Review Article

A Review of Breathable Walls and Breathable Paints: Innovations and Sustainability in Building Materials

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Abstract

Today's construction industry, are continuous focus on well-designed buildings, with innovation and technology being embraced to meet the evolving demands of modern living standards. Challenges such as urbanization and resource depletion have made it imperative to develop innovative, eco-friendly solutions that not only reduce environmental impact but also enhance indoor environmental quality (IEQ). In this context, breathable walls (BWs) and breathable paints (BPs) have emerged as promising solutions.

Breathable walls (BWs) and breathable paints (BPs), incorporating advanced formulation techniques, natural additives, and innovative application methods, address both environmental and health concerns by improving indoor air quality (IAQ), regulating moisture, and enhancing energy efficiency. By maintaining optimal humidity levels and preventing mold growth, breathable walls and breathable paints contribute to healthier and more comfortable living spaces. Additionally, they reduce reliance on heating, ventilation, and air conditioning (HVAC) systems, minimizing energy consumption and shrinking carbon footprints. Furthermore, these materials support sustainable building practices and promote the use of renewable, non-toxic substances, thereby facilitating the transition to a circular economy.

Future research should focus on optimizing the performance of these materials in response to changing environmental conditions. It is anticipated that the construction industry will continue to innovate and develop health-conscious, more energy-efficient, and sustainable building materials to meet the growing demand for eco-friendly solutions. These advancements will not only contribute to global environmental *sustainability, mitigate worldwide environmental challenges, and improve indoor environmental quality, but also enhance occupant well-being.*

Keywords: *Sustainable Building Materials, Indoor Air Quality, Breathable Walls, Breathable Paints.*

1. Introduction

In response to the global health crisis, many nations implemented various strategies to mitigate its impact [1]. One of the earliest measures taken was home isolation [2]. While this was a key strategy in limiting the spread of the virus, it also had unintended consequences, particularly in poorly ventilated spaces. These conditions led to a range of health problems, including irritability, respiratory issues, and heart disease, highlighting the urgent need to improve indoor air quality (IAQ) in residential spaces [3, 4].

An important issue of housing quality is reported to be strongly related to building envelopes, which are the most durable building components that serve during the entire building lifetime. Moreover, envelopes have been confirmed to be the most problematic ones. Note that ~80% of building failures are related to them [5]. A wall should not just be an enclosure but should provide far more than just protection. A correctly built and laid out wall is an important part of the house and has a long-term effect on occupant safety. A proper wall should be designed to provide multiple benefits such as it conducts self-regulation of moisture all year round, heat storage in winter, and cooling in summer and provides an appropriate environment that reduces energy consumption [6]. A common limitation is how to attain the thermal comfort of buildings by providing innovative solutions with low energy consumption. A smart building accommodates the most effective approaches of meeting its occupants' demands and adapting to the internal and external conditions [7]. Therefore, a type of smart and safe wall, breathing walls (BWs), will be discussed and pivoted on the use of pores in the wall itself to reduce temperature humidity, and thus increase the quality of indoor air using natural or industrial materials or both [6].

In today's industrialized societies, where individuals spend more than 90% of their lives indoors, the quality of the indoor environment has emerged as a crucial determinant of health, well-being, and productivity. With advancements in the construction industry, there is a growing emphasis on optimizing indoor environmental quality. However, modern buildings often struggle to provide safe and conducive indoor conditions. In this context, the choice of materials used in construction is vital for enhancing indoor air quality. Urban population growth is increasing the demand for effective and sustainable construction practices [8,9]. The migration of people to cities has led to many individuals starting to live in urban areas, and as a result, they spend 90% of their time at home. This shift necessitates measures to improve indoor environmental quality (IEQ) to mitigate health risks in densely populated areas. Climate change is reshaping the construction sector by prioritizing the use of sustainable materials and energy efficiency. Innovative green building materials and breathable structures play a significant role in adopting a more environmentally and health-conscious approach. These materials aim to enhance indoor air quality, thereby improving the quality of life. Sustainable construction practices seek to reduce energy consumption, minimize carbon footprints, and ensure healthier living spaces for future generations [10].

According to the U.S. Environmental Protection Agency (EPA), about 30% of newly constructed or renovated buildings experience serious indoor air quality (IAQ) issues. These problems are largely due to the accumulation of harmful chemicals and pollutants, which can lead to adverse health effects. Breathable structures, along with breathable walls and paints, are instrumental in improving indoor air quality and promoting occupant health. Traditional building materials frequently trap moisture and air pollutants, while breathable structures facilitate the movement of water vapor and gases, thereby helping to maintain optimal indoor conditions. Breathable walls are specifically designed to be vapor-permeable, effectively managing moisture levels and mitigating the risk of mold growth. For instance, wall systems made from calcium silicate not only aid in moisture control but also enhance overall indoor health. Likewise, breathable paints are formulated with low volatile organic compound (VOC) content, allowing for moisture diffusion while supporting indoor humidity management and preserving aesthetic qualities [9]. These paints are vital for improving indoor air quality, as they minimize the release of harmful chemicals commonly found in traditional coatings. An essential concept in understanding breathable structures is the role of hygroscopic materials. Organic substances such as wood, wool, and cotton possess the ability to absorb and release moisture, contributing to a balanced indoor climate. This dynamic underscores the importance of indoor climate control, where optimizing temperature and humidity is crucial for enhancing both comfort and air quality. Furthermore, the thermal comfort of a space—characterized by appropriate temperature, humidity, and airflow—can be significantly improved through the strategic selection of breathable materials.

Breathable structures not only improve indoor air quality and thermal comfort but also enhance energy efficiency by effectively regulating moisture and airflow. By doing so, they reduce the need for mechanical ventilation and air conditioning, which in turn lowers energy consumption. These structures contribute to a healthier indoor environment by preventing the buildup of harmful pollutants, such as volatile organic compounds (VOCs), and controlling humidity levels, which can help reduce the risk of mold growth and respiratory issues. To further clarify their impact on indoor air quality

(IAQ), it is important to explore the specific roles of these materials in regulating air quality, moisture control, and pollutant reduction. Key terms and concepts related to breathable walls, paints, and materials are summarized in Table 1 as a reference for understanding their roles in IAQ [10].

Table 1: Key terminology in indoor air quality (IAQ) and sustainable construction.

Term	Defination	Examples
Indoor Air Quality (IAQ)	The condition of air inside a building as it relates to the health and comfort of its occupants.	Use of air filtration systems, ventilation, and low-emission building materials.
Breathable Structures	Structures that allow water vapor and gases to pass through, enhancing indoor air quality (IAQ) and preventing moisture buildup.	Calcium silicate or natural stone-based wall systems that maintain indoor moisture balance.
Breathable Walls (BW)	Walls designed to be vapor-permeable, helping regulate moisture and improve indoor health by preventing mold growth.	Wall panels incorporating calcium silicate that help control indoor humidity.
Breathable Paints (BP)	Coatings that allow moisture diffusion, typically with low volatile organic compound (VOC) content, which helps regulate humidity and enhance air quality inside buildings.	Filli Boya®'s interior paints: Momento Life®, Momento Plus®; Filli Boya®'s exterior paints: Aqusto Silan®, Aqusto Sil®, Nucleus®; Nippon Paint®'s interior paints: Minoa Premium Series®
Volatile Organic Compounds (VOCs)	Chemical compounds in building materials that can harm health and degrade air quality (IAQ).	Chemicals such as acetone, benzene, and formaldehyde commonly used in construction and painting processes.
Indoor Environmental Quality (IEQ)	The overall quality of the indoor environment, focusing on factors such as air quality, lighting, acoustics, and ergonomics.	Strategies such as controlling VOC emissions and optimizing ventilation.
Hygroscopic	Materials that absorb and release moisture, playing a significant role in regulating indoor air quality and ensuring a balanced indoor climate.	Organic materials like wood, wool, cotton, and stone wool which help maintain humidity levels and comfort.
Active Air Management	Systems that regulate indoor airflow to optimize temperature, humidity, and air quality (IAQ).	Automated ventilation systems equipped with smart sensors and energy recovery devices.
Particulate Matter (PM)	Tiny particles suspended in the air that can negatively impact health and air quality (IAQ).	$PM_{2.5}$ and PM_{10} particles found in vehicle emissions and industrial pollution.

Heating, Ventilation, and Air Conditioning (HVAC)	Systems used to regulate indoor temperature, humidity, and air quality.	Air conditioning systems, forced-air heating systems, and smart climate control systems.
Environmental Protection Agency (EPA)	A U.S. government agency responsible for regulating and ensuring clean air, water, and land.	EPA guidelines for indoor air quality (IAQ) and building ventilation.
Indoor Climate Control	The process of optimizing temperature, humidity, and airflow to ensure comfort and air quality. Breathable structures enhance the efficiency of these systems.	Passive solar energy systems, natural ventilation, and climate control mechanisms such as ceiling fans.
Thermal Comfort	The comfort level of a space based on temperature, humidity, and airflow. Breathable structures help maintain optimal thermal comfort.	Ideal temperature range of 20-22 °C and humidity levels of 30-60% for comfortable indoor conditions.
Energy Efficiency	Energy-saving practices in buildings focus on efficiency, with breathable structures enhancing energy measures through moisture regulation and airflow.	Solar panels, high-efficiency insulation, and energy recovery systems integrated into breathable designs.
Stream Diffusion (SD)	A concept used to model how air, water vapor, or gases move through a building's envelope.	Diffusion of moisture through porous materials like breathable walls.
Sustainable Construction	Practices aimed at minimizing environmental impact while creating livable spaces for future generations.	Projects using recycled materials and supported by green building certifications (LEED, BREEAM).
Dynamic Insulation	Insulation systems that adjust based on external conditions to optimize energy efficiency and comfort.	Materials and systems that adapt to temperature and humidity changes, enhancing energy performance.

The integration of breathable structures improves energy efficiency and air management. These materials reduce energy use while supporting sustainable practices that minimize environmental impact. Automated systems optimize airflow, temperature, and humidity, promoting a healthier indoor environment.

Indoor air quality (IAQ) primarily relates to ambient air in mechanically and naturally ventilated buildings [11]. The IAQ effect from the infiltration of outdoor air to the indoor environment depends on the type and operation of the ventilation system of a building, which could be natural, mechanical, or hybrid [12,13]. Typically, indoor air quality (IAQ) is affected by three primary groups of pollutants; the first group is those primarily generated in households, namely, occupant-related pollutants such as carbon dioxide (CO_2), bio-effluents, and particulate matter (PM) in different size ranges such as personal activities (smoking, cooking, body odor, and cosmetic odors), which will be discussed here later; the second group is outdoor air pollutants such as carbon monoxide (CO); and the third group is building-related pollutants such as typically volatile organic compounds (VOCs) [14]. Material selection and construction practices have a significant impact on indoor environmental quality (IEQ), influencing occupant comfort by affecting thermal comfort, daylight, and air quality [15]. While research has focused on how building materials affect thermal comfort and daylight, further investigation is needed on their impact on indoor air quality (IAQ) in hot, arid climates like Egypt [16].

The available indoor air quality (IAQ) standards for residential buildings in Egypt are limited and do not always account for the country's climate-specific challenges [17]. Modern construction relies on materials like concrete, steel reinforcement, and clay bricks, which provide structural stability but may worsen IAQ in poorly ventilated spaces. In contrast, traditional materials and methods, which prioritize natural ventilation and locally sourced materials, could offer better alternatives for improving IAQ in some cases. According to the 2012 World Health Organization report, the highest death rates are linked to acute respiratory infections in children and heart disease due to indoor air pollution [18]. This underscores the urgent need to reassess construction materials and practices, particularly in regions where indoor air pollution poses a significant health risk.

To address indoor air quality (IAQ) issues, the Momento Health-Conscious Paints® series from Filli Boya® offers an innovative solution for creating healthier living environments [19]. Specifically designed to positively impact IAQ, Momento Life® paints are made from natural, non-toxic ingredients, free of formaldehyde and volatile organic compounds (VOCs). The paints feature a high-performance acrylic binder modified with natural silicates, enhancing both durability and breathability. As a result, they resist cracking, peeling, and blistering over time, while maintaining excellent coverage. Additionally, they contribute to cleaner indoor air by reducing pollutants and allergens, which is especially important in spaces with poor ventilation or high indoor pollution [20].

The Momento Life® series includes a range of formulations tailored to specific needs [20]. For instanc, the Momento Life Kids® line is designed for children's rooms, while Momento Clean Ceiling Paint® helps improve air quality by binding harmful chemicals like formaldehyde [21,22]. The Momento Life Shield Primer® adds an extra layer of protection, shielding against electromagnetic waves, making it ideal for environments with high-tech appliances or for individuals sensitive to such emissions. With these products, Filli Boya® integrates air-purifying and health-conscious solutions into everyday living spaces, making them suitable not only for homes but also for hospitals, schools, and other high-standards environments [23].

By incorporating Momento Life® paints into building designs, it is possible to meet the growing demand for breathable, sustainable, and non-toxic building materials. These paints help reduce the environmental impact of construction while improving the quality of life for inhabitants. Momento Life® is a prime example of how eco-friendly, health-conscious products can contribute to healthier indoor environments, supporting both sustainability and well-being [19,20].

Momento Life® incorporates a range of features that enhance sustainability and promote healthier indoor environments; these include [20]:

- **Water-Based and Natural Ingredients**: Momento Life® paints are water-based and made with natural ingredients, enhancing indoor air quality due to their health-conscious formulation.
- **Silanized Acrylic Binder Technology**: Developed with a high-performance acrylic binder modified with natural silicates for enhanced durability.
- **High Durability and Coverage**: Offers a unique matte finish with excellent coverage and high durability. It integrates seamlessly with surfaces, preventing cracking, blistering, or peeling.
- **High Breathability**: The paint allows surfaces to breathe, contributing to improved indoor air quality.
- **Cost and Labor Efficiency**: Its excellent spreading power reduces labor costs and ensures savings during application.
- **Free from Formaldehyde, Preservatives, and VOCs**: Made without formaldehyde, preservatives, or volatile/semivolatile organic compounds (VOC/sVOC), making it safer for indoor environments.
- **Easy to Clean**: The paint can be wiped clean with a cloth and is easy to maintain.

Momento Life Kids® is a water-based interior paint with a natural ingredient formulation specifically designed for baby and children's rooms. Momento Life Kids® is designed with health in mind, contributing to improved indoor air quality. It is formulated with special silicate-modified acrylic binder technology and contains no preservatives, formaldehyde, or volatile/semivolatile organic chemical compounds (VOC/sVOC). The paint features a unique filling structure, making it washable and easy to maintain. Its water-based composition provides a distinctive natural silk matte finish, creating a clean and safe environment for children [21].

Momento Life Kids®, MAS Certified Green labeled, ensures a healthy indoor environment by eliminating harmful chemicals like formaldehyde and volatile organic chemical compounds (VOCs), making it an ideal choice for children's spaces [21]. Specifically designed for babies' and children's rooms, the health-conscious features of Momento Life Kids® paints are as follows [21]:

- **Natural, Water-Based Formula:** The water-based paint is made from natural, ingredients, ensuring it is non-toxic and ecofriendly. Its health-conscious formula improves indoor air quality, creating a cleaner, safer space for children by reducing harmful emissions.
- **Health-Sensitive Content**: Formulated specifically for children's rooms, it is free from harmful chemicals, formaldehyde, preservatives, and volatile organic compounds (VOCs), ensuring a safer, healthier environment for both children and families.
- **Psychologist-Designed Color Collection**: The color collection has been specially developed by psychologists, in collaboration with experts, to address the developmental and emotional needs of children at various stages of life. The chosen colors aim to improve mood, learning, and overall well-being.
- **Superior Performance with Silicate-Modified Acrylic Binder**: Developed using a high-performance acrylic binder modified with natural silicates, the paint offers exceptional durability and coverage, seamlessly integrating with surfaces while resisting cracking, blistering, and peeling over time.
- **High Breathability**: This paint allows for high breathability, helping to maintain healthy air quality in the room. This is especially important for children's spaces where proper air circulation is crucial for health.
- **Easy to Clean and Maintain**: Its washable, easy-to-maintain surface allows for quick cleaning with a cloth, making it ideal for children's rooms where messes are inevitable, ensuring long-term cleanliness and durability.
- **Cost-Effective and Environmentally Friendly**: With its excellent spreading power, the paint offers cost savings by reducing labor and material usage during application. It is both an economical and eco-friendly choice for families [21].

Nippon Paint®'s Minoa Premium® product is the first and only VOC-free, health-conscious paint in Turkey, standing out with its environmentally friendly features [24]. Comprising Minoa Premium Silk Matt®, Minoa Premium Matt® and Minoa Primer®, this exclusive product line embodies the company's commitment to creating innovative, high-performance paints that not only enhance the aesthetic appeal of spaces but also contribute to healthier indoor air quality. Designed with advanced technologies and eco-conscious formulations, Nippon Paint®'s Minoa Series® offers a unique combination of durability, functionality, and safety, ensuring that both residential and commercial environments benefit from long-lasting, environmentally responsible solutions. With Nippon Paint®'s unparalleled expertise in the field, these products set a new benchmark for interior coatings, reinforcing the company's leadership in promoting sustainable and health-conscious living spaces [25,26,27].

Minoa Premium Silk Matt® is an environmentally friendly and health-conscious interior paint that is free from formaldehyde, preservatives (biocides), and volatile/semivolatile organic compounds (VOC/sVOC). It is GreenGuard Gold certified and contains a specially developed hybrid binder. This paint features a silky matte finish, which reflects light to create a sense of spaciousness and freshness in the room. Its enhanced friction resistance makes it ideal for high-traffic areas. Minoa Premium Silk Matt® is known for its excellent coverage and adhesion to surfaces, ensuring long-lasting durability without cracking, bubbling, or peeling. Additionally, its spreadability ensures labor savings during application. It is designed to integrate seamlessly with surfaces, offering an overall smooth and uniform finish [25].

Minoa Premium Matt® is another option from the Minoa series, featuring the same environmentally and health-conscious properties. Like its counterpart, it contains no formaldehyde, preservatives, or volatile organic compounds (VOCs) and is GreenGuard Gold certified. This premium matt interior paint is strengthened with hybrid binder technology, providing high durability and excellent coverage. Its special matt finish provides a refined, understated aesthetic, perfect for modern interior spaces. With a high breathability capacity, this paint ensures the surfaces can breathe, preventing the buildup of moisture and promoting a healthier indoor environment [26]. Like Minoa Premium Silk Matt®, Minoa Premium Matt® offers ease of application with excellent spreading properties, reducing labor costs.

Minoa Primer® is a high-performance interior primer designed to create a strong adhesive bridge between the substrate and the paint. This acrylic copolymer emulsion-based primer is free from harmful chemicals, such as formaldehyde, preservatives, and volatile organic compounds (VOCs). It enhances adhesion, reduces paint consumption, and ensures the even absorption of the topcoat. The primer is particularly effective when applied over solvent-based paints, improving the overall finish and providing long-lasting durability. Minoa Primer® also helps save both time and resources by reducing the amount of paint needed for coverage [27].

The Minoa Premium Series® by Nippon Paint® exemplifies the company's commitment to creating sustainable, eco-friendly, and health-conscious products. With their advanced technologies, these paints help to improve indoor air quality, create safer living environments, and provide excellent performance in terms of durability, coverage, and ease of application [24].

This review examines the contributions of breathable walls (BWs) and breathable paints (BPs) to indoor air quality (IAQ) and their role in sustainable construction practices. Breathable walls optimize air exchange between indoor and outdoor environments, improving air quality, while breathable paints offer significant aesthetic and health benefits. Supported by a literature review, this study comprehensively explores the potential of these materials to enhance environmental sustainability, reduce pollutants, and improve the overall quality of life for building occupants.

2. Breathable Walls and Breathable Paints: Defining Characteristics and Benefits

In today's world, there is growing awareness about the importance of indoor air quality and environmental sustainability, which has driven significant advancements in construction techniques and materials. This shift is particularly important in the context of rapid urbanization and industrialization, which have not only increased pollution levels but also led to the depletion of natural resources. As a result, finding innovative solutions to create healthy living spaces that support well-being while minimizing environmental impact has become more critical than ever. Breathable materials such as paints have emerged as key solution in addressing these challenges. Innovations such as breathable walls and breathable paints not only offer aesthetic appeal but also contribute to health and environmental benefits. These materials enhance indoor air quality while supporting energy efficiency, thereby fostering sustainable living environments [31,33].

Furthermore, green building practices emphasize the use of low volatile organic compounds (VOC) materials, which not only improve indoor air quality but also minimize environmental impact. Research and development efforts play a crucial role in the advancement of such innovative materials, enabling the construction of living spaces that are both comfortable and eco-friendly. Thus, breathable walls (BWs) and breathable paints (BPs) emerge as fundamental components for sustainability in the future of the construction industry.

2.1. Breathable Walls (BWs)

Breathable walls (BWs) are structural elements designed with porous materials that enhance indoor air quality by allowing moisture to escape. These walls not only improve energy efficiency but also regulate airflow, contributing to the creation of a healthy living environment. In this context, the concept of "breathing walls" represents an innovative approach to construction that enhances thermal comfort in homes by using locally sourced materials. Similarly, breathable paints serve a complementary purpose; they enable walls to "breathe" by facilitating the escape of water vapor and preventing the growth of mold and mildew [31].

As the demand for sustainable construction practices increases, the integration of breathable walls and paints into construction and renovation projects presents a promising opportunity to create more comfortable and environmentally friendly living spaces. By embracing these innovative materials, we can contribute to a healthier environment for ourselves and future generations [32]. By integrating breathable walls and paints, we can reduce indoor air pollution, regulate humidity, and enhance thermal comfort, creating healthier living environments. Additionally, these materials lower energy consumption and minimize the environmental impact of construction, fostering a more sustainable and eco-friendly future.

Building envelopes are vital for creating a comfortable indoor environment, serving as a barrier between the outside and the interior. Recent research has focused on materials and methods used to ensure the comfort of building occupants, particularly under challenging weather conditions. A well-designed wall is crucial for safety and should offer the following key benefits [31]:

- Regulates moisture levels throughout the year.
- Retains heat in winter and keeps cool in summer.
- Distributes heat and cold evenly.
- Provides radiant heating and cooling.

Design, material selection, and construction practices significantly influence a building's performance. Buildings are constructed to protect individuals from outdoor conditions and enhance their comfort, making it essential to monitor factors that may pose health risks to occupants. Indoor environmental quality (IEQ) reflects how healthy and comfortable a building is for its occupants, focusing on factors such as temperature, indoor air quality (IAQ), noise levels, and lighting. Indoor pollutants can originate from both outside and inside sources, including materials and furnishings. With the introduction of various chemicals in construction, it is important to investigate how these pollutants interact [32].

The concept of breathable walls has emerged as an effective solution for improving indoor air quality. By incorporating materials that regulate moisture and facilitate the escape of water vapor, these walls contribute to maintaining optimal indoor conditions, preventing mold growth, and enhancing occupant health and comfort [31]. Breathable walls can be constructed using both natural and industrial materials, each contributing to the improvement of indoor air quality (IAQ) within a building [33]. Particularly suitable for hot climates, breathable walls (BWs) are designed to control airflow across their entire surface, effectively cooling interior spaces through various passive cooling methods. In addition to their thermal benefits, BWs offer a biological approach to enhancing the thermal performance of traditional facades, creating a dynamic thermal atmosphere within architectural spaces [34].

Well-designed "breathable walls" or "permeable walls" can be integrated with heating, ventilation, and air conditioning (HVAC) systems. This integration reduces overall dependence on heating, ventilation and air conditioning (HVAC) systems, resulting in energy savings, while also providing filtered clean air through the building materials. Breathable wall (BW) cladding panels may appear indistinguishable from conventional building cladding to the casual observer [35]. As shown in Table 2, one of the three layers of breathable walls (BWs) is illustrated as follows [36]:

Table 2 : Structure and functionality of a breathable wall system.

	Layer	Description
1	**Rain Screen**	Provides protection against external weather conditions and acts as a wind buffer, preventing rain from entering the structure.
2	**Breathable Wall (BW)**	Any base fabric can be utilized, provided it can be formed with channels of a millimeter in length, allowing for proper airflow and moisture control.
3	**Inner Layer (Fluid Panel)**	A suitable coating should be applied to the inner wall, as some coatings (e.g., epoxy or rubber paint) can close the pores within the wall, thus hindering the three modes of moisture transfer (water vapor permeability and diffusion, hygroscopicity, and capillarity).

Ventilation air flows into the interior through the breathable wall (BW) when a pressure difference is applied, absorbing conduction heat loss as it passes through the wall while simultaneously filtering airborne pollutants [31]. The concept of breathable walls (BWs) provides significant performance gains without complicating traditional building construction, particularly when the facade is transformed into an active, integrated part of the building's environmental control system. Since the wall now acts as a heat recovery device, less energy is required to maintain the building’s temperature.

Moreover, due to the close interaction between indoor and outdoor environments, breathable buildings can filter ventilation air and expel clean air, thereby safely reducing overall airborne pollution levels in urban areas. When constructed in a modular format, this approach ensures that even the most contaminated sites can be cost-effectively built or retrofitted for a wide variety of construction applications in the future [35]. This capability offers the potential to provide future generations with high-quality, healthy indoor and outdoor environments in our cities. To enable buildings to breathe and adapt to climate change, they must be equipped with intelligent ventilation systems capable of responding to future changes rather than relying on mechanical ventilation that increases energy consumption and carbon emissions [37]. Such systems could also optimize energy use by adjusting airflow according to environmental conditions, making them more efficient and sustainable in the long term.

The definition of breathable walls (BWs) encompasses two dimensions [37]:

1. Breathing from a biological perspective.
2. Breathing from an architectural perspective such as paints.

2.2. Breathable Paints (BPs)

Water is an inherent element in buildings, making the management of moisture crucial. If water is allowed to accumulate, it can lead to problems such as dampness or, in the worst-case scenario, structural failure. When renovating and decorating older buildings, breathable mortars such as lime have been proven to effectively manage moisture. Paint coatings also play a significant role in moisture management, contributing to the preservation and integrity of the building structure [37].

A breathable paint (BP) is defined as a coating that allows the transfer of water vapour. The primary function of these paints is to permit the evaporation of water from the surface, thereby preventing the accumulation of moisture within the building fabric. However, there is no established European standard for breathable paints, which has led to the use of various methods for measuring this characteristic. Currently, the stream diffusion (SD) value or air layer equivalence, a German standard, is commonly used to measure the resistance of a paint coating and its ability to allow moisture to pass through. The lower the SD value, the more vapour-permeable the paint becomes. A breathable paint should have an SD value ranging from 0.01m to 0.5m, meaning that moisture must travel between 1cm and 50cm through static air to pass through the paint. This indicates minimal resistance, allowing vapour to pass freely without obstruction.

In contrast, conventional masonry paints typically have an stream diffusion (SD) value of 1 or higher, making moisture transfer difficult or nearly impossible. The SD value is a critical factor when selecting a vapour-permeable coating. It is essential that paint manufacturers are aware of this value, as it directly influences the paint's effectiveness in managing moisture. When referred to as "breathable", these paints are essentially being defined by their vapour permeability, which plays a significant role in regulating indoor humidity and maintaining the integrity of building structures over time. For historic buildings, the most suitable paint is one with a low SD value. However, the absorption properties of the paint also play a vital role in its performance, particularly for exterior applications. Capillary action can draw water into the fabric much more rapidly than the permeable coating can expel the moisture. This can result in saturation and moisture accumulation if the paint's absorption capacity is exceeded. In such cases, the paint's ability to regulate moisture may be compromised, leading to potential structural issues [37].

Breathable paints (BPs) allow water vapor to escape while preventing liquid water penetration, helping maintain a balanced indoor climate and reduce mold growth. Made from natural materials like lime, clay, and silicate, they support sustainable building practices and improve indoor air quality (IAQ) [37].

1. **Moisture Regulation**: One of the primary benefits of breathable paints (BPs) is their ability to manage moisture. They allow water vapor to pass through the walls, ensuring that any trapped moisture can escape without causing damage. This is particularly important for preventing issues such as condensation, which can lead to structural problems or unhealthy indoor environments.
2. **Mold and Mildew Prevention**: Excess moisture is a leading cause of mold and mildew growth in buildings. By regulating humidity levels and preventing the buildup of dampness, breathable paints (BPs) help reduce the risk of mold formation, thereby protecting both the structure of the building and the health of its occupants.
3. **Improved Indoor Air Quality**: Good indoor air quality is essential for comfort and health. Breathable paints help enhance indoor air quality (IAQ) by preventing moisture buildup, which can lead to the stagnation of air and the growth of harmful microorganisms. By controlling humidity and allowing walls to breathe, these paints help maintain a fresh, clean indoor atmosphere.
4. **Durability and Low Maintenance**: Breathable paints (BPs) are not only functional but also durable. Unlike conventional paints, which may crack or peel over time due to moisture exposure, breathable paints are designed to withstand such conditions. They require little maintenance, making them a cost-effective choice for long-term building care [37].

Breathable paints (BPs) are essential for sustainable buildings, regulating moisture, preventing mold, and improving indoor air quality (IAQ). Made from eco-friendly ingredients, they enhance performance, durability, and sustainability while reducing reliance on harmful chemicals and lowering carbon footprints. Filli Boya® offers a range of breathable paint solutions that meet aesthetic and functional needs while enhancing building performance and ensuring long-term sustainability [37].

Filli Boya®'s interior paints, such as Momento Life® and Momento Plus®, enhance breathability and indoor air quality [20,38]. Exterior paints like Aqusto Silan® and Aqusto Sil® offer superior protection and support a healthier environment [29,30].

Momento Life® is a health-conscious, water-based paint that positively impacts indoor air quality. Free from formaldehyde and volatile chemicals, it is safe for both homes and commercial spaces. With its high durability, excellent coverage, and breathability, it resists cracking, peeling, and blistering, maintaining its quality over time. Additionally, this paint integrates perfectly with surfaces and is easy to clean, contributing to a healthier indoor environment by reducing allergens and pollutants. Momento Life® offers long-lasting durability and protection, resisting cracking and blistering, while its breathable properties make it ideal for interior use by allowing moisture to escape and preventing mold growth [20].

Momento Plus® shares many health-conscious features with other products in the range but offers added practicality, with high breathability, easy application, and non-splashing, non-dripping properties, saving time and effort. Suitable for various surfaces, it ensures excellent adhesion after proper priming, preventing cracking and peeling. Additionally, Momento Plus® can be thinned with water, making it an environmentally friendly choice. Its quick application and smooth surface integration ensure high-quality results, contributing to a cleaner, healthier indoor environment [39].

Aqusto Silan® is a silicone-based, protective exterior paint developed using Filli Boya®'s innovative ''Active Silicone Technology''. This water-based, matte decorative topcoat combines maximum water repellency with maximum breathability, effectively balancing these features to provide excellent protection and durability for exterior surfaces [29]. The Duomax® protective exterior paint offers long-lasting performance, making it ideal for use on both residential and commercial buildings [40].

Aqusto Sil® also utilizes the same ''Active Silicon Technology'' and offers similar protective features as Aqusto Silan®. However, Aqusto Sil® has the added advantage of a photocatalytic property that helps keep the surface clean by breaking down accumulated dirt. This technology improves the surface's resistance to moisture, UV rays, and harsh weather, ensuring long-lasting protection and maintaining the surface's texture and color over time [30]. Aqusto Sil® is easy to apply, offers high coverage, and integrates seamlessly with the surface, preventing cracking, blistering, and peeling. Its eco-friendly, water-thinnable composition reduces environmental impact while ensuring high performance. Additionally, the odor-free application improves comfort, making it a safe choice for indoor and poorly ventilated spaces [41].

Aqusto Silan® and Aqusto Sil® have been developed in accordance with the relevant standards for water and water vapor transmission rates. These products comply with the requirements of ''TS EN 1062-3'', which specifies the liquid-water transmission rate of coatings, and ''TS EN ISO 7783-2,'' which defines the water-vapor transmission rate of coating systems. In compliance with these standards, they deliver superior performance in water repellency, breathability, and durability, providing excellent protection for exterior walls and concrete surfaces [40,41].

3. Indoor Air Quality and the Role of Breathable Materials

The indoor environment of any built structure is influenced by a variety of factors, including the building's location, climate, architectural design (both initial and any subsequent structural and mechanical alterations), construction techniques, pollutant sources (such as materials, furnishings, soil, processes, operations, and external environmental factors), and the occupants. As depicted in Figure 1, ventilation and contamination are the two key factors that impact indoor air quality (IAQ). Ventilation is governed by the amount of fresh outdoor air provided and the circulation of indoor air, typically supported by mechanical systems [31,32].

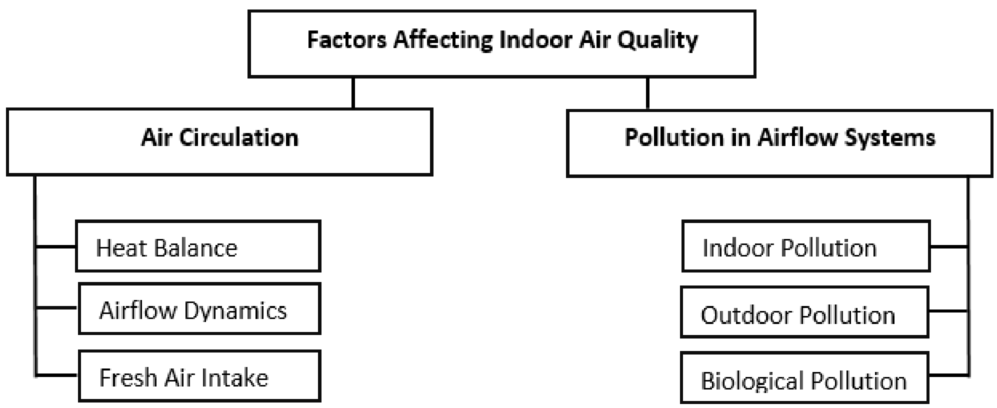

Figure 1: Essential factors determining indoor air quality (IAQ).

Factors like temperature, humidity, and airflow, which contribute to thermal comfort, are directly affected by ventilation. The introduction of outdoor pollutants through openings such as windows and doors can contribute to the contamination of indoor spaces. In addition, other contaminants originate from indoor sources, with emissions from furnishings, materials, and human activities being significant contributors. Building materials also play a notable role in the release of indoor pollutants. It is crucial to assess the impact of these various factors in both preventing and addressing indoor air quality issues [32].

Modern homes are often filled with volatile organic compounds (VOCs) such as formaldehyde, xylene, and vinyl chloride, which come from materials like manufactured wood products, paints, carpets, and synthetic textiles. Furthermore, harmful chemicals like radon, ozone emitted by electrical appliances, and fine particulate matter from various indoor and outdoor sources contribute to health risks. Airborne particles, especially those smaller than 10 microns, can cause significant lung damage. While larger particles are filtered by the body's natural defenses, smaller particles can penetrate deeper into the lungs and cause severe harm. In cold climates, concerns about allergies, weakened immune systems, and illnesses related to fungal growth in buildings are on the rise. Keeping surface relative humidity below 80% is vital in preventing fungal growth. Mold within building structures can also pose health risks if there is no interior air barrier [37,38]. Breathing walls (BW) play a critical role in preventing unwanted moisture infiltration within building structures, which significantly enhances energy efficiency and supports improved indoor air quality (IAQ).

As illustrated in Figure 2, when cold ventilation air flows through the permeable "breathing wall" into a warmer building, the direction of airflow is reversed relative to the external temperature. This phenomenon leads to the capture of heat by the cold air, which would otherwise be lost through conduction. This process leads to a reduction in the wall's thermal transmittance and an overall improvement in insulation performance. To ensure optimal functioning of dynamic insulation, it is essential that the incoming ventilation air is evenly distributed across the broadest possible area of the building's breathing space. Furthermore, minimizing air leakage through gaps, cracks, and openings such as doors and windows is vital to the system's effectiveness [38].

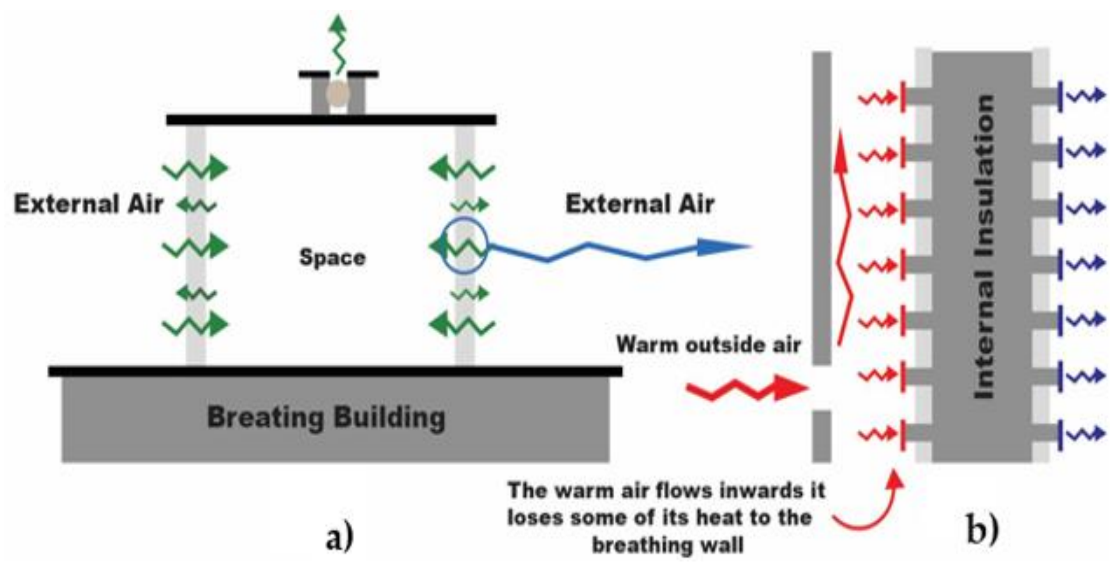

Figure 2: Thermal and moisture movement in (a) air-exchanging building, and (b) biomass wall structure.

The dynamic insulation system is comprised of permeable and breathable components integrated within the building's enclosure. These permeable elements, commonly referred to as "breathing walls," are central to the functioning of dynamic insulation. The term "dynamic insulation" refers to the alteration of heat transfer mechanisms due to the flow of air, and there are two fundamental characteristics that define such systems [36,38]:

1. In contrast to traditional heating, ventilation, and air conditioning HVAC (heating, ventilation, and air conditioning) systems that introduce fresh air through ducts, dynamic insulation ensures optimal indoor air quality (IAQ) by facilitating the circulation of air directly through the walls of the building.
2. Additionally, the building envelope acts as an efficient particulate filter. As the circulating air is conditioned (heated or cooled) according to the operational requirements, the walls serve as heat exchangers, thereby improving the energy efficiency of the entire building system.

In summary, dynamic insulation provides an innovative solution to creating a high-performance thermal envelope within buildings, contributing to significant energy conservation. This system plays a crucial role in optimizing energy use for heating and cooling while also improving overall insulation. In order to safeguard the internal climate and ensure ongoing energy savings, it is important to conduct thorough evaluations of the building's envelope performance. As sustainable construction practices continue to gain prominence, dynamic insulation systems present a viable strategy for reducing energy consumption, enhancing indoor comfort, and supporting long-term environmental sustainability.

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As sustainable construction practices gain increasing importance, dynamic insulation systems offer an effective solution for reducing energy consumption, enhancing indoor comfort, and promoting long-term environmental sustainability. For instance, Filli Boya®'s Dalmaçyalı Insulation Systems® offer a range of high-performance insulation solutions that align with these principles [42]. Figure 3 shows Dalmaçyalı®'s thermal insulation systems, including the ideal carbon thermal insulation systems, stonewool thermal insulation systems, and organic thermal insulation systems. These insulation systems are designed to optimize energy efficiency by reducing heat loss in winter and minimizing heat gain in summer, contributing to more stable indoor temperatures. By incorporating these advanced materials, buildings can reduce their overall carbon footprint, lower energy costs, and promote a more sustainable built environment.

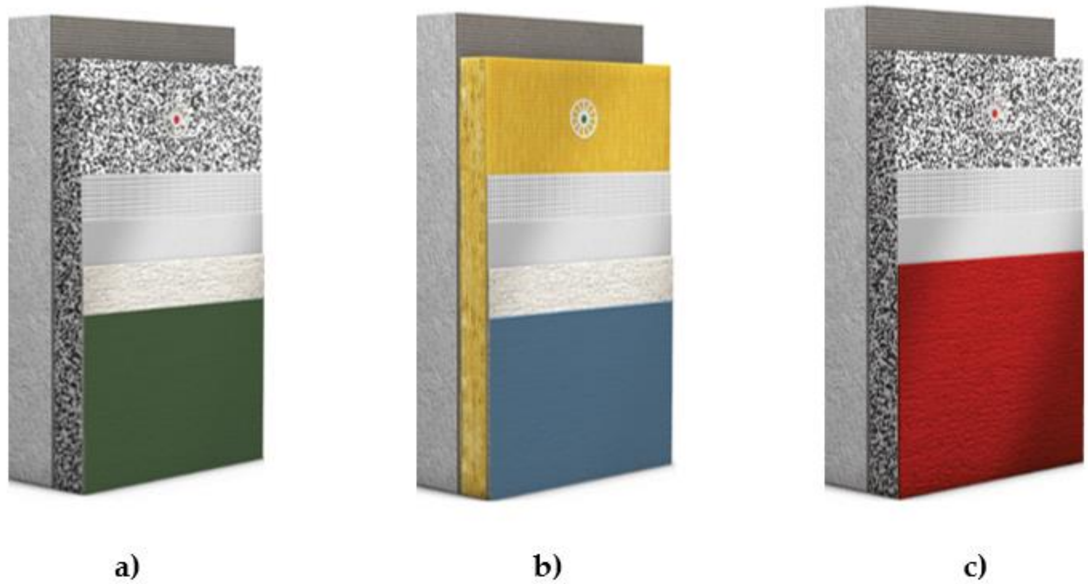

Figure 3: Dalmaçyalı Thermal Insulation Systems®: a) Dalmaçyalı Ideal Carbon Thermal Insulation System®, b) Dalmaçyalı Stonewool Thermal Insulation System®, and c) Organic Thermal Insulation System®.

a) The Dalmaçyalı Ideal Carbon Insulation System®: It provides high thermal insulation performance and ease of application with an ideal carbon balance by ensuring superior energy efficiency, minimizing heat loss, and offering a lightweight structure that simplifies installation while being environmentally friendly [43].

- High thermal insulation performance (λD: 0.034 W/mK).
- Impact resistance in compliance with standards.
- Flexibility compatible with building physics.
- High breathability performance.

b) The Dalmaçyalı Stonewool Insulation System®: It offers excellent thermal, fire, and sound insulation performance for exterior facades, enhancing energy efficiency and providing long-lasting durability through its cross-curing technology [44].

- High thermal insulation performance (λD: 0.035 W/mK).
- Fire and sound insulation.
- High water repellency.
- Impact resistance in compliance with standards.
- Flexibility compatible with building physics.
- High breathability performance.

c) The Dalmaçyalı Organic Insulation System®: It offers fast application with ready-to-use acrylic products, providing superior thermal insulation and impact resistance, while also offering flexibility for prefabricated and moving facades [45].

Organic Insulation System® solutions demonstrate how dynamic insulation solutions can enhance energy efficiency and indoor comfort, contributing to both environmental sustainability and long-term energy savings [45].

- Fast and practical application.
- Use with ideal or double carbon boards.
- 5 times higher impact resistance than relevant standard (10 Joules).
- Dowel-free application with EPS boards (Max: 10 m).
- Flexibility compatible with prefabricated and moving facades.
- High breathability performance.

3.1. Causes of Indoor Air Pollution

Indoor air pollution significantly impacts people's comfort, health, and performance. The main categories of indoor pollutants include inorganic contaminants, organic contaminants, and particulate matter [34].

- **Organic Contaminants**: These include bacteria, fungi, viruses, molds, pollen, and dander, which can negatively affect air quality.
- **Inorganic Contaminants**: These are emissions from materials like adhesives, furnishings, flooring, and wall coverings, as well as other chemicals such as fuels, cleaners, and combustion by-products.
- **Particulate Matter (PM)**: PM is divided into coarse, fine, and ultrafine particles. It originates from dust, construction activity, smoking, combustion, and other indoor and outdoor activities.

Well-known pollutants like formaldehyde and $PM_{2.5}$ (fine particulate matter) pose significant health risks, which make controlling indoor air quality (IAQ) crucial. Formaldehyde, commonly found in building materials, furniture, and household products like cleaning agents and adhesives, can cause eye and nasal irritation, and long-term exposure has been linked to respiratory issues and an increased risk of cancer. Similarly, $PM_{2.5}$, which is composed of tiny particles that can penetrate deep into the lungs and bloodstream, is associated with a wide range of health problems, including chronic respiratory conditions, cardiovascular diseases, and lung cancer [34].

Research indicates that exposure to these pollutants, especially in confined indoor environments, significantly impacts overall health and productivity. For instance, indoor levels of formaldehyde and $PM_{2.5}$ are influenced by outdoor pollution sources, such as vehicle emissions and industrial activity, which fluctuate with the seasons. During colder months, heating systems often exacerbate indoor air pollution by recirculating indoor contaminants. Furthermore, the concentration of indoor CO_2, a major indicator of ventilation effectiveness, is directly affected by the number of people occupying the space. Poor ventilation, which is more common during winter, can lead to higher CO_2 levels, further compromising air quality. Ventilation rates, which also vary seasonally, play a crucial role in determining the concentrations of both formaldehyde and $PM_{2.5}$, highlighting the importance of adequate air exchange to mitigate indoor air pollution and protect occupant health. Therefore, maintaining optimal indoor ait quality (IAQ) through appropriate ventilation, filtration, and the use of low-emission materials is essential in safeguarding both health and productivity in indoor environments [34]. To effectively address these challenges, it is crucial to integrate advanced air filtration systems and sustainable building materials that help reduce pollutant levels. These proactive measures not only enhance IAQ but also contribute to creating healthier, more comfortable living and working spaces.

Table 3 highlights a variety of indoor air pollutants, their sources, and the associated health risks. As observed, these pollutants can have significant short- and long-term effects on human health, ranging from respiratory issues to neurological damage and even cancer.

Table 3: Classification of indoor air pollutants based on their sources and health risks.

Contaminant	Sources	Health Risks
Particulate Matter (PM)	Outdoor air, combustion activities, cooking fumes, tobacco smoke, cleaning.	Early mortality, heart disease, asthma, respiratory tract issues, lung function decline, and aggravated cardiovascular conditions.
Volatile Organic Conpounds (VOC_s)	Paints, varnishes, pesticides, air fresheners, treated wood, fuels.	Eye irritation, headaches, dizziness, organ damage (e.g., liver, kidneys), long-term cancer risk, and neurological symptoms.
Radon (Rn)	Soil gas, building materials, tap water.	Lung cancer (especially in non-smokers), respiratory issues, and long-term health complications from chronic exposure.
Nitrogen Dioxide (NO_2)	Gas stoves, heaters, tobacco smoke, fireplaces.	Asthma exacerbation, lung irritation, coughing, reduced lung

		function, and increased susceptibility to respiratory infections.
Ozone (O_3)	Photocopiers, air purifiers, disinfectants, certain types of air fresheners.	DNA damage, asthma, aggravation of existing lung conditions, and long-term lung issues like emphysema.
Carbon Monoxide (CO)	Fuel-burning devices (e.g., stoves, heaters, fireplaces), smoking, incense.	Fatigue, chest pain, cognitive decline, dizziness, confusion, loss of consciousness, and even death in high concentrations.
Heavy Metals (Pb,Cd,Hg)	Cigarettes, construction materials (e.g., lead paint, pipes), consumer goods (e.g., toys, batteries).	Neurological damage, cognitive and developmental delays in children, cancer risk, respiratory diseases, kidney damage.
Sulfur Dioxide (SO_2)	Cooking stoves, fireplaces, industrial emissions, burning of fossil fuels.	Respiratory impairment, exacerbation of asthma, cardiovascular effects, and irritation to the eyes, nose, and throat.
Aerosols	Cleaning supplies, consumer products, tobacco smoke, paints, cooking fumes.	Allergies, asthma exacerbation, lung cancer, cardiovascular diseases, and respiratory infections.
Pesticides	Insecticides, herbicides, disinfectants, agricultural chemicals.	Irritation to skin and eyes, neurological damage, cancer risks, reproductive system harm, and long-term chronic illness.
Biological Allergens	Pet dander, mold, cockroaches, pollen, dust mites.	Allergies, asthma attacks, respiratory infections, sinusitis, and exacerbation of chronic conditions such as COPD (chronic obstructive pulmonary disease).
Microorganism	Bacteria, viruses, fungi, including molds and pathogens.	Respiratory infections, allergies, asthma exacerbation, viral infections (e.g., flu, cold), fungal infections, and bacterial diseases (e.g., pneumonia).

Effective indoor air quality (IAQ) management requires addressing multiple factors, such as reducing pollutant sources from furniture, cleaning products, and appliances, and improving ventilation systems to maintain fresh air flow. Incorporating low-emission materials during construction or renovation is equally essential, alongside implementing measures like air purification, moisture control, and the use of sustainable, non-toxic building materials. These efforts significantly reduce indoor air pollution, helping to prevent respiratory issues, allergies, and other health problems while fostering a healthier, more comfortable, and productive indoor environment.

3.2 . Comprehensive Strategies for Enhancing Indoor Air Quality

Several effective methods can help create healthier indoor environments, particularly in modern buildings. These methods include enhancing ventilation, using air filtration systems, and minimizing pollutant sources. Proper ventilation ensures a continuous flow of fresh air while expelling contaminated air, helping maintain a healthy indoor environment. Air purifiers with HEPA (High-Efficiency Particulate Air) filters capture fine particles like dust, pollen, and pet dander, while activated carbon removes harmful gases, further improving air quality [46].

Additionally, selecting low-emission building materials, such as paints, adhesives, and finishes with low volatile organic compounds (VOCs), helps reduce harmful chemical release into indoor spaces. Controlling humidity is another key factor in maintaining indoor air quality (IAQ) by preventing mold growth and the spread of allergens. Hygroscopic materials, such as breathable paints and moisture-regulating components, play a significant role in maintaining optimal indoor humidity levels. By addressing both pollutant sources and the environmental conditions within a building, these strategies contribute to a more sustainable, comfortable, and health-promoting indoor environment [46].

- **Preventative Measures: The First Line of Defense**

The first step in improving indoor air quality (IAQ) is to avoid materials that release harmful chemicals, such as solvents, glues, and plastics, which emit volatile organic compounds (VOCs) and other toxins. Natural alternatives, such as natural paints, glues, cork, bamboo, and clay, can replace these harmful materials. Additionally, textured surfaces and breathable paints offer another valuable solution. Using non-toxic, sustainable finishes like lime-cement plasters, solid wood, and concrete can further reduce VOC concentrations, promoting a healthier indoor environment [46].

For instance, Filli Boya®'s Momento Life Series®, a range of interior paints, is formulated with innovative technology that eliminates the use of formaldehyde, preservatives, and volatile/semivolatile organic compounds (VOC/sVOC) [20]. This makes it an ideal choice for those seeking a non-toxic, durable, and breathable solution for indoor spaces. Similarly, Nippon Paint®'s Minoa Premium Silk Matt® is an eco-friendly and health-conscious interior paint, free from harmful chemicals such as formaldehyde, antimicrobial agents, and volatile organic compounds (VOCs). Featuring an advanced hybrid binder, this product offers a sustainable, non-toxic solution for creating healthier living spaces [25]. Its composition also enhances indoor air quality, contributing to the development of safer, more sustainable environments.

In addition, Nippon Paint®'s Minoa Premium Matt®, a GreenGuard Gold certified interior paint, provides another excellent option for those looking to enhance indoor air quality with an eco-friendly, low-VOC paint. This highly durable, high-coverage paint is free from harmful chemicals, ensuring it contributes to both human health and environmental safety [26].

Maintaining appropriate surface humidity is crucial to prevent mold growth, which can damage both air quality and building integrity. Materials like drywall paper and ceramic tiles can harbor mold when exposed to high moisture levels, leading to health issues and structural damage. Controlling moisture through ventilation and moisture-resistant materials, as well as keeping wall temperatures consistent, can prevent humidity buildup and mold growth. These measures help maintain optimal, indoor air quality (IAQ), reduce health risks, and create a more sustainable, comfortable indoor environment. These strategies help ensure optimal indoor air quality (IAQ) by addressing both the materials used and the environmental conditions within the space. By reducing harmful chemicals and controlling moisture, buildings can provide a healthier, more sustainable, and comfortable living or working environment [46].

- **Pollutant Removal: Enhancing Air Quality**

A critical factor in improving indoor air quality (IAQ) is the exclusion of pollutants. Radon (Rn), a naturally occurring radioactive gas, is a harmful indoor pollutant that can infiltrate buildings from the ground. To manage its levels, an airtight foundation or basement is essential. Sealing cracks and gaps in floors, walls, and around pipes creates a barrier that prevents its entry. Additionally, mitigation systems such as sub-slab depressurization can further enhance control and improve IAQ.

Similarly, preventing outdoor pollutants—such as vehicle exhaust, pollen, and industrial emissions—requires a well-sealed building envelope. Applying an air barrier system on the interior side helps keep these pollutants out while also controlling indoor contaminants like off-gassing, particulates, and mold spores. By limiting air movement between indoor and outdoor environments, these measures significantly improve indoor air quality (IAQ), creating a healthier and more comfortable living or working space [46].

- **Excluding Harmful Elements: Protecting Indoor Air**

Exclusion plays a crucial role in maintaining clean and healthy indoor air. One of the most effective ways to prevent harmful pollutants is by implementing airtight foundations and basements, which are essential in stopping radon infiltration. Radon, a naturally occurring radioactive gas, can seep into buildings through cracks in the foundation, posing serious health risks. By ensuring that the foundation is properly sealed and airtight, radon entry can be effectively prevented, safeguarding the indoor environment.

Similarly, protecting the building from outdoor pollutants, such as particulates, chemicals, and mold spores, requires a well-sealed building envelope. An airtight structure prevents these harmful elements from entering the indoor space, significantly improving indoor air quality (IAQ). The building envelope, which includes walls, windows, and doors, must be sealed tightly to stop pollutants like dust, exhaust fumes, and allergens from entering. In addition to protecting against outdoor contaminants, airtight construction also helps to control indoor pollution sources, such as off-gassing from furniture and building materials. By excluding these harmful elements, buildings can provide healthier, cleaner indoor environments that promote the well-being of their occupants [46].

- **Holistic Approach: Optimizing Indoor Air Quality**

A comprehensive, integrated approach is crucial for achieving optimal indoor air quality (IAQ). While avoiding materials that off-gas harmful chemicals is an important first step, it must be paired with other strategies for the best results. Effective ventilation ensures the continuous circulation of fresh air, reducing the buildup of indoor pollutants. Additionally, air barriers help prevent the infiltration of outdoor contaminants, such as dust, allergens, and vehicle exhaust, keeping the indoor air cleaner. These elements together lay the foundation for a healthy indoor environment.

Incorporating humidity control and maintaining consistent surface temperatures are also vital for indoor air quality (IAQ). Humidity control prevents the growth of mold and mildew, which can lead to respiratory issues and other health problems. Consistent surface temperatures reduce the chances of condensation, which can cause moisture-related damage and mold growth. When all of these strategies—ventilation, air barriers, humidity control, and temperature consistency—are integrated, they form a holistic solution that not only improves IAQ but also creates a more comfortable and sustainable indoor environent [46].

In conclusion, enhancing indoor air quality (IAQ) requires a holistic approach that includes preventive measures, pollutant removal, and the exclusion of harmful elements. Using breathable materials, controlling humidity, and ensuring effective ventilation improve both health and comfort. Airtight construction and low-emission materials further support IAQ. These strategies promote sustainability while improving the quality of life for building occupants.

4. Literature Review on Breathability in Building Materials

In the literature, breathing walls (BWs) are described as a dynamic insulation system that utilizes permeable air layers, allowing airflow to bring about significant changes in the air quality within a room [47]. This concept integrates a large portion of a building's exterior envelope into the ventilation system, functioning both as a heat recovery unit and a filter. The key components of BWs rely on materials that permit airflow, serving not only as heat exchangers but also providing active insulation [48]. These air-permeable elements, which can be traversed by natural or forced airflow, utilize porous materials to serve as heat exchangers for energy recovery, while reducing conductive heat flow. As a result, BWs are seen as a promising technology for reducing energy consumption in residential buildings [49]. It has been confirmed that a variety of materials can be employed in BWs, provided they can be constructed with millimeter-scale air channels, such as wood, glass, or concrete. For instance, wood planks showed near 100% heat recovery, while concrete and glass materials achieved approximately 60% [36]. In addition to their thermal benefits, BWs play an important role in ensuring high indoor air quality (IAQ) and preventing mold growth [50].

Despite their advantages, some people misunderstand the concept of breathing walls (BWs), mistakenly assuming that these walls function like lungs. In this context, the term "breathable" refers to materials that allow water vapor to pass through but block the passage of liquid water. The concept of BWs originated in Germany in 1969, with the idea of enhancing indoor air quality (IAQ) by using natural or industrial materials, or a combination of both, to form the building structure [33, 51]. BWs are particularly suited for hot climates, as they can manage airflow across the building's surface and cool the interior spaces in various ways. Inspired by biological systems' concept of breathing (inhalation and exhalation), BWs are designed to improve the thermal performance of traditional facades while creating a dynamic thermal atmosphere inside the building. This concept was applied to walls made of natural materials, which not only allow air to pass through but also absorb moisture from the air, thereby cooling the space through evaporative processes. The resulting breathing buildings are both sustainable and easy to implement [52]. To the untrained eye, BW cladding panels may appear to be similar to traditional building materials. However, breathability in buildings involves more than just air transmission—it also includes water transmission, both in the form of vapor and liquid, inside and outside the building, as well as within the walls, floors, and roofs. Understanding the impact of water on buildings involves three key concepts: vapor permeability and diffusion (the ability of materials to allow water vapor to pass through), hygroscopicity (the capacity to absorb or release water vapor based on relative humidity), and capillarity (the absorption of liquid water) [50].

Breathing wall (BW) systems are composed of three distinct ventilation layers. The outermost layer serves as a weather-resistant rain screen, designed to protect the structure from external elements such as wind and rain. This layer is typically made from materials that are weatherproof and durable, with an isolated barrier to manage any incoming water. The middle layer consists of permeable material, chosen specifically for its ability to create narrow air channels that allow air to flow through at a millimeter scale, which is crucial for the system's function [52]. The innermost layer functions as a "fluid panel" and is coated with materials that preserve the wall's permeability. It's important to avoid coatings like epoxy or rubber paints, which can obstruct the natural moisture transmission of the wall by blocking its pores, impacting the vapor permeability, hygroscopicity, and capillarity of the system [50].

For finishing the walls, thick materials provide an excellent foundation for applying natural stucco and plaster finishes. These materials allow for the creation of a porous surface that facilitates the adhesion of scratch coats, thereby simplifying the construction process and reducing labor costs by eliminating several traditional construction steps. Ideal finishes for breathable systems include clay or lime plaster for the interior, and natural stucco on the exterior, ensuring a fully breathable wall from the inside out. Furthermore, using natural mineral silicate paints on external stucco enhances both breathability and durability while offering waterproofing benefits. For instance, clay can absorb up to 50% of its weight in moisture vapor, significantly improving the wall's ability to naturally regulate indoor humidity levels. When applied correctly, these finishes are long-lasting and require minimal maintenance, while also offering the flexibility to be tinted in various colors. Interior plaster finishes can achieve a smooth, polished look similar to drywall and are compatible with gypsum board partition walls for a seamless aesthetic [50].

The construction industry has increasingly embraced sustainability, with a growing focus on creating structures that not only minimize environmental impact but also contribute to healthier, more comfortable living spaces. Sustainable buildings prioritize energy efficiency, the use of locally sourced materials, and designs that promote better indoor air (IAQ) quality and overall well-being. Innovations such as breathable walls and eco-friendly insulation are gaining attention, as they help reduce both energy consumption and the carbon footprint of buildings.

The use of local materials and traditional building methods has been identified as a sustainable solution across various geographical and climatic conditions [53]. These materials are often readily available, offering ecological advantages by reducing the carbon emissions linked to transportation and industrial manufacturing. As sustainable construction practices gain momentum worldwide, there has been a renewed interest in these materials, especially in developing regions where traditional techniques are still widely practiced. Among these materials, clay stands out for its availability, versatility, and historical significance in construction. However, it does present some challenges, particularly during the drying process, where high axial shrinkage may lead to cracking. To avoid this, the ideal clay soil for construction should contain at least 15-16% clay, ensuring it has the right plasticity and durability for the finished product. Clay bricks typically experience linear shrinkage between 3-12% in softer mixtures, or 0.4-2% in drier mixtures, depending on moisture content and processing methods [54].

The thermal performance of clay is another important consideration in its use for construction. The material's apparent density, which typically falls between 1,600 and 2,000 kg/m^3, is often used as a guideline to achieve optimal thermal insulation [54]. While clay has relatively low thermal conductivity, which makes it suitable for thermal mass, its insulation properties depend on the specific mixture and density. The mechanical strength of clay is another crucial factor, with compressive strength being one of the most important indicators. Various standards have set different minimum compressive strength values for clay-based walls, depending on the region and type of construction.

Alongside traditional materials like clay, there has been a notable increase in the use of alternative thermal insulation materials, many of which offer more environmentally friendly solutions. Conventional materials, such as fiberglass and stone wool, still dominate the market, comprising about 87% of insulation products. However, alternative materials like straw bales, hemp, and sheep wool are increasingly being considered for their sustainable and eco-friendly properties [56]. These alternatives not only provide excellent thermal insulation but also promote the principles of a circular economy by utilizing renewable resources and reducing waste.

Straw is an agricultural product that has been used in construction for centuries. Unlike many conventional materials, the production, use, and disposal of straw have minimal environmental impact [57]. Straw is biodegradable and can be sourced from agricultural by-products, making it a particularly attractive option for sustainable building.

Hemp, a fast-growing plant that has been cultivated for over 12,000 years, offers exceptional durability and resistance to rot. When processed into composites, hemp is twice as strong as wood. It is completely organic and highly versatile, as every part of the plant can be utilized, making it an ideal choice for sustainable construction practices. As a renewable resource with low environmental impact, hemp is a sustainable building material that supports eco-friendly construction [58].

Sheep wool is another promising insulation material that has been studied for its potential in building applications. Although its use is not as widespread as other materials, it has many desirable qualities. Sheep wool is a natural, renewable fiber with excellent thermal and acoustic insulation properties, even when wet. It is hygroscopic, meaning it can absorb water vapor without losing its insulating properties. Additionally, wool can absorb harmful chemicals, such as formaldehyde, improving indoor air quality (IAQ) [59]. Its ability to retain its shape and volume over time also makes it a durable option for long-term use.

When evaluating insulation materials, it is crucial to consider not only thermal performance but also other factors such as human health and environmental impact. These considerations include the potential for dust or fiber emissions, biopersistence, and operational safety. Moreover, the fire behavior, toxicity in case of fire, and affordability of materials are important aspects to consider when choosing insulation options [39]. As the construction industry strives to balance environmental, social, and economic goals, these broader factors will continue to shape the development of sustainable building materials [60,61].

As the demand for environmentally conscious building practices rises, the integration of alternative materials such as hemp, straw, and sheep wool is becoming more prominent in the construction industry. These materials not only offer practical benefits like energy efficiency and improved indoor air quality (IAQ) but also support the broader goal of reducing the industry's carbon footprint. By adopting these sustainable solutions, the construction sector can play a pivotal role in addressing climate change and conserving natural resources. Various natural raw materials were used to produce environmentally friendly building materials in this research. The materials included sandy clay, wheat straw, hemp fibers, and sheep wool [62]. The Figure 4 presents the components used: clay, sand, straw, and hemp. These materials were chosen for their sustainability and ability to improve the thermal and mechanical properties of construction materials.

Figure 4: Eco-friendly building materials: clay, sand, straw and hemp.

The incorporation of these natural substances aimed to create eco-friendly alternatives that minimize environmental impact and improve energy efficiency in building materials. These materials were selected due to their sustainability and their potential to enhance the thermal and mechanical properties of construction products. Figure 5 illustrates the particle size distribution of the sandy clay, highlighting its interaction with other materials in the mixture and contributing to its properties [62].

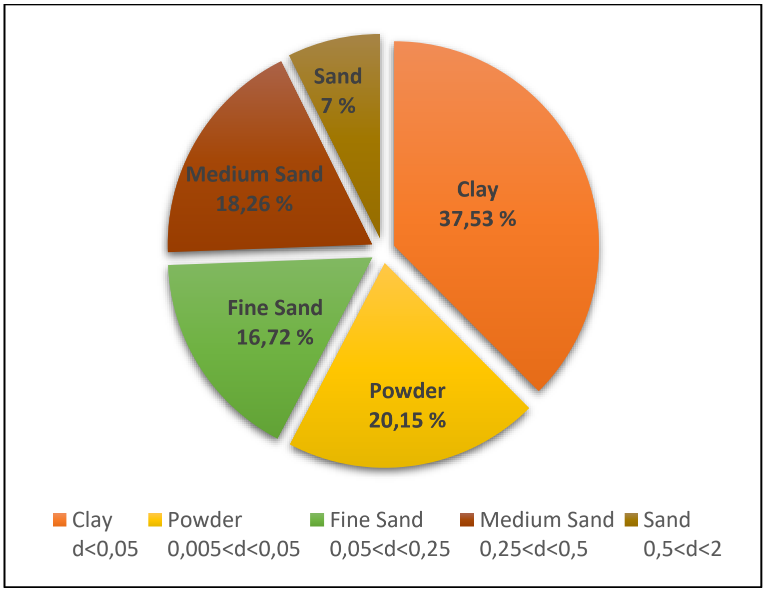

Figure 5: Particle size distribution of sandy clay.

Table 4 presents the oxide composition of the sandy clay. A breakdown of the oxides present in the sample influences the material's mechanical and thermal properties in construction. These oxides impact factors like strength, durability, and heat resistance, helping assess the material's suitability for various building applications. Due to its high water absorption capacity, wheat straw was immersed in water before being added to the clay mixture [63].

Table 4: Distribution of oxides in sandy clay.

Oxides	SiO_2	Al_2O_3	$Fe2O_3$	CaO	MgO	Ka_2O	Na_2O	TiO_2	PC
Content (%)	74.17	12.74	4.38	0.7	1.0	1.43	0.73	0.05	4.78

Hemp fibers were sourced commercially and used as they were. The plant materials were incorporated into the clay mixture based on volume percentages, which consisted of 34% sand, 64% clay, 2% lime, and 1.25% bone glue solution. Hemp fibers were added at 10% by volume, and wheat straw at 40% [63].

The straw and fibers were cut to approximately 7 cm in length, and the bone glue was dissolved in warm water before being added to the mixture [63]. From the prepared mixtures, three prismatic specimens were produced from each and tested for parameters such as density, axial shrinkage, mechanical strength, and thermal conductivity.

Sheep wool was first washed, mechanically combed, and pressed into small layers. This material, a nonwoven product, was made from a mixture of recycled Polyethylene Terephthalate (PET), Polyethersulfone (PES) fibers, natural sheep wool, and plant fibers. After processing, it was formed into thick, fluffy mattresses with a structure similar to basalt wool [64,65].

The thermal insulation properties of the wool-based composite material were tested according to relevant standards. The tests on 40 mm thick wool mattresses included bulk density, tensile strength, water absorption capacity, thermal conductivity, and compressive strength. The final product was processed for use as efficient thermal and acoustic insulation in homes [64,65]. The properties of the wool-based composite material were tested in accordance with thermal insulation standards. Tests on the 40 mm thick wool mattresses included bulk density, tensile strength (perpendicular to the surfaces), short-term water absorption, long-term water absorption, tensile strength in the longitudinal and transversal directions, thermal conductivity, and compressive strength. Figure 5 illustrates clay with straw, clay with hemp fibers, sheep wool insulation, and wool-based natural insulation materials, which are sustainable, natural insulation materials used to enhance energy efficiency and reduce environmental impact in buildings [62].

Figure 5: Natural insulation materials and raw components for earthen plasters.

This research demonstrates the potential of using natural materials such as clay, wheat straw, hemp fibers, and sheep wool for environmentally friendly building materials. The findings highlight the effectiveness of these materials in enhancing thermal insulation and mechanical properties when incorporated into building mixtures. Additionally, the work emphasizes the importance of evaluating various physical characteristics, such as density, shrinkage, and water absorption, to ensure the performance and durability of eco-friendly construction materials [66].

Finally, a mortar mixture was prepared for plastering the sheep wool mattresses, consisting of 45.5% clay, 45.5% sand, 9% hydraulic lime, and 3% bone glue solution. This research demonstrates the potential of using natural materials such as clay, wheat straw, hemp fibers, and sheep wool for environmentally friendly building materials. The findings highlight the effectiveness of these materials in enhancing thermal insulation and mechanical properties when incorporated into building mixtures. Additionally, the work emphasizes the importance of evaluating various physical characteristics, such as density, shrinkage, and water absorption, to ensure the performance and durability of eco-friendly construction materials [66].

Research on breathable paints highlights their significant contribution to environmental sustainability in the construction industry. These paints play a crucial role in reducing the carbon footprint of building materials while also enhancing the energy efficiency of buildings. In addition to regulating moisture within walls, breathable paints improve indoor air quality (IAQ), supporting the broader shift toward sustainable construction practices. As eco-friendly alternatives, these paints are increasingly recognized for their ability to contribute to the sustainability goals of the construction industry [67].

The selection of appropriate coatings and paints for buildings has always been a critical aspect of construction, not only for aesthetic reasons but also for their protective and functional properties. Over time, the growing understanding of the interaction between building materials and environmental factors has led to advancements in paint technologies, particularly in terms of moisture management and durability. One of the key challenges in building maintenance is ensuring that exterior coatings can withstand exposure to varying weather conditions while also allowing for the regulation of moisture within the structure. Historically, ''acrylic paints'' were favored for their ease of use, versatility, and relatively low cost. However, as awareness of moisture-related issues, such as mold growth, efflorescence, and the deterioration of building materials, increased, new solutions were sought. This shift led to the adoption of specialized paints, such as silicate and silicone resin emulsion paints, which are known for their ability to manage moisture and enhance breathability. These paints have proven to be highly effective in preserving the structural integrity of buildings, especially in conservation projects and older buildings exposed to harsh environmental conditions. In parallel, modern paint manufacturers have developed high-performance acrylic paints that also address these concerns, offering a balance between moisture regulation, durability, and aesthetic appeal [67,71].

Filli Boya® offers a diverse range of high-performance acrylic paints, carefully formulated to meet the unique demands of various building applications. These paints are designed to provide robust protection against the elements, ensuring long-lasting durability and resilience. In addition to offering excellent resistance to weathering, they effectively regulate moisture levels, helping to prevent issues such as mold growth, peeling, or cracking. Whether used for interior or exterior applications, Filli Boya®'s acrylic paints enhance the aesthetic appeal of surfaces while offering superior protection, contributing to the longevity of the building and maintaining a healthier, more comfortable living environment.

Betakril®, an acrylic copolymer emulsion-based exterior paint, is one such example. Developed with a specially formulated pigment and filler system, Betakril® provides excellent coverage, UV resistance, and breathability, ensuring that moisture can escape from the surface. Its superior adhesion ensures durability even under harsh environmental conditions, making it an effective solution for exterior applications [68].

Expert Acrylic Exterior Paint®, another popular choice from Filli Boya®, offers high covering power and long-lasting protection, with a matte finish that resists sunlight, weathering, and pollution. This paint is particularly effective for use on a variety of surfaces, including raw concrete, plastered walls, and previously painted areas. Its breathability feature ensures that vapor can pass through building components, contributing to healthy indoor air quality and preventing moisture-related damage [69].

Another product from Filli Boya®'s Dalmaçyalı brand is the Organic Silicone Coating – Fine Grain Texture (1.5 mm) ®, an acrylic-based, fiber and silicone-reinforced, pigmented finishing surface coating. This coating achieves a natural appearance with its fine grain texture, creating a homogeneous pattern on the surface. Ready-to-use and self-colored, it is ideal for use in thermal insulation systems as well as for the renovation of painted old surfaces. It offers high impact resistance, along with excellent water resistance and breathability. The coating provides long-term durability against outdoor weather conditions, and its high elasticity helps cover surface imperfections. With a non-cracking and non-peeling structure, it ensures easy application and pattern creation. It is suitable for both interior and exterior use [70].

According to Table 5, both paints share similar material properties that promote breathability. For instance, they have a high pH value, which is beneficial for preventing fungal and bacterial growth, as these microorganisms typically thrive in acidic environments [71].

Table 5: Material properties of mineral silicate paint.

Material Properties	Results
pH Value	11
Liquid Water Permeability ($kg/m^2h^{0.5}$)	0.12

As presented in Table 6, both paints demonstrate a high water vapor transmission rate, which quantifies the rate at which moisture evaporates from the walls. This property is essential for maintaining the breathability of the walls and preventing moisture accumulation within the substrate [71]. The combination of these characteristics ensures the paint's moisture resistance, indicating that both silicate and silicone resin emulsion paints are breathable and suitable for high-humidity environments.

Table 6: Material properties of silicone resin emulsion paint.

Material Properties	Results
pH Value	9.70
Porosity (%)	3.8
Capillarity (g/min) on Bligon	0.016
Capillarity (g/min) on Brick Wall	0.216

Various research efforts have compared different commercial acrylic paints, including Paint A and Paint B, both of which are free from volatile organic compounds (VOCs), according to their technical data sheets. Paint A is an acrylic-based paint designed for indoor applications, while Paint B, also acrylic-based, is suitable for both indoor and outdoor use. In additional research, Paint B was modified by incorporating two unconventional fillers, F1 and F2. These fillers were introduced in two distinct ways: either by adding them directly to the commercial formulation, resulting in Paint B-F1 and Paint B-F2, or by completely replacing the conventional siliceous filler (183 cm^3 per kg of paint). In this case, the fillers were added exclusively to the resin, leading to the creation of Bresin-F1 and Bresin-F2 formulations [72].

Characterized by high porosity and specific surface area, F1 and F2 are polar fillers that are effective in adsorbing heavy metals, dyes, oils, and acting as molecular sieves in gas separation processes. Table 7 presents the grain size distribution and physical properties of both fillers [72].

Table 7: Physical properties of the filling materials.

Filling Materials	Code	Surface Area	Density	Water Uptake After 24 Hours
Filler 1	F1	750	1310	86
Filler 2	F2	600	1600	22

In the literature, a study investigated the application of both Paint A and Paint B on inert and real mortar substrates to assess their effects on material properties. The study also focused on exploring Paint B's potential to enhance indoor air quality (IAQ) by incorporating highly porous, adsorbent fillers into its formulation. These fillers were either added directly to the commercial formulation or used to completely replace the conventional siliceous filler in the paint. The findings of the study demonstrated that both Paint A and Paint B had a strong capacity to inhibit biological growth, making them effective in preventing issues like mold and mildew [72].

When comparing the two paints, Paint A was found to offer superior breathability and moisture buffering capacity compared to Paint B. Paint A maintained the substrate's breathability and moisture buffering properties without significant alterations when applied to the mortar substrate. In contrast, Paint B resulted in a 50% reduction in the substrate's breathability and an 18% decrease in its moisture buffering capacity. However, the addition of unconventional fillers, particularly F1, to Paint B helped restore, and in some cases even improve, the original properties of the mortar substrate. For instance, the breathability loss induced by Paint B was partially recovered by up to 75% with the inclusion of F1, and the reduction in moisture buffering capacity was mitigated by up to 29% [72].

The researchers observed that neither Paint A nor Paint B exhibited significant depolluting effects in terms of volatile organic compound (VOC) adsorption when used alone. However, the incorporation of unconventional fillers into Paint B was found to significantly enhance its ability to adsorb VOCs. Specifically, the addition of fillers F1 and F2 increased Paint B's VOC adsorption capacity by 20% and 16%, respectively. This demonstrates that the inclusion of these fillers not only improved the paint's functional properties, such as breathability and moisture control, but also enhanced its environmental performance by increasing its capacity to capture harmful VOCs [72].

Fillers used in the study were in the saturated surface-dried (SSD) condition to minimize modifications to the paint's rheology by absorbing or releasing water. When the fillers completely replaced the volume of the conventional siliceous filler, the fluidity of the paint (Paints Bresin-F1 and Bresin-F2) remained unchanged. However, when fillers were added to the formulation, especially F1, the fluidity of the paint (Paints B-F1 and B-F2) decreased slightly, as shown in Figure 6 [50].

Figure 6: Visual comparison of paint B before and after the addition of fillers.

This reduction in fluidity did not affect the applicability of the paints, ensuring their usability. In conclusion, while Paint B initially negatively affected the beneficial properties of the mortar substrate in terms of indoor air quality (IAQ), the addition of unconventional fillers, particularly F1, successfully restored or even improved these properties. The incorporation of F1 and F2 fillers not only enhanced volatile organic compounds (VOC) adsorption but also mitigated the loss in breathability and moisture buffering capacity, making the paint formulation more effective without compromising its applicability [72].

The literature highlights that breathable walls and paints provide significant environmental benefits while improving indoor air quality (IAQ). Research indicates that materials with high porosity not only enhance energy efficiency but also promote healthier environments by effectively controlling humidity levels. Breathable paints, for instance, allow walls to breathe, preventing the growth of mold and mildew, which can negatively impact IAQ. These paints also play a crucial role in moisture regulation, enhancing both the long-term durability of buildings and the overall sustainability of the built environment. In addition to their moisture-regulating properties, they contribute to energy savings by reducing the need for mechanical ventilation systems. By promoting the adoption of energy-efficient and eco-friendly building practices, breathable paints and materials are essential to the creation of healthier and more sustainable buildings in the future.

As part of Filli Boya® 's innovative range of breathable paints, Nucleus® introduces an advanced solution for exterior surfaces by combining cutting-edge ‘’Frontier Polymer Technology®’’ with Silicone-grafted® technology. This product stands out by offering an exceptional blend of durability, aesthetic appeal, and long-term performance. Designed to meet the demands of modern architecture, Nucleus® not only enhances the visual quality of exterior surfaces but also ensures optimal protection and sustainability. With a focus on high water repellency, breathability, and easy maintenance, Nucleus® is the top choice for those seeking high-performance solutions for building exteriors. These key features include [73,74]:

- **Maximum Water Repellency and Breathability:** Nucleus® offers both maximum water repellency and maximum breathability, ensuring that moisture is expelled efficiently while protecting surfaces from harsh weather conditions.
- **Superior Color and Gloss Retention:** The unique pigments and binder system developed with Frontier Polymer Technology® ensure vibrant organic colors and pastel-toned inorganic shades with high resistance to fading. The superior UV-reflection performance guarantees that colors and gloss remain intact for years, while the soft gloss finish strikes a balance between aesthetics and durability.
- **Photocatalytic Self-Cleaning Properties:** Nucleus® features photocatalytic centers that break down accumulated dirt by oxidizing it, helping keep surfaces clean and reducing the need for maintenance over time.
- **Excellence in Moisture and Water Management:** With the integration of Silicone-grafted® Frontier Polymer Technology®, the paint offers maximum breathability, effectively expelling moisture from surfaces and preventing deformation. Its high water repellency provides long-term protection, even under harsh weather conditions.
- **Easy Application and Labor Savings:** Nucleus® offers excellent coverage and spreading properties, making it easy to apply and reducing both labor and material costs. The product’s minimal splashing and dripping provide a cleaner application.
- **Free from Harmful Chemicals:** Nucleus® is free from harmful chemicals such as formaldehyde, preservatives, and VOCs, making it safer for both the environment and indoor spaces [73,74].

In conclusion, breathing walls (BWs) provide an innovative solution for enhancing energy efficiency and indoor air quality. By utilizing air-permeable materials, BWs reduce energy consumption, improve heat recovery, and prevent mold growth. These systems contribute to healthier and more sustainable buildings, making them a promising technology for the future of architecture.

5. Conclusions and Future Perspectives

In today's rapidly evolving architectural landscape, the integration of sustainable building materials is becoming increasingly crucial. As global challenges such as climate change and resource depletion intensify, architects and engineers are seeking innovative solutions that address both environmental and health concerns. In this context, technologies like breathable walls (BWs) and breathable paints (BPs) have emerged as important innovations. Not only do they enhance indoor air quality (IAQ), but they also improve energy efficiency and regulate moisture, contributing to more sustainable and resilient buildings. These materials are key components of sustainable construction, supporting the creation of environmentally friendly and health-promoting structures while improving the overall indoor environmental quality (IEQ). By aligning with the principles of green building, these materials further support the transition towards more sustainable, energy-efficient, and health-conscious built environments.

Breathable walls and paints hold significant potential in improving both environmental sustainability and health outcomes in modern buildings. With their ability to regulate humidity and reduce indoor pollutants, these materials offer a practical solution for enhancing indoor air quality (IAQ) and supporting occupant well-being. By preventing moisture-related issues like mold and mildew, breathable walls (BWs) and breathable paints (BPs) contribute to the creation of long-lasting, healthier indoor environments. Furthermore, these materials support energy-efficient building designs by optimizing thermal performance, which enhances the overall energy efficiency of the structure, reduces the environmental footprint, and aligns with green building principles. The integration of these materials into buildings not only improves comfort but also enhances the building's indoor environmental quality (IEQ) by effectively balancing thermal comfort, air quality, and moisture control.

In conclusion, breathable walls and paints represent a key advancement in sustainable construction technologies. Their ability to improve indoor air quality (IAQ), regulate moisture, and enhance energy efficiency makes them essential for creating healthier, more resilient buildings. As the construction industry continues to prioritize sustainability, occupant health, and green building principles, these materials will play a crucial role in shaping the future of architecture. Innovation in this field will be critical as sustainable building materials gain wider adoption. Future research should focus on optimizing the performance of these materials across various climates and architectural contexts. Additionally, integrating life cycle assessments (LCAs) will be vital for evaluating their environmental impact, ensuring their widespread use, and supporting the development of more sustainable, health-conscious, and green buildings.

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