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Impregnation Properties of Nigerian-Grown *Gmelina arborea* Roxb. Wood

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Abstract: The success of any wood treatment process and the measure of protection conferred on treated wood are determined by the uptake and penetration of the treatment chemicals, in addition to the efficacy of the chemicals used for the treatment. Hence, the level of treatability of wood species should be pre-determined prior to the wood treatment to ensure the overall protection of the treated wood. *Gmelina arborea* wood, due to its low durability, requires impregnation with chemicals for preservation or chemical modification to enhance its durability. However, more details are required to establish the influence of its anatomy on impregnation to recommend appropriate treatment methods. Therefore, gmelina wood samples were treated under pressure to determine the solution uptake and penetration, while anatomical studies were carried out with light microscopy, scanning electron microscopy (SEM), and energy dispersive X-ray spectroscopy (EDX) measurements. Variations in stem heights, stem diameters, and samples from other tree stands were considered. The outcome of the study showed that the liquid uptake was generally low for gmelina wood among the selected stands (16%–23%) and there was no significant difference in stem diameters; meanwhile, penetration was less than 4 mm in the axial direction, and very low in the lateral (radial and tangential) direction. Vessels of gmelina wood have abundant tyloses, while crystalline structures with needlelike shapes are present in a large proportion of the ray parenchyma cells, and are confirmed with SEM-EDX to be made up of calcium oxalate. The low liquid uptake and penetration in gmelina wood suggest that the impregnation of chemicals into its microstructure is next to impossible. Hence, alternative treatment methods other than those involving impregnation with chemicals should be sought to enhance its durability.

Keywords: Gmelina wood; impregnation; anatomy; Nigerian-grown; uptake; light microscopy; SEM-EDX

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1. Introduction

The rising demand for wood as a construction material has led to the over-exploitation of durable wood species indigenous to various forests in many countries of the world. Hence, attention is now being shifted towards the use of hardwoods from planted forests to meet the teeming demand for wood and wood products due to increasing population levels around the world. To balance the gap in the supply and demand for timber, the establishment and utilization of tree species such as *Gmelina arborea* comes to the fore.

Gmelina trees are grown in tropical and subtropical nations of the world, and being a fast-growing species, it can attain a maximum diameter at breast height (DBH) in the range of 60 to 80 cm within a rotation age of 20 years [1]. *Gmelina arborea* has be widely established in tropical areas due to its fast growth, ease and low cost of establishment, and regeneration (through coppicing) after it is harvested. In Nigeria alone, Onyekwelu et al. [1] previously reported that up to 112,000 ha of land was covered by gmelina plantations in 1996, and it was also projected that 800,000 ha of land would be covered by gmelina plantations in both the tropical and subtropical regions by the year 2020 [2]. Gmelina wood is very versatile

and is utilized for a variety of products ranging from pulp and paper, medium-density fiberboards, laminated veneer lumber, particleboards, pencils, match sticks, furniture, and a host of other products [2]. Gmelina wood shows great promise to be utilized in the future for the production of high-value wood products for building applications [3]. It is then clear that the scope of use of *Gmelina arborea* wood should be expanded beyond pulp and paper or furniture products [4]. Gmelina wood has a low durability [5], and in order to be used outdoors, it needs to be treated with preservatives or modification technology.

In wood treatment processes, chemicals are impregnated into the wood, and emphasis is placed on the level of uptake and penetration of the impregnated liquid. Aside from the fact that the adequate protection of wood substance is guaranteed by the toxicity or effectiveness of the active ingredients in the treatment chemicals, adequate uptake and deep penetration into the wood's structure are additional requirements to consider when treating wood with conventional wood preservatives or carrying out chemical modifications of large dimensions of timber. As the treated timber is expected to undergo further processing before it can become a final product, achieving only a shallow, superficial penetration or uptake will mean that most of the treated surfaces will be removed, thereby exposing the untreated wood. This makes the treated wood product suffer the same fate as the untreated product, leading to eventual failure and a shortened service life.

Achieving either a shallow or deep penetration or uptake in any wood species is dependent on the treatability of such species. Treatability has been previously described by Tarmian et al. [6] as the measure of the extent to which porous materials can be impregnated with liquids. The terms "liquid" here may refer to impregnation with wood preservatives in conventional wood treatments, with chemicals for wood modification purposes, or during chemical pulping. Sapwood and heartwood of several wood species have varying treatability classes as described in EN 350 [7] as: easy to treat (class I), moderately easy to treat (Class II), difficult to treat, especially when the lateral penetration is not more than 3 to 6 mm (Class III), and extremely difficult to treat (Class IV). The treatability of wood vis-à-vis its permeability to the treatment liquid is of great importance in the wood industry, especially for technical processes, such as preservative treatments, chemical modification, wood drying, and processes involving the surface modification of wood. This is to enhance the resistance of treated wood to biotic and abiotic factors (such as fungi, insects, bacteria, fire, weathering); all of these require the treatment chemicals to penetrate a certain depth beneath the wood surface [8].

Several methods have been used to improve the treatability of difficult-to-treat wood species in previous studies, but many of them are not effective, economically impracticable for large-scale wood treatments, or are only developed at the laboratory scale [6]. Pre-steaming and heat treatment methods have been used for roundwood and sawn timber to improve the penetration of preservatives into refractory wood species. However, most of these processes have shown inconsistent outcomes due to the differing effects that steaming has on different wood species [9]. The heat treatment of wood prior to impregnation may lead to the development of micro-cracks, breakdown of tyloses, rupturing of pits, and collapses of vessels and fiber tracheids; all of these may result in a slight improvement in the liquid uptake [10,11]. Meanwhile, Ahmed et al. [12] performed a heat treatment on European aspen and downy birch but found that the heat treatment resulted in the low uptake of tung oil and pine tar. Incising is a mechanical method in which steel knives or needles are used in making slits on the wood's surface to improve the liquid penetration and uptake. Incised wood has a lower aesthetic value and is not feasible for use for high-end products; additionally, incisions have a negative influence on the mechanical strength depending on the size of the timber incised, incision patterns, and incisions densities [13–15]. Other methods have been used to investigate the treatability refractory wood species, such as the use of penetration-enhancing liquids such as buffered amine oxide [16], heating of preservative solutions [17], pressure treatments through full-cell and empty-cell processes [18,19], microwave irradiation [20], and bio-incising involving the use

of fungi [8,21]. However, only incised wood is on the market but it has a problem with its aesthetics. The others are more or less at the research phase and are not used in practice.

Wood, being a heterogenous porous material, has a wide variety of factors influencing its treatability. Some of these factors include the microstructural anatomy, wood moisture content, drying method, preservative formulation (e.g., viscosity), and treatment techniques, such as pressure or non-pressure processes [6]. As the pathways for the movement of liquids are more diverse in hardwoods, the influence of wood anatomy becomes a major factor to consider in terms of their treatability. The vessels constitute the major channel for the movement of liquids in the axial direction, while the movement in the lateral direction depend mainly on the rays, and the level of pitting between the ray parenchyma cells and the adjoining vessels [22]. The treatability of wood becomes difficult in the axial direction with the blockage of vessels, and may be more complicated when lateral penetration through the rays and ray parenchyma cells becomes inaccessible.

It has been shown within the available studies that *Gmelina arborea* grown in India and Bangladesh has a very low uptake and its heartwood is classified as extremely difficult to treat [23]. Its penetration is higher in the axial direction compared to the lateral (radial and tangential) directions in gmelina and other wood species [22,24]. Our goal here is to find out if gmelina wood grown in Nigeria has similar behaviors in terms of the solution uptake and penetration as those that have already been investigated from other countries, and to investigate further the possible reasons for the difficulties in the impregnation of the wood. Furthermore, this study is directed at revealing the variation in the solution uptake within and among the stems of gmelina wood and to provide an in-depth understanding of the liquid uptake behavior of gmelina wood through microscopy of its anatomical structure.

2. Materials and Methods

2.1. Sample Procurement

Gmelina trees for this study were harvested from the mixed plantation of gmelina and teak trees (Figure 1a) at the Federal University of Technology Akure, Nigeria. Location of the harvested trees within the mixed plantation within the university's premises is N7.18303, E05.07468 and N7.30875, E05.13142. The age of the plantation is between 25 and 30 years, while the average diameter at breast height of the trees is 46.1 cm. Four trees were sampled to determine percentage uptake, but as uptake was similar among the sampled trees, one of the trees was investigated in detail. The harvested stems of the trees consist essentially of heartwood as only a thin layer of sapwood was present (see Figure 1b). Harvesting and initial processing was performed with a chain saw, and the samples were initially processed into average dimensions of 1500 mm × 340 mm × 71 mm. The wood samples were initially air-dried for three months before being shipped to the Department of Wood Biology and Wood Products, Georg-August-University Goettingen, Germany for further research.

2.2. Sample Preparation

Samples for the experiment were prepared with dimensions of 200 (ax.) × 30 × 30 mm and 25 (ax.) × 30 × 30 mm. A total of one hundred and sixteen samples were prepared for impregnation from the tree selected for detailed investigation: top position (40), middle (41), base (35), outer wood (23), and inner wood (32). From the other three trees, 20 samples each were selected, irrespective of their position within the tree, making a total of 60 samples. As the moisture content of the samples was initially above fiber saturation point, they were initially dried at 60 °C for 48 h to average moisture content of 19%. The oven-dry density of the wood samples was determined to be an average of 442 kg m^{-3}. End-grain sealing was performed with Sikaflex® (Sika Deutschland GmbH, Stuttgart, Germany) for most of the batches of samples to allow penetration in the lateral direction. For a set of another 30 samples with dimensions of 25 (ax.) × 30 × 30 mm, all ends were sealed except for one end to allow penetration of liquid only in the axial direction (along the grain). This sample

dimension was taken based on initial trial, showing that penetration in the axial direction was lower than 10 mm.

Figure 1. (**a**) Mixed plantation of gmelina and teak showing one of the harvested trees. (**b**) Halved stem of harvested gmelina with a thin band of sapwood.

2.3. Sample Impregnation

Initial dry mass (W1) of wood samples was measured before impregnation with a dye-bearing water solution (0.05% rhodamine b solution). Rhodamine b is known to behave comparably to an aqueous wood preservative from earlier trials [25]. It is characterized by intense purple color, and its intense staining enables the optical detection of the distribution of the penetrated solvent in the wood material. Samples were impregnated by applying an initial vacuum for 2 h and 5 h of pressure at 9 bar. After impregnation, samples were drained of excess liquid using paper towels and the mass of impregnated samples was measured (W2). Additionally, uptakes in % and kg m^{-3} were calculated after impregnation according to the following equation:

$$\text{Uptake (\%)} = ((W2 - W1)/W1) \times 100 \quad (1)$$

2.4. Penetration Measurement

Wood samples were air-dried for one week before this measurement. Impregnated samples with dimensions of 25 (ax.) × 30 × 30 mm were used for this purpose. A set of 30 samples for lateral penetration had their sealed ends removed by cutting them off, while samples for axial penetration were cut in half to reveal the depth of the colored solution. Images of the cut surfaces were taken with Expression 11000XL flatbed scanner (Seiko Epson Corporation, Suwa, Japan), while penetration depths were measured from scanned images using ImageJ software.

2.5. Data Analysis

To determine the significant differences in uptake and penetration, analysis of variance and follow-up test with Duncan's multiple range test (DMRT) were performed with the SPSS Software, V20.0 (IBM Corporations, Armonk, NY, USA).

2.6. Light Microscopy

By using a rotating microtome HistoCore AUTOCUT (Leica, Wetzlar, Germany), the cross-sectional surfaces of the samples were flattened so that the cellular structure of the wood was clearly recognizable. The prepared surfaces were examined using a Zeiss Axioplan 2 Imaging reflected light microscope (Zeiss, Oberkochen, Germany) with an objective magnification of 10. Due to the 10x ocular magnification of the Axioplan, this corresponds to a 100× magnification. The microscopic images were taken with the Nikon

Digital Sight DS-U3 camera system (Nikon, Tokyo, Japan) in combination with the capture software NIS Elements Basic Research (Br) (Nikon Instruments Europe B.V., Amstelveen, The Netherlands).

2.7. SEM/EDX Analysis

For SEM/EDX analysis, sub-samples (approx. 10 × 10 × 5 mm) were taken and subsequently prepared using a HistoCore AUTOCUT (Leica, Biosystems GmbH, Nussloch, Germany) automated rotary microtome equipped with disposable blades. For this purpose, the test specimens were clamped in the intended holding device of the microtome, moistened with water, and pre-trimmed with a section thickness of 40 µm at a speed setting of 3, before the final sectioning was performed (section thickness 20 µm, speed 1). The prepared specimens were applied to SEM aluminum stubs (Plano GmbH, Wetzlar, Germany) using carbon adhesive pads. Afterwards, the stubs were placed in a sputter coater, type SC7620 (Quantum Design GmbH, Darmstadt, Germany), and made electrically conductive by vapor deposition with gold/palladium for 120 s at set plasma current of 18 mA. The selected vapor deposition time resulted in an approximate coating thickness of 10 mm. Electron images were taken using an EVO LS 15 SEM (Carl Zeiss Microscopy GmbH, Oberkochen, Germany). The generation and storage of well-focused electron images of the examined specimen sections were carried out with the parameters listed in Table 1.

Table 1. Selected basic parameters for generating the electron images.

Parameter				
EHT [kV]	**I Probe [pA]**	**WD [mm]**	**OptiBeam Mode [-]**	**Mag [-]**
10	700	8.5	Depth/Resolution	variable

To generate elemental distribution images, the software AZtec® (Oxford Instruments plc, Abingdon, UK) was used. Image scan settings were selected as follows: Image scan size = 2048 Px; dwell time = 5 µs; and number of frames = 1. The energy range and the number of channels were left at the default setting: "Automatic". The manually controlled recording time was 10 min.

3. Results and Discussion

Gmelina wood has a diffuse porous structure, and being a hardwood species, it has varieties of flow paths, such as vessels, fibers, and ray parenchyma cells, to enable the liquid flow into the wood's microstructure. However, as presented in the following results, the uptake and penetration of the liquid is significantly low, and hence, anatomical investigations were conducted to reveal the likely causes of the low uptake and penetration of liquids into the wood's microstructure.

3.1. Variation in Uptake within Stems and Stands of Gmelina Wood

The results presented in Figure 2a show the variation in the liquid uptake along the height and across the stem diameter of the gmelina wood. The wood samples selected from the top position recorded a somewhat higher liquid uptake, while the differences in the uptake appear similar (not significantly different) between the outer and inner wood for the samples selected from the top, middle, and basal positions. Along the stem height, there is a significant difference in the uptake (as shown in Table 2), with the wood samples selected from the base having the lowest uptake. From the same table, it can also be observed that the percentage of the solution uptake is low among the two sample dimensions (small-sized and large-sized sample dimensions) impregnated. The effect of the sample dimension did not play any significant role in the solution uptake, as also observed in a previous study by Sint et al. [24]. The influence of the tree height on the uptake and permeability of liquids in wood has been discussed in previous studies; it plays a major role as the permeability increases from the base to the top [26,27]. According to Siau [28], permeability is defined as

the measure of the ease with which fluids are transported through a porous solid under the influence of a pressure gradient, and it is affected by pore sizes and distributions, as well as the level of interconnectivity of the pores. From the above definition of permeability, it is expected that gmelina wood with its numerous pores should have little or no difficulty with the impregnation of water-based solutions.

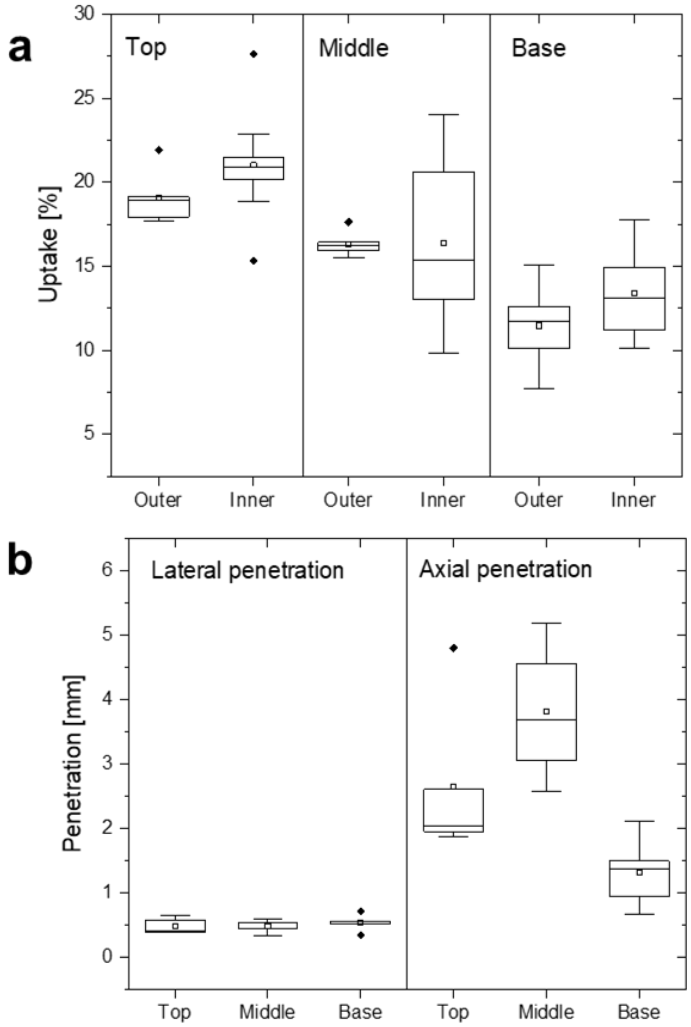

Figure 2. (**a**,**b**) Solution uptake and penetration depth of colored liquid in *Gmelina arborea* wood. The interpretation of the box plot is as follows: the centre line = the median, open square = the mean, box length = 25th to 75th percentile, whiskers 5th to 95th percentile, the black rhombus are the outliers.

In Figure 2b, the liquid penetration into the gmelina wood is higher in the axial direction compared to the lateral direction, which comprises both the radial and tangential directions. The liquid penetration in the axial direction is facilitated by the longitudinal cells, vessels, and fibers, while the lateral penetration of the fluid is mainly through the ray parenchyma cells. After five hours of pressure treatment and impregnation, the mean uptake is in the range of 12.12% to 20.41% along the stem's height and across the stem's diameter. The axial penetration and lateral penetration, which consists of both radial and tangential penetration, were a maximum of 3.81 mm and 0.58 mm, respectively. This low percentage uptake and penetration of fluids in the axial and lateral directions distinguishes gmelina wood as extremely difficult to treat according to the classification by EN 350 [7] for wood treatability with aqueous preservatives. The uptake and penetration of liquid into gmelina wood's microstructure are generally low compared to the values previously reported for other hardwood species. For example, Sint et al. [24] examined the treatability of some of the lesser-used Myanmar hardwood species and found that the penetration

in the lateral directions was in the range of 8 mm to over 20 mm, except for in *Tetrameles nudiflora* which had a penetration depth of 5 mm to 6 mm. The longitudinal penetration for the wood species investigated in the same study ranged from 200 mm to 400 mm in both small-sized specimens and large-sized specimens, respectively. Sujatha and Venmalar [23] evaluated the treatability of some plantation timbers from India, including *Gmelina arborea*. The study found that most of the plantation hardwoods examined for their treatability had a low solution uptake and penetration index, showing that the heartwood is refractory to treatments. Another study by Ahmed and Chun [22] showed that *Gmelina arborea* from Bangladesh had a low penetration to a safranine solution, and the penetration in both the sapwood and heartwood was less than 3 mm. Comparing these results from various studies to those of the present one, it could be inferred that the impregnation properties and behaviors of *Gmelina arborea* wood are strikingly low compared to those of the other hardwood species previously investigated. Furthermore, Nigerian gmelina wood's behavior for the uptake of solutions is not in any way different from that of those from other countries, showing that the species is generally refractory to impregnation.

Table 2. Mean values for solution uptake and penetration of colored liquid into *Gmelina arborea* wood (standard deviation in parenthesis) along the stem height and across stem diameter.

	Density	**Solution Uptake**		**Penetration Depth**	
	kgm^{-3}	**(%)**		**(mm)**	
		Large Sized Samples	**Small-Sized Samples**	**Axial**	**Lateral**
Along the stem height					
Top	455	20.41(2.54) ^{a}	19.03(6.04)	2.65(1.23) ^{b}	0.48(0.13) ^{a}
Middle	429	16.37(3.35) ^{b}	18.68(4.51)	3.81(1.07) ^{a}	0.48(0.10) ^{a}
Base	436	12.12(2.58) ^{c}	14.55(2.57)	1.31(0.56) ^{c}	0.53(0.13) ^{a}
Across the stem diameter					
Outer wood	n/a	14.93(3.66) ^{a}	n/a	n/a	n/a
Inner wood	n/a	17.82(4.43) ^{a}	n/a	n/a	n/a

Means with the same letter vertically are not significantly different (p >0.05).

This study further investigated wood samples from other gmelina trees grown within the same plantation for any possible variation in the solution uptake (Table 3). From this table, it is evident that density of the sampled gmelina trees is quite similar and may not be a major determinant for solution uptake and penetration. Density is a determinant of many of wood's properties, and relative density is often taken into consideration when calculating porosity and the void volume filled [29]. In many cases, the relationship between the relative density and porosity may be useful in determining the permeability, treatability, or impregnability of wood with liquid chemicals. The abundance of vessels in hardwoods should be a major advantage for low-density wood such as gmelina; however, these passages have been occluded with tyloses, as will be discussed later on. The similarity in the density of gmelina wood among the selected gmelina trees is consistent with their similarity in solution uptake. Halverson and Lebow [30] also concluded in an earlier study that a consistent relationship between the wood density and solution uptake should not be expected due to the interconnectivity of other factors that influence treatability of timber. This may be the reason that tree 3, which had a higher density compared to that of the other trees and a solution uptake that was statistically significantly different from that of other trees, had a comparably low solution uptake. Furthermore, the results shown in Table 2 did not show any pattern of variation when the density along the axial position is compared to solution uptake. The results showed that the difficulty of gmelina wood in taking up

liquids does not depend on the density variation, but may point to a general problem in the wood's structure.

Table 3. Mean values (standard deviations) for solution uptake among the sampled trees of *Gmelina arborea*.

Sampled Trees	Density (kgm^{-3})	Solution Uptake (%)
Tree 1	440	16.61(4.33) ^{b}
Tree 2	452	16.23(5.43) ^{b}
Tree 3	457	23.32(12.37) ^{a}
Tree 4	420	17.69(1.76) ^{b}

Means with the same letter vertically are not significantly different (p >0.05).

3.2. Influence of Anatomy on Impregnation Properties of Gmelina Wood

The penetration of liquids along the axial direction is mostly obstructed by the presence of tyloses in the vessels. Since the liquid movement in the vessels constitutes a major pathway to flow in the axial direction, the relative abundance of tyloses in gmelina wood may constitute a major impediment to solution uptake in the axial direction (Figure 3a,b). The presence of tyloses in the vessels of gmelina wood has been reported several times in the literature in investigations in different countries [22,31,32]. Even with variations in the ecological environments of the trees, tyloses comprise a prominent structure in the vessels of gmelina wood. Tyloses are developed as protrusions from the adjoining pit between vessels and parenchyma cells, and are stimulated in many hardwood species as a response to environmental stress, resistance to pathogens, or during the transformation of sapwood to heartwood [33]. The presence of tyloses in difficult-to-treat wood species has led to the development of pre-treatment methods, such as incising, used to improve solution uptake and penetration [34]. However, treatments such as incisions cause mechanical damage to the wood and consequent strength losses as well as aesthetics losses.

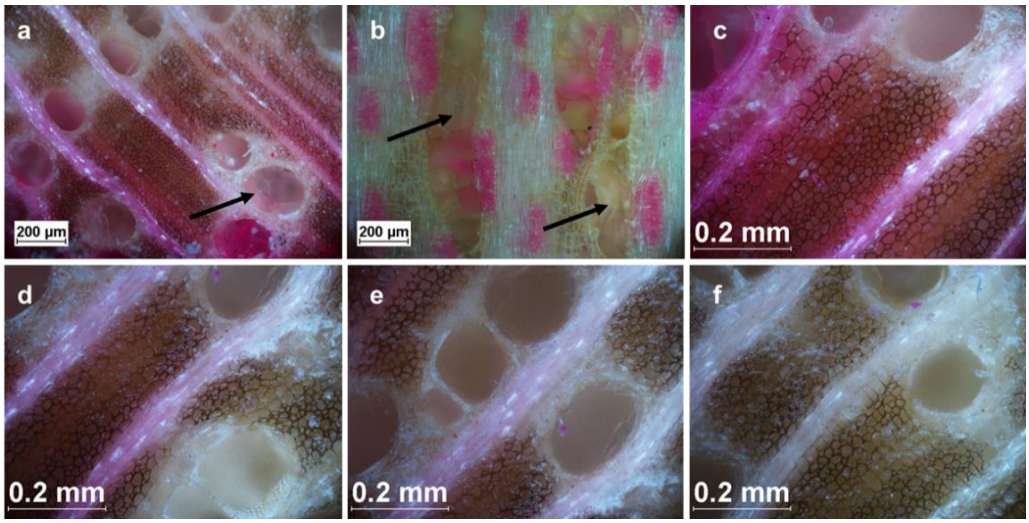

Figure 3. (**a**,**b**) Presence and abundance of tyloses (black arrows) in vessels revealed in cross-section and radial direction. Movement of colored liquid within a few micrometers from the edge of the sample and a discontinued penetration especially along the rays (**c**–**f**). Crystal-like substances are abundant in the rays, and movement of colored solution in the rays appeared to be discontinued due to crystal-like structure. Images in (**c**–**f**) were taken in sequence from the edge of the impregnated sample.

The mapping of the penetration of the liquids in the lateral directions provided more information to explain the severely low solution uptake in gmelina wood, as shown in

Figure 3c–f. The liquid penetration started initially but appears to have been impeded by some crystal-like structures in the ray cells. These crystal-like structures may have formed deposits, which could serve as blockages and thus reduce the permeability of the wood to liquids [35]. Looking at the sequence from the edge of the impregnated sample, as shown in the same figure, it becomes clear that the colored solution was initially moving along the rays until it started fading out. The uptake of the liquid into the wood's structure may have occurred within the first minute of starting the impregnation, as previously observed by Ahmed and Chun [22], who recorded that penetration rate of safranine in gmelina wood was the highest within the first minute, but gradually decreased with the impregnation time.

Further investigations into the nature of these crystals were carried out with scanning electron microscopy (SEM) and EDX. The measurements revealed the nature and composition of the crystals in the wood structure. As shown in Figure 4a–d, these crystals are needle-like structures and are abundant in the ray parenchyma cells of the gmelina wood. They were identified with EDX as calcium oxalate crystals (Figure 4e,f), and the ways in which they are distributed at the end of the ray parenchyma cells and also in the wood fibers showed that they may serve as blockages, leading to difficulties in the solution uptake in the axial and lateral directions. Another possibility of the effect of the calcium oxalate crystals on the difficulty in the impregnation of gmelina wood may arise from their non-solubility to polar liquids.

Solution uptake along the radial direction is more critical in achieving better impregnation especially, when impregnating wood with large dimensions. However, as it appears for gmelina wood, it is even much more difficult getting a reasonable depth of penetration in the lateral directions, as shown in Table 2. In an earlier study, gmelina wood was classified as being refractory to impregnation, with a penetration index of 0.15 [23], and from this study, it became clear why the heartwood of gmelina is refractory to treatments. Furthermore, the inability of gmelina wood to take up liquids may serve as a limitation to processes such as impregnation with preservatives and chemical modification processes. Although several methods, such as incisions, have evolved over time to improve the solution uptake of refractory wood species such as gmelina wood, many are either impracticable or may lead to strength loss. The incising of wood involves making slits with sharp objects along the wood's grain to open up the wood's structure and increase uptake and penetration. The limitation of such a method is that, while the optimum penetration may not be reached, the structural elements in the wood are damaged, posing a limitation to their use. Difficult-to-treat species are not completely immune to destructive biological agents, which suggests that in cases in which the impregnation of such species is not possible, other methods of protection are required. One alternative may be to incise wood prior to treatments to increase solution uptake; however, this has a limited effect due to the depth of the incisions and the reduction in the aesthetic value of the wood product. Another alternative is to thermally modify it for improved dimensional stability and durability. The choice of an alternative treatment for these difficult-to-treat species requires compromises to be made between the available possible alternatives. Previous reports by Winandy and Morrell [36] have shown that the combined effect of incising and preservative treatments of wood resulted in a 10% loss in the modulus of elasticity (MOE), a 15 to 25% loss in the modulus of rupture (MOR), and a between 30 and 50% loss in the work to maximum load (WML). Strength losses due to thermal modifications from previous investigations showed that the proportionate loss in MOE is somewhat influenced by the increase in the treatment temperature. When thermally modifying Scots pine sapwood and heartwood under a high-pressure reactor, Rautkari et al. [37] found that at 180 °C, the loss in the static MOE was less than 1%, while the proportionate loss in the MOR at the same treatment temperature was about 30%. Therefore, a suitable compromise in the treatment of gmelina wood is to choose thermal treatments. However, it should be noted that this process is species-dependent, and must be further developed to find a suitable optimum treatment plan for gmelina wood. With thermal treatment, a lower loss in strength can be achieved,

coupled with other advantages in terms of the dimensional stability and durability to biological agencies. In comparison, the use of incisions has limited efficacy and results in the aesthetic loss of the treated wood product.

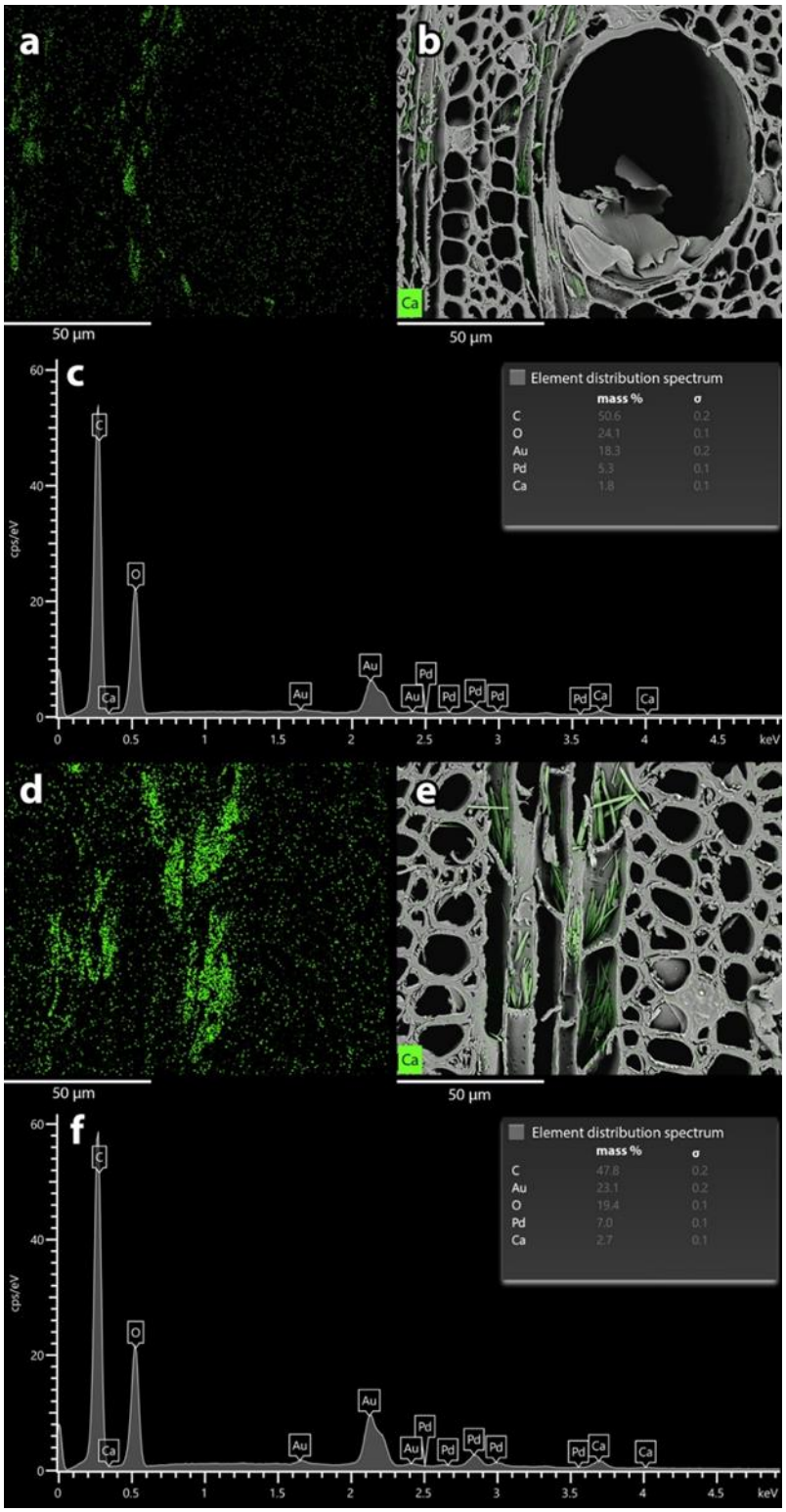

Figure 4. Needle-like crystalline structures found in the ray parenchyma cells of gmelina wood (**a**–**d**), present in large proportions and identified as calcium oxalate in the EDS spectrum (**e**,**f**).

4. Conclusions and Outlook

The outcome of this study has shown that solution uptake and penetration in gmelina wood is significantly low compared to those of other wood species, and they are too low to protect the wood. The reasons for gmelina wood's low uptake and difficulties in penetration are the presence of tyloses and needle-like shaped crystals identified as calcium oxalates, serving as blockages to the fluid movement in the lateral directions. As earlier studies on gmelina wood from other countries have shown, the difficulty in impregnation and treatability of this species is more of a general problem and not limited only to gmelina trees grown in Nigeria. The implication of the difficulty in impregnating gmelina wood is that an improvement in the dimensional stability and durability of gmelina wood may not be feasible through chemical impregnation either via conventional preservatives or through chemical modification. Therefore, other suitable modification alternatives should be employed. For example, thermal modification does not entail the impregnation of wood and may be suggested as an alternative modification or treatment for gmelina wood. It should be noted that selecting a method such as thermal modification may pose some limitations to the end-use of gmelina wood, especially for structural applications. However, thermally modified gmelina wood can be safely used in cases in which the dimensional stability and durability are of more importance compared to the structural uses. Subsequent studies will focus on the thermal modification of gmelina wood, comparing the influence of different temperature regimes and the method of thermal treatments, such as open- and closed-thermal processes using a thermal reactor. The open process is performed in an open reactor system using superheated steam at atmospheric pressure, while the closed system is performed under a pressurized gas atmosphere, which increases the rate of heat transfer to wood. Both processes have varying influences on the wood's properties, and in the end, a suitable thermal modification plan with beneficial effects on the dimensional stability, strength, and durability of gmelina wood should be chosen.

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