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The Effectiveness Of Using Essential Oils From Spice Plants To Prevent Moss Growth In The Cultural Heritage Area Of The Fort In Ternate City

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Abstract

The research results show that essential oils from nutmeg seeds, clove flowers, and cinnamon bark at concentrations of 10–20% are very effective in inhibiting the growth of leaf moss. Meanwhile, for crustose lichens, only clove flower essential oil has proven to be very effective, while nutmeg seed and cinnamon bark essential oils are less effective. Thus, essential oils, particularly clove essential oil, have the potential to be used as natural materials for the conservation of stone cultural heritage sites thru the control of moss growth.This finding shows that the utilization of essential oils from local spice plants not only supports the preservation efforts of cultural heritage sites but also provides a more environmentally friendly conservation alternative compared to the use of synthetic chemicals. The use of essential oils from cloves, nutmeg, and cinnamon can be a sustainable solution in maintaining the physical condition of the historic fort in Ternate City, while also enhancing the value of utilizing local biological resources as part of a sustainable cultural heritage conservation strategy.

Keywords: Essential oil of spice plants, moss, fort.

INTRODUCTION .

Cultural Heritage is a tangible cultural heritage in the form of cultural heritage objects, cultural heritage structures, cultural heritage sites, cultural heritage areas on land and/or in water,

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as well as cultural heritage buildings that need to be preserved because they have important value for history, science, education, religion, and or culture thru a designation process. An object can be said to be Cultural Heritage if it has gone thru the designation process. Without the designation process, a cultural heritage with significant value cannot be considered a cultural heritage site(Asmita et al., 2025).

One of the cultural heritage treasures of the cities of Ternate and Tidore, which holds historical value and has the potential to attract both national and international tourists to visit this area, is the cultural heritage of colonial fortresses. The colonial fortifications located in the city of Ternate consist of 7 forts, including Fort Orange, Fort Tolluko, Fort Kalamata, Fort Willemsstad, Fort Santosa, Fort Kastela, and Fort Pedro e San Paulo. Meanwhile, the cultural heritage fortifications in the city of Tidore consist of 8 forts, including Fort Tomanyira, Fort Maresco, Fort Mare, Fort Tore, Fort Tahula, Fort Roem, Fort Cobo, and Fort Biji Negara. The existence of these forts also inherently signifies a phase of the global political economy. This fort, which is around 470 years old, is likely already experiencing damage caused by several factors)(Tabaika et al., 2024).

Various historical relics designated as cultural heritage sites and tourist destinations can still be witnessed by future generations if preventive measures are taken to reduce the level of damage caused by aging and the growth of moss. Moss is one of the microorganisms that can cause damage and decay to stone-based cultural heritage sites, such as fortresses, both mechanically thru the penetration of hyphae into the rock pores and chemically thru the production of organic acids that decompose the minerals composing the stone (Cozzolino et al., 2022). Therefore, it is necessary to take preventive measures to reduce the growth of moss on the surface of fort stones by using traditional materials, one of which is essential oil that can be used as a natural pesticide to address the moss problem.

The raw materials for essential oils come from spice plants found in the cities of Ternate and Tidore, namely nutmeg, clove, and lemongrass. These three types of plants have a high content of essential oils(Tabaika et al., 2024). In nutmeg plants, especially the young seeds, in clove plants, especially the flowers, there is a high content of essential oils, and in lemongrass plants, there is a high content of essential oils because the parenchyma tissue contains cells (oil glands)(Murni & Rustin, 2020). The objectives of the research include: Analyzing the effectiveness of using essential oils from spice plants to prevent moss growth in the cultural heritage area of the fort in Ternate city, Analyzing which type of essential oil from spice plants can prevent moss growth on the fort stones in Ternate city, and Analyzing at what concentration essential oils from

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spice plants can prevent moss growth on the fort stones in Ternate city.

OVERVIEW OF CONNECTIVISM .

Onnectivism, introduced by Siemens , conceptualises knowledge as a dynamic network generated through interactions among individuals, institutions, technologies, and diverse information sources. Unlike traditional learning theories that emphasise individual cognition, connectivism argues that the ability to establish, maintain, and continuously update knowledge networks is essential for addressing increasingly complex scientific and societal challenges(Siemens, 2007) . Consequently, knowledge is viewed as an evolving system that develops through interdisciplinary collaboration, digital connectivity, and continuous exchange of information(Downes, 2012).

Within the context of cultural heritage conservation, connectivism provides a valuable framework for understanding how sustainable conservation strategies emerge through the integration of multiple scientific disciplines. Biodeterioration of historic stone structures involves biological, chemical, environmental, and material processes, requiring expertise from microbiology, phytochemistry, conservation science, and environmental management. Accordingly, the development of environmentally friendly conservation technologies depends on interdisciplinary collaboration rather than isolated disciplinary approaches.

The present study reflects this connectivist perspective by integrating knowledge from plant biology, phytochemistry, microbiology, and cultural heritage conservation to evaluate essential oils derived from indigenous North Maluku spice plants as natural biocides. Beyond scientific integration, effective heritage conservation also relies on collaboration among universities, conservation agencies, researchers, local governments, and communities. Thus, connectivism provides a conceptual basis for understanding how interdisciplinary knowledge networks and local biodiversity can be combined to generate innovative, sustainable, and environmentally responsible approaches to preserving stone cultural heritage.

OVERVIEW OF CONSTRUCTIVISM

Constructivism explains that knowledge is actively constructed through experience, observation, reflection, and interaction with the surrounding environment rather than passively received. Piaget argued that individuals develop knowledge through the processes of assimilation and accommodation(Piaget & Inhelder, 2008), while Vygotsky emphasized the importance of social interaction and cultural context in shaping understanding. Accordingly, scientific knowledge

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evolves through observation, experimentation, interpretation, and evidence-based reasoning, making constructivism an important foundation for empirical scientific inquiry(Vygotsky, 1978).

Within the context of cultural heritage conservation, constructivism provides a theoretical basis for understanding how knowledge regarding biodeterioration and conservation strategies is generated through systematic investigation. In the present study, understanding the effectiveness of essential oils was constructed through field experiments, direct observation of colour changes in foliose moss and crustose lichens, comparative analysis of treatment responses, and interpretation of phytochemical evidence reported in previous studies. Consequently, the findings represent knowledge developed from empirical investigation rather than merely confirming existing theoretical assumptions.

From a constructivist perspective, the development of environmentally friendly conservation technologies is a continuous process of scientific knowledge construction. Through observation, hypothesis testing, experimental validation, and critical interpretation of evidence, researchers refine existing understanding while generating new insights into the interaction between natural bioactive compounds and biodeteriogenic organisms. Therefore, this study contributes not only to expanding scientific knowledge in conservation science but also to supporting the development of sustainable, evidence-based, and environmentally responsible strategies for preserving stone cultural heritage.

SOCIAL LEARNING THEORY

Social Learning Theory (Teori Pembelajaran Sosial) was developed by Albert Bandura which explains that individuals acquire knowledge, skills, and new behaviors thru the processes of observation, imitation, and interaction with the social environment(Bandura, 1977). Bandura emphasizes that learning occurs not only thru direct experience but also thru the observation of others' actions and the consequences that follow. In this theory, the learning process is influenced by four main components, namely attention, retention, reproduction, and motivation. Therefore, the success of an innovation is greatly influenced by the ability of individuals and groups to observe, understand, and adopt proven effective practices.

In the context of cultural heritage conservation research, Social Learning Theory explains that the application of essential oils as natural biocides is not only the result of laboratory research and field experiments but also requires a collaborative learning process among stakeholders. Cultural heritage managers, conservators, local government, academics, and the community need to observe empirical evidence regarding the effectiveness of essential oils in inhibiting moss

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growth, and then adopt these practices as part of routine conservation activities. Thus, the success of conservation innovation is not only determined by the effectiveness of the materials used but also by the process of knowledge transfer and social learning that occurs among conservation practitioners.

From the perspective of Social Learning Theory, scientific findings become valuable only when they are transformed into shared knowledge that can be observed, understood, and adopted by broader communities of practice. Within cultural heritage conservation, empirical evidence generated through scientific research serves as a foundation for developing conservation guidelines, professional training, technical assistance, and collaborative learning among heritage managers, conservation practitioners, researchers, and government institutions. Through these processes, environmentally responsible conservation practices can be progressively internalised and incorporated into routine conservation activities, thereby strengthening the long-term sustainability of cultural heritage managemen

Furthermore, Social Learning Theory emphasizes that collective learning can accelerate the dissemination of innovations in cultural heritage preservation. The use of local spice plants such as nutmeg, cloves, and cinnamon as conservation materials represents an integration of scientific knowledge and local wisdom that can be passed down to future generations thru a process of continuous learning. Thus, this theory provides a conceptual foundation that the success of conservation does not only depend on technological innovation but also on the ability of communities and institutions to learn from each other, share experiences, and collaboratively build a culture of preserving cultural heritage.

THEORETICAL INSIGHT

This research is built on the theoretical understanding that the damage to stone cultural heritage sites is the result of a complex interaction between physical, chemical, and biological factors. In the perspective of Biodeterioration Theory, organisms such as foliose lichens, crustose lichens, algae, fungi, and bacteria are the main biological agents that accelerate stone weathering thru the penetration of vegetative structures into the stone's pores, increased moisture retention, and the production of organic metabolites that hasten the degradation of the stone's mineral components(Perry IV et al., 2005). The process of biodeterioration has become one of the main challenges in the conservation of historical buildings in tropical areas with high humidity, including the colonial forts in the city of Ternate. Therefore, modern conservation strategies are not only focused on repairing damage but also on preventive conservation actions that can control the

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growth of organisms causing biodeterioration without damaging the original building materials.

In line with the concept of Green Conservation, the use of natural materials is becoming an increasingly developed alternative in the conservation of cultural heritage. This approach emphasizes that conservation materials must have high biological effectiveness, be safe for cultural heritage materials, environmentally friendly, and not leave harmful residues for ecosystems or human health. Essential oils are one of the biological materials that meet these characteristics because they contain bioactive compounds such as eugenol, sabinene, and cinnamaldehyde, which have been proven to have antimicrobial, antifungal, and antibiofilm activities against various microorganisms causing biodeterioration. Thus, the utilization of essential oils not only supports the effectiveness of conservation but also aligns with the principles of sustainable development and green conservation.

This research also provides theoretical insights that the effectiveness of essential oils is influenced by the biological characteristics of the target organisms. The research results show that the essential oils of nutmeg seeds, clove flowers, and cinnamon bark effectively inhibit the growth of foliose lichens, while only the essential oil of clove flowers is highly effective against crustose lichens. The difference indicates that the mechanism of action of bioactive compounds is greatly influenced by the biological structure of the organism. Lichens are symbiotic organisms composed of fungi (mycobiont) and algae or cyanobacteria (photobiont), thus having different levels of tolerance to antimicrobial compounds compared to mosses. This finding expands the theoretical understanding that the selection of natural biocides in cultural heritage conservation should consider the biological characteristics of the organisms causing biodeterioration, not just the chemical content of the active ingredients.

Furthermore, this research reinforces the perspective that the utilization of local biological resources can be part of innovation in local wisdom-based conservation. Spices such as nutmeg, cloves, and cinnamon, which are typical commodities of North Maluku, not only have economic value but also possess scientific potential as natural biocides in the preservation of cultural heritage sites. The integration of ethnobotanical knowledge, biology, chemistry, and conservation science results in a conservation model that is more adaptive to tropical environmental conditions and supports the development of sustainable conservation technologies. Thus, this research not only provides empirical contributions regarding the effectiveness of essential oils but also enriches the theoretical framework on green conservation based on local biological resources for the protection of stone-based cultural heritage.

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CULTURAL EVOLUTION AND PRIMARY EDUCATION

Cultural Evolution Theory explains that culture develops through continuous processes of knowledge transmission, innovation, adaptation, and cumulative learning across generations (Boyd & Richerson, 1988). In cultural heritage conservation, this perspective suggests that conservation is not limited to preserving the physical integrity of historical monuments but also includes safeguarding traditional ecological knowledge, conservation practices, and cultural values that sustain heritage over time.

In the present study, the utilisation of indigenous spice plants nutmeg (*Myristica fragrans*), clove (*Syzygium aromaticum*), and cinnamon (*Cinnamomum burmannii*) illustrates how local ethnobotanical knowledge can evolve through scientific research into environmentally friendly conservation technologies. By integrating biology, phytochemistry, and conservation science, this study demonstrates that local biological resources can be transformed into sustainable conservation innovations while maintaining their cultural significance.

Within this framework, Primary Education is understood as the initial stage of intergenerational transmission of conservation values rather than as the direct focus of this research. Although primary education was not investigated empirically, scientific findings from this study have the potential to support environmental and cultural heritage education by introducing local biodiversity, sustainable conservation practices, and cultural awareness from an early age. This perspective is consistent with UNESCO's view that education is fundamental for promoting sustainable development and responsible citizenship(United Nations Educational, 2020).

Overall, this study suggests that essential oil-based conservation represents not only a technological innovation for controlling biodeterioration but also part of an evolving cultural knowledge system in which scientific evidence, local wisdom, and educational processes collectively contribute to the long-term sustainability of cultural heritage.

TOWARD GREEN HERITAGE CONSERVATION: A CONCEPTUAL SHIFT

The findings of this study indicate that the application of essential oils derived from nutmeg, clove, and cinnamon represents more than an alternative method for controlling moss growth on historical stone structures. Rather, the findings demonstrate a broader conceptual transformation in heritage conservation, moving from conventional conservation approaches toward sustainable, bio-based, and locally driven conservation practices. This transformation aligns with contemporary perspectives in preventive conservation, biodeterioration management,

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and green conservation, which emphasize environmentally friendly interventions, biodiversity utilization, and long-term preservation of cultural heritage(Cozzolino et al., 2022).

Based on the experimental findings, this study proposes six conceptual shifts that characterize sustainable heritage conservation in tropical cultural heritage environments.

Table 1. Six Conceptual Shifts toward Sustainable Heritage Conservation

Conceptual Shift	Conventional Conservation	Sustainable Conservation Proposed in this Study
Chemical → Bio-based Conservation	Uses synthetic chemical biocides.	Uses natural essential oils as eco-friendly biocides.
Curative → Preventive Conservation	Treats deterioration after damage occurs.	Prevents biological colonisation before severe deterioration.
Imported Materials → Indigenous Resources	Relies on commercial conservation products.	Utilises locally available North Maluku spice plants.
General Treatment → Target-Specific Management	Applies the same treatment to all organisms.	Selects essential oils according to target organism characteristics.
Material Preservation → Ecosystem-Based Conservation	Focuses on protecting stone materials only.	Integrates heritage preservation with environmental sustainability.
Heritage Protection → Sustainable Heritage Management	Preserves monuments as historical objects.	Integrates biodiversity, local knowledge, and sustainable conservation.

SOCIAL LEARNING THEORY - ACADEMIC PERSPECTIVE

Social Learning Theory, originally developed by Bandura, has evolved beyond its Social Learning Theory(Bandura, 1977), originally proposed by Bandura , extends beyond educational psychology to explain how scientific knowledge and technological innovation are disseminated through observation, collaboration, communication, and institutional learning. From an academic perspective, research findings acquire broader significance when they are shared, critically evaluated, and adopted by researchers, professional organisations, and policy institutions. Consequently, the theory provides a useful framework for understanding how scientific evidence contributes to the advancement of knowledge and evidence-based conservation practices.

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Within cultural heritage conservation, the adoption of environmentally friendly technologies depends not only on scientific discovery but also on interdisciplinary collaboration and institutional implementation. Universities, research institutes, conservation agencies, museums, and government organisations function as interconnected learning communities where scientific evidence is translated into practical conservation strategies. In this context, the present study contributes to conservation science by providing scientific evidence for the application of indigenous North Maluku spice plants as natural biocides for controlling biodeterioration of stone cultural heritage.

Furthermore, Social Learning Theory emphasises that the long-term impact of scientific research relies on effective knowledge exchange through academic publications, professional training, scientific collaboration, and community engagement(Ting, 2023). Accordingly, this study demonstrates that innovations based on locally available spice plants can become part of a broader academic learning network that promotes interdisciplinary collaboration, evidence-based conservation, and the sustainable preservation of cultural heritage while supporting the principles of Green Heritage Conservation.

CONNECTIVISM'S IMPLICATIONS FOR TEACHING AND LEARNING

The theoretical framework of Connectivism provides a number of practical implications for teaching, learning, and knowledge development within the field of sustainable cultural heritage conservation. In this perspective, scientific knowledge is generated through interconnected networks that integrate multiple disciplines, institutions, technologies, and stakeholders rather than through isolated learning processes(Siemens, 2007). The present study demonstrates that environmentally friendly conservation innovations emerge from the integration of biology, phytochemistry, microbiology, conservation science, and indigenous knowledge concerning the utilisation of spice plants. Accordingly, connectivism offers an appropriate conceptual foundation for designing learning environments that promote interdisciplinary collaboration and continuous knowledge exchange in heritage conservation.

The implications of Connectivism for teaching and learning include the following:

1. Establish interdisciplinary learning networks integrating biology, chemistry, microbiology, environmental science, ethnobotany, and heritage conservation.
2. Promote educators as learning facilitators who integrate scientific evidence, local knowledge, and practical conservation experience.

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3. Implement authentic field-based learning through investigation of biodeterioration and sustainable conservation practices.
4. Integrate digital technologies and scientific networks to support collaboration and access to current conservation knowledge.
5. Assess interdisciplinary problem-solving skills based on scientific evidence and sustainable conservation strategies.
6. Utilise authentic learning environments, including heritage sites, conservation laboratories, botanical resources, and local communities.

Collectively, these implications position connectivism as a theoretical foundation for strengthening interdisciplinary education and research in cultural heritage conservation. By connecting scientific investigation, indigenous ecological knowledge, technological innovation, and collaborative learning networks, the present study illustrates how environmentally friendly conservation strategies can be transformed into sustainable educational resources that support professional capacity building, evidence-based conservation practice, and the long-term preservation of stone-built cultural heritage.

CONSTRUCTIVISM'S IMPLICATIONS FOR TEACHING AND LEARNING

The findings of this study provide important constructivist implications for teaching and learning in sustainable cultural heritage conservation. Constructivism views scientific knowledge as being actively constructed through observation, experimentation, reflection, and interaction with authentic problems rather than passively transmitted(Piaget & Inhelder, 2008) In the present study, understanding of biodeterioration control was developed through field experiments evaluating essential oils derived from indigenous spice plants, demonstrating that meaningful learning emerges from direct engagement with real conservation challenges.

From this perspective, conservation education should emphasise inquiry-based learning grounded in authentic field observation and scientific experimentation. Students and practitioners should be encouraged to investigate biodeterioration processes, analyse experimental evidence, and evaluate environmentally friendly conservation materials. Furthermore, the integration of indigenous ecological knowledge with modern conservation science provides contextual learning experiences that strengthen environmental awareness while promoting the principles of Green Heritage Conservation through the use of sustainable, locally available biological resources.

The study also highlights the importance of evidence-based reasoning and interdisciplinary collaboration in heritage conservation. The different responses of foliose mosses and crustose

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lichens to essential oils demonstrate that conservation decisions should be based on empirical evidence rather than general assumptions. Consequently, teaching and learning should integrate biology, microbiology, phytochemistry, environmental science, ethnobotany, and conservation science to develop comprehensive, sustainable, and scientifically informed approaches to protecting cultural.

DISCUSSION

Environmental Characteristics of Fort Kastela as a Biodeterioration Site

Fort Kastela, located in Kastela Village, Ternate Island District, Ternate City, North Maluku, is one of the oldest Portuguese colonial fortifications in Indonesia and has been designated as an important cultural heritage site. The fort is situated approximately 100 m from the Kastela coastline (N 00°45'67.2"; E 127°18'72.4"), where it is continuously exposed to a tropical coastal environment. Architecturally, the fort was constructed using andesite stones and coral limestone bonded with lime mortar produced from burnt coral. The outer walls range from 1.75 to 2.70 m in thickness, while the interior partition walls are approximately 40 cm thick. The porous characteristics of these natural stone materials enable prolonged moisture retention, creating suitable substrates for the colonisation of biological organisms such as foliose mosses and crustose lichens.

Table 2. Environmental characteristics of Fort Kastela during the experimental period

Parameter	Observation
Study site	Fort Kastela, Ternate City, North Maluku
Geographic setting	Approximately 100 m from the coastline
Main construction materials	Andesite stone, coral stone, lime mortar
Average air temperature	**36.6°C**
Average relative humidity	**89.6%**
Average light intensity	**7.4** (field measurement)
Observation period	15–21 May 2023
Rainfall during experiment	One rainfall event on the second day after treatment

Field observations conducted during the five-day experimental period indicated that the surrounding environment remained predominantly dry, although a rainfall event occurred on the afternoon of the second day after essential oil application. Despite the relatively high daytime

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temperature (36.6°C), the average relative humidity reached 89.6%, indicating that the stone surfaces retained sufficient moisture to support continuous moss growth. Extensive biological colonisation was observed on shaded wall surfaces and moisture-retaining stone blocks, where foliose mosses and crustose lichens formed dense biological coverings prior to treatment.

These environmental conditions explain why biodeterioration constitutes one of the principal conservation challenges at Fort Kastela. According to Biodeterioration Theory, biological deterioration of stone cultural heritage occurs through the interaction between environmental factors and living organisms that colonise the stone surface(Warscheid & Braams, 2000). High humidity, stable warm temperatures, and porous mineral substrates facilitate the attachment, growth, and persistence of mosses, lichens, algae, fungi, and other microorganisms. Once established, these organisms accelerate stone deterioration through mechanical penetration of rhizoids or fungal hyphae into stone pores, prolonged moisture retention, secretion of organic acids, and biochemical weathering of mineral components.

The climatic conditions recorded during this study correspond closely with environmental requirements for moss development. Previous studies have demonstrated that humidity, temperature, and light intensity are among the most influential environmental factors controlling moss growth and distribution(Mulyani et al., 2014) . The average humidity of 89.6% recorded at Fort Kastela therefore provides highly favourable conditions for continuous moss regeneration, explaining the extensive biological colonisation observed on the fort walls throughout the study period.

The environmental characteristics of Fort Kastela also provide the scientific rationale for implementing preventive conservation rather than relying solely on periodic mechanical cleaning. Because the tropical coastal climate continuously promotes recolonisation of biological organisms, conservation strategies should focus on suppressing biological growth while preserving the integrity of the original stone materials. This consideration underpins the present study, which evaluates essential oils extracted from indigenous North Maluku spices nutmeg (*Myristica fragrans*), clove (*Syzygium aromaticum*), and cinnamon (*Cinnamomum burmannii*)as environmentally friendly natural biocides. The adoption of locally available botanical resources aligns with the principles of Green Heritage Conservation, which advocate sustainable, low-toxicity conservation methods that minimise environmental impacts while ensuring the long-term preservation of stone-based cultural heritage

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Effectiveness of Nutmeg Essential Oil Against *Foliose* Moss

The effectiveness of nutmeg (*Myristica fragrans*) essential oil in inhibiting the growth of foliose moss was evaluated through visual observations over a five-day monitoring period using a standardized leaf colour scoring system. Table 2 and Figures 1–3 demonstrate that the untreated control (0%) showed no significant colour change throughout the observation period, indicating that the moss remained physiologically active under the prevailing environmental conditions. In contrast, treatments with nutmeg essential oil at concentrations of 10% and 20% produced progressive discoloration from healthy green to yellowish-green and eventually brown, reflecting a gradual reduction in moss vitality.

Table 3. Changes in foliose moss colour scores following treatment with nutmeg essential oil

Treatment	Day 1	Day 2	Day 3	Day 4	Day 5	Interpretation
Control (0%)	2	2	2	2	2	No inhibition
Nutmeg EO 10%	2	7	7	7	8	Effective inhibition
Nutmeg EO 20%	7	8	8	8	9	Highly effective inhibition

Note: Higher colour scores indicate greater loss of green pigmentation and stronger inhibition of moss vitality.

At a concentration of **10%**, the colour score increased from 2 on the first day to 7 during Days 2–4**,** before reaching 8 on Day **5**. A stronger inhibitory response was observed at **20%**, where the colour score increased from 2 to 7 on the first day, remained at 8 during Days 2–4**,** and reached 9 on the fifth day. The more rapid and pronounced colour change at the higher concentration indicates that the inhibitory activity of nutmeg essential oil is concentration-dependent, with higher concentrations producing greater suppression of foliose moss growth. These observations clearly demonstrate that nutmeg essential oil effectively reduced moss vitality within a relatively short treatment period while the untreated control continued to exhibit normal physiological activity.

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Figure 1. Progressive visual changes in foliose moss following treatment with 10% nutmeg (*Myristica fragrans*) essential oil during the five-day observation period.



Figure 2. Progressive visual changes in foliose moss following treatment with 20% nutmeg (*Myristica fragrans*) essential oil during the five-day observation period.

The inhibitory response observed in this study is consistent with previous phytochemical investigations reporting that nutmeg essential oil contains a high proportion of **sabinene** (approximately **78%**), together with α-pinene, β-pinene, myristicin, limonene, and several monoterpenes possessing antimicrobial and antifungal activities(Tabaika et al., 2023) ,Although the present study did not perform GC–MS analysis, the observed suppression of foliose moss is consistent with the biological activity previously attributed to these compounds. Sabinene has been reported to interfere with microbial cell membrane integrity, increasing membrane permeability and disrupting essential metabolic processes, thereby reducing cellular viability and inhibiting biological growth(Valente et al., 2013). The gradual colour transformation recorded during the experiment therefore provides visual evidence that the bioactive constituents of nutmeg essential oil progressively reduced the physiological activity of moss colonising the stone surface.

Interestingly, the inhibitory effect of nutmeg essential oil was observed only in foliose moss**,** whereas its effectiveness against **crustose lichens** was considerably lower. This difference

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suggests that the susceptibility of biodeteriogenic organisms depends not only on the chemical composition of the essential oil but also on the biological characteristics of the target organism. Foliose mosses possess relatively simple vegetative tissues that are more directly exposed to bioactive compounds, whereas crustose lichens consist of a complex symbiotic association between fungal partners (mycobionts) and photosynthetic algae or cyanobacteria (photobionts). This structural complexity may provide greater tolerance against antimicrobial compounds, thereby reducing the effectiveness of nutmeg essential oil on crustose lichens (Roziaty, 2016). Consequently, the present findings indicate that the selection of natural biocides for cultural heritage conservation should consider both phytochemical composition and the biological characteristics of the organisms responsible for biodeterioration.

From the perspective of Green Heritage Conservation, the utilisation of nutmeg essential oil represents an environmentally friendly alternative to conventional synthetic biocides. Unlike chemical biocides that may leave toxic residues and potentially damage historic stone materials, essential oils are biodegradable, renewable, and generally exhibit lower environmental toxicity. Moreover, nutmeg is one of the most important indigenous spice commodities of North Maluku, making its utilisation particularly relevant for promoting local biological resources in sustainable cultural heritage conservation. Therefore, the findings of this study not only demonstrate the effectiveness of nutmeg essential oil in suppressing foliose moss growth but also support the development of preventive conservation strategies that integrate local biodiversity, scientific innovation, and environmentally responsible heritage management.

Comparative Effectiveness of Essential Oils Against Crustose Lichens

Unlike foliose moss, crustose lichens exhibited markedly different responses to the three essential oils evaluated in this study. As summarised in Table 4**,** nutmeg (*Myristica fragrans*) and cinnamon (*Cinnamomum burmannii*) essential oils produced only slight discoloration at both 10% and 20% concentrations, indicating relatively weak inhibitory activity against crustose lichens. In contrast, clove (*Syzygium aromaticum*) essential oil caused pronounced colour changes from grey-green to brown after five days of treatment. At the 20% concentration, the crustose lichens became visibly detached from the stone surface, demonstrating a substantially greater inhibitory effect than the other essential oils. These observations indicate that crustose lichens respond differently to essential oil treatments than foliose moss and that the effectiveness of natural biocides depends on the biological characteristics of the target organisms.

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Table 4. Comparative response of crustose lichens to three essential oils

Essential oil	Concentration	Visual response after 5 days	Interpretation
Nutmeg (*Myristica fragrans*)	10%	Slight colour change	Low inhibition
Nutmeg (*Myristica fragrans*)	20%	Slight colour change	Low inhibition
Cinnamon (*Cinnamomum burmannii*)	10%	Slight colour change	Low inhibition
Cinnamon (*Cinnamomum burmannii*)	20%	Slight colour change	Low inhibition
Clove (*Syzygium aromaticum*)	10%	Brown discoloration	Effective inhibition
Clove (*Syzygium aromaticum*)	20%	Brown discoloration with partial detachment from stone surface	Highly effective inhibition

Note: Visual responses were evaluated after five consecutive days of treatment. Greater discoloration and detachment indicate stronger inhibition of crustose lichen vitality.

The comparative observations presented in **Table 4** are visually illustrated in **Figures 3 and 4** which demonstrate the limited response of crustose lichens to nutmeg and cinnamon essential oils compared with the pronounced discoloration and partial detachment observed following treatment with clove essential oil.



Figure 3 ***Visual changes in crustose lichens following treatment with 10% clove (Syzygium aromaticum) essential oil after five days of observation, showing progressive discoloration from grey-green to brown, indicating inhibition of lichen vitality.***

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Figure 4 ***Visual changes in crustose lichens following treatment with 20% clove (Syzygium aromaticum) essential oil after five days of observation, demonstrating extensive browning and partial detachment of the lichen thallus from the stone surface, indicating the highest inhibitory activity among the treatments.***

The contrasting responses observed between foliose moss and crustose lichens indicate that the inhibitory activity of essential oils is strongly influenced by the biological characteristics of the target organisms. Foliose moss consists primarily of relatively simple vegetative tissues that are directly exposed to antimicrobial compounds, whereas crustose lichens represent complex symbiotic organisms composed of fungal partners (mycobionts) associated with photosynthetic algae or cyanobacteria (photobionts). This symbiotic organisation produces a compact thallus that adheres tightly to mineral substrates, thereby providing greater physiological protection and increasing resistance to external antimicrobial agents(Roziaty, 2016) . Consequently, compounds that effectively inhibit foliose moss may not necessarily exhibit comparable activity against crustose lichens.

The superior performance of clove essential oil observed in this study is closely associated with its phytochemical composition. Previous phytochemical investigations have demonstrated that clove essential oil contains high concentrations of eugenol, constituting approximately 72–90% of its total volatile compounds (Kamatou et al., 2012). Eugenol is a hydrophobic phenolic compound capable of disrupting cytoplasmic membrane integrity, increasing membrane permeability, inducing leakage of intracellular components, and ultimately causing irreversible cellular damage (Devi et al., 2010). These mechanisms explain the pronounced discoloration and subsequent detachment of crustose lichens from the stone surface following treatment with 20% clove essential oil. In contrast, the dominant compounds present in nutmeg (sabinene) and cinnamon (cinnamaldehyde), although effective against foliose moss, exhibited considerably lower inhibitory activity against the structurally more resistant crustose lichens.

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From the perspective of Biodeterioration Theory, these findings demonstrate that biological deterioration of stone cultural heritage cannot be effectively controlled using a universal treatment. Biodeteriogenic organisms differ substantially in their morphology, physiology, ecological adaptation, and interactions with mineral substrates. Therefore, conservation materials should be selected according to the biological characteristics of the organisms responsible for stone colonisation rather than applying identical treatments indiscriminately. Such organism-specific approaches are more likely to achieve long-term preventive conservation while minimising unnecessary chemical intervention(Warscheid & Braams, 2000)

The present findings also reinforce the principles of Green Heritage Conservation. Rather than relying exclusively on synthetic chemical biocides, the use of locally available essential oils derived from North Maluku spice plants offers a renewable, biodegradable, and environmentally responsible alternative for controlling biodeterioration. The utilisation of indigenous botanical resources not only reduces potential environmental contamination but also promotes sustainable conservation practices by integrating local biodiversity with scientific innovation. Among the three essential oils evaluated, clove essential oil demonstrated the greatest potential as a natural biocide for controlling crustose lichens, whereas nutmeg and cinnamon essential oils appear more suitable for managing foliose moss colonisation.

Overall, the findings indicate that the selection of natural biocides should be guided by the biological characteristics of biodeteriogenic organisms rather than relying on a single treatment for all forms of biological colonisation. This organism-specific approach represents an important contribution to sustainable stone heritage conservation by demonstrating that effective biodeterioration management requires the integration of phytochemical properties, organism biology, and environmental conditions.

CONCLUSION

This study demonstrates that essential oils derived from indigenous North Maluku spice plants possess considerable potential as environmentally friendly natural biocides for the preventive conservation of stone cultural heritage. The experimental results revealed that all three essential oils effectively inhibited the growth of foliose moss, with inhibitory activity increasing as essential oil concentration increased. Clove (*Syzygium aromaticum*) essential oil exhibited the strongest inhibitory effect, followed by cinnamon (*Cinnamomum burmannii*) and nutmeg (*Myristica fragrans*), as indicated by progressive discoloration of moss tissues during the

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five-day observation period. In contrast, crustose lichens showed markedly greater resistance to nutmeg and cinnamon essential oils, whereas clove essential oil, particularly at a concentration of 20%, produced substantial discoloration accompanied by partial detachment of the lichen thallus from the stone surface.

These findings indicate that the effectiveness of natural biocides is determined not only by the phytochemical composition of essential oils but also by the biological characteristics of biodeteriogenic organisms. The superior performance of clove essential oil is attributed to its high eugenol content, while the inhibitory effects of nutmeg and cinnamon essential oils are associated with the presence of sabinene and cinnamaldehyde, respectively. Consequently, conservation strategies should adopt an organism-specific approach when selecting natural biocides rather than applying a single treatment to all forms of biological colonisation. This finding represents the principal contribution of the study by demonstrating that biodeterioration management should integrate phytochemical properties with the biological responses of target organisms.

From the perspective of Green Heritage Conservation, the utilisation of locally available spice plants offers a renewable, biodegradable, and environmentally responsible alternative to synthetic chemical biocides. Beyond its practical implications, this study contributes to the advancement of sustainable cultural heritage conservation by integrating local biodiversity, phytochemical science, and biodeterioration theory into a preventive conservation framework. Future studies are recommended to investigate longer treatment periods, evaluate additional concentrations, perform in situ GC–MS analyses of the essential oils used, and assess the long-term effects of repeated applications on both stone materials and biological recolonisation under natural environmental conditions.

FUTURE DIRECTIONS

Future research should investigate the long-term effectiveness of repeated essential oil applications under natural environmental conditions to evaluate their durability in preventing biological 4283ecolonization on stone cultural heritage. Further studies are also recommended to include a wider range of essential oil concentrations, conduct in situ phytochemical analyses (e.g., GC–MS) of the extracted oils, and examine their potential effects on the physical, chemical, and mechanical properties of historic stone materials. In addition, expanding the investigation to other biodeteriogenic organisms, different types of cultural heritage substrates, and diverse climatic conditions would provide a more comprehensive understanding of organism-specific natural biocides. Such studies will strengthen the scientific basis for developing sustainable,

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environmentally friendly conservation strategies that integrate local biodiversity, phytochemical innovation, and Green Heritage Conservation principles for the long-term preservation of cultural heritage.

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