INTEGRATED ENGINEERING APPROACHES TO ENVIRONMENTAL RISK, ADVANCED MATERIALS, AND SMART TECHNOLOGIES

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PREFACE

This book consists of five distinct chapters that address significant scientific, technological, and social challenges through an interdisciplinary perspective. Each chapter, authored by experts in their respective fields, offers in-depth analyses, innovative solutions, and practical insights for readers.

In the first chapter of the book, a multi-layered perspective is adopted to examine Santorini's activities over time, with the evolving contributions of scientists, policymakers, governments, educators, and citizens being highlighted. The critical need for formulating sustainable disaster management strategies through integrated governance, urban planning, education, and environmental policies is underscored.

The second chapter analyzes the effects of psychosocial, physical, and psychological factors on accidents and productivity in mining activities. The mining sector is recognized as directly affecting workers' physical, social, and mental well-being. Working conditions, accident prevention, and their impact on productivity are evaluated. Risk factors are examined in line with relevant legal regulations.

In the third chapter, the application of artificial intelligence (AI), the Internet of Things (IoT), and blockchain technology in electronic waste (e-waste) management is investigated. The potential of smart waste monitoring, machine learning-based classification, and consumer-oriented incentive models is evaluated to enhance recycling efficiency and promote environmental sustainability. The significance of these technologies in offering long-term and sustainable solutions to the electronic waste problem is emphasized.

In the fourth chapter, antibacterial test methods for stereolithography-printed nanocomposite surfaces are compared. The effects of surface properties and nanoparticle additives on antibacterial performance are examined. The importance of test method selection for accurate evaluation is emphasized.

The fifth chapter examines the potential of mycelium-based biomaterials as sustainable alternatives in historical building restoration. It highlights their environmental advantages, such as biodegradability, low carbon footprint, and energy efficiency, while addressing technical challenges like limited mechanical strength. The chapter emphasizes how mycelium composites can support sustainable architecture and the long-term preservation of cultural heritage.

We hope this book will serve as a valuable source of knowledge for academics, researchers, industry professionals, and all interested readers. We extend our sincere gratitude to all the authors and contributors who made this work possible.

29/04/2025

Prof. Dr. İlke TAŞÇIOĞLU

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CHAPTER 1

SEISMIC AND TSUNAMI THREATS IN SANTORINI IN CHRONOLOGICAL APPROACH: A MULTIDISCIPLINARY APPROACH TO RISK ASSESSMENT AND MITIGATION

Assoc. Prof. Dr. Gamze DOĞDU YÜCETÜRK

Assist. Prof. Dr. Seda Nur ALKAN

INTRODUCTION

Santorini, a volcanic island in the South Aegean, is among the most seismically active areas in the Mediterranean, formed by recurrent tectonic shifts and intense volcanic eruptions. The most devastating catastrophe in its geological history was the Minoan Eruption (~1600 B.C.), which expelled over 60 km³ of lava, resulting in the caldera's collapse, and instigated catastrophic tsunamis reaching heights of 35 meters (Nomikou et al., 2016). The tsunamis are thought to have had a role in the downfall of the Minoan civilization in Crete, representing one of the earliest documented occurrences of a natural disaster profoundly affecting human culture (McCoy & Heiken, 2000). Santorini has seen numerous volcanic and seismic events over the centuries, notably the eruptions from 1866-1870, 1925-1928, 1939-1941, and 1950, resulting in considerable terrain deformation, structural damage, and population displacement (Fytikas et al., 1984).

Figure 1: A view from Santorini after the earthquake of July 9, 1956 (Source: URL1)

A seismic crisis from 2011 to 2012 recently resulted in a 14 cm rise in the caldera floor, increasing apprehensions regarding the reactivation of the Santorini volcano (Parks et al., 2012). Historical occurrences of earthquakes and tsunamis highlight the gravity of these threats. In Figure 1, a view from Santorini shows an eruption of the Santorini volcano and a massive tidal wave after the earthquake of July 9, 1956. The 1956 Amorgos Earthquake (Mw 7.5), erupting from a fault zone adjacent to Santorini, generated a tsunami with waves reaching 20 meters, significantly affecting the island's coastal regions and resulting in extensive destruction (Papadopoulos et al., 2014). Likewise, the 1926 earthquake (Mw 7.3) caused significant structural failures due to inadequate seismic-resistant design, highlighting the necessity for enhanced engineering methodologies (Stiros & Pytharouli, 2014). These occurrences emphasize the twin problem of seismic activity and tsunami hazards, necessitating proactive planning and engineering fortitude. Being part of an active volcanic system, it continues to be a concern. Since January 31, 2025, seismic activity has intensified in a 2,500 km² region northeast of Santorini, near the fault associated with the July 9, 1956, Amorgos earthquake and tsunami (Leclerc et al., 2024), heightening concerns. Figure 2 presents a photo from Santorini volcano in 2025.

Figure 2: Santorini volcano in 2025 (Source: URL2)

Engineering solutions are essential for improving earthquake and tsunami resilience in light of these threats. Structural rehabilitation is crucial for Santorini's old unreinforced stone edifices, especially vulnerable to seismic damage. Steel reinforcement, fiber-reinforced polymers (FRPs), and base isolation have been effectively utilized in high-seismicity areas to enhance structural durability (Lourenço et al., 2019). Furthermore, energy dissipation technologies, including viscoelastic and tunable mass dampers, are advised for important infrastructure to alleviate seismic vibrations (Sakellariou et al., 2017). A crucial aspect of tsunami mitigation involves the utilization of breakwaters and artificial reefs, which have successfully diminished wave energy before impact (Papadopoulos et al., 2019). Deploying early warning systems (EWS) utilizing seismic and oceanographic sensors may facilitate real-time alerts, enabling prompt evacuations and reducing fatalities (Lavigne et al., 2021). Architectural modifications enhance safety, such as elevated evacuation buildings and tsunami-resistant designs modeled after Japanese and Indonesian examples (Suppasri et al., 2013). In addition to engineering solutions, urban planning, and environmental engineering methods are essential for long-term catastrophe resilience. Sustainable water management strategies, including permeable pavements and rainwater harvesting systems, can mitigate the danger of seismic-induced liquefaction and flooding. Moreover, green infrastructure, encompassing resilient public spaces, offers secure areas for post-disaster assembly and mitigates urban heat island effects, which can intensify climate-related vulnerabilities (Gao et al., 2022). Collaboration among environmental engineers, architects, urban planners, and policymakers is crucial for formulating comprehensive catastrophe mitigation plans. Engineering solutions prioritize structural reinforcements and tsunami mitigation, whereas architectural resilience underscores adaptive construction methods and the preservation of history. Combining geospatial analysis, real-time hazard surveillance, and data-informed urban planning can substantially improve Santorini's readiness for impending seismic and tsunami occurrences. This chapter aims to establish a comprehensive framework that integrates engineering developments, urban planning methodologies, and insights from historical disasters to enhance Santorini's resilience. This action enhances the general debate on disaster risk mitigation in volcanically and tectonically active areas, promoting sustainable development and protecting public safety.

1. Geological and Seismic Background of Santorini

Santorini is situated within the Hellenic Arc, a geologically active tectonic zone resulting from the subduction of the African Plate beneath the Eurasian Plate. This process, which transpires at an average rate of 35 to 40 millimeters per annum, engenders significant seismic activity and is instrumental in forming the South Aegean Volcanic Arc (Papazachos & Papazachou, 2003). The distinctive geological configuration of Santorini, located at the northern segment of this arc, renders it especially susceptible to seismic and volcanic hazards. Numerous active normal faults traverse Santorini, some associated with moderate to intense seismic events. The Columbo Seismic Zone, a submarine fault system located northeast of Santorini, has been responsible for significant seismic activity, including the 1650 eruption of the Columbo volcano, which caused a catastrophic earthquake and tsunami (Nomikou et al., 2012). The 1956 Amorgos Earthquake (Mw 7.5), one of the most substantial known seismic occurrences in the Aegean, inflicted considerable structural damage and landslides in Santorini, in addition to producing a tsunami with waves reaching 20 meters that impacted the island's coastline (Papadopoulos et al., 2014). The Santorini seismic crisis of 2011-2012, characterized by a 14 cm caldera uplift, heightened apprehensions over possible volcanic reactivation, illustrating the intricate relationship between deep magmatic processes and fault dynamics (Parks et al., 2012). Future seismic hazards are a considerable concern, with models predicting that Santorini and its adjacent areas may encounter earthquakes beyond Mw 6.5-7.0, especially along the Columbo and Kameni fault systems (Kazantzidou-Firtinidou et al., 2018). A comprehensive report compiled by experts and shared with international scientific bodies (UNESCO, 2025) documents a substantial earthquake swarm near Andros Island in the Aegean Sea between January 25 and February 7, 2025. Over 1,200 seismic events ranged from minor tremors to a significant magnitude 5.2 earthquake. A notable 129 of these events exceeded magnitude 4.0, most occurring at focal depths between 10 and 15 kilometers. The swarm, exhibiting a northeast-southwest trending cluster east of Anydros Island, is situated within the Anydros Uplift, a region bounded by the Anydros and Santorini-Anafi faults. Notably, the early phase of the swarm saw an increase in earthquake magnitudes. In addition to the seismic analysis, the report includes numerical modeling of potential tsunami scenarios, considering the surrounding islands' active tectonic and volcanic features, specifically Santorini, Amorgos, Astypalaea, and Anafi. These scenarios are examined to assess the potential impact of tsunamis on the Aegean coast of Türkiye (Yalçıner et al., 2025). Considering its historical susceptibility and contemporary dependence on tourism and infrastructure, comprehending Santorini's geological structure and fault dynamics is crucial for disaster risk mitigation and urban resilience strategies.

2. Environmental Impacts and Health Hazards in Santorini

Santorini is a component of the Hellenic Volcanic Arc, an area characterized by considerable volcanic activity. These eruptions can trigger various health and environmental problems. Furthermore, volcanic pollution, including gases and ash, can harm ecosystems and far downwind communities. This is due to the ability of ash and gases to travel long distances through the air, whether released during active eruptions, ongoing degassing, ash fallout, or the stirring up of previously deposited volcanic material (Tomašek et al., 2020). Volcanic eruptions pose a range of direct and indirect threats to human health. The population is at substantial health risk due to volcanic debris and gases, including sulfur dioxide and particulate matter. In addition to elevating the likelihood of cardiovascular diseases, prolonged exposure to these pollutants can exacerbate respiratory conditions, including asthma (Jenkins et al., 2015). Exposure to fine ash and volcanic gases can worsen or trigger breathing problems and irritate the eyes and skin (Tomašek et al., 2020). The eruption in 1650 CE precipitated a tsunami that resulted in extensive devastation and fatalities, chiefly attributable to exposure to toxic gases (Katsigera et al., 2024). Recent research suggests that a forthcoming eruption of Kolumbo may significantly endanger the northern and eastern beaches of Santorini, with possible tsunamis and ashfall impacting the island and other areas (Katsigera et al., 2024). In addition, the psychological and socioeconomic effects of volcanic eruptions and their associated hazards can profoundly affect the local population. Effective communication and preparedness strategies were underscored by the 2011–2012 chaos, which resulted in elevated anxiety and uncertainty among residents (Aspinall & Woo, 2014). The financial consequences of volcanic activity, such as the loss of tourism revenue and damage to infrastructure, exacerbate the obstacles that the island's communities face (Kazantzidou-Firtinidou et al., 2018). Beyond these direct effects, eruptions can contaminate drinking water and food sources, and the stress of the event can lead to significant psychological trauma (Tomašek et al., 2020). Water sources and soil can be contaminated by volcanic activity, which can harm both human health and agricultural productivity. The accumulation of harmful substances in the food chain can result from the discharge of toxic metals from hydrothermal vents, and ash falls (Nomikou et al., 2022; Doğan et al., 2025). Public health and ecosystem stability are at risk as a result of this contamination in the long term. For centuries, historical eruptions, including the Minoan eruption, resulted in pervasive soil degradation and disrupted agricultural practices (Doğan et al., 2025; Druitt & Francaviglia, 1992). Soil erosion and nutrient depletion are further exacerbated by the island's rugged terrain and contemporary agricultural practices (Marinos et al., 2017).

3. Tsunami Hazards in Santorini

Past volcanic activity, including the 1650 AD eruption of the Kolumbo submarine volcano, caused severe flooding and destruction along Santorini's coast (Nomikou et al., 2014). Tsunamis can result from volcanic eruptions, landslides, and caldera collapses. The 2011-2012 volcanic unrest highlighted the risk of landslide-induced tsunamis due to flank instability (Necmioglu et al., 2023). Santorini has experienced multiple tsunami events, with the Minoan eruption being one of the most catastrophic, causing large-scale devastation in the Aegean. The 1956 Amorgos earthquake (Mw 7.5) triggered a tsunami with recorded waves up to 20 meters high, impacting Santorini and nearby islands. The Kolumbo volcano poses a risk through shallow submarine explosions and pyroclastic flow interactions with the sea (Nomikou et al., 2014). The Kolumbo submarine volcano northeast of Santorini remains an active hazard for future tsunami generation (Katsigera et al., 2024). Recent numerical tsunami models indicate that a moderate Kolumbo eruption could trigger waves up to 5 meters on Santorini's eastern coastline. A local tsunami warning system is crucial for addressing the rapid onset of tsunamis, with maximum amplitudes reaching up to 60 m within minutes (Necmioglu et al., 2023). The limitations of current warning systems for non-seismic sources have been demonstrated by the 2018 tsunami, which originated from Anak Krakatau. This event was a valuable lesson for Santorini, underscoring the necessity of community preparedness and customized early warning systems in response to atypical tsunami sources (Necmioglu et al., 2023; Nomikou et al., 2022). Understanding cascading geohazards, such as those triggered by rifting events, is vital for comprehensive risk assessments (Preine et al., 2022).

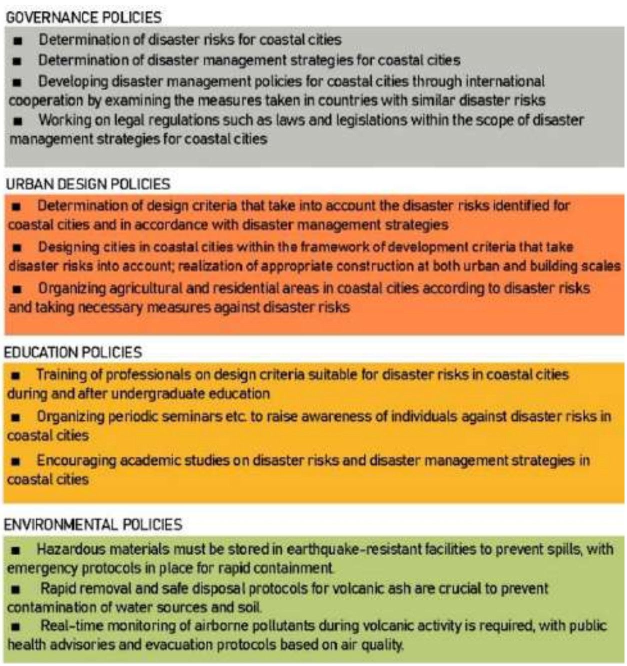
4. Seismic and Tsunami Interconnections between Santorini, the Aegean Sea, and Izmir

The Aegean Sea is characterized by significant tectonic activity, with faults capable of generating tsunamis, as evidenced by the 2020 Samos-Izmir earthquake, which triggered a tsunami that affected coastal areas in both Türkiye and Greece (Yalciner et al., 2023; Heidarzadeh et al., 2021). Santorini's volcanic unrest poses a potential tsunami risk due to possible landslides, which could generate local tsunamis with amplitudes reaching up to 60 meters (Necmioglu et al., 2023). The 30 October 2020 earthquake (Mw 6.9) near Samos resulted in a tsunami that caused moderate damage and fatalities, illustrating the direct impact of seismic events on tsunami generation in the region (Aktas et al., 2022). Previous tsunamigenic earthquakes in the Eastern Mediterranean have also demonstrated the region's susceptibility to such disasters, necessitating ongoing monitoring and risk assessment (Heidarzadeh et al., 2021). Establishing a multiparametric monitoring platform in the Aegean Sea aims to enhance understanding of seismic and volcanic activities, providing crucial data for tsunami hazard assessments (Parks et al., 2015). Santorini, the Aegean Sea, and Izmir are interconnected through shared seismic and tsunami risks. The tectonic forces governing the region, including subduction processes near Santorini and active fault zones near Izmir, create a continuous hazard chain observed through historical and modern earthquake-tsunami events. The Aegean Sea is one of the most seismically active regions in the Mediterranean due to the interaction of the Eurasian and African tectonic plates. The Santorini volcanic complex, which experienced a significant eruption around 1600 BCE, has historically triggered tsunamis that affected nearby coastlines, including western Türkiye. The 2020 Samos earthquake (Mw 7.0), located in the eastern Aegean, resulted in a tsunami that impacted the coastal areas of Izmir, Türkiye. This highlights the direct connection between seismic activity in the Aegean and tsunami risks along the Turkish coast (Triantafyllou et al., 2021). Studies indicate that the Santorini eruption may have produced tsunami waves that traveled across the Aegean, affecting Crete, Türkiye, and beyond. Recent seismic activity in the Hellenic Arc south of the Aegean has been linked to tsunami generation, posing risks to Greek islands and Turkish coastal cities like Izmir (Altınok et al., 2011). The 2020 Izmir earthquake (Mw 6.9) caused extensive damage and fatalities in western Türkiye. It also triggered a small tsunami in the Aegean, similar to past seismic events. The 1956 Amorgos earthquake near Santorini generated tsunami waves reaching Türkiye's Aegean coast, demonstrating a historical link (Meng et al., 2021). distinctive and dynamic environment. Since January 28, 2025, earthquakes have been clustered in a 35x20 km zone between the Kolumbo Volcano (south) and Amorgos Island (north), influenced by the Ios Fault and Santorini-Amorgos Fault. The activity suggests a combined tectonic and volcanic system, with three possible outcomes: 1) A major earthquake (M7+) occurs first, triggering volcanic activity; 2) Volcanic activity precedes a significant earthquake (M7+); and 3) The activity subsides temporarily, with potential future recurrence (Dokuz Eylul University, 2025). A potential volcanic eruption near Santorini could result in ashfall reaching Türkiye's Aegean coast, Western Anatolia, and parts of the Eastern Mediterranean, as seen in past eruptions (1600 BC, 1950 AD). This could lead to air pollution and increase the risk of tsunamis due to submarine landslides. Additionally, a strong earthquake (M7+) in the region could generate tsunami waves up to 2 meters high, impacting coastal areas from Çanakkale to Fethiye, with inundation extending up to 500 meters inland in low-lying regions. The estimated tsunami arrival time is approximately 30 minutes for southwestern Türkiye and up to 3 hours for the northwest. In terms of ground shaking, M7.5 earthquakes near Santorini would cause moderate shaking (V on the intensity scale) along Türkiye's Aegean coast, but areas with softer ground, such as İzmir Bay and Kuşadası Bay, could experience more vigorous shaking (VIII), necessitating rapid structural assessments and precautionary measures (Dokuz Eylul University, 2025).

4. A Multidisciplinary Approach to Risk Assessment and Mitigation

A multidisciplinary approach is essential to understand the processes experienced in the past, take precautions, and produce solutions by evaluating today's conditions. The actors, scientists, lawmakers, governments, educators, and citizens should work together interactively. Considering the issues listed above, Figure 3 presents a multi-layered proposal with specified fundamentals based on the previous proposal by Doğdu Yücetürk and Alkan (2025).

Figure 3: Multi-layered proposal



Based on these issues, it is foreseen that a detailed examination of the issues listed below for this risky region and the determination and implementation of disaster management and strategies will contribute:

- Establishment of a scientific committee that allows experts from different disciplines to work together and comprehensively study the relevant disciplines' past, present, and future. Developing and implementing effective strategies to resolve the multifaceted risks of Santorini's volcanic activity is contingent upon the collaboration of scientists, policymakers, and stakeholders,
- Modular methodologies for risk assessment, exemplified in Lima, Peru, provide significant insights for local adaptation and resilience enhancement (Gómez Zapata et al., 2023).
- Mitigating the risks of natural hazards necessitates effectively monitoring seismic and volcanic activity. The capacity to identify precursors to tsunamis and volcanic eruptions has been enhanced by the implementation of sophisticated sensors and the advancement of early warning systems, including the SANTORY project (Nomikou et al., 2022; Katsigera et al., 2024). These systems facilitate prompt evacuations and mitigate the likelihood of economic losses and casualties.

- Integrating multi-hazard risk assessment within policy frameworks is crucial for tackling Santorini's intricate difficulties.
- AFAD (The Disaster and Emergency Management Presidency) and international tsunami warning networks are operational to enhance disaster preparedness, and residents are encouraged to install smartphone applications for real-time alerts.
- Government agencies should issue multilingual informational bulletins on tsunami and volcanic risks to ensure accessibility for foreign residents. Additionally, local authorities, universities, and AFAD must collaborate on community-based disaster management by conducting training exercises, preparedness drills, and public awareness campaigns to strengthen resilience against potential seismic and volcanic hazards (Dokuz Eylul University, 2025).
- A dense network of seismometers is needed for real-time monitoring of seismic activity and early warning dissemination.
- A dedicated data analysis center, staffed by experts, must be established to interpret seismic data and issue timely warnings.
- Advanced tsunami detection buoys and prediction models should be deployed to monitor sea levels and anticipate potential tsunamis.

- An integrated warning system, utilizing sirens and mobile alerts, is crucial for effective communication during emergencies.
- Moreover, hazard management necessitates community engagement and preparedness. Local populations' resilience can be improved by implementing evacuation plans, emergency exercises, and education campaigns (Katsigera et al., 2024).
- Regular community preparedness workshops are necessary to educate residents and tourists on emergency procedures.
- Coastal protection measures, such as seawall construction, should be implemented to mitigate tsunami wave impacts.
- Local authorities in Santorini experience difficulties related to constrained financial and personnel resources, mainly depending on higher levels of governance.
- Regulations preventing hazardous material storage in lava flow areas and containment measures to protect sensitive environments must be implemented,
- Critical infrastructure, including roads and utility networks, requires immediate reinforcement to maintain functionality post-disaster.
- Environmental impact assessments, considering seismic and tsunami risks, are mandatory for all new development projects.

- Public awareness campaigns should educate tourists and residents on the island's geological risks and responsible behavior during emergencies.
- Sustainable tourism practices should be promoted to minimize environmental impact and infrastructure strain.
- Adaptation to climate change and the protection of coastal ecosystems are frequently relegated despite their essential significance for enduring resilience (Kontopyrakis et al., 2024; Amin et al., 2024).
- Clear, regularly practiced evacuation routes, including maintained emergency escape ports, are essential for rapid response during a tsunami warning.
- While the focus on volcanic and tsunami threats is critical, it is also important to consider the broader implications of climate change and human activities that may exacerbate these natural hazards in the region.
- Wastewater infrastructure should be reinforced to prevent earthquake leaks and establish emergency treatment protocols.
- Erosion and landslide control measures must be implemented to stabilize vulnerable slopes, including vegetation restoration.
- Upgraded wastewater treatment facilities are essential to prevent coastal water contamination, which could worsen tsunami impacts.

5. Conclusion

Santorini is a seismically active volcanic island in the South Aegean. Therefore, it is necessary to be aware of this and take precautions based on scientific approaches. In this study, the activities of Santorini are examined from multi-layered perspectives, including the roles of scientists, lawmakers, governments, educators, and citizens throughout chronological order. To propose sustainable and effective disaster management, governance, urban design, education, and environmental policies must be developed.

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CHAPTER 2

THE IMPACT of PSYCHOSOCIAL FACTORS on MINING ACCIDENTS

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INTRODUCTION

The concept of occupational health and safety is defined in the TS 18001 Occupational Health and Safety Management System as "conditions and factors that may affect the health and safety of employees in the workplace, including temporary workers, subcontractor personnel, visitors, and other people in the working area" (TS 18001, 2012). According to Article 8 of the Occupational Health and Safety Risk Assessment Regulation, in the section on hazard identification, it is stated that "hazards arising from or the interaction of physical, chemical, biological, psychosocial, ergonomic, and similar sources of danger present in the working environment should be identified and recorded, taking into account the relevant regulations in occupational health and safety legislation, and considering those who will be affected and how they will be affected" (Occupational Health and Safety Risk Assessment Regulation, 2012).

The main aim of the steps taken in occupational health and safety is to protect the employee, improve the workplace for the worker, increase work productivity, and ensure the safety of the workplace. The Occupational Health and Safety system, which aims to eliminate both material and moral losses, should be prioritized for employees, employers, and the government.

For employees to complete their careers as they began, without disrupting their physical, psychological, and social structure, it is essential to maintain this integrity. This can only be achieved if effective occupational health and safety practices are adopted in the work environment. According to data from the International Labour Organization (ILO), 50% of work accidents can be easily prevented, and 48% can be avoided through disciplined work practices, making these accidents predictable. The remaining 2% are considered unavoidable or unforeseeable accidents. Since work accidents cannot always be anticipated in terms of their occurrence, the consequences and costs of such accidents are also difficult to calculate. The costs borne by employees, employers, and the country's economy resulting from these accidents are much higher than the costs that could have been incurred to prevent the causes of the accidents. Therefore, employers, administrators, and the government have significant responsibilities under the duty to protect and supervise workers. Once this awareness is achieved, the unwanted financial burdens caused by work accidents will decrease, the success of companies in their goal of profitability will increase, and substantial savings can be made in the country's economy by taking simple preventive measures.

Work accidents and occupational diseases vary according to job categories, sectors, and hazard classes.

Psychosocial risks, a significant component of occupational health and safety, refer to the likelihood of hazards that affect employees' mental health, job satisfaction, interpersonal relationships, and overall psychological and social well-being, leading to stress (Dollard et al., 2007; ISO, 2021; ILO, 2020). Considering the health problems caused by work-related stress, psychosocial risk factors are viewed as a phenomenon that negatively impacts an employee's performance. Increased work-related stress leads to a rise in smoking, alcohol, and drug use, which, in turn, affects not only the employee's working life but also their family and social life.

Psychosocial risks are one of the least known and discussed areas in occupational health and safety, and they are also the least defined and understood in terms of solutions. The productivity losses caused by psychosocial risks, increased absenteeism, rising health care costs, theft, sabotage, injuries, and early retirement payments place a significant financial burden on employers.

In conclusion, addressing psychosocial risks is crucial for improving employee well-being, reducing workplace accidents, and ensuring the overall safety and productivity of the workforce.

The term "psychosocial" is used only once in the "Regulation on Occupational Health and Safety in Mining Workplaces," which was published in the Official Gazette on 19.09.2013 (Issue: 28770). In Article 5, under the section on "Obligations of Employers and Employees," it states, "The identification and assessment of risks, including psychosocial risks that employees may be exposed to in the workplace." The regulation was prepared in parallel with the European Union directives 92/104/EEC (3/12/1992) and 92/91/EEC (3/11/1992), with the aim of setting minimum requirements for ensuring the health and safety of employees.

1. Mining and Mining Accidents

With the population growth around the world, the transition to mass production has significantly increased the demand for raw materials. This surge in demand has directly impacted the production levels in the mining industry, leading to an increase in the risks associated with mining. While all industries carry the risk of accidents, mining is particularly dangerous due to its unique characteristics. It involves interconnected risks, where a single adverse event can trigger a chain reaction. To minimize these risks, expertise, experience, and continuous supervision are essential. Mining is considered one of the most dangerous and challenging industries globally (MMO, 2010).

The mining sector is one of the most hazardous industries, with approximately 8.71% of work accidents, 49.20% of occupational disease cases, 26.76% of permanent disability cases, and 10.05% of fatal accidents occurring in this field.

Mining accidents often involve specific types of incidents, including:

- Gas explosions (Grizu explosions)
- Coal dust explosions
- Cave-ins
- Mine fires
- Flooding
- Slope failures

The mining accidents that occurred between 1983 and 2024 are presented in Table 1, while their graphical representation is provided in Figure 1.

Table 1: Mining Accidents and Their Causes (1983-2024) (MMO,2024, Tüyander, 2025)

1983	Armutçuk Grizu Disaster: On March 7, 1983, a gas explosion occurred at a coal mine in Armutçuk, Zonguldak, resulting in the death of 103 workers.
1987	A cave-in at the TTK Zonguldak Kozlu coal mine resulted in the deaths of 8 workers in January.
1990	*Amasra Gas Explosion: On January 31, 1990, a gas explosion in a coal mine in Amasra killed 5 workers. Amasya Gas Explosion: On February 7, 1990, a gas explosion at a coal mine in *Yeniçeltek, Amasya, resulted in 2 workers being burned alive, and 66 others were trapped under rubble and perished.
1992	Kozlu Grizu Disaster: On March 3, 1992, a series of gas explosions at the Kozlu coal mine in Zonguldak resulted in 263 fatalities and 550 injuries. This is one of the deadliest mining disasters in Turkey's history.
1995	On March 26, 1995, a gas explosion at the Matsan Mining Company’s coal mine in Yozgat caused the deaths of 38 workers due to a collapse.
2003	*On August 8, 2003, a firedamp explosion occurred at the Kükürtlü Mine in Aşkale, Erzurum, resulting in the deaths of 7 workers. (A report prepared by JMO states that 9 workers died, while a report by MMO mentions 8 workers.)

	*On November 22, 2003, a firedamp explosion at a coal mine operated by a private company in Ermenek, Karaman, resulted in the deaths of 10 workers. Their bodies were recovered days after the incident.
2004	*In August 2004, a firedamp explosion at a private mining operation in Bayat, Çorum, resulted in the deaths of 3 workers. *On September 8, 2004, a fire broke out in an underground copper mine in Küre, Kastamonu, when a 150-meter-long conveyor belt used for ore transportation caught fire. As a result of carbon monoxide and other toxic gases, a total of 19 workers, including a mining engineer, lost their lives. *According to a report prepared by JMO, 8 people lost their lives in Karadon.
2005	In April, a firedamp explosion at a private mining operation in Gediz, Kütahya, resulted in the deaths of 18 people..
2006	On June 1, 2006, an explosion at a lignite coal mine operated by a private company in Odaköy, Dursunbey, Balıkesir, resulted in the deaths of 17 miners.
2009	On December 10, 2009, a firedamp explosion caused a collapse at a mine in Bükköy, Mustafakemalpaşa, Bursa, resulting in the deaths of 19 workers.
2010	*Odaköy Mining Accident: On February 23, 2010, a firedamp explosion occurred at a mine in Odaköy, Dursunbey, Balıkesir, where a total of 47 workers were employed. The explosion resulted in the deaths of 17 people and injured 30 others. *Karadon Mining Accident: On May 17, 2010, a firedamp explosion and subsequent collapses at a coal mine operated by

	the Karadon Hard Coal Enterprise in Zonguldak resulted in the deaths of 30 people. *Küçükdoğanca Mining Accident: On July 7, 2010, a fire and subsequent collapse at a mine in Küçükdoğanca, a neighborhood of Keşan, Edirne, resulted in the deaths of 3 people. *On October 26, 2010, an accident at a chrome mine in Orhaneli, Bursa, resulted in the deaths of 2 workers.
2011	In February, a landslide at the Çöllolar mine, operated by a private company in Afşin-Elbistan, resulted in the deaths of 11 workers..
2013	*On January 8, 2013, a methane gas explosion at a coal mine owned by the Turkish Hard Coal Enterprise in Kozlu, Zonguldak, caused a collapse, resulting in the deaths of 8 workers. The facility had experienced previous accidents, with the deadliest disaster occurring in 1992, when 263 workers lost their lives. *On January 18, 2013, a miner lost his life in a mining accident in Soma, Manisa, after being trapped between falling iron supports.
2014	On April 26, 2014, a firedamp explosion occurred at a coal mine owned by Elmas Mining near Gülyazı village in Gülşehir, Nevşehir. The explosion resulted in the death of one worker, while six others were injured due to exposure to the released gas. *On May 13, 2014, a fire at a coal mine in Soma, Manisa, resulted in the deaths of 301 workers and left at least 88 others injured. The disaster stands as the deadliest industrial and mining accident in the history of the Republic of Turkey. *On June 1, 2014, a worker died in a mining accident in

	Elbistan, Kahramanmaraş, after being struck on the head by a coal-crushing machine. *On June 11, 2014, a collapse at a mine in Kemerli, Şırnak, resulted in the deaths of three workers, two of whom were brothers. *On June 18, 2014, a collapse at a mine in Dağkonak, Şırnak, resulted in the death of one worker. *On October 28, 2014, a flood at a coal mine near Pamuklu, Ermenek, Karaman, trapped and killed 18 workers. *On November 1, 2014, a collapse at a mine in Amasra, Bartın, resulted in the deaths of two trapped Chinese workers, while another Chinese worker was injured. On the same day, in Gelik, Zonguldak, a worker lost his life after being struck by a coal wagon in an unlicensed coal mine. *On November 6, 2014, a worker lost his life after being trapped under a falling rock at a mine in Alacakaya, Elazığ. *On November 13, 2014, a firedamp explosion at a private coal mine in Altınyazı village, Uzunköprü, Edirne, resulted in the deaths of three workers. *On November 19, 2014, a worker lost his life, and another was seriously injured after being run over by a truck at a mine in Genç, Bingöl.
2015	*On January 21, 2015, a collapse at a mine in Gemerek, Sivas, resulted in the death of one worker and injured another. *On February 7, 2015, a worker was killed after being trapped under a dislodged rock at a mine in Fethiye, Muğla. *On March 10, 2015, a collapse at a mine operated by the Turkish Hard Coal Enterprise in Kandilli, Karadeniz Ereğli,

	Zonguldak, led to the death of one worker and injured another. *On June 8, 2015, a collapse at a mine in Suluova, Amasya, resulted in the death of one worker and left two others injured. *On July 21, 2015, a worker lost his life after being trapped under a fallen support beam at a mine in Milas, Muğla. *On July 27, 2015, a worker died after being struck by a material transport wagon at a mine in Nallıhan, Ankara.
2016	On November 17, 2016, a landslide at a copper mine near Madenköy in Şirvan, Siirt, resulted in the deaths of 16 workers.
2018	At a coal mine owned by Şentaş Mining in Odaköy, Dursunbey, Balıkesir, a firedamp explosion resulted in the deaths of 18 workers.
2019	*On January 13, a mining accident in Soma, Manisa, resulted in the death of one worker and injured another. *In December, a firedamp explosion in Gelik, Kilimli, Zonguldak, led to the death of one worker, injured another, and left one worker trapped inside the mine.
2021	*In January 2021, various mining accidents resulted in the deaths of at least 5 miners, including 1 mining engineer, and left 8 workers injured. *In February, at least 4 miners lost their lives, and at least 9 others were injured in workplace accidents at mines. *In March, at least 3 miners died, while at least 10 miners and 1 mining engineer were injured in mining accidents. *In April, mining accidents caused the deaths of at least 3 miners and injured at least 7 others. *In May, at least 3 miners lost their lives, and at least 18 miners were injured in workplace accidents.

	*In July, research on workplace accidents revealed that at least 6 miners had died and at least 7 others had been injured. *In October, according to a report by Dev. Maden-Sen, at least 5 miners died, and at least 5 others were injured in mining accidents.
2022	*In February, two separate mining accidents in Zonguldak resulted in the deaths of 2 workers and left 1 worker injured. *In March, accidents at a privately operated marble quarry in Derebağ, Kavaklıdere, Muğla, and a zinc mine in the Aladağlar region of Yahyalı, Kayseri, led to the death of 1 worker and injuries to 2 others. *On October 14, 2022, an explosion at a mine in Amasra, Bartın, resulted in the deaths of 42 workers.
2024	On February 13, 2024, a collapse at the Çöpler Gold Mine in Erzincan resulted in the deaths of 9 workers.

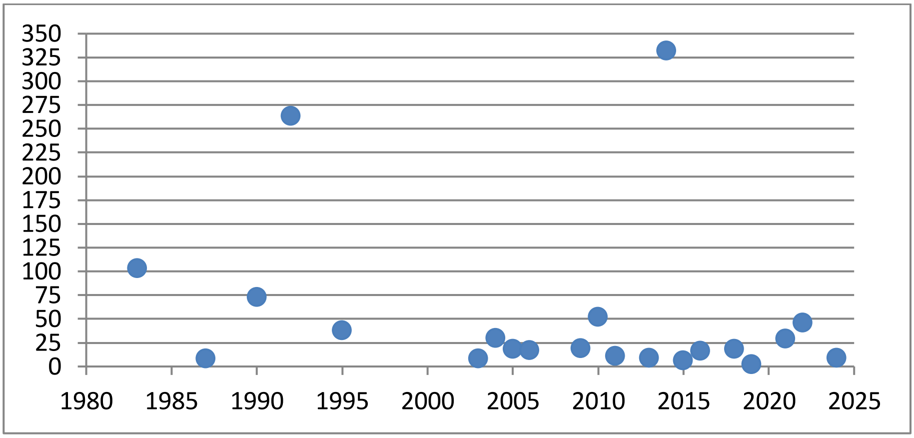

Figure 1. Mining Accidents and Fatalities Between 1980 and 2024

As seen in the table, most accidents are caused by firedamp explosions, collapses, dismantling operations, explosions, and other mining incidents. Nearly all of these accidents are preventable. The devastating nature of these disasters stems from their being "uncontrollable" at the moment they first occur.

Survivors of mining accidents have been found to suffer from psychological issues such as insomnia, antisocial behavior, claustrophobia, fear of graves and death, fear of darkness and inability to sleep in the dark, nightmares related to the accident, reliving the event, and memory loss. These psychological disorders were later added to the International Labour Organization's (ILO) List of Occupational Diseases (2010).

The daily and social lives of most miners, as well as their family relationships, are shaped by their work life. The inability to find sufficient time for personal and social life outside of work, lack of an active social life, insufficient wages, job insecurity, and sleep problems are major factors that reduce their quality of life.

Mining-specific working conditions—such as the risk of death and accidents, shift work, the heavy reliance on human labor, sleep deprivation, and relationships with colleagues and supervisors—create psychosocial risk factors for mental health problems. Workers in the mining sector often experience psychotic disorders, mood disorders, and anxiety disorders (especially panic disorder, post-traumatic stress disorder, and obsessive-compulsive disorder). They may also suffer from poor sleep quality, anxiety-related issues, alcohol and substance dependency, and psychosomatic illnesses. In Turkey, the first studies on the impact of underground mining conditions on worker health indirectly highlight mental health concerns.

2. What is Psychosocial Risk?

Psychosocial risks are defined as factors arising from inadequate job design, organization, and management that can lead to physical and mental illnesses in employees and/or administrative issues such as reduced productivity and absenteeism.

In recent years, precarious employment, flexible work arrangements favoring capital, heavy workloads, long working hours, increased work pace, and heightened emotional responsibility have contributed to work-related psychosocial effects, primarily stress. Stress, violence (including psychological violence, threats, harassment, abuse, and bullying) are also recognized as key contributors to psychosocial risks for workers.

The relationship between workplace psychosocial factors and employee health highlights the importance of stress and stress management as critical topics that workplaces need to address through appropriate strategies and policies. Both the nature of the job and the work environment can lead to stressful experiences, which may result in stress-related illnesses. Moreover, the impact of workplace psychosocial factors varies across individuals, societies, and organizations (Figure 2).

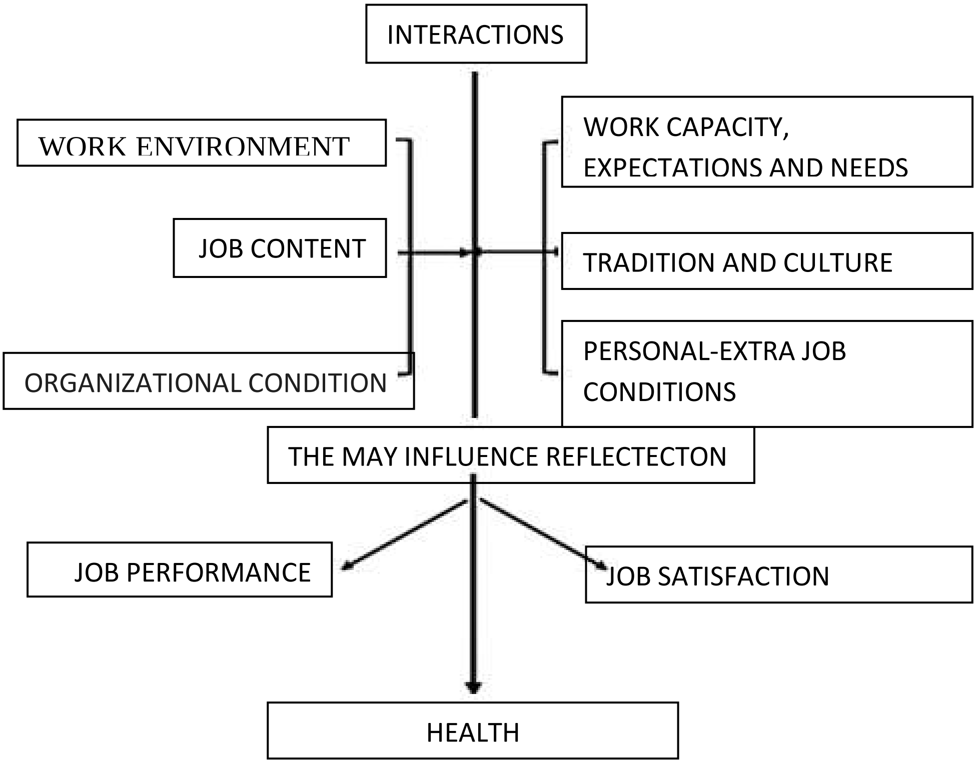

Figure 2. Psychosocial Factors in the Workplace (M. Pizarro, F. Fuenzalida, 2021)

Psychosocial risks are workplace and work-related risks that affect employees, just like physical and chemical risks, impacting workers' health. This area is one of the least known and discussed aspects of occupational health and safety and is also one of the least clearly defined in terms of its identification and solutions.

Compared to physical and chemical risk factors, identifying and preventing psychosocial risks is significantly more challenging. The biggest shortcoming in this field is the lack of clear understanding regarding what these risks are, how they should be assessed, and how they can be improved.

Psychosocial risks were added to the EU's Directive No. 89/131, which came into force in 1989 (Legal regulation and risk analysis in businesses). The framework directive on the risk assessment process, which is one of the most fundamental preventive methods related to occupational health and safety, must be adapted to the national law of the respective country. Psychological disorders were included in the latest revision of the 2010 ILO Occupational Diseases list. Turkey has taken the EU as a reference for risk determination. The Occupational Health and Safety Law No. 6331 mandates preventive measures against risks in the workplace and requires businesses to conduct risk assessments; however, the legislation regarding risk identification is insufficient. Additionally, Law No. 6331 does not address the psychosocial dimension of occupational health and safety. The assessment of physical risks and psychosocial risks differs significantly. In Turkey, data on workplace violence can be obtained to a limited extent from Social Security Institution (SGK) occupational accident statistics. However, since these data mainly focus on cases of homicide and severe injury, psychosocial data are almost unrecorded.

2.1. The Impact of Workıng Hours and Wage Policy in Mines

Every individual has the right to work and receive a fair wage in return so that they and their families can access essential services such as nutrition, healthcare, and education for a decent standard of living.

According to Article 63 of the Labor Law, the maximum weekly working hours are set at 45 hours. However, for workers engaged in underground mining operations, the working hours are limited to a maximum of seven and a half hours per day and thirty-seven and a half hours per week.

In mining, quarrying, or any type of work conducted underground or underwater, the time required for workers to descend into shafts, tunnels, or primary work locations and return from these places is considered part of their daily working hours.

According to the additional Article 9 of the Mining Law No. 3213, in workplaces extracting “Lignite” and “Hard Coal,” classified as Group 4 mines, the wages paid to underground workers cannot be less than twice the minimum wage.

For example, in 2025, the gross minimum wage is 22,104.67 TL. A worker employed underground in a lignite or hard coal mining operation can receive a gross salary of up to 46,700.00 TL. However, it is important to note that this regulation applies only to workplaces extracting lignite and hard coal and does not cover other mining operations or underground workplaces.

Article 41 of the Labor Law No. 4857 states that workers in underground mining cannot be required to work overtime. However, in cases of necessity (Article 42) or extraordinary situations (Article

43), overtime work may be imposed. In such cases, workers performing overtime will receive an increased wage for each hour exceeding thirty-seven and a half hours per week, with an additional payment of at least 100% of their normal hourly wage (Koçak, 2025).

The changes in miners' salaries over the years are presented in Figure 3.

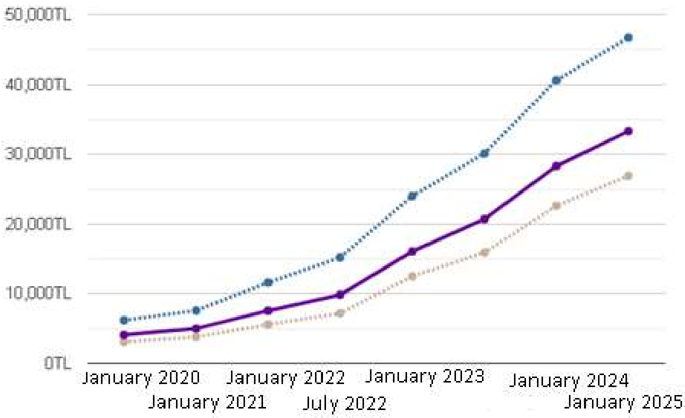

Figure 3. Salary Change Graph of the Mining Sector Over the Years

As of February 2025, the monthly food expenditure required for a family of four (poverty threshold) has been calculated as 23,324 TL, while the total household income needed for all basic expenses, including food (poverty line), amounts to 75,973 TL.

This wage inadequacy has been highlighted by the Turkish Medical Association, emphasizing that health is defined as a state of complete physical, mental, and social well-being. Therefore, hunger, poverty, and inequality are considered public health issues.

2.2. Mental Factors Affecting Mining Accidents

Mental factors include short-term memory, expectations, information retention capacity, risk prediction, decision-making errors, perceptual limits, physical limits, and environmental stress.

To reduce workplace accidents, it is crucial to focus not only on physical safety measures but also on the psychological and mental well-being of workers, as these factors play a significant role in accident prevention (Table 2).

Table 2. Mental Factors in Mining (Tüyander, 2025)

Mental Factor	Description
Short-Term Memory	Many mining accidents occur because workers forget what they need to do, misremember information, or act incorrectly as a result.
Expectations	People tend to develop expectations about the consequences of certain events and act accordingly, which can sometimes lead to misjudgments.
Information Retention Capacity	There is a limit to the amount of information a person can retain in their memory. Expecting workers to remember everything about their tasks and additional factors can lead to errors.
Risk Prediction	Accidents may occur when workers fail to correctly assess or underestimate the risks present in a situation.
Decision-Making Errors	Humans have a natural tendency to make errors in decision-making. Studies show that inaccurate

Mental Factor	Description
	judgments increase the likelihood of accidents.
Perceptual Limits	Human perception is limited. Underground workers can only sense what they see and hear around them. Hazards outside their field of vision or beyond their ability to hear often contribute to accidents.
Physical Limits	Workers tend to remove personal protective equipment or machine guards when they perceive them as obstacles to their work. These actions, taken for convenience, often result in severe accidents.
Environmental Stress	Poor thermal comfort, inadequate lighting, and excessive noise create workplace stress. This stress can lead to reduced performance, loss of focus, and ultimately, workplace accidents.

As prevention and solution suggestions, psychological support and training programs can help employees cope with stress and maintain their mental health. Shorter working hours and adequate rest periods can reduce the risk of burnout and fatigue. Occupational safety training can help employees develop safe working habits both physically and mentally. Providing social support can alleviate employees' psychological burdens and create a safer work environment.

To manage psychosocial risks in mines, measures such as occupational safety precautions, workplace psychological support systems, initiatives to strengthen employees' social support networks, and appropriate working hours are important.

3. Psychosocial Risk Assessment

Psychosocial risks, which are an essential component of occupational health and safety, refer to the likelihood of hazards that affect employees' mental health, job satisfaction, and interpersonal relationships, leading to stress (Dollard et al., 2007; ISO, 2022; ILO, 2020). Legal regulations require workplaces to conduct psychosocial risk assessments and establish psychosocial risk prevention programs.

Establishing a "Starting Point" is crucial when implementing a psychosocial risk prevention policy. This point varies for each workplace and should be identified by relevant stakeholders within the organization. Various methods and tools, including surveys, scales, interviews, and observations, are used to measure psychosocial risks.

The Copenhagen Psychosocial Questionnaire (KOPSOR) has been adapted into 18 languages and implemented across approximately 40 countries in various sectors and industries. Due to its extensive applicability, it is used by both researchers and occupational health professionals in workplace risk assessments.

With financial support from the Republic of Türkiye and the European Union (EU), a project was launched in Zonguldak to assess, prevent, and improve the working conditions of employees in the mining sector regarding psychosocial risks. The project, titled "Capacity Building for Workplace Physicians in Assessing and

Preventing Psychosocial Risks of Mining Sector Employees," was designed for this purpose.

The data collected were grouped into categories based on KOPSOR components, including interpersonal relationships and leadership, job insecurity, influence and development, and demands. Segment examples under these headings highlight the high-risk position of coal mine workers from the perspective of mining engineers and occupational safety specialists working in the sector (Işık İ et al., 2022).

4. Conclusion

This article examines the effects of psychosocial, physical, productivity, job satisfaction, safety, and other psychological factors on accidents and work productivity in mining activities.

The mining sector is directly related to the physical, social, and mental well-being of miners. Therefore, it is essential to assess working conditions, accident prevention measures, and the psychological, physical, and social impacts related to productivity in mining industries. These effects manifest in at least two ways: directly through physical conditions and indirectly through stress.

According to Article 3/1 of Law No. 6331, employers are required to conduct or commission risk assessments to ensure, maintain, and improve the health and safety of the working environment and employees. Additionally, Article 8 of the Risk Assessment Regulation states that psychosocial risks must also be identified.

To manage psychosocial risks in organizations, sources of hazards and risks should first be assessed, and then action plans should be developed to reduce them. However, since each workplace is unique, the most effective combination of control measures should be determined based on the size, structure, and field of activity of the organization.

A comprehensive approach to mental health in mining should be established and monitored both nationally and internationally through relevant policies. Psychosocial risks should be classified as workplace risks that require assessment. Any legislation or workplace-based initiative in this field should be developed with a worker-centered perspective, prioritizing employee participation and demands.

It is also crucial that psychosocial risk assessments are conducted independently by institutions and professionals to ensure objectivity and effectiveness.

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CHAPTER 3

ARTIFICIAL INTELLIGENCE INTEGRATION IN SUSTAINABLE COLLECTION OF ELECTRONIC WASTE

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INTRODUCTION

The rapid advancement of technology has also led to an increase in electronic consumer goods. Electronic equipment waste, or e-waste, is considered the fastest-growing solid waste stream, and it has become a global problem (Gaur et al., 2025). The devices that people use constantly to continue their daily routines, from computers (personal/laptop) to televisions, auxiliary electronic devices (printers/scanners, etc.) and various other devices, are at the basis of e-waste generation (De Almeida et al., 2011). While the increase in these electronic devices, which seem to make people's work easier, is a positive approach, it is a threat that negatively affects human health and the environment (Awasthi et al., 2018). There are hazardous components such as mercury, cadmium, lead, and chromium in electronic waste that threaten human health (Brindhadevi et al., 2023). If this e-waste is not disposed of correctly, it will harm the environment and humans. When these pollutants mix with groundwater, they can easily spread throughout the ecosystem. While mercury causes kidney and brain damage, lead can cause irreversible neurological abnormalities (Ilankoon et al., 2018). Some of the possible contaminants in an e-waste recycling facility are flame retardant (1,3-phenylene bis(diphenyl phosphate) (PBDPP), bisphenol A bis(diphenyl phosphate) (BPA-BDPP), triphenyl phosphate (TPHP), tetrabromobisphenol A (TBBPA), and polybrominated diphenyl ethers (PBDEs)) (Matsukami et al., 2015) dust in indoor dust (i), polybrominated diphenyl ethers in dust settled on the ground (ii), and high concentrations of some metals (such as Ni, Pb, Sn and Zn) (iii) (Ilankoon et al., 2018; Wannomai et al., 2020).

Due to its critical components and exponential increase, traditional electronic waste collection and separation have become insufficient disposal processes. To ensure effective management of this e-waste, technologies such as the Internet of Things (IoT) should be used. This way, a robust and cost-effective method will protect the environment and human health. The IoT-based e-waste management process is also thought to increase efficiency by optimizing recovery from secondary sources (Choubey et al., 2024; Jauhar et al., 2023). In addition, the control/disposal of e-waste will increase the quality of life in urban areas, contribute to the economy through recovery and recycling, and most importantly, minimize the e-waste problem (Choubey et al., 2024; Qu et al., 2022).

This study aims to explain how electronic waste (e-waste), which poses a serious threat in terms of environmental pollution and resource waste, should be evaluated in general terms with IoT-based sensor technologies and artificial intelligence-supported waste management. The initial cost of establishing such an electronic waste system may seem high. However, with simplified and easy-to-follow systems, it will be an efficient and highly functional system in the medium and long term.

ELECTRONIC WASTE

The collection, classification and disposal of electronic waste is quite difficult. In fact, it can be said that the waste management system and control are lacking in developing countries (Ada et al., 2023). Due to the deficiencies in the system for the disposal of these wastes, only storage is done. Today, rapid technological developments cause electronic devices to complete their lifespan and become waste quickly. Considering the environmental problems and human health that separation can create, these wastes are also stored.

Due to insufficient storage space and the evaluation of secondary resources, the simultaneous application of smart technologies has begun to be discussed (Kannan et al., 2024; Lin et al., 2022). The collection and classification of electronic waste can be divided into two. The first is industry, and the other is civil society. Production systems can become more efficient with interconnected and intelligent automation within the industry. This can be possible with the combined use of technologies such as artificial intelligence and cloud systems that can make analytical decisions by processing data received from the Internet of Things (IoT) (Govindan, 2024; Kannan et al., 2024).

SMART WASTE MANAGEMENT SYSTEM COMPONENTS

Smart waste management systems are made more efficient and sustainable by integrating sensor technologies, data transmission protocols and artificial intelligence-based analysis methods. The components of these systems are detailed below:

- **Sensor Layer**

Waste bins have integrated sensors to monitor various environmental and operational parameters, including fill level, temperature, and humidity. Ultrasonic sensors are particularly favored for accurately measuring bin fill levels due to their reliability and cost-effectiveness. Additionally, gas sensors may be employed to assess the presence and concentration of toxic gases emanating from waste, providing critical insights into potential health and environmental hazards (Ali et al., 2024).

- **Data Transmission Layer**

The transmission of sensor-generated data to centralized systems is facilitated through low-power wide-area networks (LPWANs). Among these, LoRaWAN is widely utilized in waste management applications, owing to its extended communication range and minimal energy requirements. Similarly, Narrowband Internet of Things (NB-IoT) protocols are increasingly adopted for their broad network coverage and energy efficiency, making them suitable for continuous data transmission in smart waste management infrastructures (Govindan, 2024).

- **Data Processing Layer (Artificial Intelligence)**

Collected sensor data are processed and analyzed using artificial intelligence (AI) techniques to enhance decision-making and operational efficiency in waste collection systems. The Python programming language, along with machine learning libraries such as TensorFlow, is frequently employed in the development of models for waste classification and route optimization. For instance, one study demonstrated the use of LoRa-transmitted sensor data analyzed through TensorFlow-based deep learning algorithms to classify various waste types and streamline collection logistics (Sankar & Fathima, 2024).

The integration of these technological components into waste management systems enhances operational efficiency, reduces costs, and supports environmentally sustainable practices. Embedding IoT sensors into waste containers marks a significant advancement in urban sustainability efforts. Through the real-time monitoring of parameters such as fill level and waste composition, municipalities and waste management authorities can optimize collection routes and reduce logistical expenditures (Sathish Kumar et al., 2016). These smart systems typically employ ultrasonic, infrared, or load-based sensors that transmit data via wireless communication protocols, enabling a dynamic and responsive waste management approach (Anagnostopoulos et al., 2017).

Moreover, machine learning techniques play a crucial role in increasing the accuracy of waste classification by identifying patterns within the data collected from sensor networks (Abdallah et al., 2020). Empirical studies have demonstrated that such intelligent systems can substantially reduce unnecessary waste collection rounds, leading to lower fuel consumption and a measurable decline in greenhouse gas emissions, thus contributing to broader environmental protection goals (Zanella et al., 2014).

In parallel, recent advancements in artificial intelligence (AI) have the potential to further transform waste management operations through the optimization of collection schedules and routing. By leveraging real-time data from IoT devices—such as bin fill levels, geographical location, and waste type—machine learning algorithms, including neural networks and evolutionary approaches like genetic algorithms, can develop predictive models to enhance system performance (Xia et al., 2022). These AI-driven frameworks not only improve operational efficiency but also support climate-conscious objectives by minimizing emissions through route optimization of waste collection vehicles. For example, in a study implemented in a municipality in southern Brazil, daily vehicle distance was reduced by 25.44% using genetic algorithms and tabu search methods, resulting in annual savings of 1,809.60 km. In addition, an average reduction of 26.15% in greenhouse gas emissions was achieved (Ferrão et al., 2024).

AI systems can dynamically adjust waste collection schedules by analyzing real-time data from IoT sensors. This way, waste bin fill levels can be monitored, unnecessary collection trips can be avoided, and resources can be used more efficiently (Rahman et al., 2022).

Support vector machines and random forest decision mechanisms can be used in feature extraction and classification algorithms (Fang et al., 2024). Support vector machines can be used in different waste classifications by using image and sensor data. However, they may be insufficient in classifying complex and large amounts of waste. Decision tree algorithms can optimize waste collection routes by analyzing large data sets (Saka et al., 2024). In a study conducted in Nigeria, a cloud-based waste management system was developed using decision tree algorithms, increasing the efficiency of waste collection processes (Ekruyota et al., 2024). In one study, they considered the Stochastic Inventory Routing Problem for the collection of recyclable materials with uncertain bin filling levels, and modeled the waste accumulation rates with conditional density estimation and dynamic stochastic approaches. The findings show that waste managers may be willing to pay up to 81% of the total profit for perfect information and that it is important to consider the uncertainty of the bin filling level. The study revealed that ignoring uncertainty can lead to inappropriate policies. For future studies, they suggested developing the model with real-time data from sensors, applying it to larger and more realistic systems, and investigating alternative solution techniques such as Benders decomposition, Lagrangian relaxation, dynamic programming, or genetic algorithms (Spinelli et al., 2024).

SUSTAINABLE MANAGEMENT OF E-WASTE

Sustainable management of e-waste (electronic waste) requires users' active participation in the correct separation and delivery processes. Reward systems that encourage this participation can increase recycling rates by positively influencing user behavior.

- Effectiveness of Point-Based Reward Systems:

Point-based reward systems stand out as an effective method to increase users' participation in e-waste recycling. Point-based incentive mechanisms have emerged as effective tools to enhance public engagement in recycling practices. These systems enable individuals to accumulate points based on their participation in recycling activities, which can subsequently be redeemed for various rewards. Empirical evidence suggests that there are significant correlations between the willingness to participate in formal recycling programs and factors such as individual expectations, subjective attitudes, external environmental conditions, and certain consumer characteristics. Principal factor analysis and correlation analysis revealed that point-based reward systems positively influence consumer behavior, thereby contributing to the improvement of electronic waste (e-waste) recycling practices, particularly in the context of China's national waste management strategies(Zhong & Huang, 2016).

- **Electronic Bonus Card Systems (EBCS):**

Electronic Bonus Card Systems represent another approach designed to motivate consumers to correctly dispose of their e-waste. Through these systems, participants accumulate bonus points when they return their electronic waste to designated collection centers. These points may be used for product discounts or free items, effectively incentivizing proper recycling behavior. EBCS serves to address key challenges such as home storage of obsolete electronics and improper disposal with household waste. Importantly, the system also returns part of the product's residual value to the consumer, creating economic motivation for participation. Even in developing regions, EBCS has the potential to compete with informal recycling sectors. Implementation strategies may involve trade networks or recycling compliance organizations, but effective execution depends on the collaborative participation of key stakeholders—including governmental bodies, manufacturers, retailers, recyclers, and end-users (Shevchenko et al., 2019).

- **Blockchain-Based Incentive Systems:**

Blockchain technology introduces transparency, traceability, and reliability into the e-waste recycling process. In blockchain-based systems, consumers are rewarded with digital tokens upon the proper disposal of their electronic waste. These tokens can be exchanged for discounts or other benefits, fostering a structured and traceable incentive model. A recent study proposed a blockchain-enabled incentive mechanism incorporating smart contracts and a vector space model. In this framework, the blockchain network—potentially powered by platforms such as Ethereum—assigns incentives based on matched tasks and stores transaction records immutably. This innovative approach not only encourages accurate waste management practices but also supports the development of sustainable behavior through personal accountability (Alarood et al., 2023).

- **Gamification and Social Incentives:**

Gamification has also emerged as a behavioral strategy to increase participation in recycling activities. In this model, users receive virtual rewards such as badges, rankings, or achievement statuses for completing specific recycling tasks. These mechanisms can promote ongoing engagement and environmental awareness. A study investigating the impact of gamification on household recycling behavior developed a mobile application incorporating visual mapping and interactive gamified features. While the application initially attracted user interest, long-term behavior change was observed to require sustained effort and habitual integration (Rosenlund et al., 2025).

CONCLUSION

The effective management of electronic waste (e-waste) is critical for environmental sustainability and the responsible utilization of natural resources. Rapid technological advancement has accelerated the obsolescence of electronic devices, leading to a surge in e-waste generation. Given the toxic and hazardous components found in e-waste, traditional collection and sorting methods are increasingly insufficient to address the associated environmental and health risks.

In this context, the integration of emerging technologies—such as artificial intelligence (AI), the Internet of Things (IoT), and blockchain—offers transformative potential for improving the efficiency and effectiveness of e-waste management systems. Intelligent waste monitoring using real-time sensor data (e.g., fill level, temperature, humidity) not only optimizes collection routes and reduces operational costs but also minimizes environmental impact by cutting fuel usage and emissions. Moreover, machine learning and deep learning models enhance the accuracy of waste classification, allowing for more precise and sustainable recycling operations.

Simultaneously, consumer-focused incentive mechanisms—such as point-based rewards, electronic bonus card systems, and blockchain-enabled token economies—serve to increase public engagement in recycling initiatives. Notably, EBCS models provide both environmental and economic benefits by encouraging responsible disposal behavior while addressing issues like home storage and improper segregation. When combined with technological innovations and policy support, these participatory models hold significant promise for advancing global e-waste management practices. Blockchain technology strengthens users' sense of personal responsibility by providing transparency and reliability. Gamification strategies are also an effective method to increase interest in recycling processes. Badges, rankings and virtual awards that users receive in recycling activities contribute to adopting sustainable behaviors by increasing environmental awareness.

As a result, integrating modern technologies and user-oriented incentive systems can make e-waste management more sustainable. Smart systems and artificial intelligence-supported solutions can reduce environmental pollution and ensure efficient resource use by optimizing waste management. In the future, the application and development of these technologies on a larger scale will provide long-term and sustainable solutions to the e-waste problem.

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CHAPTER 4

COMPARATIVE EVALUATION OF ANTIBACTERIAL TEST METHODS FOR SLA-PRINTED NANOCOMPOSITE SURFACES

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INTRODUCTION

Additive manufacturing techniques like stereolithography (SLA) have enabled the fabrication of polymer components with embedded nanomaterial additives, yielding nanocomposite surfaces that can inhibit bacterial growth. The development of antimicrobial surfaces is driven by the needs in healthcare and food industries to curb the spread of pathogens via high-touch or implant surfaces. To validate the efficacy of such surfaces, standardized antibacterial testing methods are essential. ISO 22196:2011 (adopted as TS ISO 22196) – often considered the gold standard for antimicrobial surface testing – provides a quantitative measure of bacterial reduction on plastics and other non-porous surfaces. Complementary standards like JIS Z 2801 (a Japanese standard essentially equivalent to ISO 22196) and ASTM E2149 (a dynamic contact test) offer alternative methodologies to assess antibacterial performance under different conditions. These methods differ in approach: ISO/JIS employ a static contact assay on flat samples, whereas ASTM E2149 uses a shaking suspension to test surfaces, including irregularly shaped or leaching materials (Carvalho et al., 2024; ASTM E2149, 2013).

In parallel to testing methodologies, the surface characteristics of SLA-printed materials critically influence antibacterial performance. SLA produces parts with high resolution and relatively smooth surfaces compared to other 3D printing methods. However, including nanoparticles (e.g., Ag, ZnO, CuO, Bi_2O_3) can alter resin curing and microtexture (Vidakis et al., 2022). Surface morphology – roughness, porosity, and chemistry – affects how bacteria adhere and consequently how effectively they can be inactivated by an antimicrobial surface. Rougher surfaces generally present greater area and more “niches” for bacterial attachment. For surfaces with roughness above ~0.2 μm tend to promote higher bacterial colonization without of antimicrobials (Yoda et al., 2014). Thus, designing SLA nanocomposites with optimal nanoparticle content and surface finish is a materials science challenge intertwined with microbiological testing. This chapter provides a review of antibacterial testing methodologies applicable to SLA-fabricated nanocomposites, comparing TS ISO 22196 with ASTM E2149 and JIS Z 2801, and discussing how SLA surface features influence test outcomes. Literature examples using common antimicrobial nanoparticles – silver (Ag), zinc oxide (ZnO), copper oxide (CuO), and bismuth oxide (Bi_2O_3) are integrated to illustrate key concepts.

MATERIALS

SLA Nanocomposite Samples: In antibacterial surface testing, the materials under study are typically flat coupons or discs of the target nanocomposite, sized to fit the test protocol requirements (e.g., 50–100 mm squares for ISO 22196, or ~1 gram pieces for ASTM E2149). SLA-printed nanocomposites are produced by mixing functional nanopowders into a photocurable resin. Common antimicrobial nanopowders include silver (Ag), zinc oxide (ZnO), copper (II) oxide (CuO), and bismuth (III) oxide (Bi_2O_3), each known for broad-spectrum antibacterial activity (Gudkov et al, 2021; Rabago et al., 2023). Silver nanoparticles, for example, are well-documented to exhibit strong bactericidal effects against both Gram-positive and Gram-negative bacteria (Scuri et al., 2019). ZnO is another widely studied agent; at the nanoscale, it shows high antibacterial potential through mechanisms like reactive oxygen species generation and zinc ion release (Gudkov et al, 2021). Copper oxide nanoparticles also impart potent antimicrobial action, with studies showing efficacy against *S. aureus, E. coli, P. aeruginosa*, and other strains (Rabago et al., 2023). Emerging materials such as Bi_2O_3 are gaining attention; recent research demonstrates that Bi_2O_3-based nanostructures can inhibit a range of bacteria, offering a cost-effective alternative to noble metals (Geoffrion et al., 2021; Qayyum et al., 2022). For consistent comparisons, test specimens are usually prepared with a uniform thickness and surface finish. SLA printing can achieve smooth surfaces, but nanoparticle additives may slightly increase surface roughness or induce micro-defects due to altered curing dynamics (Vidakis et al., 2022). Post-processing techniques such as polishing and gentle sanding are frequently applied to stereolithography (SLA) printed parts to enhance surface flatness and reduce roughness, which is particularly important in the preparation of samples for standardized surface characterization. These finishing methods improve visual aesthetics and dimensional consistency across testing surfaces. However, when dealing with nanocomposite systems—especially those containing surface-active nanoparticles excessive abrasion may inadvertently remove the nanoparticle-rich surface layer. This outer layer often contributes directly to the material's functional properties, including antimicrobial, optical, or barrier performance. Consequently, the finishing process must be carefully optimized to ensure the surface is smooth enough for valid testing while still preserving the engineered functionalities imparted by surface-distributed nanofillers (Son & Lee, 2020; Bressot et al., 2020).

Bacterial Strains and Culture Media: The standard test strains are usually Staphylococcus aureus (Gram-positive) and Escherichia coli (Gram-negative) as mandated by ISO 22196 and JIS Z 2801 (microbe-investigations.com, 2025). These two bacteria represent common pathogens and offer a contrast in cell wall structure. Additional organisms (e.g., Pseudomonas aeruginosa, Klebsiella pneumoniae) may be tested depending on the application, but our focus remains on the two standard strains. Cultures are grown to a known concentration; typically ~10^5–10^6 CFU/mL for ISO/JIS tests, or ~10^8 CFU/mL for ASTM E2149. Nutrient broth or physiological saline (buffer) is used as the suspension medium. For assays requiring agar plates (e.g. determining colony counts or inhibition zones), standard agar media such as Tryptic Soy Agar (TSA) or nutrient agar are prepared. Neutralizing agents (e.g. lecithin, polysorbate) are often included in extraction buffers to quench any residual antimicrobial activity when recovering bacteria (Cunliffe et al., 2021).

Test Surface Characteristics: It is important to characterize the surfaces prior to testing. Surface roughness (Ra) can be measured by profilometry or Atomic Force Microscopy; a smooth SLA surface might have Ra< 0.1 µm, whereas inclusion of nanoparticles or improper cure can raise this value slightly (Vidakis, 2022). Hydrophobicity (water contact angle) is another relevant property; many metal-oxide nanopowders (ZnO, Bi_2O_3) tend to increase surface hydrophobicity, which can reduce bacterial attachment (Reddy et al., 2022). Each material's surface is thus a combination of chemistry (polymer + nanoparticle) and topography, both of which can influence test outcomes. All test samples are sterilized (commonly by UV light or ethanol immersion) before inoculation to ensure any observed bactericidal effect is due to the material itself. Controls include a neat resin sample without nanoparticles (negative control, expected to have no inherent antibacterial effect) and sometimes a positive control surface (e.g., a known antimicrobial material).

METHODS

TS ISO 22196 / JIS Z 2801 (Static Contact Method): ISO 22196 (identical to JIS Z 2801) measures antibacterial activity on a surface by comparing the viable bacteria count before and after a fixed incubation on the material (microbe-investigations.com, 2025). In this method, a known volume of bacterial suspension (typically 0.4 mL spread over ~5 cm^2) is placed on the test surface . A sterile polyethylene film is carefully laid over the inoculum to ensure intimate, uniform contact. The inoculated sample is then incubated at 35°C and ≥90% relative humidity for 24 hours. These conditions keep the inoculum droplet from evaporating, maintaining a "wet" environment that can allow any soluble antimicrobial agents to diffuse. After incubation, the cover film is removed and the bacteria are recovered from the surface by rinsing and gentle wiping into a neutralizing broth. Serial dilutions are plated onto agar, and colony-forming units (CFUs) are counted after overnight culture (Cunliffe et al., 2021).

The antibacterial activity value (R) is calculated as the difference in log_{10} counts between the treated sample and an untreated control of the same material (microbe-investigations.com, 2025). An R-value >2 (corresponding to >99% reduction) is typically considered significant antibacterial efficacy. ISO 22196 is straightforward and highly reproducible for non-porous, flat surfaces, which is why it's widely adopted in product testing. However, it has limitations: the continuous moist contact can exaggerate the performance of materials that rely on leaching biocides (since in real use, surfaces may dry out). Additionally, the test does not directly account for surface roughness effects because the cover film presses the bacteria onto both smooth and rough areas alike. Despite these caveats, ISO 22196/JIS Z2801 remains a core method for benchmarking antibacterial surfaces (Cunliffe et al., 2021).

ASTM E2149 (Dynamic Shake Flask Method): ASTM E2149-13a is designed to evaluate antimicrobial activity of non-leaching surfaces under dynamic conditions. Unlike ISO 22196, it does not confine bacteria to the surface under a film; instead, the material sample (usually a small coupon or a specified mass, e.g., 1 gram) is immersed in a bacterial suspension of known concentration in a flask. The flask is then placed on a shaker (often a wrist-action or orbital shaker) and agitated, typically for 1 hour at room temperature.

The shaking ensures continuous exposure of bacteria to the surface. After the contact time, aliquots of the suspension are withdrawn and plated to count surviving bacteria. The reduction in CFU in the presence of the antimicrobial sample, relative to a control flask containing an equivalent inert sample, indicates the antibacterial efficacy. One important aspect is ensuring that the test surface does not release substances that continue to kill bacteria during dilution and plating; if the material leaches antimicrobials, a neutralizer must be used to quench residual effects. ASTM E2149 is well suited for materials that are irregular in shape (fibers, pellets) or for those intended to function in liquid environments. It also mimics conditions where there is fluid flow or movement. However, this method may under-represent the performance of purely contact-killing surfaces in dry use, since the bacteria are not forced to remain on the surface and can circulate in the bulk fluid. Additionally, bacterial adhesion factors are less relevant here – highly adherent bacteria might be killed on a surface in a real scenario, but in E2149, they could simply remain attached to the sample and not be counted in the liquid's CFU, potentially skewing results. For these reasons, E2149 is often recommended only when ISO 22196 (or JIS Z 2801) is not applicable (e.g., for powders or very uneven materials) (Cunliffe et al., 2021; ASTM E2149, 2013).

Other Test Methods: In some cases, researchers employ agar diffusion tests (akin to JIS Z 2801's agar spread method or standard disk diffusion). One approach is to place the sample on an inoculated agar plate and look for a zone of inhibition around it. This is not a quantified standard in ISO 22196 but can be a quick visual indicator of leaching antimicrobial efficacy (Vadikis et al., 2022). For example, an SLA nanocomposite might show a clear halo on an agar plate if it releases biocidal ions. Another category includes adhesion assays, where, after a short contact (1–4 h), non-adherent cells are rinsed off and the bacteria that stuck to the surface are either counted or visualized. This can simulate early-stage biofilm formation conditions. While not standardized broadly for antibacterial surface claims, such tests (including flow-cell-based methods) provide insight into how surface topography and chemistry influence initial bacterial attachment (Cunliffe et al., 2021). Given this chapter's focus, we primarily discuss the standardized ISO and ASTM methods, but it is worth noting that real-world performance assessment may require a combination of test types.

Tables 1 and 2 present a structured comparison of the key methodological steps, advantages, and limitations of three commonly used antibacterial test standards: ISO 22196, ASTM E2149, and JIS Z 2801.

Table 1. Comparison of commonly used antibacterial test standards

Test Standard	**Contact Mode**	**Bacteria Recovery**	**Advantages**	**Limitations**
ISO 22196	Static, moist contact	CFU count after rinsing and neutralization	High reproducibility; directly measures surface efficacy	Not suitable for leaching materials; may overestimate biocidal release
ASTM E2149	Dynamic contact (continuous agitation)	CFU count from suspension sampling	Suitable for irregular or leaching materials	May underrepresent surface effects; relies on biocide release
JIS Z 2801	Static, moist contact	CFU count after rinsing and neutralization	Identical to ISO 22196, a standard in Japan	Same limitations as ISO 22196

Table 2. Comparison of commonly used antibacterial test standards

Test Standard	**Sample Format**	**Bacterial Inoculation**	**Covering**	**Incubation Conditions**
ISO 22196	Flat, non-	A bacterial	Covered with	35°C, ≥90%

	porous surface (e.g., 50–100 mm squares)	suspension is dropped onto the surface	sterile polyethylene film	RH, 24 hours
ASTM E2149	Small piece or ~1 gram of material	The sample is immersed in bacterial suspension	No covering	Room temperature, 1 hour agitation
JIS Z 2801	Flat, non-porous surface (same as ISO 22196)	A bacterial suspension is dropped onto the surface	Covered with sterile polyethylene film	35°C, ≥90% RH, 24 hours

RESULTS

Antibacterial Efficacy Outcomes: When evaluated using ISO 22196, SLA-printed nanocomposite surfaces demonstrated significant antibacterial activity, typically yielding bacterial log reductions between 2 and 3, corresponding to 99% to 99.9% reduction compared to unmodified control surfaces. This level of reduction indicates "good" to "very good" antimicrobial efficacy as defined in the Japanese Industrial Standard JIS L 1902:2002 (Testing Method for Antibacterial Activity of Textiles). According to this classification:

- No activity: ≤0.5 log reduction (<68.4% reduction),
- Slight activity: 0.5–1.0 log reduction (68.4%–90%),
- Medium activity: >1.0–2.0 log reduction (90%–99%),
- Good activity: >2.0–3.0 log reduction (99%–99.9%),
- Very good activity: >3.0 log reduction (>99.9%).

This classification system also distinguishes between bacteriostatic activity (90%–99.9 % reduction) and bactericidal activity (>99.9% reduction). Misstatements such as “>4 log reduction” can be misleading without standardized testing and statistical validation. For example, Scuri et al. (2019) reported silver-based polymer composites achieving >3 log reduction for *E. coli* and *S. aureus* in 24-hour ISO 22196 tests, confirming very good antibacterial efficacy.

Similarly, copper-based SLA nanocomposites demonstrated notable antibacterial activity against both S. aureus and E. coli, with inhibition zones up to 5.5 mm observed at 1.0–2.0 wt.% Cu loading, confirming the threshold for visible antibacterial effects. In contrast, both the neat resin and the 0.5 wt.% Cu-loaded specimens exhibited no measurable antibacterial activity under the same conditions, indicating that a minimum Cu concentration of ≥1.0 wt.% is required for detectable biocidal performance (Vidakis et al., 2022). In copper- and silver-nanoparticle reinforced SLA polymer nanocomposites, antibacterial performance can appear very different depending on the test method.

ASTM E2149, a dynamic suspension-based assay, involves immersing the sample in a bacterial solution and shaking it to maximize contact between the material and microorganisms. As outlined by Cunliffe et al. (2021), this method is particularly suited for evaluating materials that actively release antimicrobial agents into the liquid medium, as the efficacy is strongly influenced by the degree of biocide leaching from the composite surface.

The apparent ranking of antimicrobial efficacy can therefore vary significantly between standardized methods such as ASTM E2149 and ISO 22196. ASTM E2149, which evaluates antimicrobial activity in a dynamic liquid environment, is particularly sensitive to materials that leach active substances. This method does not capture the efficacy of contact-killing materials, which perform well under direct surface testing like ISO 22196 but may appear less effective in suspension-based assays due to their limited release of biocidal agents.

Conversely, materials that rely on leaching often excel in ASTM E2149 due to increased exposure of bacteria to the released actives in the surrounding medium. This divergence underscores the importance of selecting a test method that aligns with the expected mode of action of the antimicrobial surface under evaluation (Cunliffe et al., 2021). Studies indeed report that antimicrobial performance outcomes “vary by testing protocol,” meaning a material can appear significantly more or less effective depending on the test used (Campos et al., 2016). ISO 22196’s wet-contact conditions can even inflate efficacy values relative to real-use conditions (Carvalho et al., 2024). So, one must be cautious when comparing results. In summary, Ag/Cu nanoparticle-infused SLA prints tend to show near-complete bacterial kill in ASTM E2149 when sufficient biocide is released, whereas ISO 22196 will reliably capture their surface-contact lethality, often with high log reductions, even if leaching is minimal. Each method thus favors different antimicrobial action mechanisms, explaining why the same nanocomposite can rank differently in efficacy across the two standards (Campos et al., 2016; Cunliffe et al., 2021).

CONCLUSION

The comparative evaluation of antibacterial testing methods for SLA-printed nanocomposite surfaces highlights the significant impact of test protocol selection on perceived antimicrobial efficacy. Static contact assays like TS ISO 22196 and JIS Z 2801 are highly effective in quantifying surface-based antibacterial activity, especially for materials designed to kill bacteria upon direct contact. However, their moist conditions may artificially enhance the performance of leaching materials, necessitating careful interpretation of results (Cunliffe et al., 2021; Carvalho et al., 2024). Conversely, dynamic assays such as ASTM E2149 are more suitable for evaluating materials that function through the release of antimicrobial agents into surrounding environments, although they may underestimate the efficacy of purely contact-active surfaces (Cunliffe et al., 2021).

Moreover, the microstructural characteristics of SLA-fabricated nanocomposites including surface roughness, nanoparticle distribution, and hydrophobicity play critical roles in bacterial adhesion and subsequent inactivation. Nanoparticle selection and surface finishing processes must therefore be optimized in tandem with intended use scenarios and testing standards (Vidakis et al., 2022;

Son & Lee, 2020). Considering that SLA-printed nanocomposites infused with Ag, ZnO, CuO, and Bi_2O_3 nanoparticles consistently demonstrated good to very good antibacterial activity across standardized tests, such materials present promising candidates for applications demanding controlled antimicrobial properties.

In conclusion, a comprehensive understanding of both material properties and test method limitations is essential for accurate assessment of antibacterial performance. Future studies should emphasize multi-method evaluations to bridge the gap between laboratory efficacy and real-world conditions, ensuring reliable deployment of antimicrobial SLA nanocomposites in healthcare, food packaging, and related fields (Campos et al., 2016; Cunliffe et al., 2021).

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CHAPTER 5

THE USE OF MYCELIUM BASED BIOMATERIALS IN SUSTAINABLE ARCHITECTURE: AN INNOVATIVE APPROACH TO HISTORICAL BUILDING RESTORATION

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INTRODUCTION

Today, sustainability and reducing environmental impacts are among the priority objectives in the construction sector and emerge as one of the fundamental factors shaping the sector's future (Özkan Önür vd., 2024). To minimize the environmental impacts of the construction industry, sustainable and innovative solutions are gaining increasing importance. In this context, materials obtained from renewable and biological sources are being considered as an environmentally friendly and sustainable alternative to traditional building materials, opening new horizons in the construction sector (Şahin, vd., 2025). In light of this information, mycelium based biocomposites stand out as a promising alternative in the field of restoration with their natural structure, self regenerating properties, and environmentally friendly characteristics. Mycelium based composites are innovative biocomposites obtained by combining fungal filamentous structures, formed during their natural growth process, with agricultural and industrial lignocellulosic waste under special conditions. These advanced materials offer significant advantages compared to traditional building materials. The need for environmentally friendly and energy efficient building materials is significantly increasing with the rise of sustainable construction trends and the more pronounced effects of climate change (Emek, vd., 2025). Composites have the potential to play an important role in combating electromagnetic pollution and can provide effective solutions in reducing electromagnetic pollution brought by modern technology (Tanyer, vd., 2018). Mycelium based composites stand out as environmentally friendly materials that require minimal energy consumption in the production process, have a low carbon footprint, are completely natural and biodegradable, while also providing high energy efficiency (Sariay, vd., 2023).

Mycelium based composites are becoming increasingly widespread in the construction sector, particularly in semi structural applications such as insulation materials, structural panels, and indoor furniture production. These materials stand out with their sustainable and environmentally friendly properties. However, there are some significant limitations in the use of mycelium based composites as building materials, such as low mechanical strength values, high water absorption capacity, and the lack of fully developed standardized production methods at an industrial scale. Therefore, for mycelium based composites to find wider application and become more commonly preferred in the construction sector, technical limitations need to be overcome through research and development studies, and material properties need to be improved (Sariay, vd., 2023; Tazeoğlu Filiz, 2023).

In today's world where sustainable building materials are gaining increasing importance, mycelium based biocomposites are emerging as a promising alternative, particularly in the restoration of historical buildings. Mycelium, the root like structure of fungi, combines with organic waste to create a durable, lightweight, and biodegradable material. This natural production process occurs with minimal energy consumption and near zero carbon footprint. The resulting material stands out with its water resistance and fire retardant properties. Due to these characteristics, mycelium is considered a sustainable alternative to traditional materials in the restoration of historical buildings. Particularly successful results have been achieved in the restoration of wooden structural elements and its use as filling material (Sariay, vd., 2023). According to the findings obtained from literature reviews and examination of academic studies;

The use of mycelium based materials in the restoration of historical buildings can be considered in areas such as temporary support structures, interior cladding, and insulation applications. The lightweight nature and formability of mycelium can provide flexibility in the restoration of historical buildings with complex architectural details. Furthermore, the natural structure of mycelium can offer restoration solutions that are compatible with the original materials and aesthetics of historical buildings. The potential of biotechnological materials to enhance the long term resistance of structures against water, moisture, temperature changes, and other environmental effects is being discussed (Demir, vd., 2022).

This study, which provides a comprehensive examination of the potential of biotechnological materials offering sustainable solutions in the preservation and restoration of historical buildings, presents a comparative evaluation of traditional and modern restoration techniques, laying out in detail the fundamental information that can be used in transmitting historical structures to future generations (Kaya, vd., 2023).

This study, which provides a comprehensive review on the preservation and restoration of historical buildings, examines in detail the potential applications of biotechnological materials in the repair and reinforcement processes of historical structures. By comparing traditional restoration techniques with modern biotechnological approaches, the study provides fundamental knowledge and important insights for the sustainable preservation of historical buildings (Feilden, vd., 2018).

It examines in detail the potential use of bioremediation techniques and mycelium based materials in the restoration of structures. These techniques offer sustainable solutions, particularly in the preservation and renovation process of historical structures. Additionally, the environmental advantages of these materials, their positive effects on energy efficiency, and technical challenges encountered in application are comprehensively addressed. The long term durability and performance of the materials are also discussed within the scope of evaluation (Hernández, vd., 2020).

Mycelium, as shown in Figure 1, is the fundamental structure that forms the vegetative (growth, development, and spread) part of fungi and is a root like system that enables most fungi to maintain their vital activities. It is formed by the coming together of hyphae, a filamentous fungal structure that shows extensive branching and creates a complex network structure with each other. Each of these hyphae, as shown in Figure 2, are units that can be examined microscopically on their own but form a strong structure when combined. The mycelium network, composed of natural polymers such as chitin, cellulose, and proteins, is actually the organic part that connects the roots used by the fungus to digest nutrients and has the ability to bind many substances around it together. Thanks to this property, it plays a critical role in the fungus's life cycle. Furthermore, it is an organic substance of vital importance for the fungus as it enables nutrient absorption by connecting the underground fungal bodies. This connection system allows the fungus to utilize nutrients in the soil most efficiently and maintain its life (Islam, vd., 2017).

Figure 1. Mycelium view (URL-1; URL-2, 2025).

Figure 2. Internal structure of mycelium (URL-3, 2025).

BASIC MATERIALS USED IN THE PRODUCTION OF MYCELIUM BASED COMPOSITES

Pleurotus ostreatus (oyster mushroom): This mushroom species, which serves as a mycelium source, exhibits rapid growth characteristics in natural and cultivation environments and is widely found worldwide. The oyster mushroom, recognized by its white color, robust structure, and fan-shaped cap, holds an important place among edible species and is frequently preferred in commercial production (Manan, vd., 2021).

Lignocellulosic Substrates: Agricultural waste and by products (for example, coconut fiber, sawdust, flax stem, wheat straw, corn cob) are used to provide an ideal environment for healthy and efficient mycelium growth. These substrates provide the necessary nutrients and structural support for mushroom mycelium development thanks to their high cellulose and lignin content. Additionally, these materials are preferred due to their sustainable and economical nature (Manan, vd., 2021).

Nutritional Supplements: When necessary, specially prepared organic nutrients can be added to support healthy and balanced mycelium development. These supplements are used to optimize mycelium growth rate and increase metabolic activity. The type and amount of nutritional supplements should be carefully adjusted according to the existing nutrient content of the growing medium and the specific needs of the mycelium (Manan, vd., 2021).

PHYSICAL AND CHEMICAL PROPERTIES OF MYCELIUM

According to data obtained from literature studies, the physical and chemical properties of mycelium based materials have been examined. The results obtained in the study were evaluated in two main categories. As shown in Table 1, physical properties including lightness, heat and sound insulation capacity, and porosity structure characteristics have been detailed. Table 2 addresses the material's natural chemical properties, which include important characteristics such as biodegradability under environmental conditions, low carbon footprint during production, and having a harmless structure for living organisms.

Table 1. Physical Properties (Wang, vd., 2022).

Lightness	*Heat and Sound Insulation*	*Porosity*
Having a very low density compared to traditional building materials, mycelium can be used without compromising the load-bearing capacity of historical buildings.	Thanks to its porous structure, it functions as a natural insulation material.	Its ability to allow water vapor transmission enables historical buildings to maintain their natural moisture balance, especially in humid regions.

Table 2. Chemical Properties (Chow, vd., 2023).

Biodegradability	*Low Carbon Footprint*	*Safety*
The ability to completely decompose in soil provides an environmentally friendly restoration approach.	Due to low energy requirements during production, environmental impact is minimal.	Can be safely used in enclosed spaces as it does not emit toxic gases or chemical releases.

MYCELIUM BIO-FABRICATION PROCESSES

Substrates are sterilized in an autoclave to ensure mycelium growth in a contamination free environment. The sterilized substrates are inoculated with mushroom mycelium and incubated under conditions specified in Table 3. During this process, the mycelium colonizes the substrates to form the basic structure of the composite material (Chow, vd., 2023).

Table 3. Bio-fabrication Process (Wang, vd., 2022).

Temperature	*Humidity*	*Duration*
22–25 °C	%65–90	7–14 gün

In shaping and drying; the colonized substrate is carefully placed into meticulously prepared molds with the desired form. At this stage, incubation continues for several more days under optimal temperature and humidity conditions to allow the mycelium to completely fill every corner and void of the mold. After the incubation process is complete, a controlled drying process at 60°C is applied to completely stop microbial activity, ensure product stability, and significantly increase the mechanical strength of the material (Chow, vd., 2023).

APPLICATIONS AND LIMITATIONS OF MYCELIUM AS A BUILDING MATERIAL IN SUSTAINABLE ARCHITECTURE

The increasing demands for green products and technologies in the built environment, along with the pursuit of sustainability, have led to the emergence of a new generation of environmentally friendly and innovative materials. Within this evolving family of materials, mycelium based composites have come to the forefront. These are innovative biocomposites obtained through the controlled growth of fungi's filamentous parts on an organic substrate and processed under special conditions. Due to their low carbon footprint, minimal energy consumption and processing costs, complete biodegradability in nature, and remarkable material characteristics, these composites are receiving growing interest and demand as an alternative material in the building and construction sector (Jones, vd., 2020).

ARCHITECTURAL APPLICATIONS OF MYCELIUM

MycoTemple

MycoTemple is an environmentally conscious and fully biodegradable dome structure designed by innovative French artist Côme Di Meglio. This five meter diameter structure is built using mycelium (the vital root system of fungi). In accordance with sustainability principles, the mycelium was grown in Di Meglio's custom design workshop in Marseille using low-tech and eco friendly methods on industrial waste (particularly sawdust from furniture production). Inside the structure lies a hidden wooden skeleton, entirely handcrafted and meticulously processed, exemplifying traditional craftsmanship. As shown in Figure 3, as the mycelium naturally biodegrades over time, this wooden structure gradually emerges, dramatically symbolizing the structure's temporality and its harmonic relationship with nature (Di Meglio, 2017).

Şekil 3. MycoTemple (Di Meglio, 2019).

Hy-Fi

Hy-Fi is a groundbreaking project designed by innovative architecture firm The Living and successfully implemented in 2014 in the spacious courtyard of the prestigious MoMA PS1 in New York. This impressive 12 meter structure, pushing the boundaries of sustainable architecture, was meticulously constructed using 10,000 biological bricks made from mycelium (mushroom roots) and corn stalks. The project, realized as part of MoMA's Young Architects Program that provides opportunities for promising young architects, impressively demonstrated the immense potential of sustainable building materials in contemporary architecture. Hy-Fi's innovative bricks were developed through a special process in close collaboration with biotechnology pioneer Ecovative, created from an optimized combination of natural corn stalks and mycelium. These unique organic bricks were grown in specially designed molds over just a five day period, transforming them into lightweight and highly durable building elements that serve as an alternative to traditional construction materials. For the structure's striking upper section, molds coated with high-performance reflective film specially developed by industrial innovation giant 3M were used to optimally reflect natural light into the interior space, skillfully achieving an impressive visual effect of the structure elegantly dissolving into the sky (Living, 2014).

Şekil 4. Hy-Fi (Living, 2014).

Growing Pavilion

The Growing Pavilion is an iconic structure that was presented to visitors during the prestigious 2019 Dutch Design Week in Eindhoven, Netherlands, reflecting sustainable architectural understanding and constructed entirely from bio based materials. Its innovative design was created by experienced architect Pascal Leboucq and brought to life in collaboration with Krown.bio, a company specialized in biotechnology. This project was supported by Company New Heroes and Dutch Design Foundation, pioneering organizations in the field of sustainable design. The pavilion's exterior is covered with mycelium panels (mushroom root system), one of nature's building blocks. These innovative panels were grown using Reishi mushroom mycelium over a two week process in specially designed molds and were designed to have an organic texture. In the interior, the sustainability approach continues with the use of environmentally friendly bio-based materials such as wood, hemp, cotton, and bulrush. The Growing Pavilion not only demonstrates construction with sustainable materials but also showcases the aesthetic potential of bio-based materials. The natural texture and soft tones of the mycelium panels, which are the characteristic feature of the structure, have given the building an appearance that integrates with modern architecture (Leboucq, 2019).

Şekil 5. Growing Pavilion (Leboucq, 2019).

Research and field applications have revealed that these composites offer multifaceted potential benefits in terms of economic, technical, environmental, and sustainability criteria. These characteristics make them a highly attractive option for modern building and construction projects. However, there are some technical challenges currently being encountered. Particularly, low mechanical strength values, high water absorption capacity, and the lack of fully developed standard production methods at industrial scale limit the use of these materials to some extent in semi structural and non structural applications (such as decorative panels, interior furniture, flooring) (Johnston, vd., 2020).

Low mechanical strength: Due to the material's low structural strength, its direct use in load bearing areas is quite limited. This characteristic stems from the material's low resistance to compression, tension, and bending forces, and therefore it may need to be used in conjunction with structural support elements (Hernandez, vd., 2019).

High water absorption capacity: The material's inherently high water absorption property can affect its structural integrity when exposed to moisture for extended periods and can cause deformation in its original shape. This loss of form can negatively impact the material's lifespan and performance (Hernandez, vd., 2019).

Lack of standardization: The development process varies due to the unique growth conditions of different fungal species and the diversity of substrates used. These variations make it difficult to achieve consistent and predictable results in the production process, thus making production stability a significant challenge (Zhang, vd., 2020).

THE ROLE OF MYCELIUM IN PRESERVING HISTORICAL HERITAGE

Traditional restoration techniques have been used as indispensable and reliable fundamental methods in preserving historical structures for many years. These techniques have played a crucial role in maintaining the original character of structures and transferring cultural heritage to future generations. However, modern needs such as environmental sustainability, energy efficiency, material optimization, and economic feasibility are encouraging the research and development of innovative solutions in the field of restoration. In this context, biotechnological materials, particularly mycelium based composites, are emerging as promising alternatives in the restoration of historical structures. These materials stand out with their natural structure and environmentally friendly properties while exhibiting similar physical and mechanical properties to traditional building materials (Müller, vd., 2021).

While mycelium based biomaterials offer an innovative preservation method for historical structures, more comprehensive research and field applications are needed to make them fully compatible with traditional materials, evaluate their long term performance, and address durability issues in particular. Nevertheless, as a cost effective, sustainable, and environmentally friendly solution, these materials are expected to find increased use in future restoration work. Their ability to be produced from local resources, low carbon footprint, and recyclable properties make these materials an attractive alternative in restoration projects.

Deteriorated Stone or Brick Infill: Mycelium based composites can be applied as filling material to damaged stone or brick areas. This application helps restore the structural integrity of damaged areas while adapting to the original texture of the structure (Kara, vd., 2021).

Insulation Layers: Can be used for insulation purposes in the interior walls of historical buildings. Mycelium based composites allow the structure to breathe while performing important functions such as thermal insulation and moisture control. This supports the long-term preservation of the structure (Almpani-Lekka, 2021).

Temporary Protective Coatings: Can be used as temporary coating material to protect building surfaces during restoration. These coatings protect the structure from external factors during restoration work and can be easily removed after the procedures are completed (Hernández, vd., 2020).

CONCLUSION

The increasing demands for green products and technologies in the built environment, along with the pursuit of sustainability, have led to the emergence of a new generation of environmentally friendly and innovative materials. Within this evolving family of materials, mycelium based composites stand out as one of the promising options.

Mycelium based composites are innovative biocomposites obtained through controlled growth of fungal filaments on an organic substrate and processed under special conditions. Due to their low carbon footprint, minimal energy consumption and processing costs, complete biodegradability, and remarkable material characteristics, these composites are gaining increasing attention as an alternative material in the construction sector. Research and field applications have demonstrated that these composites offer versatile potential benefits in terms of economic, technical, environmental, and sustainability criteria. These properties make them a highly attractive option for modern construction projects. However, there are some technical challenges currently being faced. In particular, low mechanical strength values, high water absorption capacity, and the lack of fully developed standard production methods at industrial scale somewhat limit their use in semi structural and non-structural applications (such as decorative panels, interior furniture, flooring).

Through its porous structure, mycelium creates a building material that can breathe while maintaining moisture balance, and through this characteristic, it can make significant contributions to the restoration of historical buildings without damaging their original texture. Additionally, with its porous structure providing natural ventilation, this material can allow historical buildings to breathe while potentially maintaining optimal moisture balance. With these properties, it can be considered that some technical limitations such as increasing mechanical strength and water resistance while preserving the building's original character during restoration can be improved with appropriate production techniques and additives. This development process can be achieved through laboratory tests and field applications, with studies aimed at optimizing the material's performance. There are currently no documented examples of mycelium-based composites being directly used in the restoration of historical buildings. However, various research and projects are being conducted on mycelium's potential as a building material.

With comprehensive research and development work to be conducted in the future, increasing the structural durability of mycelium based composites, improving their mechanical properties, and bringing them in line with technical requirements specified in standard construction regulations will further strengthen the position of these innovative materials in the restoration and construction sector. In this process, detailed tests to be carried out in laboratory environments and data to be obtained from field applications will contribute to optimizing the material's performance (Almpani-Lekka, vd., 2021). While improving the properties of building materials, materials are characterized by analytical techniques considering application areas and requirements, examining microstructure, morphology, chemical composition, and energy distributions (Sahin, vd., 2023). Composite materials offer advantages such as energy savings and long term use while minimizing environmental impacts (Şahin, vd., 2022). In this context, biotechnological approaches not only enhance the physical integrity and durability of structures but also help us leave a more livable world for future generations by supporting the preservation of cultural heritage and ensuring environmental sustainability (Arcega, 2023).

This study demonstrates that mycelium based biotechnological materials can be considered as a sustainable alternative in the preservation and restoration of historical buildings. These fungal-based materials offer a strong alternative to both modern and traditional building materials thanks to their environmentally friendly production processes, biodegradability, low carbon footprint, and flexible design possibilities. Sustainable results are expected to be achieved in complex restoration activities such as repairing wall cracks, reinforcing damaged brick or stone surfaces with modern techniques, and designing and creating temporary or permanent protective panels to preserve the building's integrity. These applications have been carried out as a result of efforts to increase durability and safety while preserving the building's original character. Mycelium based composites can make significant contributions to the preservation of historical buildings through their properties. While their lightness puts minimal load on the structure, their biodegradability can support environmental sustainability. Additionally, thanks to their natural and environmentally friendly structure, they can help transfer historical buildings to future generations while preserving their original character.

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