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FROM INTELLIGENCE TO SUSTAINABILITY: AI-OPTIMIZED ADHESIVES AND SEALANTS FOR NEXT-GENERATION GREEN BUILDINGS

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ABSTRACT

Adhesives and sealants, while frequently underestimated, are crucial for the effectiveness, longevity, and environmental friendliness of high-performance green buildings. This review thoroughly analyses their diverse contributions to energy efficiency, structural stability, indoor air quality, and lifecycle circularity. Conventional formulations, mainly derived from petroleum, present challenges due to the emission of volatile organic compounds (VOCs), restricted recyclability, and negative environmental impacts. New bio-based alternatives provide sustainability advantages but often fall short in terms of durability and performance.

Artificial Intelligence (AI) and Machine Learning (ML) are revolutionizing the fields of formulation design, performance forecasting, and lifecycle assessment. Models driven by AI facilitate the optimization of adhesive systems across multiple objectives, ensuring a balance between mechanical strength, environmental compliance, and cost efficiency. The use of physics-informed ML frameworks and digital twins (DTs) significantly improves predictive maintenance and real-time monitoring of sealant joints, thereby prolonging service life and minimizing energy losses during operations.

This review compiles recent developments in material chemistry, adhesion mechanics, durability modelling, and regulatory adherence, while also addressing techno-economic and ethical considerations. It promotes a systems-thinking perspective, emphasizing that adhesives and sealants should be regarded as vital elements in sustainable construction rather than mere peripheral components. Upcoming developments may include open-access datasets, reversible bonding chemistries, and AI-enhanced lifecycle design, which aim to close the divide between innovation and practical application.

Keywords: Green Buildings, Adhesives And Sealants, Artificial Intelligence (AI), Machine Learning (ML).

1. INTRODUCTION

1.1 Background

The construction sector is a major contributor to global greenhouse gas (GHG) emissions, responsible for nearly 39% of annual CO_2 emissions worldwide when factoring in both operational energy use and the embodied carbon found in construction materials [1]. In the pursuit of creating advanced green buildings, much attention has been directed towards improving insulation, incorporating renewable energy solutions, and designing materials with a circular economy approach. Nevertheless, oftentimes neglected components—adhesives and sealants—are just as vital in affecting the energy efficiency, durability, and ecological footprint of buildings. Although they represent a relatively minor fraction of the total material weight in a structure, adhesives and sealants play an essential role in ensuring the robustness and sustainability of high-performance building envelopes [2].

Abbreviations

Abbreviation	Full Form
AI	Artificial Intelligence
ML	Machine Learning
DT	Digital Twin
VOC	Volatile Organic Compounds
IAQ	Indoor Air Quality
LCA	Life Cycle Assessment
EPD	Environmental Product Declaration

LEED	Leadership in Energy and Environmental Design
NZEB	Net-Zero Energy Building
ASTM	American Society for Testing and Materials
ISO	International Organization for Standardization
EN	European Norm
GB/T	Guobiao Standards (China)
SMP	Silane-Modified Polymer
PU	Polyurethane
PSA	Pressure-Sensitive Adhesive
HALS	Hindered Amine Light Stabilizer
FEM	Finite Element Modelling
PINN	Physics-Informed Neural Network
XAI	Explainable Artificial Intelligence
ROI	Return on Investment

1.2 Adhesives and Sealants as Sustainability Enablers

Adhesives and sealants impact various aspects of sustainability:

Energy efficiency: Sealants enhance HVAC performance by ensuring airtightness and reducing thermal bridging, thereby decreasing infiltration [3].

Material efficiency: Adhesives facilitate lightweight construction and composite systems that use less material than mechanical fasteners [4].

Durability: Effective sealing prevents moisture penetration and deterioration, thereby prolonging the lifespan of building elements [5].

Indoor environmental quality: The formulations of adhesives affect the emissions of volatile organic compounds (VOCs) and other harmful substances, which have a direct impact on occupant health [6].

Moreover, adhesives often determine the end-of-life outcomes for building materials, as their permanent bonding can complicate disassembly and recycling efforts [7]. This dual function—enhancing performance while limiting circularity—places adhesives and sealants in the position of being both a facilitator and an obstacle to sustainable construction.

1.3 Challenges in Current Practices

Conventional adhesives are mainly made from petroleum-based, solvent-laden mixtures that possess high embodied carbon, release significant VOC emissions, and have limited recyclability. Even alternatives that are waterborne or labelled as "low-VOC" can still emit harmful substances as they cure or over time. Though bio-based adhesives sourced from lignin, tannins, soy, or polysaccharides are becoming more popular, they typically show less durability and lower resistance to moisture, UV exposure, and hygrothermal conditions compared to their petrochemical counterparts. Additionally, the formulation of adhesives and sealants has largely relied on empirical methods—driven by trial-and-error adjustments and standardized testing procedures. This gradual, step-by-step process struggles to address the pressing need for climate action and the intricate task of balancing performance, health, and sustainability.

1.4 The Promise of Artificial Intelligence (AI)

Artificial intelligence (AI) and machine learning (ML) are becoming influential instruments in materials informatics, allowing for quicker discovery and refinement of functional materials [10,11]. In the realm of adhesives and sealants(Ref Table 1)

Table 1: Possibility of AI in Adhesives & Sealants

AI can:				
Anticipate connections between chemical composition and	Enhance formulations with multiple components to reduce VOCs,	Support physics-informed ML models that combine mechanistic insights	Assist in conducting lifecycle sustainability evaluations,	When integrated with digital twin (DT) models of building envelopes,

performance metrics (such as adhesion strength, flexibility, and durability).	optimize curing rates, and improve cost-effectiveness.	(fracture mechanics, viscoelastic behaviour, hygrothermal degradation) with data-driven forecasts.	encompassing embodied carbon, recyclability, and environmental product declarations (EPDs).	AI can aid in real-time monitoring and predictive upkeep of sealant joints, helping to maintain airtightness and energy efficiency over the long term [12].

2. ROLE OF ADHESIVES AND SEALANTS IN HIGH-PERFORMANCE GREEN BUILDINGS

2.1 Introduction

Adhesives and sealants are essential to contemporary construction because they provide for longevity, environmental control, and structural integration. Adhesives disperse stress over wide regions, lower weight, and make it possible to employ innovative material systems like glass façades, composites, and lightweight panels—all of which are in contrast to mechanical fasteners, which offer confined point-load connections. Conversely, sealants guarantee acoustic, moisture, and air sealing in building envelopes, halting performance deterioration throughout the course of the building's life [13,14]. Adhesives and sealants are not only useful in high-performance green buildings, but they also influence energy efficiency, indoor air quality, recyclability, and lifecycle carbon emissions, among other sustainability outcomes.

2.2 Enabling Energy Efficiency and Airtightness

In inadequately sealed structures, air infiltration and moisture penetration frequently account for 20–30% of heating and cooling loads, making them significant drivers of building energy loss [15]. A first line of protection is provided by sealants applied to joints in windows, roofs, façades, and HVAC penetrations. Without strong sealing systems, high-performance buildings—like those that adhere to Passive House or Net-Zero Energy Building (NZEB) standards—could not be airtight. For example, silicone and polyurethane sealants are frequently used in glazing and curtain wall systems to improve thermal efficiency and decrease infiltration [16].

Predictive joint durability may be made possible by AI-optimized sealants, enabling data-driven maintenance plans to maintain energy efficiency throughout the course of a building's lifespan. This is especially important for building envelopes that are supported by digital twins (covered in Section 13), as sealant deterioration has a direct effect on thermal models.

2.3 Structural Integrity and Safety

In order to create lightweight and visually pleasing designs, structural adhesives are being employed more and more in glass façades, modular construction, and composite systems in place of conventional fasteners [17]. In structural glazing, silicones, epoxies, and silane-modified polymers (SMPs) are particularly crucial because they offer resistance to impact, seismic forces, and wind loads [18]. In addition to being aesthetically pleasing, structural bonding lowers thermal bridging, which indirectly lowers operating energy costs.

However, safety concerns present difficulties, especially when exposed to fire. Adhesives can increase structural efficiency, but when they burn, many formulations emit harmful chemicals and smoke (see Section 6). Therefore, fire safety and human health issues are inextricably linked to adhesives' sustainability function.

2.4 Durability and Service Life Extension

Because materials with longer service lives require fewer replacements and the embodied carbon that goes along with them, durability is a crucial sustainability indicator. While adhesives guarantee that structural linkages hold up against mechanical strain and creep, sealants shield building envelopes against water intrusion, freeze-thaw damage, and UV deterioration [19].

However, durability is also a weakness of a lot of green adhesives. When it comes to long-term moisture resistance, bio-based sealants frequently fall short of petroleum-based silicones [20]. By finding hybrid formulations that strike a compromise between sustainability and long-term durability, AI may be able to close this gap (e.g., bio-sourced precursors modified with synthetic stabilizers). AI-based methods for predicting hygrothermal aging might lessen the need for cautious safety precautions even further, saving money without sacrificing functionality.

2.5 Indoor Air Quality and Occupant Health

Adhesive and sealant compositions have a direct impact on indoor air quality (IAQ), especially on volatile organic compounds (VOCs) released during curing and long-term off-gassing. According to studies, indoor levels of formaldehyde, phthalates, and isocyanates—all of which are frequently present in adhesives—can surpass acceptable limits, causing respiratory ailments and "sick building syndrome" [21,22]. Adhesives and sealants are subject to strict VOC limitations in green building certifications like LEED v4 and WELL Building Standard.

A major conflict here is that high-performance adhesives frequently include solvents and reactive chemicals that lower IAQ. AI-driven formulation techniques might be used to find solvent-free or low-VOC substitutes without compromising mechanical performance, resulting in adhesives that meet occupant health and energy efficiency objectives.

2.6 Barriers to Recyclability and Circularity

Adhesives' effects on the management of end-of-life construction materials are among its most underappreciated functions. By joining disparate components (such as glass-metal composites and multilayer insulating panels) into inseparable systems, adhesives and sealants frequently prevent recyclability. Actually, one of the main causes of composite construction debris being landfilled rather than recycled is adhesives [23]. This creates a conundrum from the standpoint of sustainability: adhesives prolong service life but prevent circularity. Reversible or debond-on-demand adhesives, which break their connections in response to light, heat, or pH changes, represent the next frontier [24]. By simulating reversible bonding processes at the molecular level, artificial intelligence (AI) can speed up the identification of such chemistries, bridging the gap between durability during use and recyclability at the end of life.

2.7 Critical Perspective

Thus, adhesives and sealants play a paradoxical role in high-performance green buildings: they prolong service life by preventing premature material failures; they promote energy efficiency through airtightness and decreased thermal bridging; they also hinder recyclability, increase volatile organic compounds (VOCs), and may jeopardize fire safety.

This contradiction emphasizes the necessity of adopting a systems-thinking strategy in which adhesives and sealants are viewed as essential sustainability players rather than as peripheral ones. AI and data-driven approaches provide a means to balance sustainability and performance, but only if combined with changing regulations and industry readiness to embrace new formulas.

3. MATERIALS LANDSCAPE AND CHEMISTRY

There are many different chemistries available in the adhesive and sealant market for green buildings, each with special benefits, drawbacks, and chances for innovation driven by artificial intelligence (AI).

One of the oldest systems is epoxy, which is made up of crosslinked thermosets that are created by curing epoxy resins with amines or anhydrides [25,26]. Because of their high strength, superior chemical resistance, and robust adherence to concrete and metals, they are frequently utilized in flooring, façade bonding, structural bonding, and crack repair applications [27,28]. However, there are serious sustainability issues with their brittleness, high embodied carbon, lack of flexibility, and non-recyclability. Here, artificial intelligence (AI) can help with toughened epoxy formulation design, durability prediction under service circumstances, and the identification of bio-based epoxies [27].

Polyols and isocyanates, or cyclic carbonates and amines in the case of non-isocyanate polyurethanes (NIPUs), are the starting materials for the synthesis of polyurethanes (PUs), including their isocyanate-free equivalents [29,30]. They are often used in glass, flooring, expansion joints, and insulation bonding [31]. They are hampered by isocyanate toxicity, volatile organic compound (VOC) emissions, hydrolytic/UV degradation, and reliance on petrochemical feedstocks [30-32], but their main advantages include flexibility, weather tolerance, and high adhesion to a variety of substrates [29]. Promising research directions include cure optimization, predictive service-life modeling, and AI-guided molecular design of NIPUs [32,33].

In weatherproofing, movement joints, curtain walls, and glazing, silicones—which have polysiloxane backbones and cure by condensation or addition mechanisms—are essential [34,35]. They provide exceptional flexibility, long service life, and resistance to weather and UV rays [35]. However, they are costly, occasionally show poor adherence to particular substrates, and neutral-curing varieties have comparatively low mechanical strength and sluggish curing [36]. AI technologies have the potential to significantly improve performance, especially in the areas of predictive durability modeling, computer vision-based defect identification, and adhesion promoter selection [35].

MS polymers, also known as silane-modified polymers (SMPs), are polyether-based polymers containing silane end-groups that cure in the presence of ambient moisture [37]. Because of their primerless adhesion, low volatile organic compound content, paintability, and balanced mechanical performance, they are being used more and more in flooring adhesives, jointing, and façade sealants [38]. They exhibit poorer long-term weatherability than silicones, and their greater price makes them less competitive with polyurethane and acrylic systems [38]. SMPs may be better positioned as sustainable substitutes with AI-driven formulation improvement and VOC reduction [37].

Floor adhesives, membranes, tapes, and window films can all benefit from the use of acrylics and pressure-sensitive adhesives (PSAs), which are based on acrylate or methacrylate monomers made by emulsion or solvent polymerization [39,40]. Their primary advantages are affordability, simplicity of use, quick curing, and the availability of watery grades [40]. VOC emissions from solvent-based solutions, creep under continuous load, reduced long-term durability, and UV sensitivity are some of the limitations [41]. AI provides answers by supporting predictive life cycle assessments (LCA), allowing low-VOC acrylic design, and improving the tack-peel balance [40,41].

Roofing membranes, vapor barriers, and sound insulation are the primary applications for butyl and bituminous adhesives, which are usually based on polyisobutylene or asphalt mixes altered with polymers and fillers [42]. They have cheap cost, good impermeability, and vibration damping [43], but they have high embodied carbon [42,43], poor UV stability, and plasticizer migration. The creation of predicted weathering and aging models as well as filler optimization can be aided by machine learning (ML) [42].

Bio-based adhesives are becoming more and more popular. They are made from renewable feedstocks such lignin, tannin, soy protein, terpenes, and saccharides [44,45]. They are mostly used in interior usage, wood bonding, and new façade systems [45,46]. Because of their biodegradability, renewable source, and reduced carbon footprints, these systems provide sustainability advantages [44-46]. Nevertheless, they frequently encounter scale-up obstacles, have variable raw material quality, are sensitive to moisture, and lack adequate mechanical strength [46,47]. The construction industry may embrace AI techniques more quickly, such as feedstock screening, hybrid bio-synthetic adhesive design, and sustainability trade-off modeling [46,47].

All things considered, this materials landscape emphasizes the trade-offs between sustainability, affordability, and performance, highlighting the part AI plays in allowing next-generation green sealants and adhesives that strike a balance between environmental safety, durability, and circularity.

4. MECHANICS OF ADHESION, COHESION, AND INTERPHASE ENGINEERING

The principles of adhesion (interfacial bonding), cohesion (internal strength), and interphase engineering (transition zone qualities) essentially control the performance of adhesives and sealants in green buildings. Potential bonding is determined by chemistry, while long-term dependability under service circumstances is determined by the multiscale interactions between polymer networks, fillers, and substrates. Since the drive for bio-based, low-VOC, or recyclable adhesives might jeopardize mechanical strength if not optimized, these mechanics become even more crucial in sustainable building [48-50].

4.1 Adhesion Mechanisms

A number of processes combine to produce adhesion:

Mechanical interlocking: infiltration into the rough surface of porous materials, such as wood or concrete [51].

Surface forces and adsorption: for polar substrates, van der Waals, hydrogen bonding, and acid-base interactions predominate [52].

Chemical bonding: silanes, primers, or coupling agents can form covalent or ionic bonds (essential for silicones and SMPs) [53].

In polymer–metal or polymer–oxide systems, electrostatic interactions are less significant but nonetheless significant [54].

The way these processes interact depends on the substrate; for instance, silane-modified polymers adhere to glass and metals by using both siloxane linkages and hydrogen bonds.

4.2 Cohesion and Bulk Properties

Filler dispersion, polymer network structure, and crosslink density all affect cohesiveness. Dense crosslinking gives epoxies their strength, but it also makes them brittle, whereas silicones retain their flexibility at the expense of low modulus [55]. One of the primary challenges is still balancing stiffness, hardness, and durability. In order to determine the best crosslink densities and hybrid formulations, machine learning (ML) has started mapping the links between structure, property, and performance [56].

4.3 Interphase Engineering

Real-world performance is frequently determined by the interphase, a nanometric area between the adhesive and substrate. Interphase chemistry is shaped by surface treatments, impurities, and imperfect wetting [57]. AI-driven coupling agent design and physics-informed models of interphase fracture mechanics are increasingly being used to augment traditional methods (primers, plasma treatment, nanofillers) [58]. Interphase deterioration is frequently the predominant failure mechanism in building envelopes, where sealants must endure moisture, UV rays, and cyclic stressors [59].

4.4 Failure Modes

The following are typical adhesive/sealant failures: (Ref Table 4.1)

- Adhesive failure (poor surface preparation, weak contact)
- Cohesive failure (weariness, creep, and bulk cracking)
- Failure of the interface and interphase (combined deterioration)
- Failure aided by the environment (UV, hydrolysis, thermal cycling)
- Digital twin modelling for prediction and multi-scale testing (nanoindentation, fracture mechanics, accelerated weathering) are necessary to comprehend these [60,61].

Table 4.1: Mechanics of Adhesion, Cohesion, and Interphase in Green Building Applications

Mechanism	Description	Example Systems	Challenges in Green Buildings	AI Opportunities	Refs
Adhesion	Adsorption, chemical bonding, and mechanical interlocking at the substrate surface	Silicones on glass, epoxy on concrete	Variability of surfaces, contamination, and bio-based resin wetting	AI for wetting prediction; ML-guided primer /coupling agent selection	[51-53]
Cohesion	Crosslink density and bulk polymer strength.	High-strength epoxies and flexible silicones.	Strength and flexibility are traded off, with VOC-free systems being weaker.	Using generative AI to optimize network topology.	[55,56]
Interphase	Zone of transition between substrate and adhesive.	PU primers with silane-modified polymers.	Moisture, aging, and inadequate bio-based formulation adhesion.	ML informed by physics for predicting fracture and deterioration.	[57-59]
Failure Modes	cohesive, interfacial, environmental, and adhesive.	Curtain-wall sealants flooring adhesives	Long-term resilience to UV and cyclic stress	Using digital twins to model weariness and deterioration	[60,61]

5. DURABILITY: HYGRO-THERMAL AGING, UV, CHEMICALS, CREEP, AND FATIGUE

One of the most important variables influencing adhesives' and sealants' long-term performance in green building applications is durability. Even though the adhesion strength may be high at first, if environmental stressors like moisture, temperature fluctuations, UV radiation, chemical exposure, creep under heavy loads, and mechanical fatigue are not adequately addressed, degradation mechanisms can significantly shorten service life [62-64].

Because adhesives absorb water by diffusion, causing plasticization, hydrolysis of vulnerable bonds, and interfacial weakening, hygrothermal aging is a predominant mechanism of deterioration [65]. Filler content, crosslink density, and polymer chemistry all have a significant impact on how much water is absorbed. Joint reliability is evaluated by simulating moisture-temperature cycles using accelerated aging methods (e.g., ASTM D1183, ISO 9142) [66].

In polymers, especially acrylics and polyurethanes, UV light may cause photo-oxidation, which can lead to chain scission, chalking, and embrittlement [67]. Silicones are favored for exposed joints and façade glazing because of their better UV resistance, which is attributed to their Si–O backbone [68]. To increase photostability, additives like UV stabilizers, hindered amine light stabilizers (HALS), and nanoparticles (TiO_2, ZnO) have been investigated [69].

When adhesives are exposed to solvents, de-icing solutions, or acid rain, chemical resistance is essential. Epoxy adhesives, for instance, are very resistant to a variety of solvents, although they are susceptible to alkaline attack [70]. Additionally, sealants for building façades need to be impervious to air pollutants, cleaning chemicals, and urban pollution [71].

Long-term mechanical deterioration mechanisms are represented by creep and fatigue. Joint displacement and ultimately failure can result from viscoelastic deformation (creep) in adhesives subjected to prolonged pressures, such as roofing membranes and curtain walls [72]. Similar to this, fatigue fracture initiation and propagation can be brought on by cyclic forces from wind, seismic activity, or thermal expansion, especially in brittle systems like epoxies [73]. To reduce these dangers, hardened adhesives and hybrid solutions are being developed [74].

By combining field monitoring, molecular simulations, and accelerated aging data, emerging methods use AI models guided by physics to forecast durability [75]. Predictive frameworks like this might lessen the need for drawn-out experimental procedures and speed up the process of finding formulations with the best environmental resilience.

6. HEALTH, SAFETY, AND COMPLIANCE (VOC, IAQ, FIRE, SMOKE TOXICITY)

Adhesives and sealants must be used in high-performance green buildings that meet safety, health, and regulatory requirements in addition to mechanical and durability requirements. Emissions from building materials have a direct impact on interior settings, where people spend up to 90% of their time. For this reason, volatile organic compounds (VOCs), indoor air quality (IAQ), fire performance, and smoke toxicity are important factors to take into account [76-78].

6.1 Volatile Organic Compounds (VOCs) and Indoor Air Quality (IAQ)

Traditional solvent-based sealants and adhesives are significant sources of volatile organic compounds (VOCs), which can irritate the respiratory tract, contribute to the development of ground-level ozone, and raise the risk of developing chronic illnesses [79]. Strict VOC standards are enforced by regulatory frameworks as the California Air Resources Board (CARB) restrictions, the US EPA Method 24, and the European Decopaint Directive (2004/42/EC) [80,81]. Furthermore, the use of low-emitting adhesives is encouraged by voluntary programs like as LEED v4, BREEAM, and the German AgBB scheme, which are confirmed by chamber testing (ISO 16000 series, ASTM D5116) [82]. A significant industrial change toward compliance is shown in the transition toward waterborne, hot-melted, and 100% solids formulations (such as reactive PUR hot melts and silane-modified polymers) [83].

6.2 Fire Performance and Smoke Toxicity

Adhesives and sealants can provide risks in fire situations in addition to air quality. When burning, many polymers, especially polyurethane foams, emit harmful gasses such CO, HCN, and NOx along with thick smoke [84]. Standards like ASTM E84 (surface burning characteristics), EN 13501-1 (response to fire classification), and ISO 5659-2 (smoke density and toxicity) are followed in fire performance testing [85]. Because silicone sealants are naturally thermally stable, they often work well, but organic polymer systems need flame-retardant additives (such aluminum trihydrate, phosphorous compounds, and nanoclays) to comply with regulations [86]. However, the desire for sustainable, halogen-free alternatives is being driven by the toxicological and environmental issues raised by flame retardants themselves [87].

6.3 Regulatory and Compliance Landscape

Sustainability and human health protection are now included into compliance frameworks. For example, hazardous monomers, solvents, and additives are subject to regulations under the US Toxic Substances Control Act (TSCA) and the European REACH legislation [88]. Low emissions, fire safety, and recyclability are all linked into comprehensive compliance evaluations by green building certifications, which are progressively using life-cycle-based criteria [89]. Manufacturers may now visually check formulas for compliance prior to scale-up thanks to the development of digital tools and AI-enabled emission prediction algorithms [90].

6.4 Critical Challenges and Opportunities

There is conflict in the area between the need for compliance and performance. Adhesion strength, cure time, and durability are frequently trade-offs in low-VOC and halogen-free systems [91]. However, improved nanocomposite flame retardants and bio-based adhesives (such as soy, tannin, and lignin-derived systems) provide interesting avenues for balancing performance, safety, and health in sustainable building [92].

7. SUSTAINABILITY ASSESSMENT: LCA, EPDS, CIRCULARITY & END-OF-LIFE

Adhesives and sealants for green buildings need to be assessed for sustainability across their whole life cycle, from the sourcing, formulation, and application of raw ingredients to their durability, recyclability, and ultimate end-of-life (EoL) destiny [93,94]. The environmental effect of auxiliary products like adhesives and sealants, which are frequently disregarded, is coming under more scrutiny because the building industry is responsible for around 40% of worldwide CO_2 emissions [95].

7.1 Life Cycle Assessment (LCA)

A systematic approach to measuring environmental effects throughout raw material extraction, manufacturing, application, use phase, and end-of-life scenarios is offered by life cycle assessment, or LCA [96]. Methodology is guided by standards like ISO 14040/14044 and EN 15804, and inventory data is provided by databases like Ecoinvent and GaBi [97]. The global warming potential (GWP) of adhesives made from fossil fuel-derived petrochemicals is often higher than that of bio-based formulations made from lignin, tannins, or soy proteins [98]. There are trade-offs, though: bio-based resins could lessen their carbon footprint, but they might also need more energy or additives to achieve performance requirements [99].

7.2 Environmental Product Declarations (EPDs)

Transparent, independently certified environmental profiles of construction materials are provided by Environmental Product Declarations (EPDs), which are created in accordance with ISO 14025 and EN 15804 [100]. EPDs allow specifiers to assess products on a quantitative sustainability basis for adhesives and sealants by capturing consequences such embodied carbon, acidification potential, and resource depletion [101]. Green building rating systems, such as LEED v4, DGNB, and BREEAM, are increasingly rewarding goods with validated EPDs, making them important differentiators in the market [102].

7.3 Circularity and End-of-Life Management

The irreversible crosslinking of thermosets, the difficulty of debonding adhesives from surfaces, and the absence of defined recycling streams make circular economy methods for adhesives and sealants difficult to implement [103]. In order to facilitate more effective disassembly and recycling of building components, research on debond-on-demand adhesives—stimuli-responsive systems that use heat, light, or magnetic fields—is accelerating [104,105]. Other approaches include the development of bio-based solutions that break down more readily in the environment or thermoplastic adhesives that can be recycled [106].

7.4 Critical Perspectives

Data accessibility and methodological flaws in LCA and EPDs continue to be major drawbacks despite advancements [107]. Many of the evaluations that are now in use are cradle-to-gate, which means they don't account for long-term durability or real end-of-life behavior. Furthermore, adoption of circular techniques may be hampered by the performance sacrifices or higher costs they frequently entail [108]. Potential in this area is provided by artificial intelligence, which may speed up the creation of adhesives that are optimized for sustainability and performance by allowing predictive LCAs through data-driven modeling [109].

8. STANDARDS, CODES, AND TEST METHODS (ASTM/ISO/EN/GB/T)(REF TABLE 8.1)

Standardized test procedures and regulatory frameworks are crucial for validating the performance, safety, and sustainability of adhesives and sealants in green buildings. Standards provide data comparability, product dependability, and adherence to environmental and safety laws in international marketplaces. They are particularly important for building envelopes, since failure of adhesives or sealants can jeopardize indoor air quality, energy efficiency, and structural safety [110].

Table 8.1: Comparative Summary of Adhesive and Sealant Standards (ASTM, ISO, EN, GB/T)

Standards Body	Scope & Key Standards	Strengths	Limitations	Sustainability / IAQ Integration
ASTM (US)	ASTM C920 (sealants), ASTM D1002 (lap shear), ASTM D903 (peel), ASTM E2129 (sustainability) [111-113]	Widely recognized; strong focus on mechanical & durability tests; well established in North America [111]	Fragmented across multiple documents; limited sustainability scope beyond ASTM E2129 [113]	Emerging coverage (ASTM E2129 for sustainability); IAQ/VOC standards limited [113]
ISO	ISO 11600 (sealant	Global harmonization;	Sometimes generic,	Strong LCA focus

(International)	classification), ISO 4587 (lap-shear), ISO 9142 (durability), ISO 14040/44 (LCA), ISO 16000 series (IAQ) [114-116]	broad coverage from mechanical to IAQ; integration with LCA frameworks [114]	requiring adaptation to regional needs; adoption uneven across countries [115]	(ISO 14040/44); comprehensive IAQ standards (ISO 16000) [116]
EN (Europe)	EN 15651 (sealants), EN 12004 (tile adhesives), EN 15804 (EPDs), EN 15416 (wood adhesives) [117-119]	Linked to EU CPR → mandatory compliance (CE marking); strong integration of EPDs and sustainability [117,119]	High compliance burden for global manufacturers; mostly Euro-centric in application [118]	EN 15804 widely used for EPDs; strong link to CPR sustainability criteria [119]
GB/T (China)	GB/T 13477 (sealant test methods), GB/T 14683 (silicone structural sealants), GB/T 24267 (VOC limits for adhesives) [121,122]	Rapidly expanding framework; strong focus on IAQ/VOC; aligns with China's green building agenda [120][122]	Some overlap with ISO/ASTM; limited international recognition; frequent revisions [121]	Explicit VOC and harmful substance limits (GB/T 24267); emerging alignment with green building standards [122]

9. DATA FOUNDATIONS FOR AI IN ADHESIVES AND SEALANTS

The quality, availability, and structure of underlying materials and performance statistics are critical factors in the use of artificial intelligence (AI) in adhesive and sealant research. The heterogeneous and multiphase structure of adhesives and sealants, in contrast to conventional structural materials (such as steel and concrete), poses a significant difficulty for data collecting and standardization [123].

9.1 Data Types and Sources

Information pertaining to the performance of adhesives and sealants includes information at the molecular, formulation, processing, and application levels:

Chemical and molecular descriptors include functional group chemistry, crosslinking density, and monomer type [124].

Additives, fillers, catalysts, solvent/solid concentration, and mixing ratios are examples of formulation variables [125].
Conditions of the Process: Cure temperature, pressure, humidity, and mixing order [126].

Adhesion/cohesion strength, durability (UV, hygrothermal, creep), environmental emissions (VOC), and IAQ contributions are examples of performance outputs [127].

Academic papers, industrial test reports, patents, standard compliance records, and high-throughput screening are some examples of data sources [128]. However, the utility of this data for AI-driven models is limited since a large portion of it is still proprietary or dispersed across incompatible formats.

9.2 Data Quality and Curation Challenges

The following are important issues with adhesive/sealant data foundations:

Fragmentation: Non-comparable datasets are produced by several test standards (ASTM, ISO, EN, and GB/T) [129].
Sparse Data: There aren't many long-term durability studies or unfavorable findings available [130].
Representativeness & Bias: Petrochemical-based systems are overrepresented in comparison to bio-based formulations [131].
Multi-scale Complexity: Interphase events are frequently not well quantified, which leaves datasets unfinished for machine learning models [132].

Ontology creation, metadata standardization, and the FAIR data principles (Findable, Accessible, Interoperable, Reusable) are necessary for curating high-quality collections [133].

9.3 Digital Infrastructure and Data-Sharing Initiatives

There are initiatives underway to fill in these data gaps:

Researchers studying adhesives have been motivated to create systematic formulation-performance databases by the Materials Genome Initiative (MGI) [134].

Although coverage is currently restricted, polymer/adhesive datasets are beginning to appear in Elsevier's Materials Platform and the NIST Materials Data Repository [135].

To speed up benchmarking and the implementation of AI, industrial consortia (such the European Adhesive Manufacturers Association) are experimenting with common databases [136].

9.4 Critical Perspective

The largest obstacle to the field's application of AI is still the lack of extensive, publicly available adhesive datasets [137]. Next-generation data techniques need to:

1. Combine simulation and experimental data (such as molecular dynamics and finite element modeling) in order to close this gap.
2. Make cross-standard harmonization possible (GB/T, ISO, EN, and ASTM).
3. Add adjectives that are pertinent to sustainability (VOC profiles, recyclability, embodied carbon).
4. Use secure data exchange made possible by blockchain technology to safeguard industrial intellectual property while permitting pre-competitive cooperation [138].

10. MACHINE LEARNING FOR FORMULATION DESIGN AND OPTIMIZATION

Adhesive and sealant formulation is a multifaceted design problem that takes into account performance objectives, production circumstances, and chemical makeup. Conventional trial-and-error techniques are expensive for the environment, time, and resources [139]. Rapid exploration of formulation spaces is made possible by the use of machine learning (ML), which lessens the need for physical testing while offering predictive insights into material behavior.

10.1 Traditional vs. ML-Driven Formulation Strategies

Traditional formulation design is based on supplier requirements, empirical information, and small adjustments. This method frequently results in less-than-ideal performance, especially when attempting to balance opposing qualities like durability vs. sustainability or adhesion strength vs. flexibility [140].

On the other hand, ML-driven methods employ data-driven models to uncover hidden relationships between output performance measures (such lap shear strength, peel resistance, and VOC emissions) and input descriptors (like molecular structure, curing conditions, and additive concentrations) [141].

10.2 Supervised Learning Applications

The following applications of supervised learning techniques (such as Random Forests, Gradient Boosting, and Neural Networks) have been used:

Forecast adhesion strength based on interphase characteristics and chemical composition.

To get desired performance while lowering energy consumption, optimize the curing conditions (temperature, humidity, and catalyst dose) [142].

Take into account a variety of trade-offs, including cost effectiveness, environmental compliance, and mechanical strength [143].

Neural networks trained on polymer formulation datasets, for instance, have outperformed conventional regression models in the prediction of viscosity and tensile strength [144].

10.3 Unsupervised and Generative Models

To map chemical formulation spaces and find uncharted territory, unsupervised learning techniques like clustering and dimensionality reduction (PCA, t-SNE) are being utilized more and more [145].

Variational autoencoders (VAEs) and generative adversarial networks (GANs) are two examples of generative models that have demonstrated promise in the creation of new polymer backbones and the prediction of bio-based glue substitutes [146]. These methods significantly cut down on development time by enabling the virtual screening of hundreds of possible formulations prior to experimental validation.

10.4 Reinforcement Learning and Bayesian Optimization

Reinforcement learning (RL) and Bayesian optimization have been used in recent work to formulate adhesives. By choosing plausible formulations, getting input on expected performance, and adjusting its approach, the algorithm repeatedly explores the design space in this framework [147]. In high-dimensional and sparse datasets, where brute-force experimental screening would be impractical, these methods have proven very successful.

10.5 Integration with Sustainability and Green Chemistry

Including sustainability measures in ML optimization is a crucial viewpoint. Current formulations frequently ignore environmental factors including carbon footprint, volatile organic compounds (VOCs), and end-of-life recyclability in favor of just optimizing for mechanical or durability criteria [148]. These characteristics are being included into machine learning algorithms in recent studies to hasten the creation of circular and bio-based adhesives [149].

10.6 Limitations and Future Prospects (Ref Table 10.1)

Despite advancements, there are still significant obstacles to ML applications in adhesive formulation:

- Data imbalance and sparsity, especially in datasets pertaining to bio-based adhesives [150].
- Problems with transferability, as models developed for one class of adhesives (like polyurethanes) might not translate to another (like silicones).
- Black-box interpretability, which undermines material scientists' confidence in AI-generated suggestions [151].

To enhance interpretability, future research will focus on the following areas:

- Hybrid ML + physics-based models.
- Active learning frameworks, in which trials are guided by machine learning to close knowledge gaps.
- Real-time adaptive formulation by integration with digital twins of adhesive joints [152].

Table 10.1: Comparing Conventional and Machine Learning Methods for Formulating Adhesives and Sealants

Aspect	Traditional Formulation Design	ML-Driven Formulation Optimization	Key References
Design Process	Empirical, trial-and-error; relies on experience and supplier guidelines.	Data-driven exploration of high-dimensional formulation spaces using supervised, unsupervised, or generative ML.	[139-141]
Time & Cost	Long development cycles; costly experimental iterations.	Rapid virtual screening; reduced experimental burden and faster optimization.	[141-143]
Performance Trade-offs	Balances only a few properties (e.g., adhesion strength vs. durability); limited multi-objective optimization.	Simultaneous optimization of mechanical, chemical, environmental, and economic criteria.	[144,145]
Novelty of Formulations	Incremental modifications of existing formulations; difficulty in discovering novel chemistries.	Generative models (e.g., GANs, VAEs) enable discovery of new polymer structures and bio-based alternatives.	[146,147,149]
Data Utilization	Limited by fragmented and proprietary datasets; heavy reliance on physical tests.	Integrates experimental, computational, and high-throughput screening (HTS) data; active learning fills knowledge gaps.	[42,147,149]
Sustainability Consideration	Often neglected; environmental performance rarely included in design.	Sustainability descriptors (VOC, LCA, recyclability) embedded into optimization objectives.	[148,150]
Scalability & Transferability	Knowledge restricted to specific adhesive systems; poor generalization across chemistries.	Transfer learning + hybrid physics-ML models extend insights across different adhesive classes.	[144,151,152]
Interpretability	Transparent (human-driven), but slow and less adaptable.	“Black-box” models risk low trust, mitigated by explainable AI (XAI) approaches.	[151]

11. PHYSICS-INFORMED AND MECHANISTIC ML FOR PERFORMANCE PREDICTION

Multi-scale, multi-physics interactions including surface adhesion, polymer viscoelasticity, environmental degradation, and interfacial stress distribution naturally control the performance of adhesives and sealants in green buildings. Even though classical machine learning (ML) is quite good at identifying patterns in big datasets, it sometimes lacks the capacity to be physically interpreted and extrapolated outside of training regimes. Predicting long-term durability, creep, or fatigue under various service circumstances becomes difficult as a result. In order to bridge this gap, hybrid mechanistic-ML frameworks and physics-informed machine learning (PIML) are becoming important facilitators of prediction reliability in next-generation formulations.

11.1 Physics-Informed Neural Networks (PINNs)

The training loss functions of physics-informed neural networks incorporate governing equations (such as the Navier-Stokes for moisture diffusion, viscoelastic constitutive relations, and fracture mechanics) directly. PINNs are very significant for forecasting hygrothermal aging, diffusion-limited oxidation, or stress concentration in sealant joints because they guarantee thermodynamic consistency and lessen reliance on exhaustive labeled datasets [153,154].

11.2 Hybrid Mechanistic-ML Models

In hybrid techniques, ML regression or surrogate models are used with fracture mechanics theories, cohesive zone modeling (CZM), and finite element modeling (FEM). This eliminates the need for computationally costly simulations and enables quick performance screening of adhesive joint designs and sealant shapes. For example, joint failure loads under varying temperature and humidity have been predicted with >90% accuracy by ML surrogates trained on FEM datasets [155,156].

11.3 Transfer Learning for Cross-Chemistry Prediction

Generalization is challenging due to the large range of adhesives (epoxies, silicones, polyurethanes, and bio-based polymers). Utilizing physics-informed descriptors (such as glass transition temperature, free volume, and modulus) across chemistries through transfer learning allows predictions to be made, even for new formulations with limited data [157].

11.4 Mechanistic Descriptors and Explainable AI (XAI)

Diffusion coefficients, cohesive energy densities, and crosslink densities are examples of mechanistic descriptors that aid in bridging the gap between ML-driven predictions and physical knowledge. When used in conjunction with XAI techniques, they enhance interpretability, guaranteeing that models show structure-property-performance correlations in addition to predicting failure modes [158,159].

11.5 Role in Sustainability and Circularity

By enabling predictive modeling of end-of-life degradation pathways (e.g., hydrolysis, depolymerization), physics-informed machine learning speeds up the creation of low-VOC, recyclable, and bio-based adhesives. In order to create life-cycle performance assurances that adhere to LEED, BREEAM, and WELL green building certifications, such models are essential [160].

12. SENSING, QA/QC, AND IN-FIELD MONITORING (BIM/DT INTEGRATION)

In addition to laboratory performance, in-field monitoring under various service situations is also necessary for the long-term dependability of adhesives and sealants in green buildings. Adhesive performance may now be constantly monitored throughout the building lifetime thanks to the development of smart sensing technologies, IoT-enabled quality assurance (QA/QC), and integration into digital twin (DT) and building information modeling (BIM) systems.

12.1 Smart Sensing for Adhesive Joints

Real-time detection of microcracking, delamination, and interfacial debonding at adhesive joints is now possible because to recent developments in embedded sensors, such as fiber Bragg gratings, strain gauges, acoustic emission sensors, and humidity/temperature microsensors [161,162]. These sensors allow for non-destructive assessment (NDE) without interfering with building operations. They can be placed via surface-mounted thin films or embedded in sealant beads.

12.2 QA/QC in Manufacturing and Construction

Historically, destructive testing of specimens and visual examination have been the main methods of quality assurance in adhesive application. These methods are expensive and have limited representativeness. In order to identify incorrect mixing, voids, or surface contamination during application, emerging AI-assisted QA/QC combines machine vision with infrared thermography, ultrasound, and hyperspectral imaging [163,164]. Combining these with predictive analytics guarantees adherence to ASTM/EN/ISO standards and minimizes rework.

12.3 IoT and Wireless Monitoring

Wireless sensor networks (WSNs) based on the Internet of Things (IoT) allow for the continuous gathering of data on curing kinetics, moisture intrusion, and adhesive joint tension. In applications where failures might jeopardize occupant safety, such systems are essential for glass sealants, high-rise facades, and structural bonding. Cloud-based solutions receive streams of data for scheduling predictive maintenance [165,166].

12.4 Integration with BIM

Material specifications, installation logs, and maintenance information are all digitally stored using Building Information Modeling (BIM). Stakeholders can attain verifiable material histories and performance-based compliance auditing by integrating adhesive and sealant sensor data into BIM platforms [167]. For instance, when adhesives run outside of acceptable temperature or humidity ranges, automated notifications are made possible by BIM-integrated QA/QC.

12.5 Role of Digital Twins (DTs)

Digital Twins (DTs) are dynamic, real-time representations of building components that go beyond static BIM. DTs may be used to:

- Model joint deterioration under cyclic thermal/hydro stresses in the context of adhesives and sealants.
- Forecast methods for extending service life (such as resealing schedules).
- Make what-if analysis possible for material replacements and retrofits.

Closed-loop validation for adhesive dependability is created by combining PIML (Section 11) with DTs, which updates predicted performance models with field sensor data on a regular basis [168,169].

12.6 Sustainability and Risk Management

Premature failures, material waste, and expensive repairs are decreased by smart monitoring, which is consistent with the ideas of the circular economy and sustainability. Furthermore, safety compliance in the event of a fire, earthquake, or severe weather is improved by real-time QA/QC, which is crucial for climate-resilient green buildings [170].

13. DIGITAL TWINS FOR BUILDING ENVELOPES AND SEALANT JOINTS

An innovative method for designing, tracking, and maintaining building envelopes—including sealant joints—is the use of digital twins, or DTs. Through sensors, Internet of Things (IoT) devices, and Building Information Modeling (BIM) systems, a digital twin is a virtual representation of a physical asset that continually receives real-time data. DTs offer a thorough grasp of the lifetime and performance of building components, especially sealant joints, which are essential for structural durability, watertightness, and thermal insulation [171,172], by combining simulation and predictive analytics.

13.1 Applications in Sealant Performance Monitoring

Predictive Maintenance: By examining mechanical stress, material aging, and environmental stresses, DTs can predict how sealant joints will deteriorate. This allows for proactive maintenance and lowers the possibility of leaks or structural damage [172,173].

Performance Optimization: Digital twins can enhance joint design and sealant material selection by modeling various environmental circumstances, such as temperature swings, UV exposure, and wind pressure [173,174].

Energy Efficiency: Real-time thermal performance monitoring of building envelopes is made possible by integrating DTs with energy management systems, which guarantees ideal insulation and lowers energy losses [171,174].

13.2 Integration with BIM and IoT

BIM Integration: To simulate the precise geometry, material requirements, and installation circumstances of sealant joints, digital twins use BIM data [171].

IoT Sensors: To improve prediction accuracy, embedded sensors provide real-time data to the digital twin by measuring temperature, moisture content, and joint strain [172].

13.3 Case Example

Due to improved monitoring and predictive interventions, a recent deployment in high-rise commercial buildings showed that utilizing a digital twin for silicone-based sealant joints increased joint longevity by up to 15% and decreased maintenance costs by 25% [174].

13.4 Difficulties and Prospects

Data management: For real-time analysis of massive amounts of sensor data, reliable cloud computing and AI algorithms are needed [172].

Standardization: To include sensor outputs, deterioration models, and sealant material parameters into DT platforms, consistent processes are required [173].

Scalability: It takes a substantial financial commitment and interdisciplinary cooperation to expand DT applications from pilot projects to full metropolitan infrastructure [171,174].

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14. CASE STUDIES AND BENCHMARKS

Validating materials, design approaches, and digital twin applications is made possible by case studies and benchmarking, which offer vital insights into the actual performance of building envelopes and sealant joints. Additionally, they make it easier to compare measures related to sustainability, cost-effectiveness, and cutting-edge technology [175,176].

14.1 Case Study: High-Rise Commercial Buildings

Proper joint design in conjunction with digital twins for predictive monitoring decreased water leakage incidences by 30% and maintenance expenses by 25%, according to a research on silicone-based sealants used in high-rise commercial buildings [177]. Reduced air penetration at joints also enhanced thermal performance, demonstrating that joint details and material selection are crucial for energy efficiency [177,178].

14.2 Case Study: Residential Retrofit Projects

The endurance of polyurethane sealants under cyclic temperature and moisture loading was assessed in home retrofit projects. The advantages of contemporary sealants in long-term maintenance were highlighted by benchmarking against historical performance data, which revealed that high-performance sealants extended joint longevity by up to 40% when compared to conventional materials [176,179].

14.3 Benchmarking Digital Twin Implementation

Several building types have been used as benchmarks for digital twin integration. DT-enabled monitoring systems in buildings resulted in a 30–40% decrease in unscheduled maintenance [175,177]. A 5–10% increase in energy efficiency as a result of improved building envelope performance [175,178]. Improved joint deterioration prediction accuracy as comparison to traditional inspection techniques [176,178].

14.4 Lessons Learned

- Movement capabilities, compatibility with neighboring materials, and exposure to the environment must all be taken into account when choosing a sealant material [179].
- Digital twins' real-time monitoring greatly improves lifecycle management and predictive maintenance.
- Validating innovations and evaluating performance across projects need the use of standard benchmarking metrics [176,177].

15. TECHNO-ECONOMIC & RISK ASSESSMENT

To examine the viability, cost-effectiveness, and possible uncertainties related to building envelope systems and sealant joints, techno-economic and risk evaluations are crucial. To offer a thorough framework for decision-making, these assessments incorporate digital technologies such as digital twins, building techniques, maintenance plans, and material performance [180,181].

15.1 Techno-Economic Assessment

Material prices: Compared to traditional materials, advanced sealants like silicone or polyurethane have greater initial prices but provide better durability and flexibility [182]. Life-cycle cost evaluations, however, demonstrate that longer service life and less frequent maintenance frequently outweigh the initial outlay [183].

Labor and Installation: To prevent early failures, proper joint installation is essential. Building height, complexity, and access needs all affect labor expenses. While increasing uniformity, automation and prefabrication techniques can lower installation costs [183,185].

Digital Twin Integration: Sensors, software, and data management are additional upfront expenses when using digital twins. However, long-term savings are achieved through predictive maintenance and better energy performance; ROI improvements over a 5-year period have been found to range from 10% to 20% [180,182].

15.2 Risk Assessment

- Material Degradation: Environmental elements that might hasten sealant aging include moisture intrusion, temperature changes, and UV exposure. To anticipate maintenance requirements and prevent unplanned breakdowns, risk models incorporate these variables [181,184].
- Structural Movement: Sealant joints may be compromised by movement of the building envelope brought on by seismic activity, wind loads, or thermal expansion. Early indicators of stress and deformation can be found using monitoring sensors and digital twins [180,183].
- Risks related to regulations and compliance: It is essential to make sure that sealant materials adhere to environmental rules, fire safety requirements, and building ordinances. Project delays, liabilities, and monetary fines are possible outcomes of non-compliance [182,184].
-

15.3 Integrated Decision-Making

Stakeholders may choose materials, create collaborative configurations, and deploy monitoring systems that optimize performance while lowering cost and risk by combining techno-economic analysis with risk assessment. Sensitivity analysis can help guide investment and maintenance planning by identifying the most important elements influencing durability and lifecycle costs [181,183].

16. ETHICAL, REGULATORY, AND WORKFORCE IMPLICATIONS

Adoption of digital twins, sealant materials, and sophisticated building envelope technologies raises important workforce, ethical, and regulatory issues. To guarantee the safe, fair, and legal use of building innovations, these factors must be addressed [185,186].

16.1 Ethical Considerations

- Data security and privacy: Sensors, Internet of Things devices, and building management systems all provide constant data for digital twins. To avoid abuse or breaches, important operational data must be secured and tenant privacy must be protected [186,187].
- Sustainability and Material Ethics: Sustainable procedures must be followed in the procurement, manufacturing, and disposal of sealant materials. The use of dangerous chemicals, pollutants, and non-recyclable parts raise ethical questions [188].
- Transparency in Decision-Making: When using predictive analytics for energy optimization or maintenance, it's important to keep lines of communication open with all parties involved to prevent prejudice or dependence on automated judgments [185,187].

16.2 Regulatory Implications

- International and local building codes, which include requirements for fire resistance, structural integrity, and thermal performance, must be complied with by sealants and joint designs [187,189].
- Digital Twin Compliance: Adherence to industry-specific standards and data protection laws, such as the GDPR, is essential as digital twins gather and handle operational data [186,188].
- Environmental Regulations: To ensure regulatory compliance and lessen environmental effect, materials must adhere to environmental criteria addressing VOC emissions, chemical safety, and recyclability [188,189].

16.3 Workforce Implications

- Skills Needed: Architects, engineers, and maintenance staff must get specific training in order to integrate digital twins, sophisticated sealant systems, and IoT monitoring [185,186].
- Job Evolution: Workers may be required to undergo reskilling programs as a result of automation in monitoring and predictive maintenance, which might replace manual inspection with data analysis [186,187].
- Safety Considerations: To lower occupational dangers, proper training is essential while handling sophisticated sealants and dealing with high-rise building envelopes [188,189].

16.4 Recommendations

- To protect privacy and guarantee the ethical use of digital twin data, put strong data governance structures into place [186].
- Offer workforce training programs to give staff members the know-how for sophisticated material handling and digital twin operations [185,187].
- Continually assess adherence to national and international standards for safety, energy efficiency, and materials [188,189].

17. CONCLUSION

In next-generation green buildings, adhesives and sealants are strategic facilitators of sustainability, structural integrity, and energy efficiency rather than passive building materials. The revolutionary potential of incorporating cutting-edge materials, AI-driven design, and digital monitoring tools like digital twins into adhesive and sealant applications has been emphasized in this analysis.

Important findings include:

1. Innovation in Materials Is Required but Inadequate: The sustainability benefits of bio-based, reversible, and hybrid adhesives are encouraging, but there are still significant gaps in terms of scalability, long-term durability, and lifecycle consequences. Performance and recyclability are still trade-offs for many "green" adhesives, and there's a chance of superficial acceptance without thorough testing.
2. AI and Machine Learning Speed Up Discovery: Data-driven methods are making it possible to optimize adhesives for strength, cost, and volatile organic compounds (VOCs). However, radical innovation is hampered by the present

dependence on private datasets and a lack of mechanistic knowledge. Only with mechanistic model integration, open-access performance datasets, and interdisciplinary cooperation can AI reach its full potential.

3. Digital Twins Revolutionize Lifecycle Management and Monitoring: Predictive maintenance, scenario modeling, and performance benchmarking are made possible by combining real-time sensors, BIM, and AI analytics. However, forecasting adhesive lifespans of many decades is still difficult, especially when complex environmental and occupancy pressures are present.

4. Design Must Incorporate Sustainability and Circularity: Adhesives have an impact on composites' end-of-life management and recyclability. To keep adhesives from becoming a bottleneck in the design of sustainable buildings, future systems must take into account reversible chemistries, depolymerizable adhesives, and circular-material frameworks.

5. Implications for the Workforce, Ethics, and Regulations Are Vital: New issues with data ownership, regulatory compliance, and worker skill development are brought forth by AI-driven design and monitoring. To reduce ethical and liability concerns, responsible adoption necessitates governance structures, upskilling, and thorough safety testing.

6. Prospective Research Paths:

- Creation of high-quality, standardized datasets for artificial intelligence in adhesive materials.
- Environmental and lifecycle analyses that include adhesives into the circular economy.
- Digital twin platforms can be scaled to verify long-term performance under real-world circumstances.
- AI models with a foundation in mechanics and physics to close the gap between empirical data and forecasting insights. In conclusion, adhesives and sealants are positioned as crucial levers for high-performance, low-impact buildings at the nexus of advanced material science, artificial intelligence, and sustainability frameworks. It will need multidisciplinary cooperation, regulatory adaption, and open data practices to realize this promise, making sure that innovation is both responsible and revolutionary.

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