Mold Growth and Indoor Air Quality: A Survey

Abstract

This survey paper presents a comprehensive examination of mold growth within indoor environments, emphasizing its multifaceted challenges and the necessity for effective management strategies. Mold proliferation significantly impacts human health and building integrity, driven by factors such as humidity, temperature, and material properties. The study highlights the critical role of advanced methodologies, including DNA sequencing and machine learning, in enhancing mold detection and classification accuracy. Furthermore, it explores the complex interactions within the building microbiome, which influence mold dynamics and health implications, advocating for a holistic approach to mold management that enhances microbial diversity and stability. Key findings suggest the need for standardized methodologies to assess mold and chlorophenol exposure, refine predictive models like the Improved Mold Growth Model (IMGM), and optimize insulation materials for moisture management. The survey concludes that integrating diverse research areas is essential for developing strategies that effectively address mold-related environmental, health, and structural challenges.

1 Introduction

1.1 Significance of Mold Growth in Indoor Environments

Mold growth in indoor environments poses significant challenges to human health and building integrity. Health risks associated with mold include respiratory issues, allergic reactions, and exacerbation of asthma symptoms, primarily due to the release of spores and mycotoxins that compromise indoor air quality [1]. Misunderstandings regarding mold odor further complicate risk assessment, as it may lead to both underestimation and overestimation of health threats [1].

In addition to health concerns, mold threatens the structural integrity of buildings. Moisture intrusion, often worsened by inadequate insulation, fosters mold proliferation, particularly in regions with high energy demands for heating and cooling, such as Turkey. Here, effective insulation is vital not only for energy efficiency but also for preventing moisture accumulation and mold damage [2]. Mold-induced deterioration of building materials results in costly repairs and shortened lifespan of structures, underscoring the necessity for proactive mold management strategies.

Addressing the complexities of mold growth requires a comprehensive approach that considers both health and structural factors. Effective prevention and remediation must account for the interactions among environmental variables, architectural designs, and occupant health. Studies reveal that homes with mold exhibit distinct airborne fungal ecologies compared to those without, emphasizing the need to understand these ecological differences in mold management. Factors such as insulation materials and moisture levels significantly influence mold growth, indicating that tailored building designs and materials can enhance indoor air quality and occupant health. Thus, an integrated approach is crucial for developing safe and sustainable indoor environments [3, 2, 1, 4, 5].
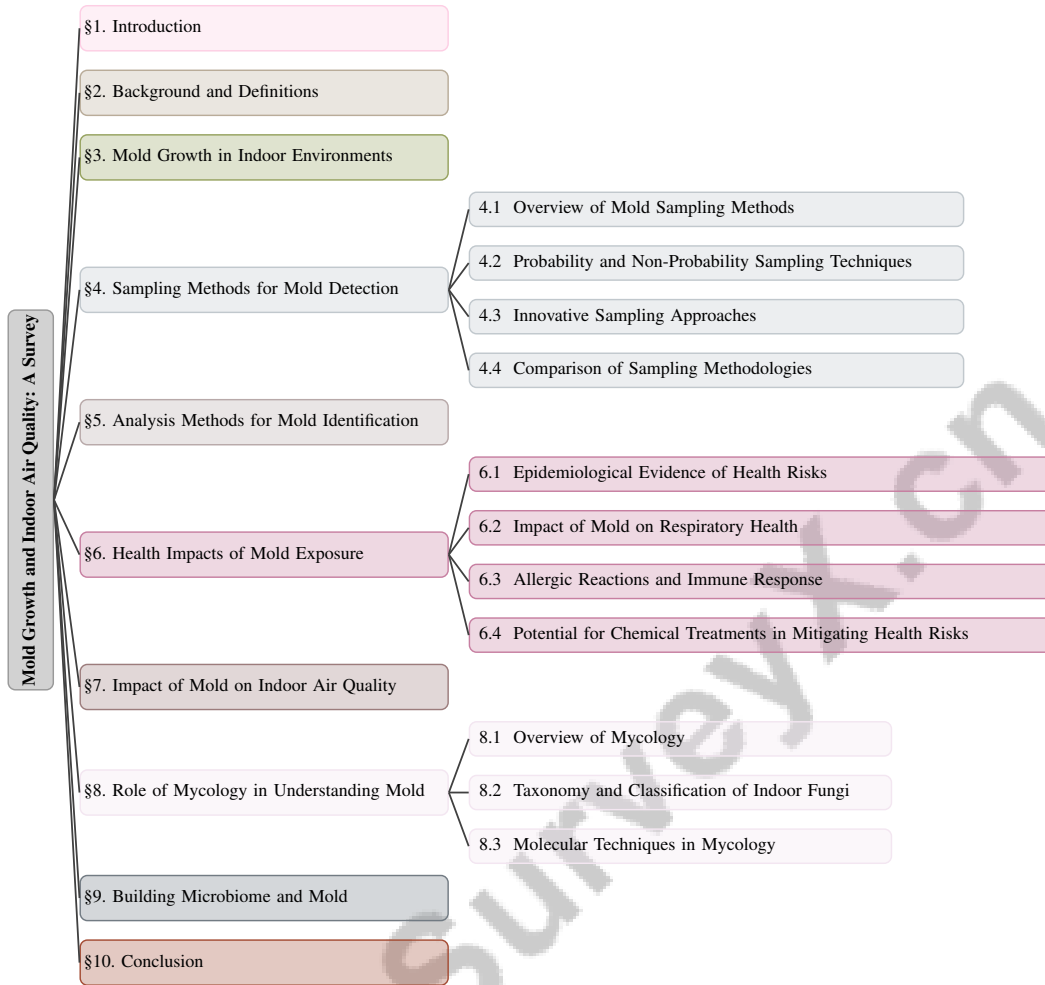
Figure 1: chapter structure

1.2 Scope of the Paper

This survey provides an in-depth exploration of mold growth in indoor environments, focusing on detection methodologies, health impacts, and interactions within the building microbiome. The methodologies section covers various sampling and analysis techniques, including advanced machine learning models that enhance the accuracy of mold inspections and mitigate health risks associated with exposure [5]. Additionally, the survey evaluates mold and moisture risk in building structures by examining the effects of different insulation materials and wall types across diverse climate zones, particularly in Turkey [2].

Regarding health impacts, the survey addresses the adverse effects of mold exposure, such as respiratory issues and allergic reactions linked to spores and mycotoxins [1]. It also analyzes snowball sampling techniques, discussing their characteristics, advantages, criticisms, and practical applications in mold research [6].

The relationship between mold and the building microbiome is examined, highlighting ecological interactions within indoor ecosystems and their implications for air quality and occupant health. This multifaceted approach stresses the importance of integrating various research disciplines, including microbial ecology and computational modeling, to formulate effective mold management strategies. Understanding the distinct airborne fungal ecologies in moldy versus non-moldy homes and the potential health implications of mold-related odors can significantly improve indoor environmental health and reduce public health risks associated with mold exposure [1, 5].

1.3 Structure of the Survey

The survey is organized to systematically examine mold growth in indoor environments, addressing key areas of interest. It begins with an introduction that outlines the significance and scope of the research, followed by a background section defining essential terms and concepts related to mold and indoor air quality. The paper then explores environmental conditions conducive to mold growth, focusing on factors such as humidity and material properties.

Subsequent sections review sampling and analysis methods for mold detection and identification, including innovative approaches that integrate DNA sequencing and machine learning. Health impacts of mold exposure are analyzed through epidemiological evidence, respiratory health issues, and allergic reactions, while potential chemical treatments to mitigate health risks are also considered.

The survey further investigates the impact of mold on indoor air quality, particularly the release of spores and mycotoxins and their implications for occupant health. The role of mycology in understanding mold diversity and taxonomy is discussed, alongside the concept of the building microbiome and its interactions with mold. The survey concludes by summarizing findings and suggesting future research directions, while also organizing current methods into stages of recruitment, challenges faced, and adaptations made when snowball sampling fails [6].The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Key Definitions and Concepts

A thorough comprehension of mold and indoor air quality (IAQ) terminology is essential to tackle the challenges of mold proliferation in indoor spaces. Microscopic mold can significantly affect health and contribute to malodors, with distinct differences in airborne fungal ecology observed between moldy and non-moldy homes [1, 4, 2, 5]. Mycology, which involves identifying and classifying indoor mold species, plays a crucial role in understanding IAQ and its implications for occupant health.

IAQ pertains to the quality of air within and around buildings, with a direct impact on occupant health and comfort. Mold growth is a critical factor influencing IAQ, as it releases spores and mycotoxins linked to respiratory issues and allergic reactions [1]. Mold also produces malodors, often associated with chlorophenol (CP)-treated wood, raising questions about the necessity of visible mold for odor production [1].

The building microbiome encompasses a diverse array of microorganisms, including bacteria, fungi, and viruses, which shape the ecological balance within indoor environments. Homes with visible mold exhibit a less diverse fungal ecology compared to those without moisture problems, underscoring microbial interactions' role in mold growth and health risks [1, 5]. These interactions deeply influence mold dynamics and IAQ.

Moisture management is crucial as excess moisture fuels mold growth. Effective insulation is essential to prevent moisture accumulation, particularly in regions with high energy demands for heating and cooling. Determining optimal insulation thickness for various wall types and materials is vital to minimize moisture and mold formation, thus safeguarding building integrity and promoting healthy indoor environments [2].

2.2 Ecological Role of Fungi in Indoor Environments

Fungi, including molds, are pivotal in indoor environments for organic material degradation and maintaining ecological balance. They facilitate decomposition by breaking down complex organic compounds and recycling nutrients within building ecosystems. While this process is essential for organic matter turnover, inadequate moisture management can lead to building material deterioration [2].

Fungal presence indoors is shaped by moisture, temperature, and substrate availability. Poor insulation and moisture control create conditions conducive to fungal growth, as evidenced by studies on various wall materials and insulation types across climate zones [2]. These conditions not only foster mold

proliferation but also impact the broader microbial community, altering the building microbiome's composition and dynamics.

Fungi influence IAQ by releasing spores and volatile organic compounds (VOCs), including malodorous substances. Historical confusion regarding mold odors and health complaints underscores the complexity of these interactions; chlorophenols (CPs), rather than mold itself, may be key odor sources [1]. Understanding fungi's ecological functions indoors is crucial for developing effective mold management strategies and enhancing IAQ. Recognizing fungi's ecological contributions allows researchers and practitioners to better address mold growth challenges and their implications for human health and building integrity.

In examining the factors that contribute to mold growth in indoor environments, it is essential to consider a comprehensive framework that encompasses various influences. Figure **??** illustrates the key factors influencing mold growth, categorizing them into three primary domains: environmental conditions, material properties, and sensory indicators. This figure highlights the critical roles of humidity, temperature, and ventilation as environmental conditions that create conducive settings for mold proliferation. Furthermore, it emphasizes the significance of material characteristics and sensory cues, such as odor and visibility, in both the detection and understanding of mold presence. By integrating these elements, we can better appreciate the complexity of mold dynamics in indoor spaces and the necessity for targeted interventions.

Figure 2: This figure illustrates the key factors influencing mold growth in indoor environments, categorizing them into environmental conditions, material properties, and sensory indicators. It highlights the role of humidity, temperature, ventilation, material characteristics, and sensory cues like odor and visibility in mold proliferation and detection.

3 Mold Growth in Indoor Environments

3.1 Environmental Conditions Promoting Mold Growth

Mold proliferation indoors is primarily governed by humidity, temperature, and ventilation. Humidity levels exceeding 60% are particularly conducive to mold spore germination and growth across various surfaces [2]. Mold species typically flourish within the 20°C to 30°C temperature range, common in indoor settings, facilitating metabolic processes essential for rapid colonization, provided there is adequate moisture [1].

Ventilation plays a crucial role in mold prevention by facilitating air exchange, reducing humidity, and mitigating mold risks, especially in moisture-prone areas like bathrooms and kitchens [1]. Poor ventilation can trap moisture and create stagnant air pockets, raising humidity levels favorable to mold growth.

The interplay of these factors underscores the importance of comprehensive moisture management strategies. Proper insulation is critical to preventing condensation and moisture accumulation, particularly in regions with significant temperature fluctuations. Research highlights that the choice and thickness of insulation can significantly influence indoor humidity, critical for mold control. Optimal insulation thickness—0.118 m in warmer climates like Izmir and 0.202 m in colder regions like Erzurum—can reduce indoor humidity below mold growth thresholds (78% in Izmir and 69% in Erzurum) [4, 3, 2, 5]. Addressing these environmental factors helps reduce mold risks and their associated health and structural impacts.

3.2 Impact of Material Properties on Mold Susceptibility

Building materials' susceptibility to mold growth is crucial in assessing mold proliferation risks. Properties such as porosity, moisture retention, and chemical composition significantly influence mold growth potential. Wood, due to its organic composition and moisture retention capabilities, is notably vulnerable. Conventional wood treatments often inadequately protect against mold, and thermal modification may increase susceptibility [3].

Current predictive models, like the VTT model, face limitations in accurately estimating mold growth across varying conditions, necessitating enhanced models for reliable predictions [4]. Other

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materials, including drywall, insulation, and carpeting, exhibit varying mold susceptibility based on their properties. Porous materials that readily absorb moisture are particularly at risk. The choice of building materials is crucial for mold prevention, as studies show that different wall types and insulation materials significantly impact moisture levels and mold risk. Specific insulation materials, such as hemp wool or aerogel blankets, can optimize humidity, reducing mold formation likelihood across climates [2, 5]. Selecting materials with low porosity and effective moisture resistance is essential for minimizing mold proliferation risks.

Understanding material properties' impact on mold susceptibility is vital for effective mold management strategies. By employing advanced predictive models to analyze airborne fungal ecology and integrating findings on material vulnerabilities, stakeholders can significantly mitigate mold proliferation risks, reducing health effects and structural damage associated with dampness and water damage [1, 4, 5].

3.3 Mold Odor and Visibility

Mold presence indoors is often detected through sensory indicators like odor and visible growth. Mold odor, typically musty or earthy, results from microbial volatile organic compounds (MVOCs) produced during mold metabolism, serving as early indicators of mold growth, often preceding visible colonization. However, odor perception is subjective, complicating its reliability as a mold presence indicator [1].

Visible mold, marked by discoloration or growth on surfaces, indicates advanced growth stages where spores have extensively colonized surfaces, signaling moisture issues and inadequate ventilation [1]. Relying solely on visibility for detection can be misleading, as mold can grow in hidden areas, remaining undetected until significant structural damage or health complaints arise.

The implications of mold odor and visibility extend to perceptions of indoor air quality and occupant health. Odors can lead to complaints about air quality even without visible mold, underscoring the need for comprehensive mold assessment strategies. Integrating sensory indicators like odor detection with advanced scientific methods, such as DNA sequencing and machine learning algorithms, enhances mold detection accuracy and evaluation in buildings. This integrated approach improves mold classification and informs effective inspection and remediation, ultimately reducing health risks associated with mold exposure [1, 4, 5]. Addressing both odor and visibility enables better management of mold-related issues, contributing to healthier indoor environments.

4 Sampling Methods for Mold Detection

Category	Feature	Method
Comparison of Sampling Methodologies	Stratified Sampling Techniques	SRSQ[7]

Table 1: This table presents a concise summary of the methods used in the comparison of sampling methodologies for mold detection. It highlights the application of stratified sampling techniques, specifically the SRSQ method, as referenced in the study by Olsen (2023). The table serves as a reference point for understanding the methodological approaches employed in this research domain.

In the realm of mold detection, a thorough understanding of the various sampling methods is essential for obtaining reliable and valid results. This section aims to explore the different approaches employed in mold sampling, highlighting their respective advantages and limitations. By categorizing these methods into probability and non-probability sampling techniques, we can better appreciate their applications and implications in research. Table 3 provides a detailed overview of the methods employed in the comparison of sampling methodologies for mold detection, emphasizing the use of stratified sampling techniques. The subsequent subsection will provide an overview of these mold sampling methods, setting the stage for a deeper examination of their characteristics and effectiveness in addressing the complexities of mold detection in indoor environments.

4.1 Overview of Mold Sampling Methods

Mold detection in indoor environments employs a variety of sampling methods, each with distinct advantages and limitations tailored to specific research needs. These methods can be broadly

categorized into probability and non-probability sampling techniques. Probability sampling methods, such as simple random sampling, stratified random sampling, systematic random sampling, and cluster sampling, are designed to ensure that each member of the population has a known chance of being selected, thereby enhancing the representativeness and generalizability of the findings [8]. These methods are particularly useful in large-scale studies where statistical rigor is paramount.

Non-probability sampling methods, on the other hand, are often employed in exploratory research where the focus is on understanding complex phenomena or accessing hard-to-reach populations. Snowball sampling is a notable non-probability technique that leverages social networks to identify and recruit participants, making it particularly effective for studies involving marginalized or hard-to-reach populations [6]. This method is instrumental in mold research, where traditional sampling frames may not adequately capture the diversity of indoor environments and occupant experiences.

In addition to these traditional methods, innovative approaches such as the use of settled dust samples have emerged as valuable tools for mold detection. For instance, a dataset was created from settled dust samples collected from homes across 11 cities in the U.S., encompassing both moldy and no mold homes, to enhance the understanding of mold presence and its implications for indoor air quality [5]. This approach allows for the collection of representative samples from a wide range of environments, facilitating a more comprehensive assessment of mold distribution and its potential health impacts.

The integration of these diverse sampling methods underscores the complexity of mold detection and the need for tailored approaches that address specific research questions and environmental contexts. By employing a combination of probability and non-probability techniques, researchers can achieve a more nuanced understanding of mold dynamics and their relationship to indoor air quality and occupant health [1].
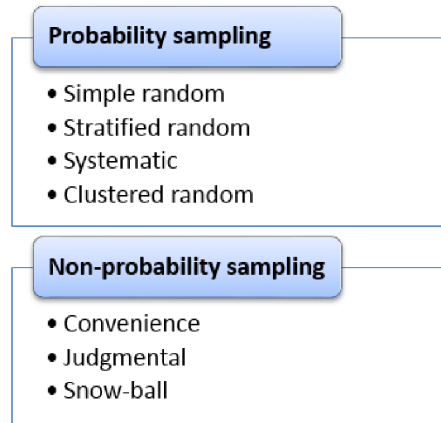
4.2 Probability and Non-Probability Sampling Techniques

The selection of appropriate sampling techniques is crucial in mold detection research, as it determines the reliability and validity of the findings. Probability sampling methods, such as simple random sampling (SRS) and stratified random sampling, are often preferred for their ability to provide representative samples that accurately reflect the population. These methods reduce selection bias and enhance the generalizability of results by ensuring that each member of the population has a known and equal chance of being selected [8]. The use of auxiliary data in SRS can further reduce external validity bias, ensuring the sample mirrors the population distribution of key characteristics, even when these characteristics are not directly observable [7].

In contrast, non-probability sampling methods, including convenience sampling, judgmental sampling, and snowball sampling, are often utilized in exploratory studies where the goal is to gain insights into specific phenomena or populations. These methods are particularly useful in situations where probability sampling is impractical due to logistical constraints or when the target population is hard to reach [8]. Snowball sampling, for example, is effective in accessing populations that are difficult to reach due to stigma or tight-knit community structures, although it is subject to challenges such as selection bias and lack of representativeness [6].

The choice between probability and non-probability sampling methods depends on the research objectives and the nature of the population being studied. While probability sampling offers the advantage of statistical rigor and generalizability, non-probability methods provide flexibility and depth in understanding complex social dynamics. For high-dimensional integration tasks, Quasi Monte Carlo methods, particularly those using Sobol' sequences, have demonstrated superior efficiency compared to traditional Monte Carlo and Latin Hypercube Sampling methods, highlighting the potential for innovative approaches in mold detection research [9]. By carefully selecting and combining these methods, researchers can effectively address the diverse challenges associated with mold detection in indoor environments.

As shown in Figure 3, In the exploration of sampling methods for mold detection, understanding the distinction between probability and non-probability sampling techniques is crucial. Probability sampling methods, as illustrated in the accompanying diagram, include techniques such as Simple Random, Stratified Random, Systematic, and Clustered Random sampling. These methods ensure that every member of a population has a known, non-zero chance of being selected, thereby enhancing the reliability and generalizability of the results. In contrast, non-probability sampling methods do

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(a) Probability and Non-probability Sampling Methods[8]
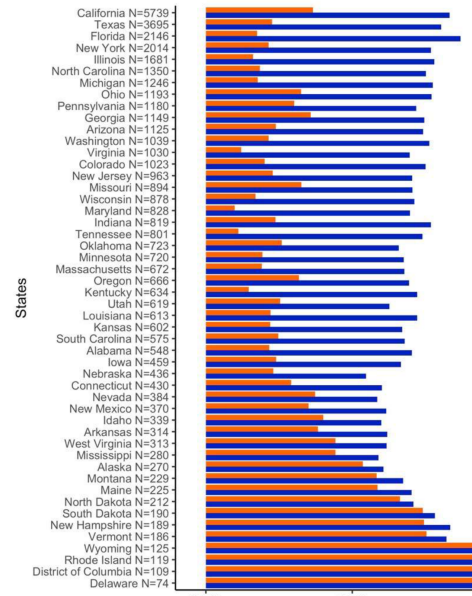
(b) States with the highest and lowest number of COVID-19 cases in the United States as of 2021[7]

Figure 3: Examples of Probability and Non-Probability Sampling Techniques

not offer this same level of randomness and include techniques where the probability of selection is unknown. The relevance of these sampling methods extends beyond theoretical application and is vividly demonstrated in practical scenarios, such as analyzing COVID-19 case distributions across different states in the United States. By employing these sampling techniques, researchers can effectively gather data that reflects the true prevalence and distribution of mold, much like how data was gathered to assess the spread of COVID-19, thereby enabling informed decision-making and targeted interventions. [**?**]elfil2017sampling,olsen2023usingauxiliarydataguide)

4.3 Innovative Sampling Approaches

Recent advancements in mold detection have led to the development of innovative sampling techniques that enhance the accuracy and efficiency of mold assessment in indoor environments. One such approach involves the use of settled dust samples, which serve as a comprehensive medium for detecting mold presence over time. This method allows for the collection of representative samples from a wide range of environments, facilitating a more thorough understanding of mold distribution and its implications for indoor air quality [5]. By analyzing settled dust, researchers can identify specific mold species and assess their concentration levels, providing valuable insights into the indoor microbial ecosystem.

Another emerging technique is the integration of DNA sequencing technologies with traditional sampling methods. This approach enables the precise identification of mold species at the genetic level, offering a detailed understanding of the fungal community present in indoor environments. The use of advanced machine learning algorithms in conjunction with DNA sequencing data further enhances the accuracy of mold detection, allowing for the classification of mold status in homes with greater precision [5]. This combination of genetic analysis and computational modeling represents a significant leap forward in mold detection capabilities, providing a robust framework for assessing mold-related health risks.

Innovative sampling methods also include the application of real-time monitoring technologies, such as electronic sensors, which can continuously track environmental parameters like humidity and temperature that influence mold growth. The sensors deliver real-time monitoring of indoor environmental conditions, facilitating the prompt identification of factors that promote mold growth, which is crucial for public health, as airborne fungal ecology in damp environments significantly

differs from that in dry, mold-free settings. This early detection can aid in timely remediation efforts, thereby reducing exposure to harmful mold and associated health risks. [1, 4, 2, 5]. By integrating sensor data with traditional sampling techniques, researchers can develop predictive models that anticipate mold growth patterns and inform proactive remediation strategies.

The adoption of these innovative sampling approaches underscores the importance of leveraging technological advancements to improve mold detection and management. By integrating traditional methodologies with advanced DNA sequencing and machine learning techniques, researchers are able to gain a deeper and more nuanced understanding of mold dynamics in indoor environments. This comprehensive approach not only elucidates the distinct airborne fungal ecologies associated with moldy versus non-moldy homes, but also aids in the accurate classification of mold presence. Consequently, these findings can inform effective inspection and remediation strategies, ultimately leading to healthier indoor environments and improved well-being for occupants by reducing exposure to hazardous mold-related health risks. [3, 2, 1, 4, 5]

4.4 Comparison of Sampling Methodologies

Benchmark	Size	Domain	Task Format	Metric	
MOLD-BENCH[2]	1,000	Building Energy Efficiency	Moisture Risk Assessment	Optimum Insulation Thickness, Moisture Content	
DNA-Mold[5]	288	Indoor Air Quality	Classification	Accuracy, F1-score	

Table 2: The table presents a comparative overview of two benchmarks utilized in mold detection research, detailing their respective sizes, domains, task formats, and evaluation metrics. MOLD-BENCH focuses on building energy efficiency with tasks related to moisture risk assessment, while DNA-Mold addresses indoor air quality through classification tasks. The metrics employed for evaluation include optimum insulation thickness, moisture content, accuracy, and F1-score, providing a comprehensive framework for assessing sampling methodologies in this field.

The evaluation of sampling methodologies in mold detection involves a critical comparison of probability and non-probability sampling techniques, each offering distinct advantages and limitations. Probability sampling methods, such as simple random sampling (SRS), are renowned for their ability to produce representative samples that accurately reflect the population. These methods minimize selection bias and enhance the generalizability of findings, making them particularly suitable for large-scale studies where statistical accuracy is paramount [8]. Simulations comparing SRS with SRSQ, a variant incorporating auxiliary data, demonstrated the latter's superior performance in reducing external validity bias, variance, and mean squared error (MSE) across various scenarios [7]. Table 2 provides a detailed comparison of representative benchmarks used in mold detection studies, highlighting their key characteristics and evaluation metrics relevant to the discussion of sampling methodologies.

In contrast, non-probability sampling methods, including techniques like snowball sampling, offer flexibility and depth in exploring complex phenomena or hard-to-reach populations. These methods are advantageous in exploratory research where traditional sampling frames may not be feasible. However, they are prone to biases that can affect the representativeness of the results, limiting the ability to generalize findings to the broader population [8].

Innovative approaches, such as the integration of Quasi Monte Carlo (QMC) methods using Sobol' sequences, have shown promise in enhancing sampling efficiency and accuracy. These methods consistently outperform traditional Monte Carlo (MC) and Latin Hypercube Sampling (LHS) methods in terms of convergence rates and accuracy, offering a robust alternative for high-dimensional integration tasks in mold detection research [9].

The selection of an appropriate sampling methodology for mold detection should be informed by the specific research objectives, the characteristics of the target population, and the unique environmental conditions present, as these factors significantly influence the validity and generalizability of the study findings. [1, 8, 5]. By carefully selecting and potentially combining different sampling techniques, researchers can effectively address the diverse challenges associated with mold detection, ultimately contributing to more reliable and comprehensive assessments of indoor air quality and mold-related health risks.

Feature	Simple Random Sampling	Stratified Random Sampling	Systematic Random Sampling
Sampling Type	Probability	Probability	Probability
Purpose	Representative Sampling	Population Stratification	Regular Interval Selection
Strengths	Reduces Selection Bias	Enhances Generalizability	Ease OF Implementation

Table 3: This table provides a comparative analysis of three probability sampling methods: Simple Random Sampling, Stratified Random Sampling, and Systematic Random Sampling. It highlights key features such as sampling type, purpose, and strengths, offering insights into the unique advantages each method brings to mold detection research. The comparison underscores the importance of selecting the appropriate sampling approach to enhance the reliability and validity of research findings.

5 Analysis Methods for Mold Identification

5.1 Integration of DNA Sequencing and Machine Learning

Integrating DNA sequencing with machine learning marks a significant advancement in mold analysis, offering a sophisticated alternative to traditional methods. DNA sequencing provides precise species identification at the genetic level, facilitating a comprehensive understanding of indoor fungal communities. When combined with machine learning algorithms, this approach enhances mold classification accuracy and efficiency, addressing the limitations of conventional methodologies [5]. Machine learning models trained on DNA data can discern complex patterns within microbial ecosystems, leading to reliable predictions of mold presence and growth dynamics, surpassing traditional predictive frameworks in parameter estimation accuracy [4]. This synergy not only refines mold status classification but also aids in identifying environmental factors that influence mold proliferation. These advanced techniques underscore the potential for leveraging cutting-edge technologies to improve mold detection and management, enhancing the accuracy of identifying and predicting mold presence in buildings. By exploiting quantitative differences in airborne fungal ecology between moldy and non-moldy environments, studies have achieved high accuracy in classifying homes based on mold status, ultimately improving indoor air quality and addressing public health concerns related to mold exposure [1, 4, 5].

5.2 Improved Mold Growth Model (IMGM)

The Improved Mold Growth Model (IMGM) represents a significant advancement in predicting mold proliferation under varying environmental conditions. Utilizing a logistic growth equation, the IMGM accurately describes mold growth dynamics by incorporating critical factors such as temperature and humidity [4]. This model addresses previous limitations by capturing the complexity of mold behavior across diverse scenarios. Empirical evaluations, including water uptake assessments, dimensional stability measurements, and accelerated mold growth experiments under controlled conditions, have validated the model's predictive capabilities, demonstrating its effectiveness in simulating mold growth patterns [3]. The IMGM provides practical tools for building managers and researchers, extending beyond theoretical predictions to enable accurate mold identification through advanced DNA sequencing and machine learning techniques. This proactive approach anticipates health risks associated with mold exposure, facilitating informed inspection and remediation strategies that can significantly reduce hazardous mold exposure in various environments [1, 4, 2, 5]. Leveraging the model's predictive power allows stakeholders to optimize building design and maintenance strategies, ultimately enhancing indoor air quality and occupant health. The IMGM's integration into mold management practices marks a critical step forward in addressing the challenges posed by mold growth in indoor environments.

6 Health Impacts of Mold Exposure

Mold exposure in indoor environments presents complex health challenges, necessitating a thorough understanding of its epidemiological impact. The prevalence of mold-related health issues underscores the urgency of addressing mold exposure as a public health priority. The following subsections delve into the epidemiological evidence of health risks associated with mold exposure, highlighting documented adverse health outcomes.

6.1 Epidemiological Evidence of Health Risks

Epidemiological studies consistently reveal a strong link between mold exposure and adverse health outcomes, particularly respiratory ailments such as asthma, allergic rhinitis, and respiratory infections. These conditions often stem from inhaling mold spores and mycotoxins, which trigger inflammatory and allergic responses, especially in vulnerable populations like children and those with pre-existing respiratory conditions [1]. Beyond respiratory effects, mold exposure is associated with skin irritations, eye discomfort, and immune suppression. The severity of these health impacts depends on mold type, concentration, and exposure duration, with prolonged exposure leading to chronic health issues [1].

Research highlights environmental factors like inadequate ventilation and high humidity as key contributors to mold growth and related health risks. Effective environmental assessments and interventions are crucial for reducing mold exposure and its health impacts, such as respiratory issues and allergies. Studies show that even microscopic mold on treated wood can emit hazardous odors, emphasizing the need for comprehensive strategies addressing mold presence and environmental factors affecting indoor air quality [1, 2, 5]. Effective mold management is essential, particularly in environments with historical water damage, to prevent conditions like asthma, allergies, and sick building syndrome [1, 4, 8, 5].

6.2 Impact of Mold on Respiratory Health

Mold exposure significantly affects respiratory health, necessitating effective management strategies. Inhalation of mold spores and mycotoxins primarily causes respiratory issues, including asthma exacerbations and allergic rhinitis, particularly in individuals with pre-existing conditions [1]. These respiratory problems result from inflammatory and allergic responses, leading to symptoms like coughing and wheezing. Chronic exposure can exacerbate these conditions, especially in environments with extensive mold growth and inadequate remediation [1].

The impact on respiratory health is influenced by environmental factors such as humidity and ventilation, which foster mold growth and increase health risks [3, 2, 1, 4, 5]. Effective moisture management and ventilation are critical to reducing mold exposure and safeguarding respiratory health.

6.3 Allergic Reactions and Immune Response

Mold exposure can trigger allergic reactions and immune responses, primarily through inhalation of spores and mycotoxins, leading to IgE-mediated reactions such as sneezing and skin rashes [1]. The immune response varies, with some individuals experiencing severe reactions due to genetic predispositions or pre-existing conditions. Chronic inflammation from mold exposure can lead to long-term health issues if not adequately addressed [1].

Environmental factors like mold spore concentration and indoor allergens influence allergic reaction severity. High humidity and poor ventilation exacerbate mold growth, increasing exposure and allergic reactions. Comprehensive environmental controls, such as moisture management and air filtration, are crucial to minimize exposure [1, 5]. Understanding mold-induced allergic mechanisms is vital for developing targeted interventions and improving indoor air quality [1, 4, 5].

6.4 Potential for Chemical Treatments in Mitigating Health Risks

Chemical treatments play a vital role in mitigating mold-related health risks by addressing mold proliferation factors. Chlorophenol-treated wood, despite lacking visible mold, can harbor microscopic mold linked to odor production, indicating potential health implications [1]. Research into alternative natural oils and formulations highlights effective mold resistance while maintaining material properties [3].

Advanced technologies like DNA sequencing and machine learning offer reliable methods for classifying moldy environments, enhancing health risk assessments and informing remediation strategies [5]. Improved mold growth models inform health risk assessments and suggest vulnerability classifications for materials, guiding chemical treatment selection [4]. Integrating these insights into

mold management enhances building energy efficiency and health standards, reducing mold risks and improving indoor environmental quality [2].

7 Impact of Mold on Indoor Air Quality

7.1 Spores and Mycotoxins Release

Indoor mold growth significantly affects air quality through the release of spores and mycotoxins, which pose health risks to occupants. Mold spores, as microscopic reproductive units, become airborne, especially during cleaning or renovation, leading to inhalation by occupants. Environmental factors such as humidity, temperature, and airflow are crucial in their dispersal, with high humidity and poor ventilation exacerbating the issue [1].

Mycotoxins, toxic secondary metabolites produced by molds, adhere to spores or mold fragments, accumulating in poorly ventilated areas and posing serious health risks, particularly to vulnerable populations like children, the elderly, and those with pre-existing conditions [1]. These toxins contribute to respiratory problems, allergic reactions, and immune suppression. The musty odor from microbial volatile organic compounds (MVOCs) serves as an early indicator of mold, though its subjective nature limits its reliability as a contamination indicator [1].

Addressing mold-related air quality issues requires comprehensive strategies targeting spore and mycotoxin sources and pathways. Effective moisture control, improved ventilation, and air filtration systems can reduce airborne contaminants significantly. Proactive management should address both visible and microscopic mold, as even non-visible mold in damp homes affects airborne fungal ecology, impacting health [1, 5].

7.2 Health Risk Assessments

Assessing health risks from mold-induced air quality degradation necessitates a thorough analysis of environmental conditions promoting mold growth and exposure pathways. Mold is a major source of airborne contaminants like spores and mycotoxins, which degrade air quality and pose health risks, particularly to sensitive populations [1].

Health risk assessments require understanding factors such as high humidity, inadequate ventilation, and poor moisture management, which drive mold proliferation and increase airborne spores and mycotoxins [1]. These conditions highlight the need for environmental controls to mitigate exposure.

Advanced technologies, including DNA sequencing and machine learning, enhance mold species identification and health impact assessments, allowing precise characterization of indoor microbial ecosystems and targeted interventions to improve air quality [5]. These tools enhance the reliability of health risk assessments and inform remediation strategies prioritizing occupant health.

Enhanced mold growth models provide insights into environmental interactions affecting mold proliferation, guiding the design of building systems and materials to minimize mold risks and promote healthier indoor environments [4]. Incorporating these advancements into health risk assessments helps stakeholders understand mold-induced air quality complexities and implement effective public health protection measures.

8 Role of Mycology in Understanding Mold

The interplay between mycology and mold research highlights the significance of fungal biology in indoor environments. Mycology underpins the taxonomy and physiology of fungi, offering practical solutions to mold-related challenges. This section provides an overview of mycology, emphasizing its core concepts and relevance to mold studies.

8.1 Overview of Mycology

Mycology, the scientific study of fungi, includes molds, yeasts, and mushrooms, and is essential for understanding fungal roles in both natural and built environments. In indoor settings, it provides insights into mold taxonomy, physiology, and ecology, crucial for addressing mold issues. Homes with

mold exhibit distinct airborne fungal ecologies compared to those without, necessitating understanding these differences for accurate mold classification and remediation. Specific mold taxa are more prevalent in moldy homes, and even microscopic mold growth can produce odors, linking mold presence to indoor air quality. Advanced DNA sequencing and machine learning models show promise in identifying mold status, aiding inspection and remediation strategies to mitigate health risks [1, 2, 5].

The importance of mycology in mold research is emphasized by its role in identifying and classifying mold species, essential for understanding airborne fungal ecologies. DNA sequencing has revealed quantifiable differences in fungal communities between moldy and non-moldy homes, identifying specific taxa associated with each condition. This molecular approach enhances species classification, aiding in developing predictive models for assessing mold presence and informing effective inspection and remediation strategies [3, 1, 6, 4, 5]. Accurate identification is crucial for assessing health risks, as different species produce varying allergens and mycotoxins. Mycological studies help develop taxonomic frameworks categorizing molds based on genetic, morphological, and ecological characteristics, essential for targeted mold management strategies.

Mycology also elucidates ecological interactions between molds and other microorganisms within the building microbiome. These interactions can significantly alter mold dynamics, influencing indoor air quality and occupant health, particularly in environments with hazardous substances like chlorophenols [3, 2, 1, 4, 5]. By exploring these relationships, mycologists contribute to models predicting mold behavior under various conditions, enhancing prevention and remediation efforts.

Advancements in molecular techniques, like DNA sequencing, have revolutionized mycological research, enabling high-resolution analysis of fungal communities. These techniques allow precise mold species identification and detection of subtle genetic variations influencing mold pathogenicity and environmental stress resistance. The integration of molecular mycology with traditional techniques creates a comprehensive framework for examining mold ecology dynamics, particularly in indoor environments, where differences in airborne fungal communities have been documented between moldy and non-moldy homes. This approach enhances understanding of mold-related health risks and aids in developing machine learning models for accurate mold status classification [3, 2, 1, 4, 5].

8.2 Taxonomy and Classification of Indoor Fungi

Taxonomy and classification of indoor fungi are foundational in mycological research, providing a framework for identifying and categorizing diverse fungal species. Accurate classification is vital for understanding ecological roles and health implications of mold species and implementing management strategies. Traditional taxonomic methods rely on morphological characteristics; however, DNA sequencing reveals these may overlook critical ecological differences among fungal communities. Studies show moldy homes have distinct taxonomic structures and reduced community richness compared to non-moldy homes, emphasizing the need for molecular approaches for accurate classification and health risk assessment [1, 6, 5]. Morphological similarities necessitate more precise classification systems.

Molecular techniques, especially DNA sequencing, have transformed indoor fungi taxonomy by enabling high-resolution analyses of genetic material. This methodology allows precise differentiation of fungal communities, revealing ecological variations between homes with and without mold growth. DNA sequencing of fungal ribosomal RNA demonstrates quantifiable differences in community richness and taxonomic structures, identifying specific taxa enriched in moldy versus non-moldy homes. These insights enhance understanding of indoor fungal biodiversity and support developing machine learning models for mold status classification, aiding inspection and remediation efforts [1, 4, 8, 5]. DNA sequencing enables species-level identification, even when morphological characteristics are insufficient, leading to the discovery of unrecognized species and insights into phylogenetic relationships. By integrating molecular data with morphological observations, researchers can construct comprehensive taxonomic frameworks reflecting true diversity and evolutionary history.

The classification of indoor fungi is further enhanced by bioinformatics tools and databases, facilitating genetic sequence analysis and comparison. These resources enable DNA sequence alignments, identification of conserved markers, and construction of phylogenetic trees illustrating evolutionary relationships among species, enhancing understanding of fungal ecology and aiding classification

[1, 6, 9, 5]. Integrating bioinformatics with molecular taxonomy provides a robust platform for studying genetic diversity and ecological dynamics.

Ecological classification systems categorize fungi based on functional roles within indoor environments, analyzing factors like substrate preference, growth conditions, and interactions with other microorganisms. Research shows moldy homes have distinct taxonomic structures and community richness, enabling nuanced fungal classification based on ecological roles and environmental influences [1, 6, 8, 5]. Understanding ecological niches is crucial for predicting behavior and impact on indoor air quality and occupant health.

Taxonomy and classification of indoor fungi are essential for understanding mold ecology's impact on indoor environments, as studies demonstrate differences in airborne fungal communities between moldy and non-moldy homes. These differences affect community richness and have public health implications, particularly regarding mold exposure and health risks. Integrating DNA sequence-based classification with computational techniques can improve mold detection and inform remediation strategies, contributing to healthier indoor air quality [2, 1, 4, 8, 5]. By leveraging molecular, morphological, and ecological classification systems, researchers can develop targeted interventions to mitigate mold-related health risks and improve indoor environmental quality.

8.3 Molecular Techniques in Mycology

Molecular techniques have transformed mycology, providing insights into genetic composition and diversity of fungal communities in indoor environments. DNA sequencing enables precise identification and classification of mold species at the genetic level, surpassing traditional morphological methods. It allows analysis of fungal genetic material, facilitating novel species discovery and elucidation of phylogenetic relationships [5].

Molecular techniques are crucial for characterizing fungal communities within the building microbiome, using DNA sequencing to differentiate airborne fungal ecologies of moldy and non-moldy environments. This approach identifies specific taxa associated with dampness and mold growth, providing insights into microbial dynamics and informing inspection and remediation strategies to mitigate mold-related health risks [2, 1, 6, 4, 5]. High-throughput sequencing technologies allow comprehensive surveys of fungal diversity, revealing indoor fungal populations' composition and dynamics. This approach provides insights into ecological interactions, critical for understanding mold behavior and its impact on air quality and health.

In addition to DNA sequencing, polymerase chain reaction (PCR) and quantitative PCR (qPCR) are widely used to detect and quantify specific fungal species. These methods offer high sensitivity and specificity, enabling rapid identification of mold species even in low-abundance samples. Integrating molecular data with machine learning algorithms enhances mold detection and classification accuracy, providing a robust framework for assessing mold-related health risks [5].

Advancements in molecular mycology, particularly through DNA sequence-based methodologies, have profound implications for mold management and remediation strategies, enabling precise classification of mold presence in indoor environments. Research highlights significant differences in airborne fungal ecology between moldy and non-moldy homes, informing targeted inspection and remediation efforts to reduce health risks. Understanding interactions between mold growth and environmental factors can enhance remediation approaches, especially in buildings with water damage or dampness [1, 5]. Accurate fungal species identification allows stakeholders to implement targeted interventions to mitigate mold proliferation and associated health risks. Moreover, molecular techniques contribute to developing predictive models that anticipate mold growth patterns under various conditions, supporting proactive measures to maintain healthy indoor environments.

Molecular techniques have revolutionized mycological research, offering tools for exploring genetic and ecological dimensions of mold in indoor settings. By employing advanced DNA sequencing and machine learning models, researchers can deepen understanding of fungal diversity and its implications for indoor air quality. This knowledge aids in identifying and classifying mold growth and informs effective management practices, leading to healthier indoor spaces and reduced exposure to mold-related health risks [3, 2, 1, 4, 5].

9 Building Microbiome and Mold

9.1 Concept of Building Microbiome

The building microbiome encompasses a diverse array of microorganisms, including bacteria, fungi, and viruses, that inhabit indoor environments. Its composition is influenced by building design, materials, occupant activities, and environmental conditions, impacting both structural integrity and occupant health. Effective moisture management is crucial, as buildings with water damage show less diverse fungal communities, highlighting the need for strategies like improved insulation to prevent mold growth and protect health [1, 2, 5].

Ventilation, humidity, and human activities dynamically shape the building microbiome. Poor ventilation can lead to moisture and microbial accumulation, while human activities introduce new microorganisms, affecting mold prevalence [1]. Understanding these dynamics aids in devising strategies to manage indoor air quality and reduce health risks from microbial exposure. DNA sequencing studies reveal that homes with dampness have distinct fungal communities, informing mold inspection and remediation efforts to foster healthier environments [1, 5].

9.2 Interactions between Mold and Building Microbiome

Mold interactions within the building microbiome significantly impact indoor air quality and health. Mold, a key player in this ecosystem, interacts with bacteria and other fungi through resource competition and production of antimicrobial compounds. These interactions influence microbial diversity and mold dominance, affecting ecological balance and air quality [1].

Mold can produce mycotoxins and VOCs that inhibit other microbes, reducing microbial diversity and potentially impacting indoor air quality. Conversely, diverse microbial communities can suppress mold growth by degrading mold cell walls or altering nutrient availability. These interactions affect mold spore and mycotoxin release, crucial for assessing mold-related health risks [1].

Understanding these interactions is essential for managing mold growth and its impact. Insights from microbial network analyses can guide interventions to optimize the building microbiome, enhancing air quality and health outcomes. Improved ventilation and moisture control can enhance microbial diversity, suppressing mold growth and promoting healthier environments [1, 2, 5].

9.3 Health Implications of Mold and Microbial Interactions

Mold interactions with other microbes in the building microbiome have significant health implications, particularly for indoor air quality. Mold releases spores and mycotoxins, causing respiratory issues and allergic reactions. The presence of other microbes can influence mold metabolism, affecting mycotoxin production and health impacts [1].

Microbial diversity plays a crucial role in mitigating health risks. A diverse community can suppress mold growth and reduce harmful substance release, while disruptions in diversity can lead to mold overgrowth and adverse health outcomes. Understanding these dynamics is vital for strategies to improve air quality and health [1].

Research shows that homes with mold exhibit reduced microbial richness and unique taxonomic structures. Insights into these dynamics aid in mold classification and remediation, reducing health risks. Strategies like optimized ventilation and moisture management help maintain a healthy indoor environment, decreasing mold-related health burdens [1, 7, 5].

9.4 Future Directions in Building Microbiome Research

Future research should focus on innovative methodologies and expanding datasets to understand microbial dynamics in diverse environments. Snowball sampling via online platforms can recruit participants from hard-to-reach populations, enhancing building microbiome studies [6].

Broadening datasets to include diverse locations and conditions will refine predictive models, improving their applicability. Integrating advanced molecular techniques with ecological assessments will enhance microbiome characterization, clarifying microbial interactions affecting mold dynamics and air quality [5].

Interdisciplinary collaborations can address mold growth challenges, as studies show distinct differences in fungal ecology between moldy and non-moldy homes. DNA sequencing identifies fungal taxa linked to moldy environments, while modeling predicts mold growth based on environmental conditions. Understanding interactions between materials and microbial dynamics can improve design and remediation practices, reducing health risks associated with mold exposure [3, 2, 1, 4, 5].

10 Conclusion

The comprehensive analysis of mold growth in indoor environments underscores the pressing need for robust management strategies to maintain indoor air quality and protect occupant health. The findings highlight the intricate relationship between environmental variables, such as humidity, temperature, and material characteristics, and their influence on mold proliferation. Incorporating advanced techniques like DNA sequencing and machine learning is crucial for improving the precision of mold detection and classification.

Furthermore, the study sheds light on the complex interactions within the building microbiome, emphasizing the role of microbial dynamics in mold development and related health risks. A comprehensive approach to mold management must consider the entire microbial ecosystem, fostering strategies that enhance microbial diversity and stability to curb mold growth and associated health threats.

Future research should focus on standardizing methodologies for evaluating exposure to chlorophenols and mold, while also clarifying the terminology related to 'mold buildings' and their health impacts. Enhancing predictive models is essential to increase their robustness and applicability across various indoor settings. The Improved Mold Growth Model (IMGM) offers a significant advancement, providing more accurate predictions of mold growth under varying conditions, highlighting the importance of refined modeling in mold management.

Moreover, the study shows that optimal insulation thickness varies significantly with climate and material type, with materials like hemp wool and hollow brick demonstrating superior moisture management capabilities. Although oil treatments improve water repellency and dimensional stability, they do not significantly enhance mold resistance, indicating a need for further investigation into alternative treatments.

This survey underscores the importance of integrating diverse research disciplines to develop comprehensive mold management strategies that effectively address the environmental, health, and structural challenges posed by mold growth in indoor environments.

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