chips with a moisture content of 15% were used.

a) *b)*

Fig. 1: a) Fraction 1- willow chips in cylindrical stick form, b) fraction 2- grinded willow chips.

Bulk density

The empty 1cm³ measuring cylinder was placed on the analytical balance and the weight (W_0) was recorded. The cylinder was filled with willow wood chipsby slowly pouring through a tunel. Compaction was avoided by not shaking or tapping the cylinder during filling. The cylinder was slightly overfilled, allowing the chips to form a natural heap above the cylinder rim. A flat spatula was used to remove excess chips by drawing it horizontally across the rim of the cylinder, ensuring a level surface. The filled cylinder was weighed on the analytical balance and the weight (W_1) was recorded. Both willow wood chips fractions were measured using this same procedure. Bulk density was calculated:

$$Bulk\ Density\ (\frac{g}{cm^3}) = \frac{W_1 - W_0}{V} \quad (1)$$

where: W_1 - weight of the cylinder with wood chips (g); W_0 - weight of the empty cylinder (g); V - volume of the measuring cylinder (1cm³).

Impregnation methods

Four types of impregnation solutionswere used as follow:*(1)*Comprehensive multi-ingredient fertilizer NPK (S) 8-24-24 (+9) ÷ 8-10,5-19,9 (+3,6), *(2)*Soluble K sulphate in the form of fine crystalline powder:K – 50% K_2O (41.5% K), sulphur – 42.5% SO_3 (17% S); *(3)*Aqueous urea nitrate solution with composition: nitric nitrogen (NO_3) 7%, amoniacal nitrogen (NH_4) – 7,0%, amide nitrogen (NH_2) 14,0%, *(4)*Magnesium sulphate ($MgSO_4$).

Impregnation was conducted in two cycles utilizing non-pressure method according to Patent No. 227594, granted to the Research and Development Centre "ALCOR" Ltd. Willow wood chips were fully submerged in a mineral fertilizer solution in the first impregnation cycle. The chips remained immersed for 24 h at a temperature of 20° ±1°C. After 24 h, the chips were drained to remove excess solution. The drained wood chips were then re-submerged in the same mineral fertilizer solution in the second impregnation cycle. The second soaking also lasted 24 h at a temperature of 20°C ±1°C. After the completion of the second cycle, the chips weredrained again. The impregnated wood chips were left to dry at ambient temperature, maintained at approximately 20°C until an air-dry condition was reached. The same procedure was used for both fractions of willow wood chips labelled as fraction 1 (sample NO/61/102)and fraction 2 (sample NO/46/70).

Analysis

The radial sections of fraction 1 were examined using optical microscope with magnification ranging from 161x to 250x. The samples were cut with a scalpel along the transverse, radial, and tangential planes. Images were taken under reflected light. Scanning electron microscopy (SEM) was conducted with an accelerating voltage of 18 kV, providing detailed imaging of the wood structure. To further confirm the presence and distribution of mineral fertilizers within the willow wood chips, Energy dispersive X-ray spectroscopy (EDS) was performed providing a comprehensive elemental analysis of K, Mg, N, P, C, O.

The chemical analysis of impregnated willow chips of *Salixviminalis*L.

The organic substance content was determined using the gravimetric method for both fractions.The determination of organic matter was based on incinerating the sample in an electric furnace at a temperature of 550°C, after prior drying to a constant weight. During incineration, the organic matter undergoes complete combustion. The raw ash content is calculated from the difference in the sample's weight before and after combustion. The dried and ground test material is weighed into a porcelain crucible with a capacity of 50 cm³, which was previously calcined in a furnace at 550°C and weighed on an analytical balance with an accuracy of 0.001 g, in an amount of 5 g. The crucibles with the content were placed in an electric furnace and incinerated at 550°C until a uniform ash was obtained. The determination was performed in two replicates according to Eq. 2 and organic matter content was calculated according to Eq. 3:

$$x = \frac{(a-b)*100}{g} \quad (2)$$

$$\% \text{ organic matter} = 100 - x \quad (3)$$

where: x - % of raw (total) ash, a – mass of the crucible with ash after the combustion of organic matter (g), b – mass of the crucible (g), g – initial weight of the sample (g), x - % of raw ash.

The total nitrogen (N) content was determined using the Kjeldahl method. The sample was ground and homogenized. Grinding was carried out using an electric grinder. A 5 g portion of the tested sample was weighed and placed in a Kjeldahl flask. 20 cm³ of concentrated H_2SO_4 was measured into the Kjeldahl flask. The sample was mixed and placed in a heating block, initially heated on a low flame and then on a strong flame. From the moment the solution became decolorized, it was kept boiling for approximately 20 min. After cooling, to allow for the possibility of repeating the distillation without the need for re-mineralization, the contents of the flask were quantitatively transferred to a 100 cm³ volumetric flask and filled up to the mark with distilled water. In flat-bottomed flasks, 20-25 cm³ of 0.05 M standardized H_2SO_4 and a few drops of Tashiro indicator were measured. A 10 cm³ portion of the solution was measured for distillation. The dilution was considered in the calculations. Distillation was started in a distillation apparatus. The following parameters were set: H_2O: 100 ml, NaOH: 70 mlboric, distillation time 6 min, steam 100%. Reactions occurring during the entire determination process. Ammonium sulphate formed during mineralization, as the final decomposition product of various nitrogen forms, decomposes during distillation in an alkaline environment, releasing ammonia. The released ammonia binds the standardized sulfuric acid solution. The nitrogen content was calculated according to the formula:

$$\%N = \frac{(V_1 - V_2\ ) * 0{,}0014 * 100 * 10}{\mathrm{g}} \quad (4)$$

where: V_1 - the volume of 0.1 M NaOH solution [cm³] used for titrating the blank sample,V_2 - the volume of 0.1 M NaOH solution [cm³] used for titrating the tested sample,0.0014 - conversion factor: 1 cm³ of 0.05 M H_2SO_4 solution binds 0.0014 g of nitrogen (N),g - the weight of the organic fertilizer sample [g].

The phosphorus pentoxide (P_2O_5) content was determined using the spectrophotometric method. The reacting mixture was prepared by mixing solutions A, B, and C in a 1:1:1 ratio in the following order: a) a 1:2 HNO_3 solution was used, b) a 0.25% ammonium metavanadate solution was added, c) a 5% ammonium molybdate solution in 0.5 M/l H_2SO_4 was incorporated, which had been prepared by diluting 28.0 cm³ of concentrated H_2SO_4 to a total volume of 1000 cm³ with distilled water. HCl was prepared as a 1:1 solution. "A" standard solution: 1.917 g of analytical grade KH_2PO_4, which had been previously dried in a desiccator over concentrated H_2SO_4, was dissolved in distilled water in a 1000 cm³ volumetric flask. After complete dissolution, the flask was filled to the mark with distilled water. Each 1 cm³ of this solution contained 1 mg of P_2O_5. "B" standard solution: A volume of 100 cm³ of solution "A" was diluted to 1000 cm³ with distilled water. Each 1 cm³ of this solution contained 0.1 mg of P_2O_5.

A portion of the 1 cm^3 primary solution obtained from mineralization was measured into a test tube. 5 cm^3 of the reacting mixture was added. The volume of the primary solution was adjusted to 5 cm^3 using a 0.5 M/l H_2SO_4 solution. The solution was filled with water to the mark and thoroughly mixed. Simultaneously, 0, 1, 2, 4, 6, 8, and 10 cm^3 of standard solution "B" were measured into test tubes. 5 cm^3 of 0.5 M H_2SO_4 1:1 (depending on the mineralization method) and 5 cm^3 of the reacting mixture were added. The solutions were filled to the mark and mixed well. The prepared standards contained: 0, 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 mg P_2O_5, respectively. The blank sample was prepared with 1.0-5.0 cm^3 of the blank sample solution from mineralization. After 1 h, the intensity of the yellow coloration of the standard and tested solutions was measured using a spectrophotometer in cuvettes with a measured layer thickness of 1-5 cm, at a wavelength of 470 nm.Calculation of P_2O_5 content was calculated as:

$$\%P_2O_5 = \frac{(a-b)*V*100}{g*x*1000} \quad (5)$$

where: a – P_2O_5 content in the tested sample read from the calibration curve [mg], b – P_2O_5 content in the blank sample read from the calibration curve [mg], V – volume of the primary solution [cm^3], g – weight of the sample [g], x – volume of the primary solution taken for analysis [cm^3].

The potassium oxide (K_2O) content was determined using the flame photometry. 1.0 cm^3 of the primary solution obtained from the mineralization was measured into a test tube. The solution was filled to the mark with distilled water and mixed thoroughly.The blank sample was prepared in the same way using the blank sample solution. Into test tubes, 0.0, 1.0, 2.0, 4.0, 6.0, 8.0, and 10.0 cm^3 of the standard "B" KCl solution were measured, corresponding to 0.0, 0.2, 0.4, 0.8, 1.2, 1.6, and 2.0 mg K_2O, respectively. 1 cm^3 of 0.5 M H_2SO_4 solution was added to each test tube, the solutions were filled to the mark with distilled water, and mixed thoroughly. Into subsequent test tubes, 0.0, 1.0, 2.0, 4.0, 6.0, 8.0, and 10.0 cm^3 of the primary $CaCO_3$ solution were measured, corresponding to 0.0, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 mg CaO, respectively. 1 cm^3 of 1:1 HCl was added, the solutions were filled to the mark with distilled water, and mixed thoroughly. Into test tubes, 0.0, 1.0, 2.0, 4.0, 6.0, 8.0, and 10.0 cm^3 of the standard NaCl solution were measured, corresponding to 0.0, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 mg Na_2O, respectively. To the NaCl standard solutions, 1 cm^3 of the KCl solution ("A" solution) and 1 cm^3 of 0.5 M H_2SO_4 solution were added, the solutions were filled to the mark with distilled water, and mixed thoroughly.The content of K_2O was calculated according to:

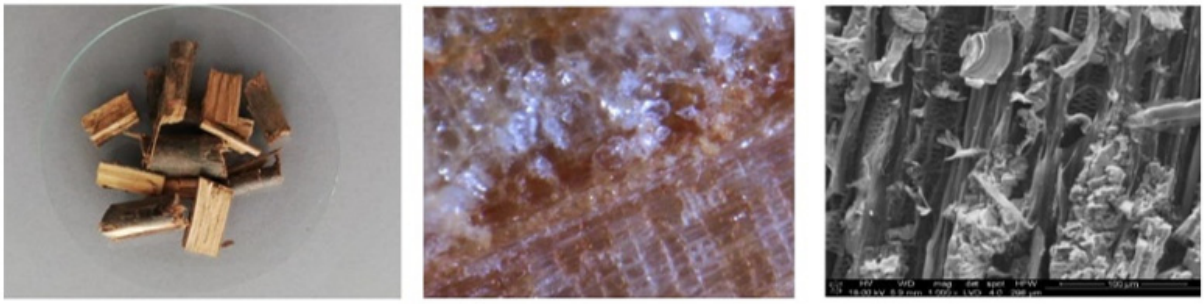
$$K_2O\% = \frac{(a-b)*V*100}{g*x*1000} \quad (6)$$

where: a – element content in the tested sample, read from the calibration curve [mg], b – element content in the blank sample, read from the calibration curve [mg], V – volume of the primary solution [cm^3], g – weight of the sample [g], x – volume of the primary solution taken for analysis [cm^3].

pH was determined using the potentiometric method. The tested material was weighed into 100 cm³ beakers in an amount of 10 g. The contents of the beaker were filled with 50 cm³ of distilled water, mixed thoroughly, and the pH measurement was performed using a pH meter.

RESULTS AND DISCUSSION

To validate the effectiveness of the impregnation process and confirm the distribution of mineral fertilizers within the wood structure, the samples underwent optical microscopy examination, followed by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) analysis. Fig.2 presents comprehensive analysis of willow wood chips impregnated with ammonium nitrate (NH_4NO_3) solution. Fig.2a illustrates the impregnated willow sample in an air-dried condition. Optical microscopy analysis (Fig. 2b) shows a section of the wood fibers, with clear differentiation between the internal fiber structure and the impregnated region.In the upper part of the image, crystalline structures are visible, which can be attributed to NH_4NO_3 deposition within the wood matrix.These deposits suggest successful penetration of the impregnant into the wood tissue. The SEM image (Fig. 2c) depicts crystalline structures of NH_4NO_3 at a 3000x magnification, revealing distinct morphological details of the crystal formation. The NH_4NO_3 crystals exhibit a well-defined, angular morphology, typical of inorganic salts, with some variation in crystal size and orientation across the image.



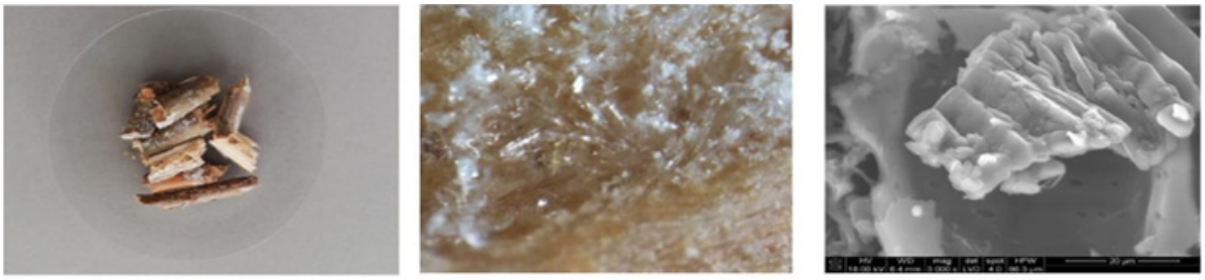
a) *b)* *c)*

Fig. 2: a) Willow wood chips impregnated with an NH_4NO_3 solution; b) optical microscopy analysis of the sample cross-section; c) SEM analysis of the sample at 3000x magnification.Source: ALCOR photo database.

The crystals present as faceted structures with sharp edges and smooth surfaces, indicating a high degree of crystallinity. Image supports the conclusion that NH_4NO_3 has effectively infiltrated the wood structure and crystallized within it.

Further, we analysed the sample of willow wood impregnated with solution of comprehensive multi-ingredient fertilizer NPK. Number of crystalline and semi-transparent deposits distributed within the wood structure is visible on Fig. 3b. The crystal-like deposits are observed within the wood's vascular structures, suggesting that the NPK solution permeated into the wood vessels and deposited nutrients upon drying. However, it appears

that larger vessels have a higher concentration of deposited material, possibly due to their greater capacity for fluid transport.

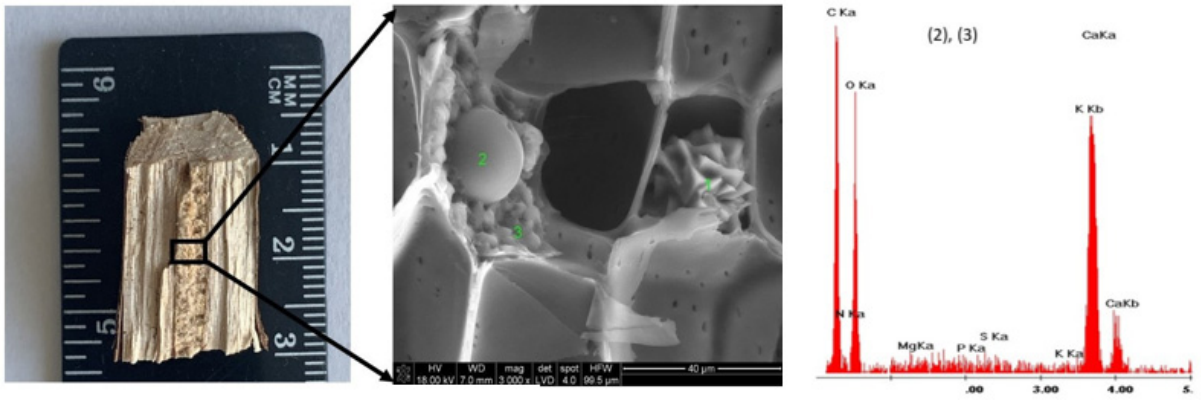


a) *b)* *c)*

Fig. 3: a) Willow chips of Salix viminalis L. impregnated with comprehensive multi-ingredient fertilizer NPK; B) optical microscopy analyse of sample cross section; c) SEM analyse of the sample at 3000x magnification. Source: ALCOR photo database.

The SEM analysis (Fig. 3c) revealed significant details regarding the distribution, size, and shape of mineral deposits within the wood matrix. The majority of deposits are small, with a strongly skewed size distribution, indicating an abundance of fine deposits interspersed with occasional larger clusters.

These findings imply that the fertilizer solution has penetrated the wood matrix with a tendency to form small, rounded deposits, concentrated within individual cells and pores. Fig. 4 presents an analysis of the parenchyma cells within the central pit of NPK-impregnated willow wood chip. The SEM analyse reveals large, spherical crystallites deposited within the parenchyma cells (Fig.4b). The EDS spectrum of the analysed sample (Fig.4c) reveals the presence of several key elements, including C,O, N, Mg, P, S, K, and Ca. These elements are present in varying concentrations, as indicated by the relative intensities of their characteristic peaks. This spectrum provides insights into the elemental composition of the sample.

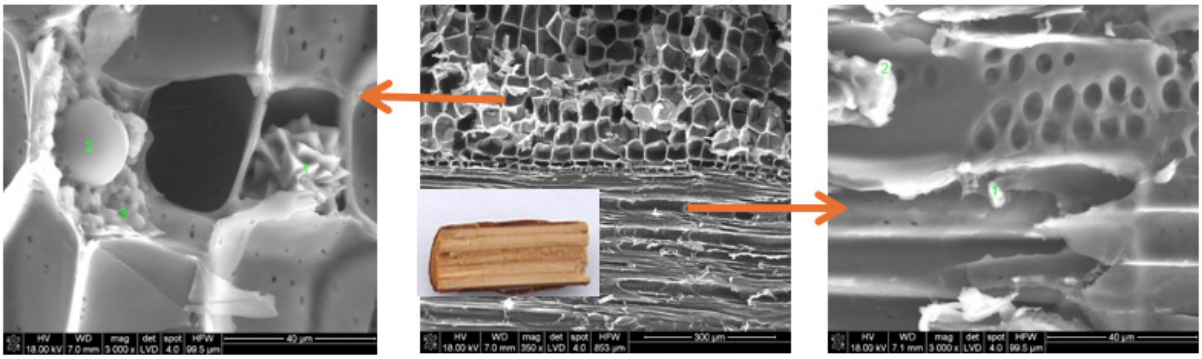


a) *b)* *c)*

Fig. 4: Crystallites deposited inside parenchyma cells of central pit of impregnated willow chips: a) cross-section of impregnated willow wood chips; b) SEM analyse; c) EDS analyse. Source: ALCOR photo database.

The significant C-Kα peak is consistent with the organic matrix of the willow wood chips. C is the primary component of the wood's cellulosic structure, and its prominence reflects the organic nature of the substrate. O, as indicated by a strong O-Kα peak, is also inherent to the wood matrix, due to cellulose, hemicellulose, and lignin. Additionally, O could be associated with $NO_3$and P groups from the NPK fertilizer. The presence of N suggests successful impregnation of the wood with nitrogenous compounds, likely from NH_4NO_3 in the NPK fertilizer. This is particularly significant as N is not typically abundant in untreated wood and indicates the incorporation of fertilizer-derived nutrients. K is anessential component of NPK fertilizers and is evident in the sample, confirming successful impregnation. The P peak confirms the addition of phosphate compounds.

Fig. 5 provides a detailed view of the crystallite mineral deposits within the core cells and xylem vessels of willow wood chips impregnated with NPK fertilizer. Fig. 5a shows large crystallite particles within the core cell. Fig.5b provides an overview of the willow wood structure, displaying both the core cells and xylem vessels in a cross-sectional view. The mineral deposits appear to follow the natural channels within the wood, which allows for the distribution of the fertilizer solution across multiple layers of the cellular structure. Fig. 5c zooms into the xylem vessels, where smaller crystallites are visible. These deposits are irregularly shaped. The observed deposit pattern suggests that the mineral solution penetrated deeply into the xylem vessels, forming crystallites within these narrow channels.



a) *b)* *c)*

Fig. 5: SEM analyse of crystallites minerals inside the core cells and the xylem vessels of willow wood chips impregnated with NPK fertilizer. Source: ALCOR photo database.

Comparative analysis of thecomposition of willow wood chips (*Salix viminalis* L.) impregnated with mineral fertilizersand a control sample not treated with mineral fertilizers is shown on Fig. 6.The analysis includes multiple measurements: three for the core, two for the xylem of the impregnated wood chips, and two for the control sample. The elemental composition of selected measurement points, indicated by green markers, was analysed using Energy dispersive spectroscopy (EDS). The results of this analysis are summarized in Tab. 1.

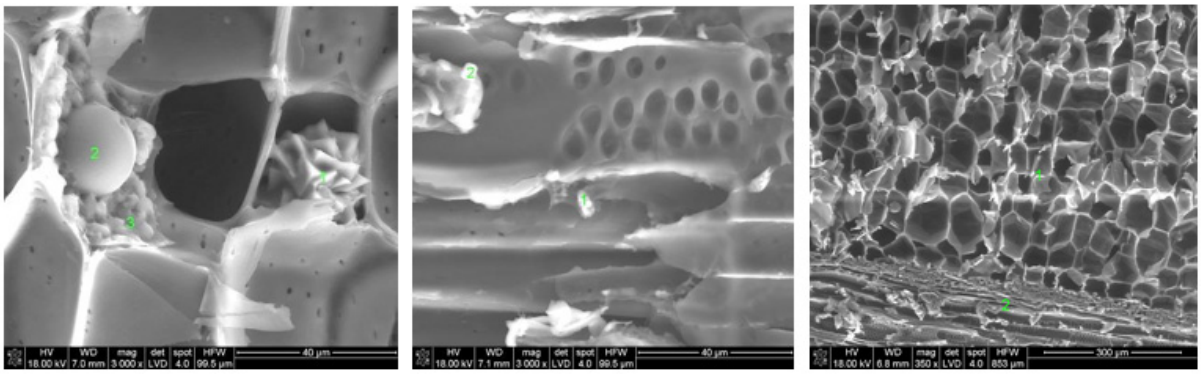


Fig. 6: Wood chips (Salix viminalis L.) impregnated with mineral fertilizers: core (a), xylem (b), and a control sample (c). Source: ALCOR photo database

The impregnation process has effectively enriched the willow wood chips with N, P and K, especially in the core, suggesting deeper penetration of fertilizers within the core structure. The control sample, untreated with fertilizers, demonstrates significantly lower or negligible levels of the primary fertilizer elements N, P and K underscoring the impact of the impregnation process in altering elemental composition of the willow wood. This analysis confirms that the impregnation treatment enhances the mineral profile of the willow wood chips.

Tab. 1: Comparative analysis of elemental composition of the organic matrix of impregnated and non-impregnated willow wood chips.

	Core			**Xylem**		**Control**	
	(% by dry matter)						
	Measurement points			Measurement points		Measurement points	
	1	2	3	1	2	1	2
Nitrogen	6,36	5,87	9,80	5,21	11,55	0,00	0,00
Phosphorus	0,18	0,42	0,97	0,29	0,18	0,00	0,15
Potassium	0,18	1,12	2,94	0,69	0,26	0,27	0,51
Magnesium	0,42	0,19	0,00	0,20	0,27	0,17	0,12
Sulfur	0,00	1,28	1,67	0,27	0,12	0,08	0,19
Calcium	18,40	0,58	0,65	0,12	0,11	0,00	0,27
Silicon	0,05	0,00	0,08	0,45	0,15	0,05	0,19

Chemical analyses

Subsequent to the optical microscopy, SEM, and EDS analyses, the chemical analysis of individual components of impregnated willow chips were conducted with the most important research results summarized in Tab. 2. Both fractions of impregnated willow chips were investigated.The chemical analysis of impregnated willow chips has successfully confirmed the presence of essential nutrients, including N over 2% both in sample NO/61/2021 and NO/46/70, P in sample NO/61/2021 (0,78%) and in sample NO/46/70 (0,86%), K in sample NO/61/2021 (2,47%) and in sample NO/46/70 (2,93%). The analysis revealed that the organic matter content in the sample NO/61/102 exceeding 90% of the dry matter (Tab.2).

Tab.2: Chemical analyse of samples.

Analyzed component	Sample NO/61/102	Sample NO/46/70
Organic matter (% of dry matter)	94,07	94,03
Total N (%)	2,59	2,59
P_2O_5 (%)	0,78	0,86
K_2O (%)	2,47	2,93
pH	3,42	3,41

Source: Research report NO/61/2021 and NO/46/2021. District agro-chemical station in Opole.

The effectiveness of impregnation of willow wood chips with mineral fertilizers has been validated through multiple measurement methods. The deposition of mineral fertilizers within the matrix of willow wood chips has been confirmed using optical microscopy, SEM, and EDS. Optical microscopy provided visual evidence of the distribution and form of the minerals within the willow chips matrix. Mineral crystallites were observed within the matrix of the willow chips, indicating successful penetration and deposition of minerals within the wood structure. SEM and EDS analyses provided high-resolution images that revealed the microstructural details and precise localization of mineral deposits, particularly N, P, and K. Subsequently, a series of chemical analyses was conducted on the components of the impregnated willow wood chips, specifically assessing organic matter content, as well as N, P, and K concentrations.

The results of this study highlight the potential of *Salix viminalis* (willow) wood chips as a medium for nutrient delivery in soil amendment applications. Willow is widely recognized for its rapid growth, high biomass yield, and adaptability to various environmental conditions (Keoleian and Volk 2005). Traditionally, willow wood chips have been utilized in applications such as mulching or biomass energy production. As demonstrated by Nyiraneza et al. 2022, using willow chips in soil applications is a good alternative to incinerating them for energy.

The study demonstrated the efficacy of the willow wood impregnation process, leveraging the intrinsic structural properties of willow (*Salix viminalis* L.) to achieve a nutrient-enriched product containing nitrogen (N) levels of at least 2%, phosphorus (P) exceeding 0.5%, and potassium (K) above 1.5%. This approach transforms willow wood chips into a value-added product with improved nutrient profiles.The utilization of willow chips in this manner aligns well with circular economy principles, promoting the valorisation of biomass residues. Additionally, this method promotes interdisciplinary collaboration, integrating wood science with agricultural, forestry, and environmental research domains.

Organic-mineral soil amendments are noted for their numerous beneficial effects particularly in enhancing soil physico-chemical properties and supporting biological functions in horticulture and agriculture (Carvalho et al. 2014; Pawlett et al. 2015; Silva et al. 2017). This type of soil amendments combine the benefits of organic matter with the efficacy of mineral nutrients and increased water holding capacity (Bouhia et al. 2022). In forestry, soil amendment studies have been carried out to aiming to improve forest soil quality via ash fertilization (Smenderovac et al. 2022;) and biochar additions (Bruckmann and Pumpanen 2019). Wood ash has potential to improve forest soil properties for instance via increased soil pH and compensate the loss of nutrients related to biomass harvesting but it also stimulates C mineralization (Helmisaari et al. 2014; Perkiömäki and Fritze 2005; Rosenberg et al. 2010).Organic amendments can aid in accelerating post-fire ecosystem resilience by

enhancing soil properties and providing essential nutrients to support plant growth (Cellier et al. 2013). This suggests that proposed impregnated willow wood chips is likely to provide similar benefits, for example, it could have a positive effect in post-fire restoration in forestry.

CONCLUSIONS

Results from this study demonstrate the successful modification of willow wood chips (*Salix viminalis* L.*)* properties by impregnating it with NPK mineral fertilizers. Specifically, the modified willow achieved nutrient profile with N levels of at least 2%, P levels exceeding 0.5%, K levels exceeding 1.5%, and an organic matter content exceeding 90% of the dry weight. Current research focused solely on the assessing the efficiency of impregnation of willow wood chips with solution of mineral fertilizers.

ACKNOWLEDGMENTS

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