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Material and Environmental Factors Impacting the Durability of Oak Mooring Piles in Venice, Italy

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Abstract: This study examines the rapid degradation of oak mooring piles caused by shipworms in Venice, Italy. In the last few decades, this problem has raised significant safety and environmental concerns, as the piles often need to be replaced every 18–24 months. The sound basic density and diameter of 22 oak piles were analysed after being exposed to shipworm attacks for 18–240 months to determine whether denser piles or larger diameters influence the rate of decay. This was performed to assess whether larger cross sections or higher densities of the piles could imply an increased durability against marine borers. The impact of environmental factors such as temperature, salinity, pH, and dissolved oxygen levels was also assessed. The results highlighted that pile density and diameter do not significantly influence the resistance against shipworms, while rising temperatures (+2 °C in the past two decades) may contribute to accelerating shipworm activity. These phenomena are worsened by the arrival of warm-water shipworms since 2013, exhibiting greater aggressiveness in wood degradation. Furthermore, the potential impact of storm surge barriers on shipworm activity remains an open research topic. Alternative materials and protection techniques introduced since 2015, such as polyurethane piles or metal stapling, face environmental and logistical challenges. Despite these alternatives, many new oak mooring piles are still installed in Venice without protection and are vulnerable to rapid deterioration. Addressing these issues requires multidisciplinary research to develop sustainable materials and preservation techniques for maintaining infrastructure in Venice.

Keywords: mooring piles; oak wood; briccole; Venice; shipworms; sustainable materials; conservation; wood properties

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1. Introduction

Many docking areas in the city of Venice (Italy) rely on wooden mooring piles, locally known as *briccole* (Figure 1), used for vessel mooring and navigation guidance [1]. The city of Venice adopts different wood species for mooring piles and protection systems for their durability [2]. The traditional wood species used for mooring piles in Venice, which are historically and architecturally significant to the city, mainly involved oak wood (*Quercus robur* and *Quercus pubescens*), chestnut (*Castanea sativa*), pine (*Pinus spp.*), and alder (*Alnus spp.*). Over the last decade, there has been an abnormal increase in marine wood-boring organisms attacking mooring piles, primarily Teredinidae species, which cause rapid deterioration of the wooden structure [1,3–8]. These phenomena are worsened by the arrival of warm-water shipworms (*T. bartschi*) [7], first detected in the Venice Lagoon in

2013. This species has demonstrated the ability to overwinter at near-freezing temperatures and exhibits greater aggressiveness in wood degradation. Now, invasive, warm-water shipworms have formed stable and abundant populations. In this context, Venice has faced emergency situations due to the sudden collapse of the mooring piles and problems related to their structural inefficiency due to material degradation. In many cases, the lifespan of the piles has decreased to just 18–24 months compared to the recorded average of 5–7 years between 2000 and 2010 [3,9] due to severe degradation caused by marine borers, commonly known as "shipworms" [1,6,7,10]. These molluscs tunnel through the wood, progressively weakening its structure and ultimately compromising the stability of the piles [10,11]. The rapid deterioration of more than fifty thousand mooring piles currently present in the Venice Lagoon has posed significant challenges for the maintenance and sustainability of Venice's maritime infrastructure. The situation also has a critical impact on navigation, as leaning piles and fractured stumps can drift through the canals, posing substantial risks to boats and vessels. With the arrival of seasonal fog, reduced visibility further amplifies the danger of collisions and potential vessel damage.

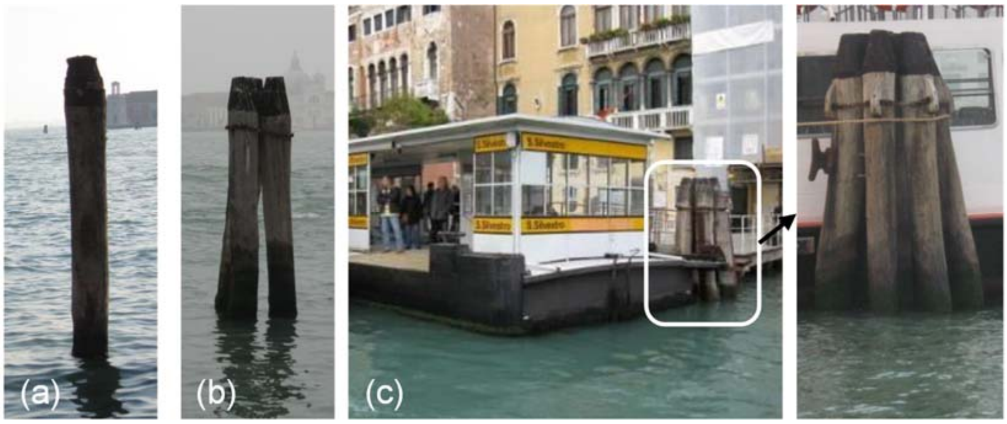

Figure 1. Mooring piles in Venice Lagoon: (**a**) single mooring pile for navigation purposes; (**b**) group of three mooring piles; (**c**) large group of mooring piles employed in a docking station in Venice (adaptation from [3]).

Although current preservation strategies aim to mitigate the impact of marine borers, they remain limited in effectively protecting wooden piles [2,6] (discussed in Section 6). Despite the natural durability of the aforementioned European hardwood species [6,12–14] employed for mooring piles, their resistance to degradation by shipworms is generally low and decreases further as water temperature rises. According to the literature, only some tropical wood species are considered resistant to shipworm attacks [15,16]. All other species are susceptible to shipworm attacks and should either be treated with preservatives or protected using mechanical barriers to prevent infestation. The primary factors influencing wood resistance to shipworms in marine environments are the wood hardness and the presence of extractives [10–12,17–19]. Hardness is influenced by wood density, meaning that more dense wood tends to have greater hardness and, consequently, better resistance to tunnel excavation. Oak wood generally exhibits a low silica content below 0.5%. This makes it not relevant against shipworm attacks, where concentrations exceeding 1% can enhance resistance to wood-boring organisms such as shipworms.

In order to address this issue, the effects of shipworms on the durability of 22 full-length oak mooring piles employed in 19 different docking areas in Venice were investigated [9], thanks to the support of the ACTV S.p.A of Venice. A total of 298 samples were extracted from the piles and analysed. The goal is to identify the physical properties of oak piles that increase the oak durability against marine borers, resulting in consequent extensions of their time in service. In particular, this study investigates the following:

(a) The impact of shipworm infestation on oak piles, to determine whether the piles' durability correlates with higher density and larger pile diameters used in Venice (see Section 3).
(b) Environmental factors such as temperature, salinity, pH, and dissolved oxygen levels influencing the speed and activity of shipworms across different sites in Venice, highlighting their potential role in affecting the durability of wooden piles [10,20] (see Section 5).

This research aims to improve the economic efficiency of infrastructure management in Venice, reducing the need for frequent pile replacement and promoting more sustainable use of wood as a construction material. The novelty of this study lies in the opportunity to conduct a large-scale empirical assessment of oak mooring piles after being used in real marine conditions, correlating their physical properties with resistance to shipworms, and offering insights for sustainable material choices in the historically and environmentally sensitive context of Venice.

2. Materials

The materials comprised 22 oak mooring piles from 19 docking areas in Venice. The mooring piles were extracted and replaced after showing extensive degradation due to shipworms. The oak piles are sourced from managed forests in France and the Netherlands (specific locations not disclosed). They are derived from plantations of *Quercus* species, with trees ranging in age from 40 to 100 years. At the time of extraction, all the piles exhibited approximately uniform degradation despite having different durations of service between 18 and 140 months. This uniform degradation allowed the authors to investigate the effects of shipworms on the material properties of the piles after varying periods of exposure to seawater. The code and name of the docking sites of the full-scale mooring piles are listed in Table 1, along with time in service and the diameter of the head (D_{head}—largest diameter of the pile head coming out of the water) and the tip (D_{tip}—smallest diameter of the bottom part of the pile inserted in the soil). Figure 2 shows the map of the docking sites according to Table 1. Three groups were made based on the time in service: 0–30 months (group A), 30–100 months (group B), and above 100 months (group C). This grouping was designed to ensure a sufficient statistical distribution of data for analysis. At the time of the laboratory test, the moisture content of the piles ranged from 12 to 30% (see Section 3).

Table 1. Preliminary data of the wooden piles analysed in 19 docking areas in Venice.

Code	Docking Site	Time in Service (Months)	D_{head} (mm)	D_{tip} (mm)
1	Punta Sabbioni Motonave	18	440	435
2	Punta Sabbioni Motonave	18	375	345
3	Lido S.M.E.	37	340	325
4	Caroman	23	335	285
5	Redentore	34	480	385
6	San Giorgio	25	355	330
6a			420	375
7	Cimitero Mura	25	310	275
8	Salute	20	355	210
9a	San Marco Vallaresso	132	330	310
9b			335	280
10	Sacca Fisola Valle Traghetto	127	430	385
11	San Servolo	29	350	330

Table 1. *Cont.*

Code	Docking Site	Time in Service (Months)	D_{head} (mm)	D_{tip} (mm)
12	Fusina	38	380	350
13a	Fusina	38	380	365
13b			385	375
14	Giardini destro	22	315	290
15	Santa Maria difesa rampa	140	330	310
16	Santa Maria difesa rampa	140	385	355
17	Cantiere S. Elena	134	265	240
18	Giardini Partigiana	57	545	475
19	Bricola 77 segnalazione canale	84	380	340

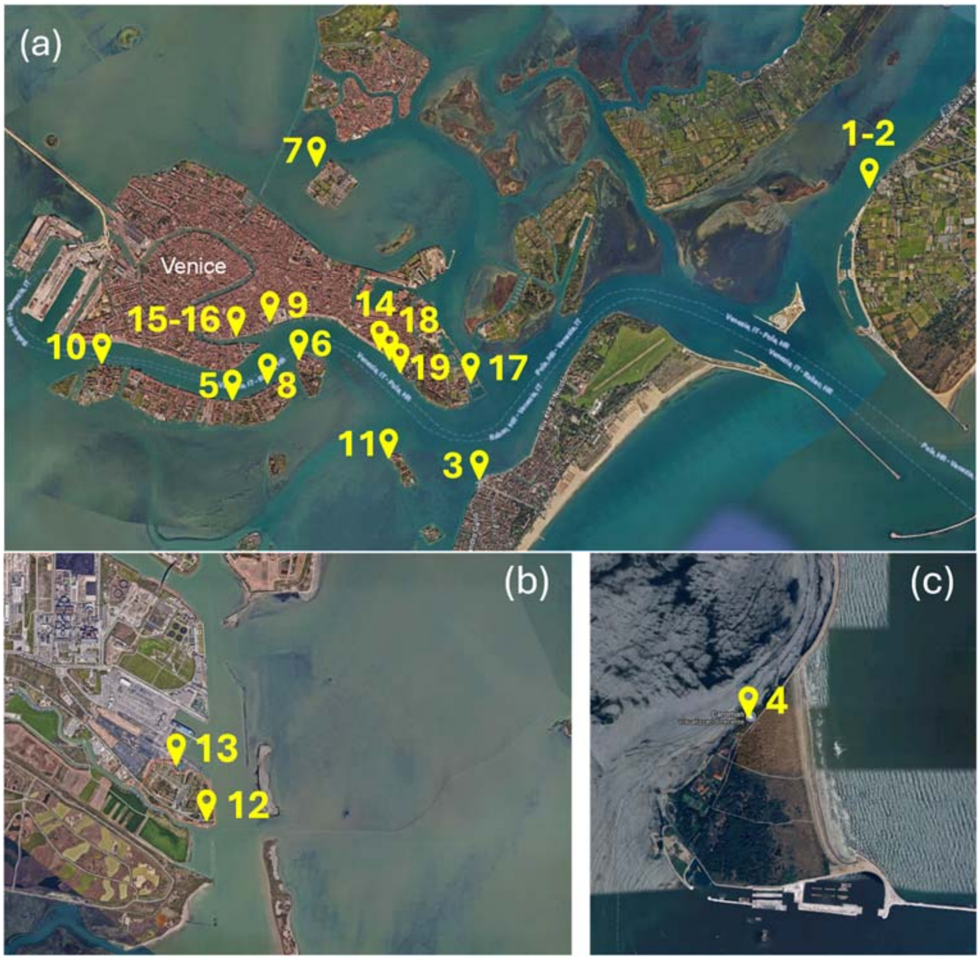

Figure 2. Map of Venice Lagoon and docking sites according to Table 1: (**a**) Venice and its surroundings, (**b**) Fusina at the west side of Venice, (**c**) Villaggio Caroman at the south side of the lagoon.

3. Methodology

The impact of shipworms on the investigated oak piles was assessed in relation to the sound basic density and pile diameter. This was performed to assess whether larger cross sections or higher densities of the piles could imply an increased durability against marine borers. This investigation aimed to explore the possibility of using oak piles with potential thresholds for pile diameters and density for an improved service life of the piles that are in direct contact with seawater and exposed to the attack of shipworms. Six parameters were investigated: wood species, density at 12% moisture content, sound basic density, residual basic density, total annual rings, and growth ring width.

In total, 22 oak degraded piles were investigated. Upon extraction, it was observed that all the piles displayed similar levels of degradation, despite varying durations of service life.

A total of 298 20 × 20 × 30 mm^3 samples were extracted along 4 slices of non-degraded discs sawn from the piles (Figure 3). The weight and volume of samples were determined at test moisture content, ranging from 12 to 30%. The dry mass and maximum moisture content were determined by oven-drying the samples according to EN 13183-1 (2002) [21]. Subsequently, the density at MC = 12% (ρ_{12}) was determined in Equation (1) as the ratio between the calculated mass m_{12} (Equation (2)) and volume V_{12} at MC = 12% (Equation (3)). The volumetric shrinkage at MC = 12% was assumed to be roughly 15% according to [13,22] for oak (*Quercus robur*) and Turkey oak (*Quercus cerris*)—which present similar physical properties—calculated on the basis of 3 assumptions: shrinkage starts at the fibre saturation point (MC = 30%); the dimensions of the pile decrease linearly with decreasing MC; and variability in volumetric shrinkage can be expressed using a coefficient of variation of approximately 15%, accounting for wood's intrinsic growth characteristics.

$$\rho_{12} = m_{12}/V_{12} \tag{1}$$

$$m_{12} = m_{dry}\ (1 + u_{ref}) \tag{2}$$

$$V_{12} = V_{wet} \cdot (1 - S_0) \cdot (1 - u_{ref}/u_{30}) \tag{3}$$

where

V_{wet} = saturated volume at test moisture content.

u_{30} = 30% moisture content at fibre saturation point (assumed equal to 30% [22]).

u_{ref} = 12% moisture content at 12%.

S_0 = 15% volumetric shrinkage from MC = 30% to MC = 0%, assumed 15% for oak.

Finally, the basic density (BD) was derived from ρ_{12} at MC = 12% by using the experimental relationship between ρ_{12} and BD outlined in [23]: BD = 0.828 ρ_{12}. The residual basic density (RBD) was determined as the ratio between the measured BD and the average basic density of sound oak (*Quercus robur*): BD = 0.68 g/cm^3 and Turkey oak (*Quercus cerris*) BD = 0.7 g/cm^3 from the same species, derived from literature [13,24–26].

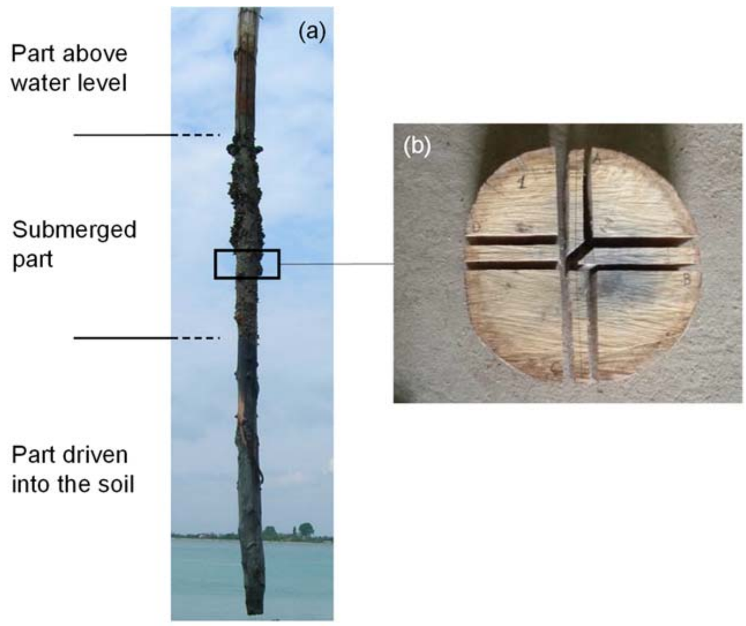

Figure 3. (**a**) Oak pile retrieved from a docking area in Venice; (**b**) pile disc from which the samples were extracted.

The wood density is influenced by growth parameters such as the diameter, number of annual rings (age), and annual ring width (ARW) [17,26–29]. These growth aspects are important to consider in relation to the wood quality in order to study the durability of wooden foundation piles against shipworms. The wood density is susceptible to the growing conditions of the trees in the forest, environmental conditions, and forest management practices [30–32]. To this end, the wood quality was assessed by measuring the average ARW using a dendro-chronograph (accuracy of 0.001 mm), proceeding along two orthogonal radii within the cross section of the pile. The ARW was then calculated as the average of the two measurements.

4. Results

At the moment of the extraction, the piles often appeared intact from the outside. Subsequent subdivision in discs (Figure 3) revealed that the piles were extensively tunnelled by Teredinidae larvae along the entire submerged section, from the seabed up to the waterline. The tunnels created by these shipworms ranged in diameter from 1 mm to 10 mm, significantly compromising the structural integrity of the piles. The situation is particularly dangerous because the damage in the piles is difficult to assess, including the extent of internal degradation and the imminent risk of structural failure. This makes it extremely challenging to predict and prevent collapses in advance.

All the analysed 298 samples were extracted from sound parts of the piles to check if the original density could have an impact on shipworm attacks. Table 2 shows the results of the physical characterisation of the piles, divided into three groups based on their time in service (0–30 months: group A; 30–100 months: group B; above 100 months: group C).

Table 2. Non-decayed physical properties of 22 piles retrieved from 19 docking areas in Venice.

Group	Code	Time in Service (Months)	D_{head} (mm)	D_{tip} (mm)	Species	ρ_{12} (g/cm^3)	BD (g/cm^3)	ARW (mm/Year)	Age (Years)	RBD (%)
A	1	18	440	435	Oak (*Quercus Robur*)	0.65	0.54	1.76	124	76
	2	18	375	345	Oak (*Quercus Robur*)	0.68	0.56	1.15	157	80
	8	20	355	210	Oak (*Quercus Robur*)	0.74	0.61	1.75	81	87
	14	22	315	290	Oak (*Quercus Robur*)	0.65	0.54	2.22	68	76
	4	23	335	285	Oak (*Quercus Robur*)	0.69	0.57	2.70	57	81
	6	25	355	330	Oak (*Quercus Robur*)	0.68	0.56	1.59	108	79
	6a	25	420	375	Oak (*Quercus Robur*)	0.69	0.57	-	-	82
	7	25	310	275	Oak (*Quercus Robur*)	0.71	0.59	1.19	123	83
	11	29	350	330	Oak (*Quercus Robur*)	0.67	0.56	1.93	88	79
B	5	34	480	385	Oak (*Quercus Robur*)	0.72	0.60	2.69	80	85
	3	37	340	325	Oak (*Quercus Robur*)	0.78	0.65	1.81	92	92
	12	38	380	350	Oak (*Quercus Robur*)	-	-	-	-	-
	13a	38	380	365	Oak (*Quercus Robur*)	0.70	0.58	1.70	110	82
	13b	38	385	375	Oak (*Quercus Robur*)	0.68	0.57	-	-	80
	18	57	545	475	Turkey Oak (*Quercus Cerris*)	0.73	0.61	2.11	121	86
	19	84	380	340	Oak (*Quercus Robur*)	0.81	0.67	2.06	87	95
C	10	127	430	385	Oak (*Quercus Robur*)	0.68	0.57	1.30	157	80
	9a	132	330	310	Oak (*Quercus Robur*)	0.73	0.60	1.15	139	85
	9b	132	335	280	Oak (*Quercus Robur*)	0.71	0.59	2.09	74	83
	17	134	265	240	Oak (*Quercus Robur*)	0.78	0.64	1.09	116	92
	15	140	330	310	Turkey Oak (*Quercus Cerris*)	0.66	0.55	1.64	98	78
	16	140	385	355	Oak (*Quercus Robur*)	0.67	0.55	1.69	109	78

Two oak wood species were identified: *Quercus robur* and *Quercus cerris*. The two species share identical anatomical features. However, *Quercus cerris* exhibits a visible colourimetric difference in its extractives, allowing it to be distinguished from *Quercus robur* [17]. Only two

Turkey oak piles were found, likely due to the species' lower abundance in the lagoon. No significant difference was found for ρ_{12} and BD of groups A, B, and C (Figure 4). The RBD values were around 80%, confirming that all the analysed samples were taken out of residual non-tunnelled parts of the piles, considered as sound [33]. The age, diameter, and ARW had no influence on the time in service of the piles, suggesting that larger pile diameters do not imply a slower attack of shipworms. In general, the results suggest that the degradation caused by shipworms on oak piles in Venice is neither related to the density nor the diameter of the piles, nor to growth characteristics such as the age and ARW.

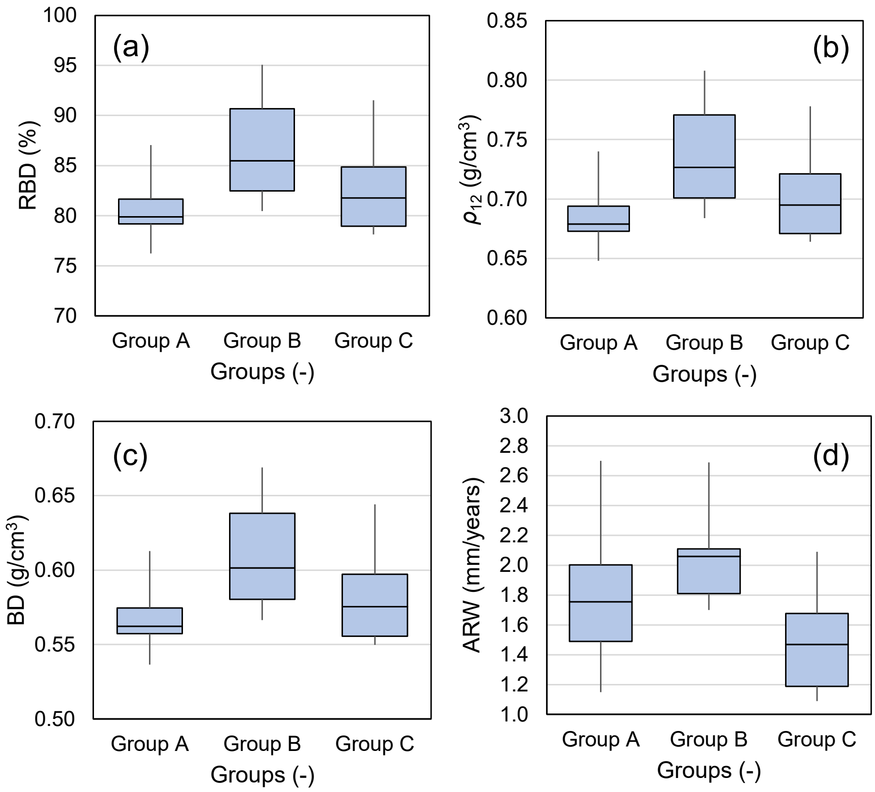

Figure 4. Box plots for (**a**) RBD; (**b**) ρ_{12}; (**c**) BD; (**d**) ARW of the three categories of oak piles (A, B, C) in Venice.

Fungi were found on the portions of the piles exposed to water flow [34–36] and submerged underwater. Certain fungi, particularly soft rot fungi, may have facilitated shipworm infestation, as reported in the literature [13,37]. However, it remains unclear whether this preferential attack on wood decayed by fungi is driven by chemical compounds produced by the fungi, such as albumin, or by the weakened structural integrity of the decayed wood. These aspects were not investigated.

5. Environmental Factors Affecting the Durability of Oak Mooring Piles

Water temperature and salinity play a crucial role in the survival of shipworms. The shipworm activity slows down below 15 °C, and salinity concentrations below approximately 8 PSU (Practical Salinity Units) act as a strong inhibitor. These values can change depending on the marine borer species [38,39]. This explains why infestations are typically less severe near river mouths, where freshwater dilutes the salinity. In the case of Venice, the average salinity of the water measured during spring 2024 was, on average, 30.5 ± 0.1 PSU (sourced from secondary data from ARPA Veneto [38]). Similar data were measured from 1961 to 2009 [40,41], suggesting that the lagoon water around Venice can be considered at steady-state. In this period, small perturbations in salinity were measured due to freshwater input from the Adriatic Sea. Over long periods, salinity has returned to its long-term average and maintained its distinct spatial distribution [40]. However, in the last decade, summer seasons have been particularly extreme in temperatures, where water temperatures reach up to 29 °C [38]. Clustering analysis showed the occurrence of summer heatwaves in 2008, 2013, 2015, and 2018, and three warm, prolonged summers (2012, 2017, 2019) coincided with higher summer water salinity peaks of 34 PSU [30,40]. These heatwaves have been linked to higher shipworm infestation rates, suggesting a direct correlation between elevated water temperatures and shipworm activity [7]. In general, the analysis of the air temperature datasets revealed an increasing trend over the Veneto Coast with values up to 0.9 °C/10 y in the city of Venice (calculated over the 2003–2020 period) [42]. This means that the temperature in Venice has increased by approximately 2 °C in the last two decades, already exceeding the global limit of 1.5 °C defined by the Paris Agreement [43]. Rising water temperatures and high salinity in the lagoon habitat may have affected the biology of the shipworms in the city of Venice, potentially making their attack on wood more aggressive. Wood species such as oak wood that were once considered resistant for longer periods of time (5–7 years) in the lagoon environment may have become more vulnerable in warmer conditions, decreasing the durability of oak wood to 18–24 months. Dissolved oxygen levels measured during spring 2024 were, on average, 102.3 ± 1.0% in the lagoon around Venice, in line with the average data recorded from 2011 to 2021 [38]. The water in Venice is a good environment where marine wood borers, like shipworms, can survive and reproduce, typically with levels of dissolved oxygen above 45% [39].

Another consideration involves the effect of storm surge barriers in Venice, such as MOSE (Experimental Electromechanical Module) [44]. The substantial storm-driven sediment supply and freshwater input are significantly reduced by the operation of storm surge barriers, which are essential factors in maintaining the lagoon's ecosystem. This highlights a critical conflict between the goals of coastal flood protection and the preservation of natural ecosystems [44]. Consequently, the alteration of these environmental factors could potentially influence the behaviour and distribution of marine species in the Venice Lagoon, including shipworms. This issue remains an open question. Further research is envisaged to study how storm surge barriers may alter the environmental conditions related to shipworm behaviour. This could provide valuable insights for balancing flood protection systems in the Venice Lagoon with the long-term sustainability of the marine ecosystem.

6. Discussion

From an environmental and sustainability perspective, the continuous use of European oak mooring piles in Venice may not be the most sustainable choice. Oak wood, requiring frequent replacement due to its rapid deterioration caused by shipworms, leads to increased resource consumption and waste generation. The environmental impact of cutting and replacing oak piles every 18–24 months, along with the associated transportation and disposal costs, could result in a significant carbon footprint over time.

6.1. Regulations on Mooring Piles in Venice

Until 2015, the use of tropical hardwoods or protective coatings was prohibited in the historic centre of Venice due to heritage regulations. These regulations mandated the use of traditional wood species that are historically and architecturally significant to the city, preventing the adoption of other wood species that could alter the cultural heritage of Venice. In 2015, new regulations were provided by the municipality of Venice [2] in response to the frequent pile replacements due to degradation, making preservation costly, not sustainable, and labour-intensive. The new regulations allow the use of two tropical hardwoods (Demerara greenheart and Azobe) and the use of piles made of expanded polyurethane and a metal core, extruded piles made of recycled or virgin polyethylene, and piles made of wood–plastic composites (WPCs) [45,46]. Even with these alternatives available, many new oak mooring piles in Venice are still being installed without any protective treatment.

6.2. Environmental Considerations of Alternative Wood Species and Materials

Although tropical hardwoods offer increased durability against marine borers, their use in Venice can contribute significantly to deforestation and incurs high environmental costs due to the long-distance transport from tropical regions to Europe [47]. The sourcing of tropical hardwood logs is often linked with deforestation, biodiversity loss, and climate change [47]. These concerns highlight the growing necessity for sustainable sourcing practices. When harvested responsibly from certified sources—such as FSC-certified forests [48]—tropical hardwoods can offer a more environmentally friendly alternative. Certification ensures that tropical hardwood logging supports biodiversity, maintains forest productivity, and preserves ecological processes in the forests.

Questions also arise regarding the use of polyurethane and polyethylene piles, particularly concerning their sustainability impact on the lagoon ecosystem and potential pollution [45]. The release of microplastics, defined as plastic particles measuring 1 mm or less, is already widely present in the marine environment of Venice Lagoon, originating from the fragmentation of larger plastic debris [49,50]. Microplastic pollution has emerged as a significant environmental concern due to its potential toxic effects caused by microplastic ingestion by marine organisms, potentially introducing toxic substances in marine food and posing a risk to human health [51]. Therefore, polyurethane and polyethylene piles need constant monitoring to assess the potential release of micro- and macroplastics into the water. Furthermore, the piles should be wrapped with metal straps (as suggested in [2]) to prevent abrasion from contact with boats while docking, which could cause further material degradation and the release of plastics into the water.

6.3. Protection Techniques: Advantages and Limitations

Two protection techniques were introduced in 2015 [2] to improve the durability of wooden mooring piles in the Venetian Lagoon environment. The first method involves protecting piles with heat-shrink tubing to prevent shipworm attacks. However, this approach is limited to mooring piles not intended for boat or ferry docking, as docking vessels can cause damage to the protective covering. The second one, known as "Metal Stapling" (*graffettatura* in Italian), is described in [2] and patented by Castagna S. [52]. Metal stapling of piles involves driving metal staples into the part of the wooden mooring pile intended for immersion. Once in water, the metal staples oxidise, creating a homogeneous ferrous oxide barrier on and underneath the water-exposed surface of the pile, protecting the wood from degradation caused by shipworms [52]. This method can extend the lifespan of oak mooring piles, with an average durability of 15 years. However, the applicability of these protection techniques is limited by the fact that piles with metal staples should be driven in the soil in the fall, when shipworm activity is lower [2,6,7]. This timing allows sufficient time—at least 4 months—for the metal staples to corrode in water and form a protective ferrous oxide layer within the wood matrix. While the methods presented offer valuable insights into their respective advantages and disadvantages, they do not exhaust all possibilities, leaving room for future research.

7. Conclusions

This study examined the rapid degradation of oak mooring piles caused by shipworms across 19 docking areas in Venice, currently leading to the frequent replacement of the piles, higher maintenance costs, and more material wastage. The density and diameter of 22 oak piles used in different locations were analysed to assess their impact on durability against shipworms. Additionally, environmental factors such as temperature, salinity, pH, and dissolved oxygen levels were considered to evaluate their role in the increasing shipworm attacks across different sites, which could significantly influence the durability of oak piles.

Significant degradation levels were found within the oak mooring piles of several docking areas of Venice, related to the attack of shipworms. The results of the material characterisation and analysis showed that quality factors of oak piles, such as the density, annual ring width, and diameter, had no significant impact on durability against shipworms. Larger or denser oak piles did not show an improved resistance against shipworm attacks after a period between 30 and 140 months.

The main environmental factors affecting the durability of mooring piles were identified as follows:

- Rising water temperature and more frequent heatwaves in summer seasons. Venice's lagoon has maintained a relatively stable salinity (ca. 30 PSU) since 1960, but rising temperatures (up to 29 °C in summer) and more frequent heatwaves in summer may intensify shipworm activity, reducing the durability of traditionally used oak piles from the recorded average of 5–7 years between 2000 and 2010 to the 18–24 months measured in the last decade. This trend may intensify in future, as air temperatures in Venice have increased by 2 °C over the past two decades, exceeding the 1.5 °C threshold set by the Paris Agreement.
- Dissolved oxygen levels (approximately 100%) continue to provide optimal conditions for shipworm survival.
- The stable and abundant population of warm-water shipworms (*T. bartschi*), present in the Venice Lagoon since 2013, exhibits greater aggressiveness and contributes to faster pile degradation.
- Storm surge barriers (MOSE barrier in Venice) may alter natural sediment and freshwater input, potentially affecting shipworm behaviour.

Despite the availability of more durable materials and preservation techniques, the continued use of unprotected oak piles in Venice highlights a critical gap in conservation practices. While tropical hardwoods offer increased durability against marine borers, their use in Venice raises concerns about deforestation and the environmental cost of transporting them from tropical regions to Europe. The sustainability of polyurethane and polyethylene piles also remains a concern, particularly regarding their potential impact on the lagoon ecosystem and pollution caused by the release of micro- and macroplastics into the water. The abrasion from boat contact during docking could accelerate material degradation and plastic pollution. For this, constant monitoring is needed, leading to increasing costs and potential sustainability issues, which contribute to a social gap that needs social investigation to determine whether this is an actual or perceived obstacle. The two protection techniques involving heat-shrink tubing and metal stapling present limitations. The first protection technique is only suitable for mooring piles not used for boat or ferry docking, as vessel contact can damage the protective covering. The use of metal stapling is also limited, both in application and by the necessity of longitudinal metal plates to shield boats from potential damage caused by the staples during docking, creating extra costs. Furthermore, piles with metal stapling must be installed exclusively in the fall, when shipworm activity is lower, to ensure the effective development of a protective ferrous oxide barrier within the wood over at least four months.

Future research is still needed to address the multidisciplinary issues related to the rapid degradation of mooring piles in Venice and the challenges associated with alternative solutions, protection techniques, the impact of storm surge barriers on environmental changes, and maintenance strategies of the mooring piles.

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