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Environmental and Economic Impacts of Hydroxyapatite Mineralized Wood: LCA and LCC Analysis

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Abstract: Wood is considered a promising raw material for the circular bioeconomy and has the ability to store biogenic carbon, and this is one reason why we want to extend the service life of the wood. In order to consider the influence of durability in our study, we used two wood species with different lifespans. Beech (*Fagus sylvatica* L.) belongs to the group of very sensitive wood species, as the durability of the untreated wood is estimated to be around 5 years; meanwhile, pine (*Pinus sylvestris* L.) belongs to the group of moderately resistant wood species, where the durability of the untreated wood is estimated to be up to 15 years. While toxic chemicals are often used for wood preservation, hydroxyapatite offers an environmentally friendly solution for wood mineralization. This study presents life cycle assessment (LCA) and life cycle cost (LCC) analyses comparing a novel hydroxyapatite (HAp) mineralization method with a service life of 50 years to a non-mineralized reference alternative. LCA was based on EN ISO 14040 and EN ISO 14044, while LCC was adapted from the European Commission's LCC tool for public procurement. The results of the LCA show that mineralized wood has a lower overall impact on the environment than surface-treated beech wood but a higher impact than surface-treated pine wood. Most impact categories were determined by electricity consumption with the exception of stratospheric ozone depletion, water consumption, and land use. Water consumption proved to be the category where the mineralization process was problematic due to water consumption during the leaching process. The LCC showed that mineralized wood is the most cost-effective solution for the exterior façade, as all costs, but especially investment costs, were lower. The differences in the LCA and LCC results are mainly due to the different lifetimes of the two alternatives. It can be concluded that if energy-intensive processes and chemicals are used in the production of the material, the extended lifetime must be sufficient to account for the additional impacts that occur during the production phase.

Keywords: environmental impacts; hydroxyapatite; life cycle assessment (LCA); life cycle cost analysis (LCC); wood mineralization

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1. Introduction

In the context of environmental pollution and climate crises, within the framework of the Sustainable Development Goals and the European Bauhaus initiative, wood has been recognized as a promising raw material for addressing these challenges. Lignocellulosic materials, which include wood, represent the potential for a sustainable value-added industry, enable the reduction in the global dependence on fossil fuels, and are valued for their ability to store carbon [1]. Precisely because of the carbon bound in wood, we want to extend the life of wood and enable as many utilisation functions as possible before the function of energy production through combustion. Despite efforts to establish a circular wood industry and promote the cascading use of wood, it is important to consider that the lifespan of wood is also conditioned by the natural resistance of wood [2]; also, scenarios of reusing wood for different functions are often not possible. The natural durability of wood can be categorized into five different durability classes, with beech and poplar being representatives of the fifth class, which is the most susceptible to decay and has an estimated lifespan of up to 5 years. Pine and larch, for example, represent the third durability class with moderate natural resistance and an estimated lifespan of up to 15 years, while robinia and chestnut represent the first class, where the estimated lifespan is 20 or more years [3,4].

As a natural hybrid composite material, wood stands out as a versatile and widely used renewable resource suitable for indoor and outdoor applications [5]. In outdoor applications, wood is exposed to biotic and abiotic degradation factors. In nature, these processes are desirable, but when we use wood for commercial purposes, the decomposition should be slowed down as much as possible. If the wood is not naturally sufficiently resistant to biotic and abiotic factors of decomposition in the chosen environment, it must be treated to enhance its durability [2]. Different methods and procedures have been used to overcome the abovementioned drawbacks. One of the solutions for wood protection is the inclusion of minerals (metal carbonates and hydroxides) in the wood and wood structure. So-called mineralization is the process by which inorganic substances, for example, carbonates, are incorporated into wood structure [6]. It is known that wood mineralization can improve both fire response [7,8] and resistance to fungi [9].

However, there are other minerals that can be introduced into the wood structure. One such mineral is hydroxyapatite (short HAp), with the chemical formula $Ca_{10}(PO_4)_6(OH)_2$. HAp is one of the most widely used biomaterials in the field of biomedicine and the main mineral component of human bones and teeth. Due to its unique properties, such as its biocompatibility and low cytotoxicity, it is used in various fields of medicine, such as coating material for metal prostheses, in dentistry, and as an antimicrobial agent [10,11].

Wood preservation processes and modification systems can be energy-intensive and often involve chemicals that are hazardous to the environment and human health [12]. Therefore, it is reasonable to evaluate and, if necessary, regulate the effects on the environment caused by individual protection processes in the short and long term. Life cycle analysis (LCA) has proven to be an effective method for determining environmental footprints, as it enables the examination of various environmental impacts throughout the entire life cycle, providing comprehensive insight into the advantages and disadvantages of processes and products [13].

Dias et al. [14] analyzed combinations of surface treatment (insecticide and fungicide) and/or vacuum impregnation (water-based biocide) on cryptomeria, spruce, pine, and eucalyptus using LCA. The natural resistance of wood proved to be an important factor in the final results. The impact categories that stood out the most in the results of the analysis were freshwater ecotoxicity and carcinogenic effects on human health. It was also found that environmental efficiency in cases of surface coatings is significantly improved by reducing the frequency of coating renewal.

When studying the impacts of a wooden terrace impregnated with a copper preparation [15], it was found that the amount of impacts of the entire life cycle of a terrace with a lifespan of several decades represents a negligible amount of impacts compared to the impacts of a household created in just one year. Bolin and Smith [15] and Hu et al. [16] also studied the environmental impacts of wood protection using a pine preparation with LCA analysis. A relatively small impact on the environment was found, especially in the combination of pine with tannins, which represents the natural protection of wood.

Montazeri and Eckelman [17] analyzed the environmental impacts of various natural-based surface coatings, most of which are not synthetic compounds. An important finding was that the share of natural components does not necessarily represent a more environmentally friendly solution when the entire life cycle is taken into account.

Because of the price of the product or services, life cycle cost analysis (LCC)—which takes into account all costs during the entire life cycle of the product (investment costs, maintenance costs, operating costs, depreciation costs, etc.)—is reasonable and often used as a support for LCA [18]. In order to achieve optimal environmental and social results, it is important that both LCA and LCC analysis are conducted and to consider the product or service from a wide variety of angles.

In this research, LCA and LCC analyses of a new type of wood mineralization using hydroxyapatite were performed. The aim of this study is to evaluate the environmental and economic effects of mineralized beech (*Fagus sylvatica* L.) and pine (*Pinus sylvestris* L.) wood and to compare them with non-mineralized alternatives.

The research questions to be answered in this study are as follows: What are the main environmental burdens of mineralized wood façades? How do the characteristics of wood species affect the LCA and LCC results? What is the most optimal solution (in terms of environment and price) among the evaluated options—mineralized beech wood, mineralized pine wood, surface-treated beech wood, or surface-treated pine wood?

2. Materials and Methods

This study assessed the differences in ecological and economic impacts between mineralized and non-mineralized wood. The latter represents the reference point for comparing the results. To account for the possible influence of different wood characteristics, both beech (*Fagus sylvatica* L.) and pine (*Pinus sylvestris* L.) wood were included in this study. The environmental impacts were assessed using the LCA method according to ISO 14040 [19], ISO 14044 [20] and the International Reference Life Cycle Data System (ILCD) Handbook [21], which serves as a quality assurance guide for the LCA study and was published by the EU via the Joint Research Centre (JRC). Most of the data related to the mineralization process were collected directly through experimental work, including the impregnation process and additional leaching, or calculated from data collected during the experiments. Some supporting data were secondary in nature and sourced from the Ecoinvent 3.9.1 database [22]. SimaPro 9.5.0.1 software [23] and the ReCiPe 2016 (H) [24] methodology were used for the calculations. The ReCiPe methodology performs its calculations at two different levels—the midpoint level and the endpoint level, where the midpoint level assesses the hazards for several impact categories and the endpoint level assesses the final damage based on the hazards of the midpoint categories. A Monte Carlo uncertainty analysis was performed for all scenarios. Secondly, an LCC analysis was conducted to assess the economic impact of mineralization for different wood species. For this purpose, the LCC tool [25] of the European Commission (2019) was adapted.

The methodology is divided into two parts: performing LCA and performing LCC.

2.1. Goal and Scope of the LCA Study

The aim of the LCA study is to assess the environmental sensibility of the novel mineralized wood process for outdoor use, e.g., for façades. Since we assume that mineralized wood offers various advantages compared to untreated and surface-treated wood (e.g., fire resistance and resistance to fungi), the main question of the study was whether mineralized wood is an ecologically appropriate solution.

The system boundaries of the analyzed “Cradle-to-Gate” approach (Figure 1) include ($1_{a,b,c}$) the production of chemicals; ($2_{a,b}$) the wood processing—pine or beech; ($3_{a,b,c}$) the impregnation process with additional drying; (4) the drying process; (5) leaching; (6) the drying before the transportation; and (7) the use phase. The system boundaries for the baseline scenario (surface-treated wood) include the same wood processing (2) and utilization phase (7); in addition, the surface treatment (8) (spray coating, 0.223 kg/m^2—the required quantity was calculated with the Silvaprodukt company web calculator for the product Silvacera [26]) with generic acrylic lacquer (Ecoinvent) was taken into account (Figure 2). In SimaPRO, the surface treatment process was defined with the production of acrylic varnish, the market activities for acrylic varnish, and the spray coating process. The emissions for all processes are based on the mass of surface coating used in the analyzed system, which was calculated based on the surface area of the samples for each wood species. For the calculation of the life cycle impact assessment (LCIA) with ReCiPe 2016, the following midpoint categories were included: global warming (GW), stratospheric ozone depletion (SOD), ionizing radiation (IR), fine particular matter formation (FPMF), ozone formation–human health (OF, HH), ozone formation–terrestrial ecotoxicity (OF, Ttox), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (Ttox), freshwater ecotoxicity (Ftox), marine ecotoxicity (Mtox), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), land use (LU), mineral resource scarcity (MRS), fossil resource scarcity (FRS), and water consumption (WC). Based on the chosen perspective of the ReCiPe methodology—hierarchical (H)—the following endpoint categories were calculated: human health, ecosystem quality, and resource scarcity. For each phase of impregnation, the environmental impacts are assigned to the main process and the residual chemicals by mass allocation as recommended by ISO 14049 [27].

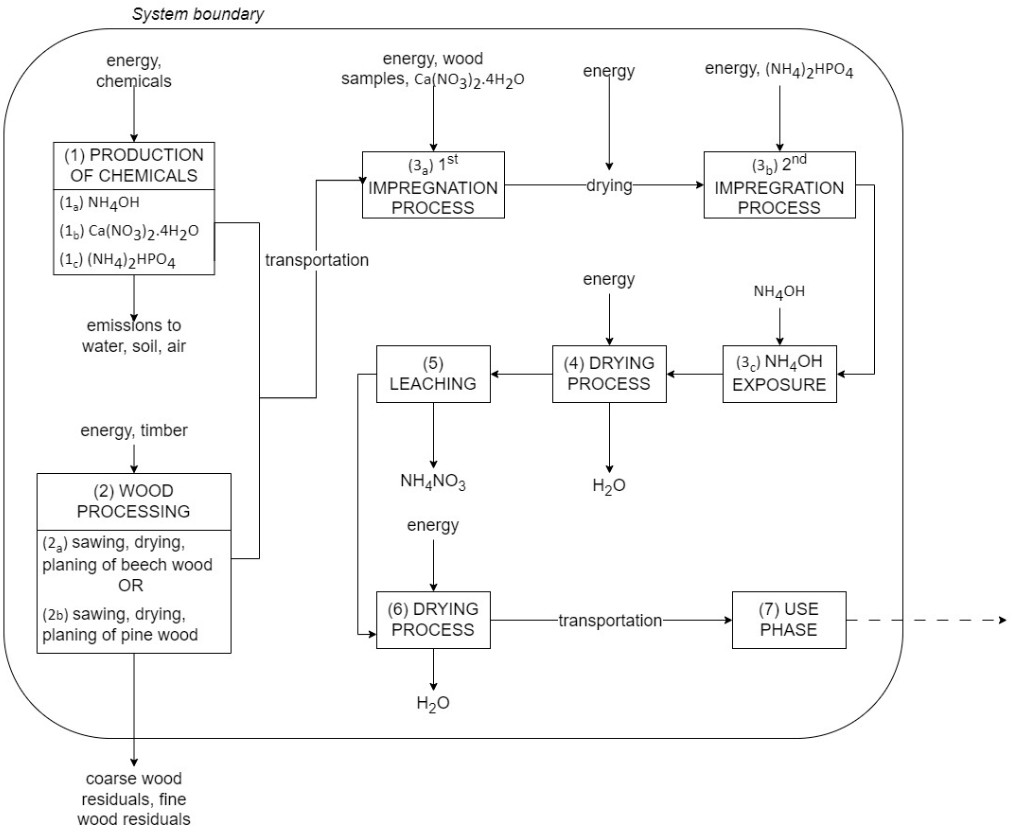

Figure 1. Process flow diagram of mineralized wood.

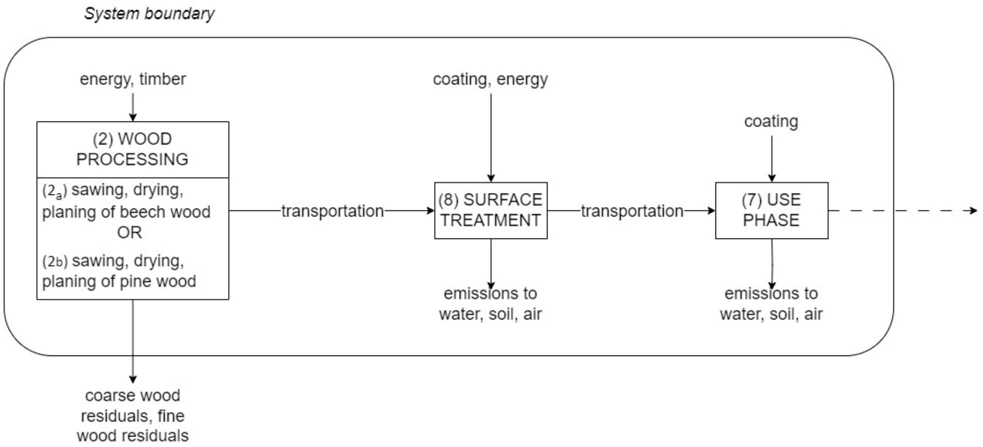

Figure 2. Process flow diagram for baseline scenario.

The equivalent functional unit (FU) for the LCA analysis of compared wood preservation methods (mineralization and surface treatment) and species (beech and pine) is defined by the durability functionality of wood and service class 2 exposure (exterior, undercover, aboveground) for 50 years.

The timeframe of the FU was defined based on the lifetime of mineralized wood, which is assumed to be 50 years regardless of the wood species (pine or beech), as it was originally developed for structural purposes, e.g., for exterior façades. The service life of 50 years was chosen based on the European Assessment Document [28]. In accordance with the natural durability of wood, a service life of 18 years was assumed for surface-treated pine wood and a service life of 8 years for surface-treated beech wood [3,4]. Even though the use of wood in exterior applications, e.g., for façades, includes many functions, such as aesthetics or fire resistance, the function of general building protection was considered in accordance with the aim of our study. The functional unit is, therefore, defined as the usability of wood for exterior applications over a period of 50 years. The reference for the LCA study was defined as the volume of 20 wood samples (375 cm^3) initially used for the experimental work.

The scenario for mineralized wood is considered once for both types of wood within the FU (50 years). The scenario for surface-treated beech wood is considered 6.25 times within the FU, which corresponds to a service life of 8 years, and the scenario for surface-treated pine wood is considered 2.78 times, which corresponds to a service life of 18 years. Scenarios that include surface treatment also take into account the need to recoat the wood, assuming that this is carried out manually every 5 years. For the surface-treated beech wood, recoating is considered 1.4 times per life cycle (8.75 times within the FU), and for the surface-treated pine wood, recoating is considered 3.6 times per life cycle (10.008 times within the FU). The end-of-life scenario and the manipulation of waste wood were not considered in the study and our system boundary.

2.2. Life Cycle Inventory—LCI

The basis for this study was previously conducted experimental work on the entire impregnation process, in which 20 beech and 20 pine samples, with the dimensions 50 mm × 25 mm × 15 mm, were impregnated following a 2-step impregnation process using a vacuum/pressure chamber. The aim of the process is to form hydroxyapatite deep inside the wood structure according to the following steps. First, 20 samples of each wood species are impregnated in 1 L solution of 1 M $Ca(NO_3)_2 \cdot 4H_2O$ using a vacuum process lasting ½ an hour at 150 mbar and a 3 h overpressure process at 10 bar. After the 1st impregnation, the samples are dried in a dryer for 24 h at 60 °C. This is followed by the 2nd impregnation, also with the wood species separated, with 1 L solution of 0.6 M $(NH_4)_2HPO_4$, using a vacuum/pressure chamber with the difference being that the vacuum process is excluded. To further explain the functional unit, we calculated the necessary quantities of the two main solutions used to protect 1 m^2 of pine and 1 m^2 of beech wood façade. Then, 3.16 L of 1 M $Ca(NO_3)_2 \cdot 4H_2O$ and 2.52 L of 0.6 M $(NH_4)_2HPO_4$ are needed to protect 1 m^2 of pine wood façade; 2.74 L of 1 M $Ca(NO_3)_2 \cdot 4H_2O$ and 2.11 L of 0.6 M $(NH_4)_2HPO_4$ are needed to protect 1 m^2 of a beech wood façade. It should be taken into account that in this study, the calculations are based on the use of smaller samples, with a thickness of 15 mm. The 2nd impregnation is followed by exposure to 0.1 L of NH_4OH solution (containing at least 25% NH_3) for 4 h at room temperature. After exposure, samples are dried in a dryer for 48 h at 80 °C and 24 h at 103 °C. In addition to hydroxyapatite, this process also produces a soluble by-product—NH_4NO_3—which is removed from the wood samples by leaching.

The LCI parameters for the system boundaries of the study are listed in Table 1. Since calcium nitrate tetrahydrate and ammonium hydroxide are not included in the Ecoinvent database, the chemicals were defined as calcium nitrate and ammonium. For all chemicals used as a solution in the impregnation process, an additional water input has been defined. All water is defined as water of natural origin from Slovenia. All transports in the system were carried out with 16–32 tonne EURO 6 lorries. Either hardwood or softwood with a moisture content of 10% was used in the system. Wood was considered to be transported from the local sawmill (20 km). Wood residues resulting from wood processing are defined as avoided products in the system and are not included in the system boundaries of the study or in the calculations, as the treatment of wood residues would be the same for all analyzed scenarios and would, therefore, not make a significant difference when comparing the results. However, it would further extend and complicate the system. For all processes that require energy, the electricity mix for Slovenia from the Ecoinvent database was used.

Table 1. LCI of the studied system—mineralized and surface-treated samples.

	Input Parameters	**Output Parameters**	**Value per FU**	
			Beech (*Fagus sylvatica* L.)	**Pine (*Pinus sylvestris* L.)**
(1_a)	Production of ammonia	-	22.5 g	
	Market activities (ammonia)	-	22.5 g	
	Water		0.1 L	
(1_b)	Production of calcium nitrate	-	236 g	
	Market activities (calcium nitrate)	-	236 g	
	Water	-	1 L	
(1_c)	Production of diammonium phosphate	-	79.2 g	
	Market activities (diammonium phosphate)	-	79.2 g	
	Water	-	1 L	
(2_a)	Sawn, planed hardwood	-	375 cm^3 (248.9 g)	
	Transport to the facility	-	20 km	
	Electricity for wood machining (cutting into samples)	-	7 kWh	
	-	Wood residues	*Avoided product*	
	Electricity for drying the samples to absolutely dry wood	-	48 kWh	
(2_b)	Sawn, planed softwood	-	375 cm^3 (221.3 g)	
	Transport to the facility	-	20 km	
	Electricity for wood machining (cutting into samples)	-	7 kWh	
	-	Wood residues	*Avoided product*	
	Electricity for drying the samples to absolutely dry wood	-	48 kWh	
(3_a)	$Ca(NO_3)_2 \cdot 4H_2O$	-	*Already included in the system*	
	-	$Ca(NO_3)_2 \cdot 4H_2O$ residue	174.6 g	165.2 g
	Electricity	-	8.75 kWh	
	Electricity for drying		48 kWh	
	-	H_2O	204.1 g	233.9 g

Table 1. *Cont.*

	Input Parameters	Output Parameters	Value per FU	
			Beech (*Fagus sylvatica* L.)	**Pine (*Pinus sylvestris* L.)**
(3_b)	$(NH_4)_2HPO_4$	-	*Already included in the system*	
	-	$(NH_4)_2HPO_4$ residue	63.3 g	60.2 g
	Electricity	-	6 kWh	
(3_c)	NH_4OH	-	*Already included in the system*	
(4)	Electricity	-	144 kWh	
	-	H_2O	232.4 g	241.1 g
(5)	-	NH_4NO_3 leaching	30.8 g	26.9 g
	H_2O	-	20 L	
(6)	Electricity for drying	-	48 kWh	
	-	H_2O	218.9 g	209.8 g
(7)	Transport to the utilization site	-	35 km	
(8)	Production of acrylic varnish	-	5.6 g	
	Market activities for acrylic varnish	-	5.6 g	
	Spray coating process	-	5.6 g	

2.3. Cost Evaluation—LCC

A life cycle cost analysis (LCC) was performed based on the European Commission's LCC tool for public procurement. As the practical application formed the basis for the implementation of the LCC, the FU was defined as the usability of 1 m^3 of external façade for a period of 50 years. The calculation (Equation (1)) includes investment costs (ICs), operational costs (OCs), service costs (SCs), other costs (OTHs), and externality costs (ECs).

$$LCC = IC + OC + SC + OTH + EC \tag{1}$$

The price of the sawn timber was adapted from the price list of the local sawmill and amounted to 310 EUR/m^3 for pine wood and 400 EUR/m^3 for beech wood [29–31]; the costs for chemicals were taken from the prices of the chemicals purchased for the experiments. The cost of wood processing, which included planning and profile cutting as well as façade assembly, was taken from the recommended price list for carpentry (the Chamber of Craft and Small Business of Slovenia) [32], while the price of mineralization/impregnation was estimated at 1466 EUR/m^3 by a group of experts in the field of wood preservation employed at the University of Ljubljana, Department of Wood Science and Technology. Experts from the logistics sector also estimated the cost of transporting wood and façade elements and the transport costs for the workers (for refurnishing the coating) at 1.5 EUR/km. The costs for chemical transport were free, as were the service costs for mineralized wood. The cost of the surface coating was based on the local manufacturer's prices (Silvaprodukt [26]), and the cost of spraying and painting was again taken from the recommended price list. The prices for screws or other metal and additional parts for the façade were not taken into account for these calculations. The refurnishing of the coating includes the price of the additional paint, the labour, and the transport costs of the worker to the construction site (15 km). The system values listed in Table 2 were calculated for one cubic metre of façade. For the costs of externalities, the method of assessing emissions and environmental impacts was used. More specifically, the Environmental Prices method was used in the SimaPRO 9.5.0.1. software to calculate the financial impact on society in our system. Thus, similar to the

ReCiPe method, different costs were assigned for different categories based on the amount of emitted substances and the price per kilogram of the emitted substance as determined by CE Delft [33,34]. For example, for human carcinogenic toxicity, a price of 5.25 EUR/kg 1,4-DCB-eq. is applied, which takes into account the impact of heavy metals and identified chemicals on human health, resulting in a disease-related burden on the health system and the economy. The cumulative environmental prices calculated for all impact categories (the categories are the same as in the ReCiPe methodology) for the European region were 44,837 EUR/m^3 for surface-treated beech wood, 19,226 EUR/m^3 for surface-treated pine wood, 30,738 EUR/m^3 for mineralized beech wood, and 30,497 EUR/m^3 for mineralized pine wood.

Table 2. Costs for system inputs.

Type of Costs		System Value [EUR/m^3]
Investment costs	Pine sawnwood	310
	Beech sawnwood	400
	Paint	60
Operational costs	Wood machining	750
	Impregnation process	1650
	Façade installation	300
Service costs	Surface recoating	84.5
Other costs	Transport of chemicals	0
	Transport of sawnwood	30
	Transport for the installation (workers and façade elements)	22.5
Externalities costs	Environmental prices	*Depending on the alternative*

3. Results

3.1. The Results of LCA Analysis (LCIA)

The results of the calculations for the midpoint categories showed that both mineralized wood species have almost identical impacts on the environment. The results of the comparison of mineralized and surface-treated wood species were normalized to the global population average, which allows the comparison of categories with otherwise different units, and are shown in Figure 3. Overall, the highest impact values can be attributed to surface-treated beech wood, while surface-treated pine wood had the lowest values of impact. Both mineralized categories achieve similar values and ranges between the two surface-treated wood types.

The highest environmental impact scores for all alternatives in the study were observed in the marine ecotoxicity category, followed by freshwater ecotoxicity, human carcinogenic toxicity, and human non-carcinogenic toxicity. The processes that contributed most to these categories were mainly associated with electricity consumption. The inventory of influential emissions showed that for marine ecotoxicity and freshwater ecotoxicity, emissions of zinc, nickel, vanadium, and chromium were the most influential for all four alternatives in the study. For human carcinogenic toxicity, emissions of chromium IV and nickel were the most influential for all alternatives, while emissions of zinc, mercury, and barium were the most influential for non-carcinogenic human toxicity for all alternatives. These categories showed significantly higher values for surface-treated beech wood compared to mineralized beech and pine wood and significantly lower values for surface-treated pine wood.

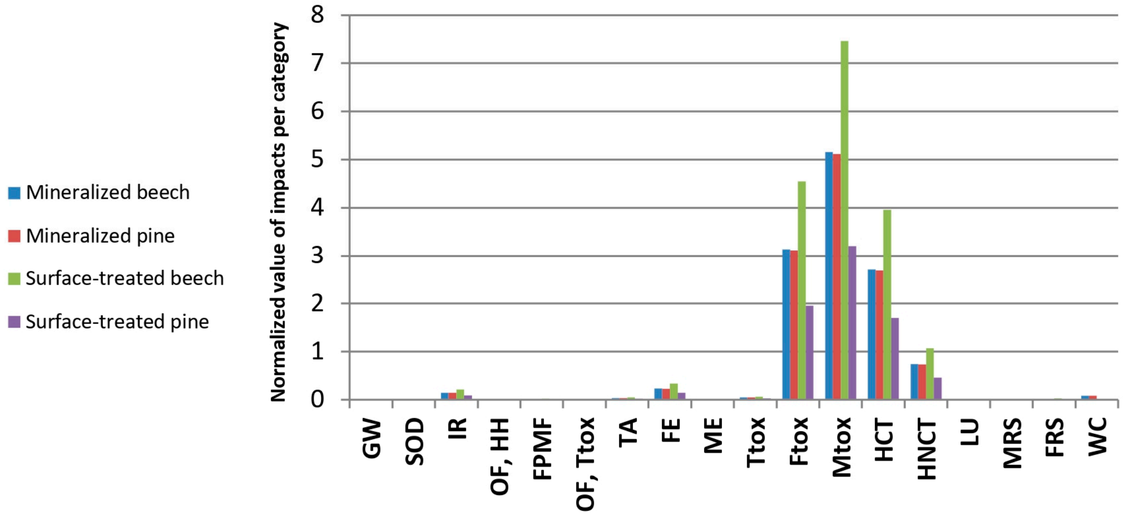

Figure 3. Results for midpoint categories after normalization when comparing alternatives 'mineralized beech', 'mineralized pine', 'surface-treated beech', and 'surface-treated pine'.

The categories stratospheric ozone depletion and water consumption show significantly lower values for surface-treated wood species compared to mineralized wood species. In addition to electricity consumption, the use of diammonium phosphate and calcium nitrate had a major influence on the environmental impact of the process for mineralized wood species. The inventory showed that nitrous oxide is the most influential emission in this category. Nitrous oxide was also the most influential emission for the surface-treated wood species but to a much lesser extent as electricity was the largest contributor for surface-treated alternatives. Water consumption is mainly associated with electricity consumption but also with the leaching process. Accordingly, water for turbine operation and water for cooling had the greatest impact. For the mineralized wood species, the water input (from unspecified origin, SI) proved to be very influential.

The categories ionizing radiation, particulate matter formation, soil acidification, freshwater eutrophication, terrestrial ecotoxicity, and fossil resource depletion showed almost identical values for the mineralized alternative, a significantly higher value for surface-treated beech wood, and a significantly lower value for surface-treated pine wood. Electricity proved to be the largest factor for all of the above categories. Radon, carbon, caesium, and noble gases were the most influential emissions for the ionizing radiation category, sulphur dioxide, and particles smaller than 2.5 micrometres for particulate matter; sulphur dioxide, nitrogen oxides, and ammonia for terrestrial acidification; phosphate and phosphorus for freshwater eutrophication; copper, zinc, vanadium, mercury, and nickel for terrestrial ecotoxicity; and for the consumption of fossil resource depletion, the influence on electricity consumption is mainly associated with the use of lignite and hard coal, natural gas, and crude oil.

For all four alternatives analyzed, particularly low values were found for global warming, ozone formation (terrestrial and for human health), marine eutrophication, land use, and mineral resource scarcity. In the global warming category, significantly higher values were found for surface-treated beech wood, almost identical values for mineralized wood species, and significantly lower values for surface-treated pine wood. For the emissions that appeared to have the greatest impact—carbon dioxide and methane—electricity was found to be the largest contributor and nitrous oxide was also found to be influential for mineralized wood species. For the categories ozone formation, terrestrial ecosystems, and ozone formation, human health showed similar values for all alternatives, with the exception of surface-treated pine, where the values were lower. The process that contributes most to ozone depletion is related to electricity consumption, with nitrogen oxides and NMVOCs being the most influential emissions. Marine eutrophication showed similar values for all alternatives, only slightly higher values for surface-treated beech wood, and slightly lower values for surface-treated pine wood. The largest contributors were nitrate emissions that were related to electricity consumption. In the land use category, the values for surface-treated beech wood were significantly higher than those for the other alternatives. The process that contributes most to the environmental impact is the use of wood (hardwood or softwood) followed by electricity. The occupation of forest land had the greatest impact. The mineral resource scarcity showed similar values for all alternatives, with surface-treated beech wood showing slightly higher values. This impact category is mainly determined by electricity consumption but also by the use of chemicals—nitrogen and calcium for the mineralized alternatives and varnish for the surface-treated alternatives. For all alternatives, emissions of uranium and nickel were found to have the greatest impact.

When analyzing the environmental impact endpoint categories, the values for surface-treated beech wood were the highest, followed by mineralized beech wood and mineralized pine wood, while the values for surface-treated pine wood were the lowest. When normalizing the impact endpoint categories, the human health impact category appears to be by far the most critical, with electricity consumption being the main contributing process followed by the leaching process in the case of the mineralized alternatives. The most influential impacts were the water turbine, the emission of sulphur dioxide, and the emission of carbon dioxide. The same impacts also determine the damage to ecosystems, while the resource category is most influenced by the use of natural gas, oil, coal, and uranium (Figure 4).

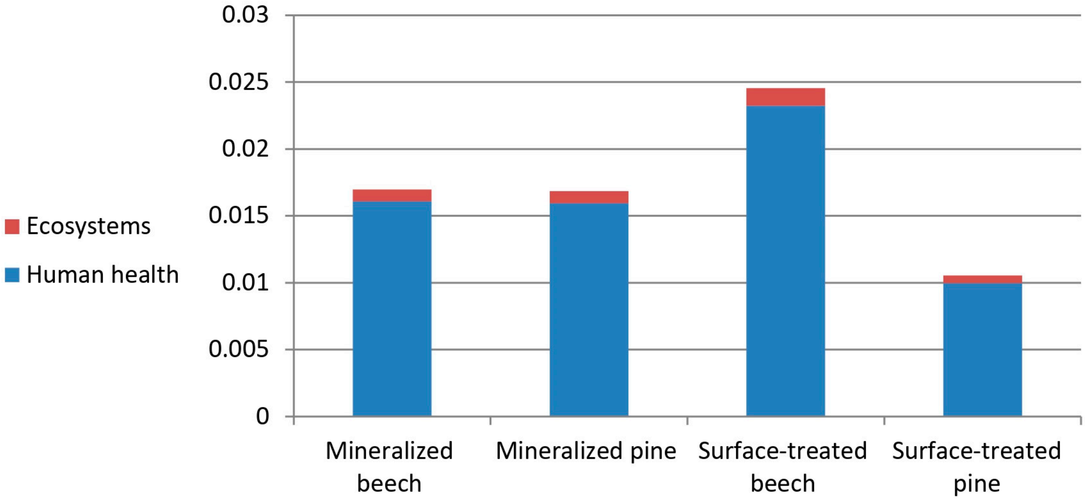

Figure 4. Results for endpoint categories after normalization when comparing alternatives 'mineralized beech', 'mineralized pine', 'surface-treated beech', and 'surface-treated pine'.

3.2. The Results of LCC Analysis

Figure 5 presents the results of the LCC analysis for the functional unit under consideration (50 years, 1 m^3 façade), excluding costs for external effects (environmental prices). The life cycle costs are lowest for both mineralized categories and highest for beech wood. In all four cases, the highest cost values are represented by the operating costs followed by the investment costs. Other costs account for a much smaller share.

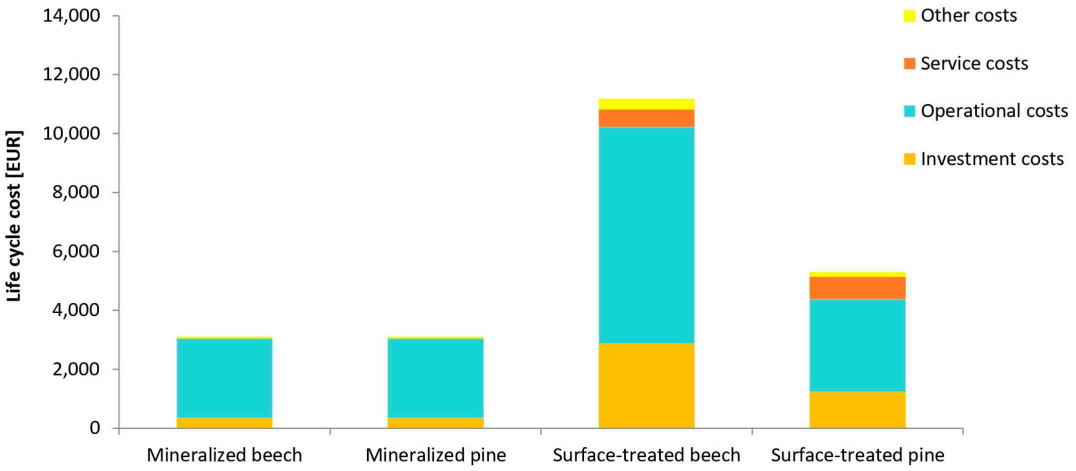

Figure 5. Graphical representation of the LCC results without costs of externalities.

The largest part of the total costs represents externalities costs (Figure 6), which are highest for the surface-treated beech façade and lowest for the mineralized pine façade.

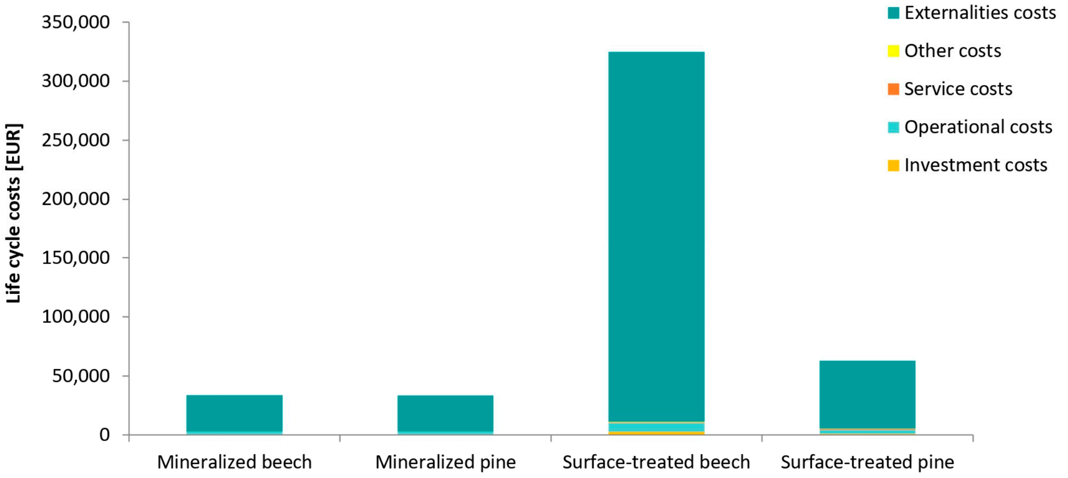

Figure 6. Graphical representation of the LCC results including costs of externalities.

4. Discussion

4.1. Discussion on LCA Results

In order to compare the environmental impacts, an LCA analysis was carried out for four different wood alternatives. The main environmental impacts of mineralized wood were marine ecotoxicity, followed by freshwater ecotoxicity and human carcinogenic toxicity. Toxicity to aquatic systems was also identified by Hu et al. [16] and Turk et al. [35] as the most influential category for the process of wood impregnation and mineralization synthesis. Turk et al. also identified non-carcinogenic toxicity to humans as a critical category in the production of chemicals required for the manufacture of other substances. Carcinogenic toxicity to humans was not considered in this study. However, in the studies by Dias et al. [14], the impregnation process was the main factor influencing human carcinogenic toxicity as a critical category, with the main difference in human toxicity values being due to the difference in energy consumption—surface treatment required less energy and the values were significantly lower than for vacuum impregnation—where the values were higher. If the energy required for wood preservation was more or less the same, the results of the study by Hu et al. showed the influence of the preservatives used. Thus, chromium proved to be the most critical, while ACQ and tannin–boron preservatives showed significantly lower values for human health effects. Our study did not include chemicals that are considered harmful to health, e.g., chromium, so the influence of these chemicals was not as significant compared to electricity consumption.

For our system, the most influential contribution to the overall environmental impact categories was electricity consumption, which is directly linked to electricity generation and the selected electricity mix from the database. Considering that the electricity mix for Slovenia from the Ecoinvent database is based on the International Energy Agency (IEA) data for 2018, it can be explained how most of the impacts could be attributed to the analyzed system. Heavy metals (chromium IV, zinc, nickel, copper, etc.), which have the greatest impact in the impact calculations for categories such as marine ecotoxicity or (non-)carcinogenic toxicity to humans, were associated with electricity generation in coal-fired power plants [36]. At the time of data collection, the share of coal-fired power generation in Slovenia was 29% [37], which has a significant influence on the results. Therefore, most impact categories were determined by electricity consumption and the chosen electricity mix. For all these categories, surface-coated beech wood showed the highest impact values, which is understandable due to the shortest lifespan of wood, as the production process had to be repeated seven times.

The mineralization process proved to be the differentiator in the stratospheric ozone layer depletion category, where the chemicals, particularly the production of diammonium phosphate, made mineralized alternatives appear to be the worst choice for the environment. The chemicals used in the system also proved to be decisive in the category of mineral resource scarcity.

Another distinguishing feature was water consumption. In addition to the water used for hydropower generation, which accounted for about 30% of the total electricity generation in Slovenia in 2018 [36], the water used for the leaching process was also consumed, while the use of additional water was not required for surface-coated alternatives.

A further distinct category in which electricity was of secondary importance is land use. Surface-treated beech wood had the highest values, as it requires more life cycles and consequently higher wood utilization. Overall, hardwood had slightly higher impact values than softwood. This difference is due to the higher energy demand for the production of hardwood and the more intensive forest conversion required for its harvesting [38]. In addition, hardwood is often associated with higher levels of illegal logging and a higher risk of deforestation [39], both of which are accounted for in the database. Similarly, Dias et al. [14] found higher values in LCA analyses when comparing surface-treated or vacuum-impregnated hardwood with softwood. In addition, the scenario with the shortest timeframe had the greatest impact on land use, regardless of the preservation method, which is consistent with the results of our study.

It is important to consider the limitations of our study in terms of system boundaries, the uncertainty of the data, and the general novelty of mineralized wood. The system boundaries of the study do not include the end-of-life scenarios for the alternatives, as the aim of our study was primarily to justify the environmental sensibility of the novel processing of mineralized wood. As the process is still relatively new, the end-of-life options need to be modelled and tested in more detail. In addition, experimental work needs to be carried out to confirm the durability of mineralized wood and/or to determine the exact service life and performance during the use phase. Furthermore, the data of the processes used in our study varied between ‘generic’ predefined processes available in Ecoinvent and more accurate data obtained from experimental work. For example, while the experiments were conducted with beech and pine wood, the wood inputs from the database described hardwood and softwood as more generic information. The greatest uncertainty in relation to the input data collected in the experimental work concerns the energy consumption in the mineralization phase, or more precisely, the drying processes during mineralization. For our experiments, a laboratory-scale drying chamber was used, which unfortunately is not as energy-efficient as industrial kilns. In addition, the energy consumption is more or less the same, regardless of the volume of the wood in the drying chamber, which is why the energy consumption for our small number of samples seems quite high.

An important difference between our study and other studies dealing with the environmental impact of wood preservation [14,16,35] is the functional unit. In other studies, it was mostly defined by the number of chemicals and preservatives required, whereas the functional unit in our study was based on the timeframe of durability due to the different process sequences in the compared methods. Nevertheless, the use of chemicals was monitored and calculated based on real-time experiments and considered in the environmental calculations. The scenarios in our study are comparable despite the differences in wood processing [27] and are urgently needed as the choice of material considered (mineralized wood) needs to be environmentally monitored and compared with other commercially available options before further development.

4.2. Discussion on LCC Results

The LCC analysis was carried out to evaluate and compare the life cycle costs of the different alternatives for the external façade. It was found that the operating costs are the highest for all alternatives, followed by the investment costs and the service costs for the surface-treated wood alternatives. The mineralized wood façade was found to be the most cost-effective for both wood types, with costs being identical for mineralized beech and mineralized pine. The LCC analysis is strongly influenced by the current economic situation and the prices of materials and services on the market, so it is important to take possible fluctuations into account. Nevertheless, it can be deduced from the results that the service life of the façade was the most influential factor in the LCC analysis. In practice, it can be assumed that maintenance costs will not be incurred at all or at least not to the extent assumed in the study. However, the lack of post-treatment of the coating could mean that the service life of the façade is shorter, which would inevitably increase the overall costs. When the costs for externalities were also included, they accounted for the largest share of the total costs. For the externalities, the environmental prices were calculated using the methodology that takes into account the ReCiPe categories and assigns the price per kilogram of emission. This approach allows a monetary assessment of the loss of social welfare. The majority of the impact is due to electricity consumption and heavy metal emissions. Human carcinogenic toxicity proved to be the most expensive category, as carcinogenic heavy metals are the most numerous pollutants in the analyzed system and at the same time cause the greatest social costs [33]. Here too, mineralized wood proved to be the most favourable option.

5. Conclusions

This study investigated the environmental impact and economic viability of the new mineralized wood. So far, life cycle assessments have been used to evaluate different preservation methods that have similar critical impact categories, as wood products are environmentally friendly overall and electricity consumption usually accounts for the majority of the impact. The categories that differed between surface-treated wood, which was our baseline scenario, and mineralized wood were ozone depletion, water consumption, and land use. Overall, mineralized wood proved to be a good choice for the environment, mainly due to the longer lifespan of the products, e.g., for wooden façades. The category in which the emissions for mineralized wood were significantly higher than for the surface-treated alternatives was water consumption, as a considerable amount of water is required for the leaching process in the mineralization phase. In addition to the LCA, an LCC analysis was carried out, which showed that mineralized wood is the more economical alternative for exterior façades, as the life expectancy is significantly higher compared to surface-treated wood. To summarize, life expectancy proved to be the most influential factor in most categories in both the LCA and LCC analyses. It is important to remember that, especially when we include chemicals or energy-intensive processes in the production system, a longer lifespan must be ensured to justify the additional environmental impact. Mineralized wood has proven to be an environmentally friendly material and, in addition to its resistance to fungi and its flame-retardant properties, offers great sustainable potential for the construction sector. The main way to improve environmental performance is to improve the leaching process to use less water and optimize the repetitive drying and humidification cycles of the wood to use less electricity.

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