

Study of Immersion Water Quality during Desalination of Waterlogged Wood from the Phanom-Surin Shipwreck

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Abstract

Waterlogged wood artifacts deteriorate as salts and dissolved substances accumulate during prolonged submersion or burial. After excavation, salts may crystallize and cause damage. Desalination is essential for conservation. This study examine water quality during desalination and relationships variables influencing desalination in waterlogged wood from the Phanom-Surin shipwreck, Samut Sakhon Province, Thailand. Total of 27 samples were immersed in RO water at a water-to-weight ratio of 10:1, a biocide (KATHON CG, 0.02% w/v). The experiment 2 batches: (1) 24 samples with weekly water replacement until electrical conductivity (EC) decreased to ≤ 100 $\mu\text{S}/\text{cm}$ and (2) 3 samples without water replacement to evaluate closed-system conditions. Water quality parameters including water temperature, EC, salinity, pH, TDS, turbidity and COD were monitored weekly. Data distribution was tested using the Shapiro–Wilk test and relationships were analyzed using Spearman’s rank correlation. The quality of immersion water as follows: water temperature = 26.90 ± 2.29 $^{\circ}\text{C}$, TDS = 0.12 ± 0.06 mg/L , salinity = 0.01 ± 0.03 ppt, pH = 4.25 ± 0.55 , turbidity = 1.21 ± 0.72 NTU and COD = 18.76 ± 15.56 mg/L . EC is sharply decreased during the first water replacement; from approximately 1,781.30 to 239.60 $\mu\text{S}/\text{cm}$, and remain constant throughout the experiment. Spearman’s correlation analysis revealed that EC was positively correlated with salinity ($r=0.521$, $p<0.01$), indicating that EC can reflect changes in dissolved salts in the immersion water. EC also showed positive correlations with COD ($r=0.529$, $p<0.01$), turbidity ($r=0.548$, $p<0.01$) and TDS ($r=0.418$, $p<0.01$). Similarly, salinity was positively correlated with COD ($r=0.448$, $p<0.01$) and turbidity ($r=0.450$, $p<0.01$). In contrast, pH showed strong negative correlations with EC ($r=-0.906$, $p<0.01$), COD ($r=-0.600$, $p<0.01$), turbidity ($r=-0.586$, $p<0.01$) and salinity ($r=-0.504$, $p<0.01$). These relationships suggest that increases in dissolved ions,

suspended particles and organic matter are associated with lower pH values in the immersion system. Overall, EC, pH, turbidity and COD can serve as key indicators for monitoring water quality and evaluating the desalination process.

Keywords

waterlogged wood, desalination, water quality parameters, correlation, Phanom-Surin shipwreck

Introduction

Waterlogged wood artifacts often accumulate minerals and dissolved substances within the wood while submerged in seawater or settled underground for extended periods. These salts, especially water-soluble salts such as chlorides, sulfates and carbonates, seep into the wood's pores and undergo changes in response to humidity. At low humidity levels, the salts crystallize and expand, creating internal pressure that causes the wood fibers to crack or break. At high humidity levels, the salts dissolve and migrate to recrystallize in other locations, creating an irreversible cycle of destruction. Furthermore, some residues, such as sulfides, may oxidize after excavation, causing discoloration or unpleasant odors in the wood. If the sulfide contains iron such as iron sulfide or pyrite, it can oxidize to produce sulfuric acid, lowering the wood's pH and accelerating cellulose decomposition. It can also react with some preservatives, leading to staining or long-term deterioration of the preservative material. While chloride containing salts can accelerate the corrosion of metal materials associated with wood, such as metal rivets or structural components, and salt crystallization on the surface affects the aesthetics and preservation of displayed artifacts, desalination is a crucial step in reducing the risk of wood deterioration after excavation. Successful conservation studies of wood from shipwrecks have shown that desalination using reverse osmosis (RO) water, over a period of more than ten years, significantly reduces the amount of salt accumulated within artifacts. Therefore, desalination is a fundamental conservation process for artifacts discovered underwater or in wet archaeological sites, as it removes water-soluble salts from artifacts after excavation (National Research Institute of Maritime Cultural Heritage, 2014). These artifacts are saturated with various salts, most notably sodium chloride (NaCl), which creates a concentration difference between the wood's interior and the immersion water. This is driven by the diffusion process of salt out of wood according to the principle of mass transfer. A case study of the Phanom-Surin shipwreck site revealed that the water in the area had a high electrical conductivity of over 40,000 $\mu\text{S}/\text{cm}$. Combined with the fact that the ships had been submerged in this environment for over 1,200 years, a large amount of salt had accumulated in the wood. Many excavated artifacts therefore required desalination, a process that must be carried out continuously under the constraints of artifact deterioration. This makes desalination the longest step in the entire conservation process. However, current studies lack complete information on water quality during the immersion of artifacts. Continuous monitoring and the identification of water quality variables affecting the process are necessary. Therefore, this study of water quality during the desalination of wooden artifacts is crucial to obtain water quality data for use as a database of water quality during the desalination process. Furthermore, the data can be used to analyze the relationship between water quality variables in the desalination process, including EC, pH, water temperature, salinity, TDS, turbidity, and COD. Data were collected from the actual sites conditions in the area of the Fine Arts Department. The tracked data can be applied to monitor water quality during the desalination process and used to inform effective planning for the conservation of large numbers of artifacts.

Materials and Methods

The study of water quality by analyzing relevant parameters during the desalination process of wooden artifacts from underwater or wetland archaeological sites involves the following steps: selecting sample, recording physical data, analyzing water quality during the desalination process under the actual conservation process according to The Fine Arts Department manual for the conservation of artifacts from the Phanom-Surin shipwreck site, and analyzing the results scientifically and statistically, as detailed below.

Sample Selection

Small wooden artifacts obtained from archaeological excavations at the Phanom Surin shipwreck site, Samut Sakhon Province, in 2013, were selected with 27 samples included in the study. These artifacts were undergoing continuous desalination and had a conductivity value below 4,000 $\mu\text{S}/\text{cm}$, measured using the EC/TDS Meter with the measurement range of 0-4,000 $\mu\text{S}/\text{cm}$ (HI98312, HANNA). Every box container had a clear registration number and was safe from deterioration during the study.

Desalination Process

The desalination process involved immersing the artifacts in a box containing a water to weight ratio 10:1 (Jang et al., 2012) and then the 0.02% w/v biocide (KATHON CG) was added (Imazu et al., 2013). All artifacts were kept in a box container at room temperature without any interruption throughout the experiment. The experiment was divided into 2 batches:

Batch 1: Weekly water replacement

The water used to immerse the artifacts was changed weekly (Rodgers, 2004). The existing water was completely drained and replaced with RO water in the same ratio. This process was repeated until the EC of the immersion water is $\leq 100 \mu\text{S}/\text{cm}$. According to the requirements in the guidelines for the conservation of artifacts from the Phanom-Surin shipwreck site of The Fine Arts Department, the desalination process was consideration complete for 24 samples.

Batch 2: Zero water replacement

The artifacts were immersed without changing the water throughout the experiment for 3 samples. RO water was used in a water to weight ratio 10:1, and 0.02% w/v biocide (KATHON CG) was added to control microbial growth throughout the immersion.

Data Collection

Data on the water quality of the immersed artifacts were collected. A total of 7 parameters: EC, pH, Water temperature, Salinity, TDS, Turbidity, and COD were measured. Measurements were taken weekly and divided into 2 parts: (1) Part 1 (Figure 1): 27 samples were collected at The Fine Arts Department, measuring 4 parameters of EC, pH, water temperature, and salinity and (2) Part 2 (Figure 2): 10 samples were preserved at 4°C and were taken for analysis to the Department of Environmental Science, Faculty of Science, Silpakorn University. These samples were randomly selected based on the weight distribution of the artifacts while wet, and analyzed for 3 parameters of TDS, turbidity, and COD.

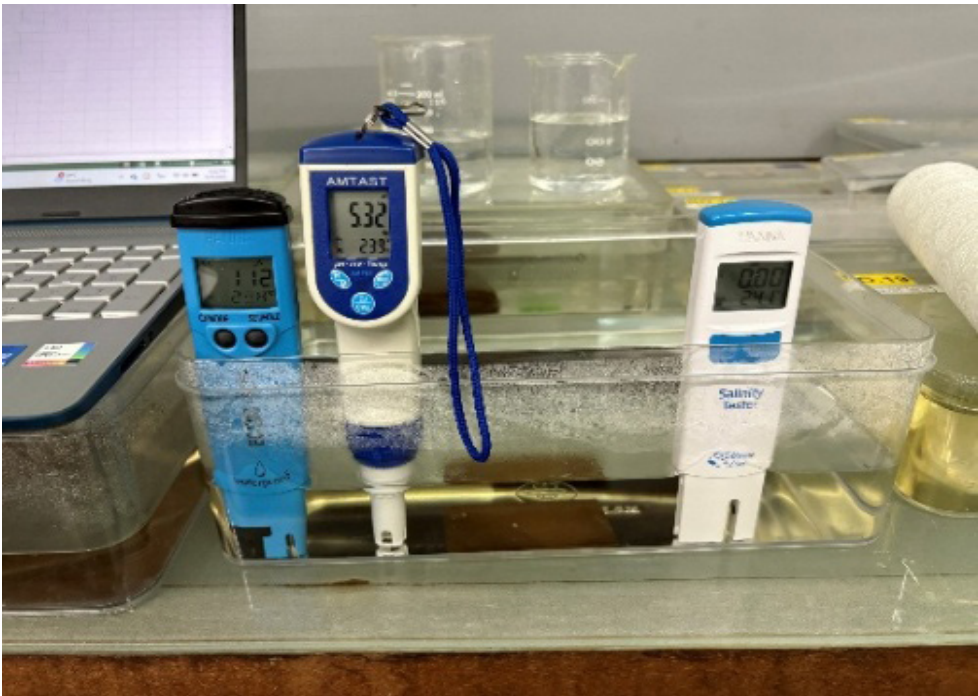


Figure 1. Measurement of EC, pH, temperature and salinity.



Figure 2. Samples for analysis of TDS, turbidity and COD.

Results and Discussion

Water quality of Batch 1 samples with weekly water replacement

Electrical Conductivity (EC)

In the first week, all samples showed relatively high electrical conductivity values, exceeding 250–500 $\mu\text{S}/\text{cm}$. A rapid decrease in EC was observed by the second week, with values dropping to approximately 100–180 $\mu\text{S}/\text{cm}$ across all samples. From the third week onwards, the rate of change became more gradual, with EC values either slowly decreasing or fluctuating within a narrower range of about 100–130 $\mu\text{S}/\text{cm}$. By the 8th–9th weeks, the EC values tended to stabilize, approaching a nearly constant level, as illustrated in the magnified view of the curve endpoints (Figure 3).

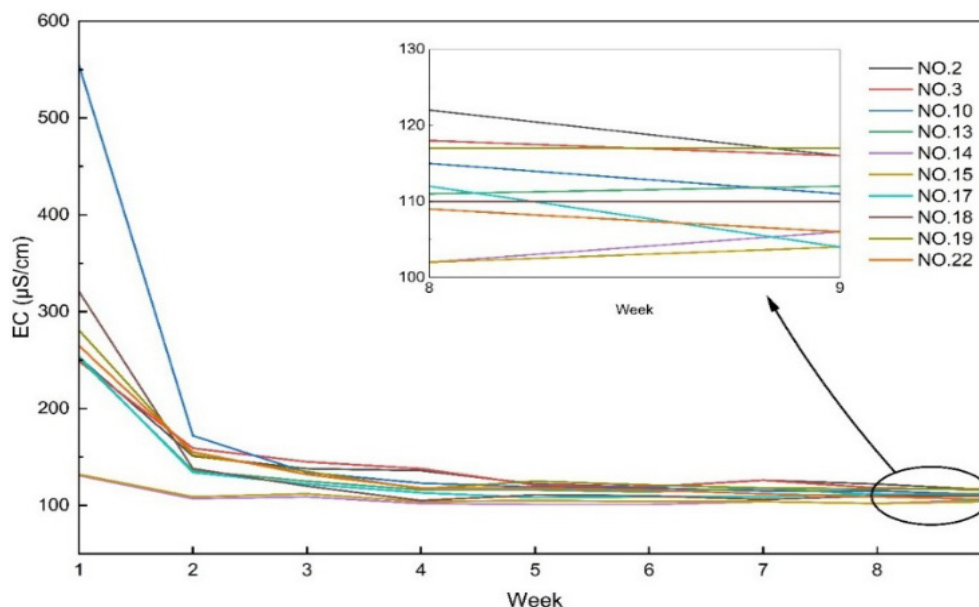


Figure 3. The electrical conductivity (EC) of the immersion water in Batch 1.

It should be noted that the RO water used in this study showed low EC (12 $\mu\text{S}/\text{cm}$), low TDS (6 mg/L), and no detectable salinity. However, the addition of Kathon CG 0.02% w/v, a biocidal preservative based on isothiazolinone compounds (CMIT/MIT) and containing ionic stabilizers, increased the EC to over 100 $\mu\text{S}/\text{cm}$. This indicates that Kathon CG contributed substantially to the background conductivity of the immersion water.

Therefore, the measured EC values may not solely reflect the release of soluble salts from the wood, particularly during the later stages when EC values approached a stable range. Instead, part of the conductivity is attributable to the presence of Kathon CG, which may explain why EC stabilized at approximately 100–130 $\mu\text{S}/\text{cm}$ rather than approaching the initial EC of the RO water.

In a large-scale desalination case study of the ancient wooden ship “Huaguangjiao I,” researchers reported that salt extraction can be effectively monitored through measurements of the EC of the immersion water, as ions released from the wood gradually diffuse into the surrounding solution and influence its conductivity Their study indicated that as long as soluble salts remain in the system, changes in EC can be used to assess the progress of desalination, with the process considered complete when EC stabilizes within the range of approximately 80–100 $\mu\text{S}/\text{cm}$ (Wang & Li, 2023).

pH

It was found that in first week, the pH of most samples ranged from approximately 3.3–4.0, indicating acidic conditions. This acidic nature is consistent with the reported characteristics of wood leachate, which typically shows a pH of about 3.3–3.9 during the early stages of formation. However, it should be noted that Kathon CG at a concentration of 0.02% (w/v), which was added to control microbial growth, is inherently acidic and may have contributed to the low initial pH values observed (Figure 4).

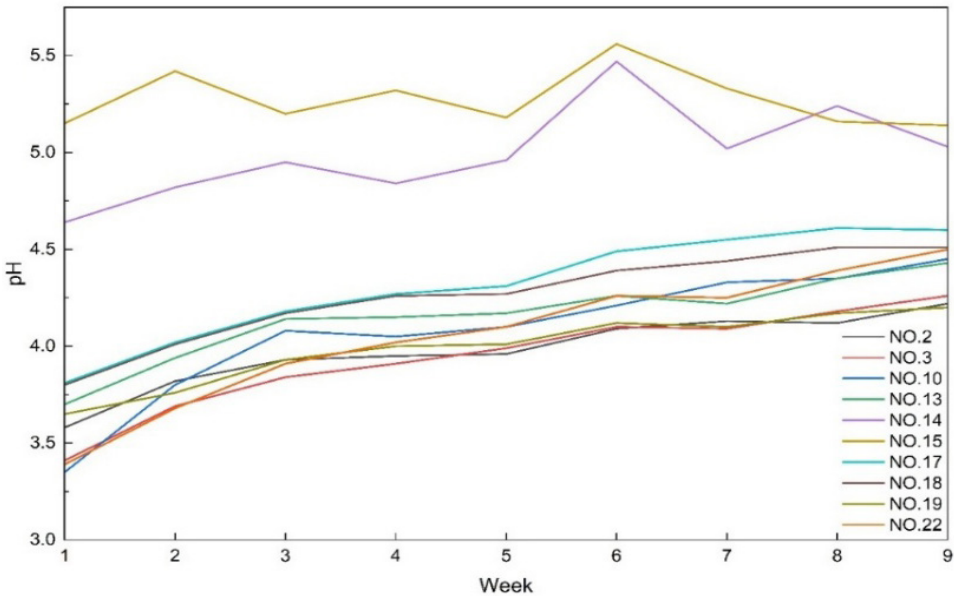


Figure 4. The pH values of the immersion water in Batch 1.

Over time, the pH of all samples showed a continuous increasing trend, particularly during the 2nd-5th weeks. Subsequently, during the 6th-9th weeks, the pH values of most samples adjusted to a range of approximately 4.2–5.5 and tended to stabilize. This gradual increase in pH is consistent with previous studies reporting that the pH of wood leachate rises with the age of the source, transitioning from highly acidic conditions in the initial stage to less acidic conditions in later stages (Tao et al., 2005). This increase cannot be attributed to a reduced influence of Kathon CG, as the biocide was replenished at a constant concentration during each water change. Instead, it is more likely due to the progressive depletion of acidic compounds leached from the wood, resulting in a gradual rise in pH over time.

Temperature

The variation in the temperature of the immersion water over the 9-week period showed that all samples exhibited a similar trend, with values ranging from approximately 23.5–31.3 °C as shown in Figure 5. This consistent pattern across all samples indicates that the temperature of the immersion water was primarily influenced by ambient environmental conditions. This is consistent with the concept that water temperature is related to air temperature, particularly in small, shallow water bodies where mixing occurs easily (Boyd, 2015).

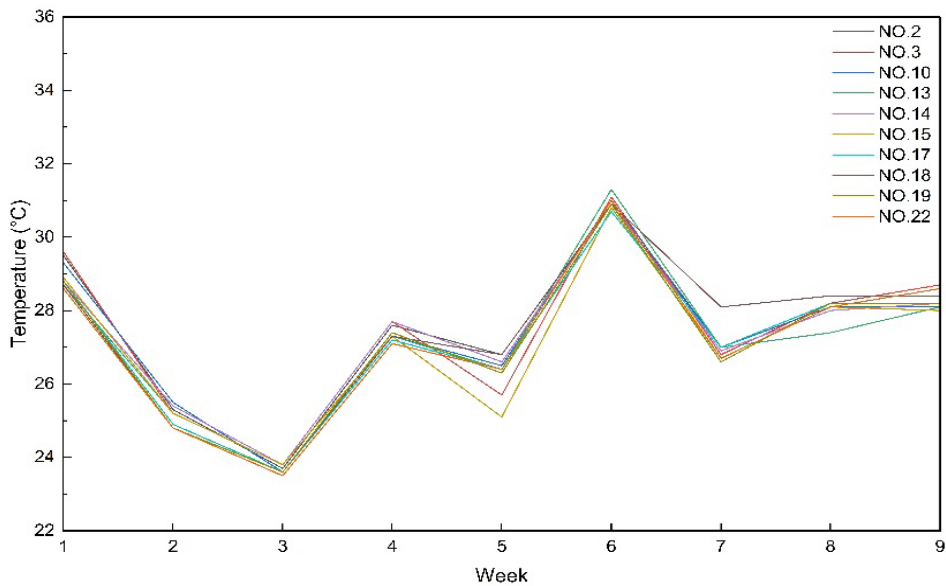


Figure 5. Temperature of the immersion water in Batch 1.

Although temperature is known to influence mass transfer processes by increasing diffusion rates, its effect was not clearly observed in this study. This is likely due to the relatively narrow temperature range (23.5–31.3 °C), which may not be sufficient to produce a significant change in diffusion behavior. In addition, the desalination process appears to be primarily controlled by the availability of soluble salts and internal diffusion limitations within the wood structure. Therefore, the influence of temperature is likely secondary compared to these dominant factors.

Salinity

It was found that salinity in the first week ranged from approximately 0.05–0.21 ppt and decreased rapidly by the second week, reaching 0.00 ppt in almost all samples from the third week onwards. Measurement of soluble salts and monitoring of ionic changes in waterlogged wood are critical aspects in the conservation of wooden artifacts, as they are directly influencing the evaluation of desalination efficiency prior to consolidation treatment (Longo et al., 2022) (Figure 6).

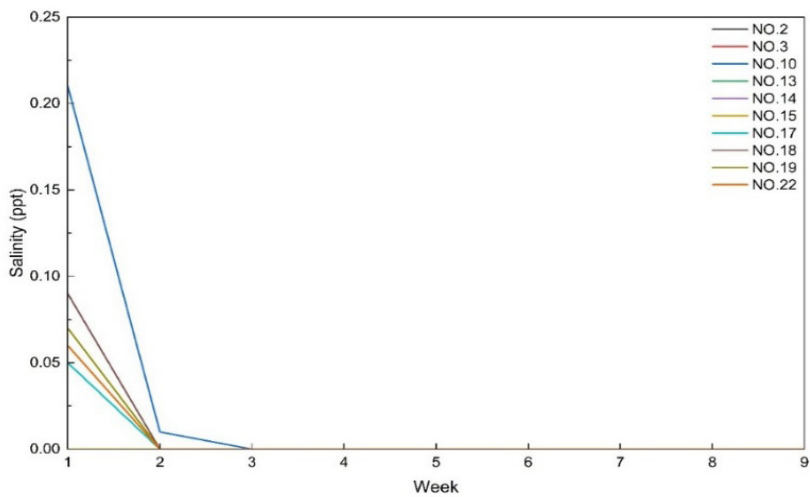


Figure 6. The salinity of the immersion water in Batch 1.

However, a reported salinity of 0.00 ppt does not necessarily indicate the complete absence of dissolved ions in the system; rather, it reflects that the salinity has decreased to a level below the detection limit or resolution of the measurement unit. In contrast, parameter such as electrical conductivity is more sensitive to low concentrations of ions. For this reason, the evaluation of solution conditions during desalination commonly relies on a combination of EC and TDS measurements to provide a more accurate assessment (Wang & Li, 2023).

Total Dissolved Solids (TDS)

Figure 7 showed that the TDS values in the first week ranged from approximately 0.10–0.30 mg/L, indicating variations in the concentration of dissolved solids in the immersion water among individual wood samples at the initial stage of the experiment.

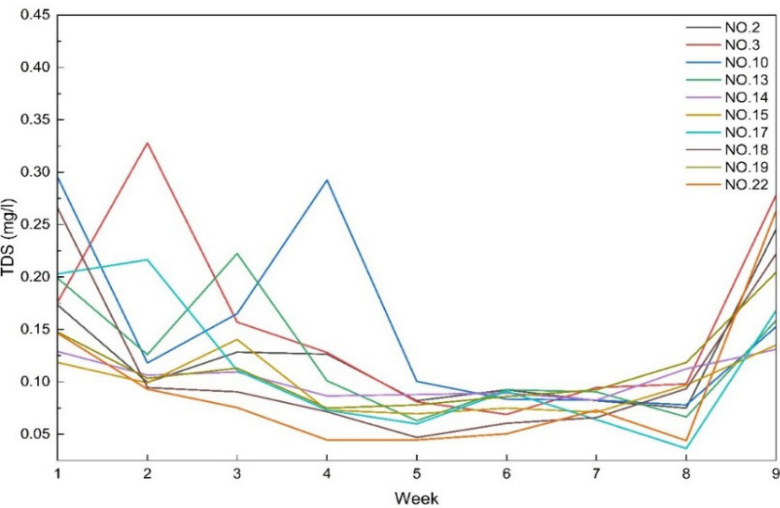


Figure 7. The total dissolved solids (TDS) values of the immersion water in Batch 1.

TDS was included as one of the water quality parameters used to monitor changes in the aquatic environment. This is consistent with previous studies on waterlogged archaeological contexts, in which TDS is measured alongside parameters such as electrical conductivity (EC), pH, dissolved oxygen (DO) and salinity to characterize water conditions (Tamantini et al., 2025).

Turbidity

According to Figure 8, it was found that the turbidity of many samples was relatively high in the first week. Specifically, samples NO.19 and NO.22 that had turbidity values greater than 4–5 NTU, while other samples were in the range of approximately 1–3 NTU. Subsequently, the turbidity values of most samples decreased significantly during the 2nd–3rd weeks and remained at low levels throughout the 4th–7th weeks. Although occasional increases were observed in some samples in certain weeks, these increases were not sustained and subsequently decreased again.

The high initial turbidity values can be compared to studies on woodchip wastewater, which reported that turbidity reflects the presence of suspended solids and organic matter in water systems. Under conditions of high organic matter and suspended solids, turbidity is also high (Azimi et al., 2019). This does not necessarily indicate a specific mechanism. However, this discussion is limited to comparing data trends with studies on industrial woodchip wastewater, which use turbidity as a similar indicator of water quality (Figure 9).

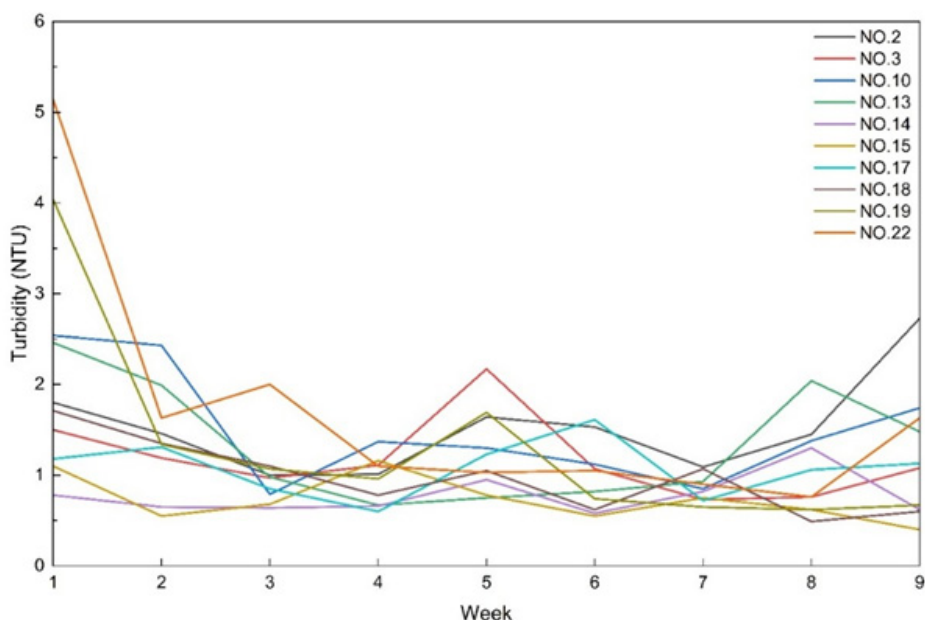


Figure 8. The turbidity of the immersion water in Batch 1.



Figure 9. Degradation behavior of wood during desalination process.

Chemical Oxygen Demand (COD)

In the first week, the COD values were high for all samples (Figure 10), especially samples NO.10 and NO.19, which were exceeding 80 mg/L. This reflects the high amount of organic matter dissolved from the wood during the initial soaking process. The high COD in the early stages is related to the presence of organic matter that requires oxygen for oxidation, which is commonly found in wood leachate. The organic matter that significantly contributes to COD includes tannin and lignin. The trend of COD changes shows a decrease with immersion time, with the COD decreasing continuously over time. This is consistent with reports that show the concentration of COD in wood leachate tends to decrease when the source of organic matter is reduced or leached away in the early stages (Tao et al., 2005).

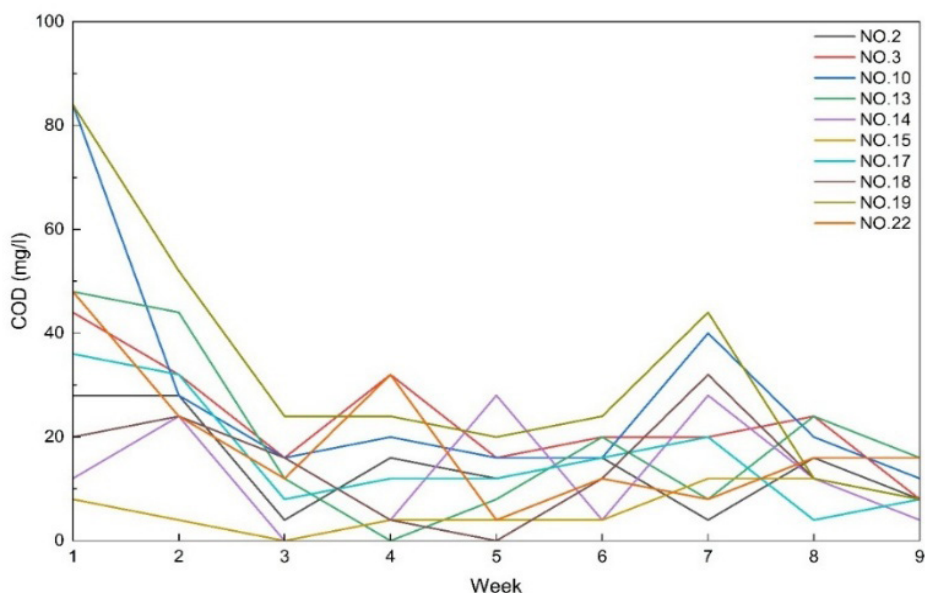


Figure 10. The chemical oxygen demand (COD) of the immersion water in Batch 1.

Water quality of Batch 2 samples with zero water replacement

Salinity measurements revealed that almost all reported values were zero. This does not indicate a complete absence of dissolved salts in the water system, but rather stems from the sensitivity limitations of the measuring instrument, which cannot detect very low salinity levels, especially in water that has undergone multiple water changes to reduce salinity, causing the salinity (ppt) to drop below the instrument's detection limit. Even though the water system still contains dissolved ions, other indicators such as EC and TDS are more suitable for assessing the tendency of desalination under very low salt concentrations. Figure 11 shows the changes in EC and pH of the water in which the wood samples were immersed without changing the water for approximately 50 days. The EC values of all 3 samples (NO.25, NO.26, and NO.27) tend to increase continuously from the beginning to the end of the experiment. The EC increased from the range of around 260–330 $\mu\text{S}/\text{cm}$ to about 300–380 $\mu\text{S}/\text{cm}$, reflecting the gradual accumulation of dissolved ions in this closed water system.

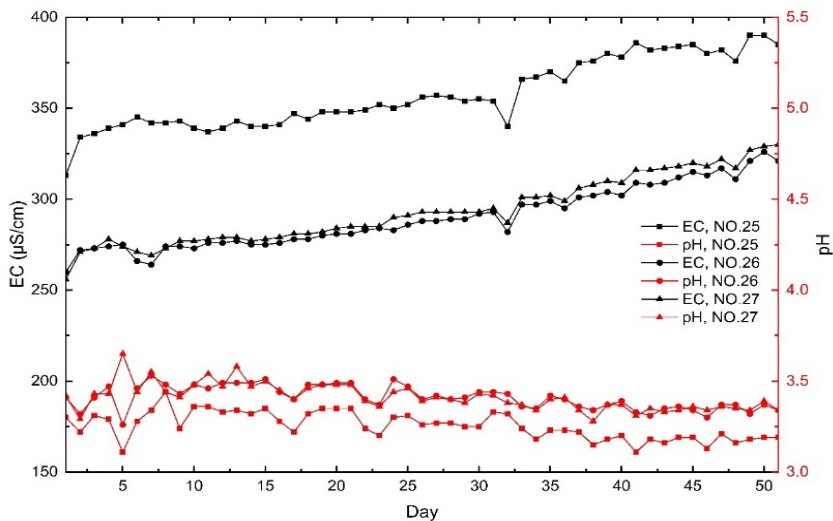


Figure 11. The EC and pH values of the immersion water in Batch 2.

Analysis of Relationships among Water Quality Parameters during the Desalination

Prior to the analysis of the relationships among water quality parameters, the data distribution was assessed using the Shapiro–Wilk test ($n = 90$). All parameters of temperature, EC, salinity, pH, turbidity, TDS, and COD showed p -values < 0.05 , indicating non-normal distribution. Therefore, Spearman’s rank correlation was applied to examine relationships among the variables.

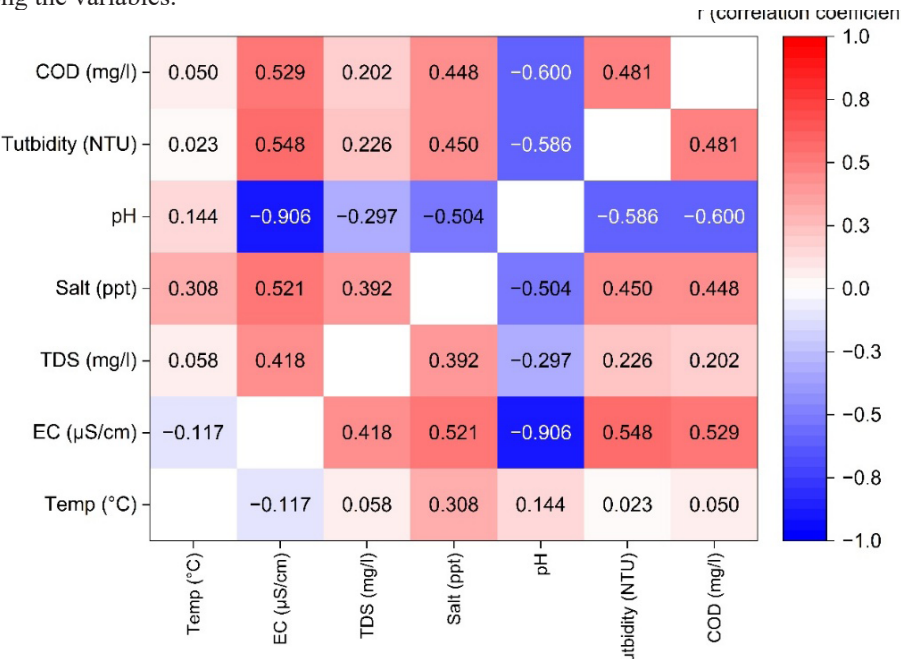


Figure 12. Correlations among 7 water quality parameters.

Spearman's rank correlation analysis revealed that several water quality parameters were significantly interrelated, reflecting the coupled physical and chemical processes occurring in the immersion system during the desalination process of wooden artifacts (Figure 12). EC showed moderate positive correlations with salinity ($r=0.521$, $p<0.01$), TDS ($r=0.418$, $p<0.01$), COD ($r=0.529$, $p<0.01$), and turbidity ($r=0.548$, $p<0.01$), indicating that increases in ionic content and organic matter were associated with higher levels of dissolved and suspended substances in the system. In contrast, pH showed strong negative correlations with EC ($r=-0.906$, $p<0.01$), COD ($r=-0.600$, $p<0.01$), and turbidity ($r=-0.586$, $p<0.01$), suggesting that higher concentrations of ions, organic matter, and suspended particles were associated with more acidic conditions. As these components were progressively removed during the desalination process, pH values gradually increased. Turbidity also showed significant positive correlations with salinity ($r=0.450$, $p<0.01$), COD ($r=0.481$, $p<0.01$), and TDS ($r=0.226$, $p<0.05$), reflecting the release of organic matter and dissolved substances from the wood matrix into the immersion water.

When considered alongside temperature, a statistically significant correlation was observed between temperature and salinity ($r=0.308$, $p<0.01$). However, this relationship should be interpreted with caution, as salinity rapidly decreased to near-zero levels in the early stage of the experiment and remained relatively constant thereafter, resulting in limited variability that may constrain mechanistic interpretation.

Summary

During the early stage of desalination, immersion water showed high EC, TDS, turbidity, and COD values due to the release of salts and organic matter from the wood. These parameters decreased and stabilized over time, while pH increased from acidic to more stable, slightly acidic conditions.

Comparison between systems with and without water replacement demonstrated that regular water exchange is essential for effective desalination. Without water replacement, EC increased continuously, indicating ion accumulation, whereas regular water replacement promoted their reduction and stabilization. As the pH level decreases in a system without water replacement.

Spearman's correlation analysis showed positive relationships among EC, salinity, TDS, turbidity and COD, and negative correlations between pH and these parameters. These findings indicate that EC, pH, turbidity and COD are suitable key indicators for monitoring desalination efficiency.

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