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IMPACT OF 3D PRINTING CONSTRUCTION ON INDOOR MICROCLIMATE AND USER COMFORT

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IMPACT OF 3D PRINTING CONSTRUCTION ON
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A THESIS APPROVED FOR THE
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This thesis is dedicated to my family, whose unwavering love, encouragement, and faith have been my greatest source of strength. Their constant support inspired me to persevere through every challenge of this academic journey. I also dedicate this work to my professors and mentors, whose guidance and insights shaped not only this research but also my understanding of the value of innovation and purpose in design. To my friends and colleagues, thank you for your encouragement and belief in this vision. And finally, this work is dedicated to everyone striving to make housing more sustainable, comfortable, and accessible through new technologies like 3D Printing - an innovation that continues to redefine the future of how we build and live.

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Abstract

The escalating demand for affordable housing has prompted the exploration of innovative construction methods, with 3D Printing emerging as a promising solution. This study investigates the indoor environmental quality (IEQ) performance of 3D-printed homes, focusing on thermal comfort, humidity control, air quality, and acoustic performance, compared to traditional construction methods.

Employing a comparative case study methodology, the research assessed a. 3D-printed home and a conventional residence in Los Angeles, California. Quantitative IEQ data were collected using instruments such as thermo-hygrometers, CO_2 monitors, and sound level meters to measure parameters like indoor temperature, humidity, CO_2 concentration, and noise levels, respectively. These measurements were compared with the ASHRAE standard for human comfort to understand how 3D-printed homes perform in terms of IEQ.

Results indicate that 3D-printed homes demonstrated superior humidity stability and acoustic insulation, with indoor noise levels averaging 35.2 dB compared to 37.0 dB in traditional homes. However, thermal mass properties led to higher heat retention, with average temperatures of 82.1°F versus 81.3°F. CO_2 levels remained within ASHRAE standards in both housing types, though occupancy patterns significantly influenced readings. These findings suggest that 3D-printed construction offers promising IEQ benefits, particularly for humidity control and noise reduction, while highlighting the need for enhanced passive cooling strategies in warm climates.

The findings offer valuable insights into the potential of 3D Printing technology to enhance livability and comfort in affordable housing solutions. By analyzing the IEQ parameters, the research seeks to contribute to the discourse on sustainable and innovative construction practices, informing stakeholders in the construction industry about the viability of 3D-printed homes as a solution to housing challenges.

Key Words: Additive Manufacturing, Affordable Housing, 3D Printing Construction, Indoor Environmental Quality (IEQ), Indoor Microclimate, Sustainable Housing, Traditional Construction

Definition of Key Terms

- **Additive Manufacturing:** Additive manufacturing, often referred to as 3D Printing, is a process where materials are added layer by layer to build an object from a digital model. In construction, this means entire walls or building components can be created directly on-site using robotics - making it faster, more efficient, and less wasteful than traditional methods (Ngo et al., 2018; Rekhi et al., 2022).
- **Affordable Housing:** Affordable housing means a home that people can realistically afford without sacrificing other basic needs. It's usually defined as housing that costs no more than 30% of a household's income. For millions of families, especially low- to moderate-income earners, having access to affordable housing is essential for financial stability and quality of life (The GAP | National Low Income Housing Coalition, n.d.).
- **3D Printing Construction:** 3D Printing construction is a modern method of building that uses large-scale printers to "print" homes layer by layer, usually with a special type of concrete or composite material. It cuts down on time, cost, and waste, and is gaining attention as a possible game-changer in affordable housing (Weng et al., 2020; Rekhi et al., 2022).
- **Indoor Environmental Quality (IEQ):** Indoor Environmental Quality (IEQ) refers to how healthy, comfortable, and pleasant the indoor spaces of a building are. It includes things like the air we breathe, how warm or cold the space feels, how much noise there is, and how much natural light comes in. All of these factors together influence how people feel, work, and live inside a space (EPA, 2023; ASHRAE, 2021).
- **Indoor Microclimate:** The indoor microclimate is the small-scale environment inside a home - things like temperature, humidity, airflow, and light. These conditions can vary

even within one room, and they play a big role in how comfortable and energy-efficient a building is (Zhang et al., 2023).

- **Sustainable Housing:** Sustainable housing is about building homes that are better for the environment and healthier for the people living in them. These homes use less energy, create less waste, and often include materials that are either recycled or eco-friendly. The goal is to reduce the environmental footprint while still meeting people’s housing needs (Bos et al., 2020; Muñoz et al., 2021).
- **Traditional Construction:** Traditional construction is the conventional way of building homes, using materials like wood, bricks, or concrete and relying heavily on manual labor. While it’s a proven and widely used method, it often takes longer and costs more, and it tends to generate more waste compared to newer technologies like 3D Printing (Muñoz et al., 2021; Weng et al., 2020).

CHAPTER I - INTRODUCTION

1.1: Background

The affordable housing crisis in the United States is more than just numbers and statistics. The cost of housing has skyrocketed over the years, far outpacing wage growth, and for many families, the dream of owning a home or even finding an affordable rental feels increasingly out of reach. This crisis affects not only low-income families but also middle-class workers, seniors on fixed incomes, and young professionals just starting out. It's a problem that has rippling effects across communities, impacting everything from economic stability to mental health and social mobility.

One of the clearest signs of this crisis is the growing number of "severely cost-burdened" households - people spending more than half of their income on rent. In 2020, this included about 11.2 million renters, leaving them little room in their budgets for essentials like food, healthcare, and savings for the future (*5 Absurd Facts About the Housing Crisis*, 2020). Despite working hard, many people are just one unexpected expense away from financial hardship or even homelessness.

The housing affordability crisis is no longer limited to major metropolitan areas. Although high-cost regions like California, Florida, and the Northeast remain severely affected, smaller cities and rural communities are increasingly experiencing similar challenges. Rising home prices and rental rates nationwide are making it difficult for people to secure affordable housing - whether in bustling urban areas or quiet suburban neighborhoods (Siniavskaia, 2024). Both renters and homeowners are feeling the strain, with recent data showing that millions in each group are burdened by housing costs. In fact, renters are facing the highest affordability challenges on record: the 2023 American Community Survey reports that over 23 million renter

Households - more than half - spend at least 30% of their income on housing. Similarly, approximately 20.6 million homeowners are also considered cost-burdened (Siniavskaia, 2024).

While some reports suggest that housing costs have slightly eased in 2024 (Kuo, 2024), such reductions are insufficient to reverse the deeper issues. Rental prices may experience temporary stabilization for a short period, but wage growth continues to lag behind, and the cost of living persists in its upward trajectory. Housing costs remain one of the biggest drivers of inflation, making it even tougher for everyday people to get ahead financially (Kuo, 2024). There are significant demand of affordable homes as only 35 affordable and available units exist for every 100 extremely low-income renter households, leaving a nationwide shortage of over 7 million units (*The GAP | National Low Income Housing Coalition*, n.d.). Decades of underbuilding, restrictive zoning laws, rising construction costs, and a shortage of skilled labor have all contributed to this crisis.

The housing crisis is about opportunity, stability, and quality of life. Without access to safe and affordable housing, families struggle to build a future, children's education suffers, and entire communities feel the strain.

1.2: 3D Printing Construction and Affordable Housing

As the housing shortage continues to grow, innovative construction methods are needed to address the affordability gap. Traditional construction, while reliable, is slow, labor-intensive, and expensive, making it difficult to keep up with rising demand. However, advancements in 3D printing construction (3DPC) offer a potential solution that could revolutionize the way homes are built. 3DPC technology leverages advanced robotics and additive manufacturing to construct homes faster, more affordably, and with greater precision than conventional methods.

Compared to traditional construction, 3DPC can reduce construction time by up to 70% and costs by up to 30%, making it a viable option for large-scale affordable housing projects (Rekhi et al., 2022). Additionally, this method minimizes material waste and requires significantly fewer workers, which helps alleviate labor shortages in the construction industry. The efficiency and sustainability of 3D Printing technology makes it a powerful tool in the fight against the housing crisis.

Along with benefits in cost and speed, 3D-printed homes are often more durable and energy-efficient, helping homeowners save on utility costs while reducing environmental impact. With its ability to streamline processes, optimize resource usage, and rapidly deploy housing solutions, 3D Printing has the potential to reshape the future of construction (Rekhi et al., 2022). By embracing this innovation, policymakers and developers can create scalable, cost-effective solutions that meet the growing demand for affordable housing and provide more families with safe, high-quality homes.

1.3: 3D Printing Construction and Microclimate

Beyond its structural and environmental benefits, 3DPC has also significant potential to enhance indoor microclimates, such as temperature, air quality, and acoustics. These factors play a crucial role in indoor environmental quality (IEQ), directly affecting occupant health, comfort, and long-term sustainability.

1.3.1: Thermal Performance and Energy Efficiency

The layered printing process of 3DCP allows for customized wall thickness and insulation properties, which is particularly advantageous in extreme climates such as deserts. These regions experience significant temperature fluctuations between day and night, requiring effective insulation to maintain indoor comfort. 3D-printed structures with high thermal mass can help regulate temperature fluctuations, reducing reliance on artificial heating and cooling systems. This passive climate control approach leads to lower energy consumption and improved occupant comfort, making 3DCP an ideal choice for net-zero energy housing (Weng et al., 2020).

1.3.2: Indoor Air Quality and Health Benefits

Traditional construction methods release dust, volatile organic compounds (VOCs), and other airborne pollutants due to the use of adhesives, synthetic materials, and off-gassing from construction products. The precision of 3DCP eliminates excessive cutting, plastering, and finishing processes, reducing dust and emissions of harmful pollutants. 3DCP improves indoor air quality and minimizes health risks associated with respiratory issues, chemical exposure, and allergies (X. Zhang et al., 2023).

1.3.3: Acoustic Performance and Noise Reduction

Acoustics play a crucial role in occupant comfort, especially in residential and office spaces. Traditional construction often involves rigid materials that create echo and poor sound absorption. 3DPC offers design flexibility that can optimize sound diffusion and absorption, improving indoor sound quality and noise reduction. The layered texture of 3D-printed walls, along with the ability to incorporate customized surface geometries, enhances sound insulation and reverberation control, making it particularly beneficial for high-density urban environments (Muñoz et al., 2021).

1.4: Research Problem

While 3D Printing in construction has been praised for being fast, cost-effective, and sustainable, its impact on indoor microclimate and user comfort in daily living hasn't been sufficiently explored. As more 3D-printed homes are built, it's important to investigate not only their affordability, but also livability, health, and occupant well-being.

This research focuses on three key issues:

1.4.1: Affordable Housing Gap

The United States is facing a major housing shortage, with over 7 million low-income households unable to find affordable homes (*The GAP | National Low Income Housing Coalition*, n.d.). Traditional construction methods have shown insufficient in addressing this deficit. This study looks at 3D Printing as a faster, more affordable way to help close that gap.

1.4.2: Indoor Microclimate Performance

Traditional homes often struggle with air quality, temperature control, and energy use, especially in extreme weather. 3D-printed homes may offer better solutions through materials and designs that naturally regulate temperature, improve ventilation, and reduce noise. This research compares both housing types to see which offers a healthier indoor environment.

1.4.3: User Comfort

User comfort is about how people feel in the spaces where they live. Environmental factors that contribute to user comfort include how warm or cool a room feels, how quiet it is, how fresh the air is, and whether the space supports everyday activities without causing discomfort or stress. Comfort isn't just a luxury; it directly affects sleep, focus, health, and overall quality of life. In this study, user comfort is viewed as a key aspect of indoor environmental quality (IEQ).

By comparing 3D-printed and traditionally built homes, this research explores how different construction methods impact the day-to-day comfort of occupants, helping us better understand what truly makes a home livable. As the field of 3D-printed architecture expands, there is a growing need to bridge the gap between structural innovation and interior design, ensuring that 3D-printed homes are not only cost-effective and sustainable but also optimized for human wellbeing.

1.5: Research Purpose

This research explores the role of 3D Printing construction technology in addressing affordable housing challenges, ensuring indoor environmental conditions and user comfort. This study compares the indoor environmental quality (IEQ) performance of 3D-printed homes and traditionally constructed homes, in terms of thermal comfort, air quality, and sound insulation. The findings from this comparison analysis will inform the potential of 3D-printed structures as a sustainable and economical alternative to conventional building techniques. By filling current knowledge gaps, the research seeks to inspire practitioners, policy makers, and designers in advancing the development of healthier, more accessible housing solutions.

1.6: Research Questions

This study aims to answer the following research questions:

RQ 1: How do the 3D-printed homes influence indoor microclimate conditions compared to conventional construction methods?

RQ 1.1: How does the thermal performance (indoor temperature regulation) of 3D-printed homes differ from that of traditionally constructed homes?

RQ 1.2: In what ways does the indoor humidity level in 3D-printed homes differ from that in conventional homes, especially regarding comfort and moisture control?

RQ 1.3: How does the indoor air quality in 3D-printed homes, measured by CO2 level, differ from that in conventionally built homes?

RQ2: To what extent do 3D-printed homes impact indoor noise levels relative to traditional homes?

1.7: Significance of Study

The affordable housing crisis in the United States continues to affect millions of families who are struggling to find safe, livable homes within their means. As of 2023, over 23 million renter households - more than half - spend at least 30% of their income on housing, while approximately 20.6 million homeowners are considered cost-burdened (Siniavskaia, 2024). The nation also faces a shortage of over 7 million affordable and available units for extremely low-income renters (The GAP | National Low Income Housing Coalition, n.d.). These challenges are driven by rising construction costs, slow production rates, restrictive zoning laws, and labor shortages.

This study explores how 3D Printing construction (3DPC) can provide a faster, more cost-effective, and environmentally sustainable alternative to traditional building methods - while also ensuring healthy, comfortable indoor environments for residents (Rekhi et al., 2022). By examining both affordability and indoor environmental quality, this research aims to offer insights into how 3D-printed housing can contribute to long-term, scalable solutions. Stable, affordable housing is more than just a structure - it's a foundation for health, dignity, and opportunity, and should be recognized as a basic human right.

1.7.1: Social Impact

3D Printing offers the potential to revolutionize how quickly homes can be built, especially in high-demand or housing-scarce regions. Compared to traditional construction, it can significantly reduce building time, enabling faster responses to urban housing needs and population growth (Rekhi et al., 2022). Beyond speed, this study also considers the livability of these structures - particularly their effects on indoor air quality, temperature control, and acoustics. Ensuring that 3D-printed homes are not only fast to build but also healthy and comfortable to live in is critical (Zhang et al., 2023). Additionally, 3D Printing presents promising applications in disaster relief, offering the ability to quickly construct safe shelters for displaced populations in areas affected by natural disasters (Weng et al., 2020).

1.7.2: Economic Impact

The economic potential of 3D-printed construction lies in its ability to reduce both material and labor costs. By streamlining the building process, it has the capacity to make homeownership more accessible and affordable for broader populations (Rekhi et al., 2022). At the same time, as the industry grows, it creates new job opportunities in robotics, sustainable material innovation, digital modeling, and automated construction technologies (Muñoz et al., 2021). This shift could reshape the future construction workforce. Moreover, studying the scalability of 3D-printed housing helps inform long-term urban planning and policymaking - especially when considering large-scale implementation across cities and communities (Rekhi et al., 2022).

1.7.3: Environmental Impact

From an environmental standpoint, 3D Printing stands out for its ability to minimize construction waste and reduce carbon emissions compared to traditional methods (Mohammad et al., 2020). Its precision and material efficiency result in cleaner, more sustainable building processes. This research also investigates the energy performance of 3D-printed homes, including whether their structure and materials can improve thermal insulation, regulate indoor temperatures, and reduce overall energy consumption (Zhang et al., 2023). Furthermore, there is growing interest in using eco-friendly materials, such as bio-based composites or recycled substances, to make 3D-printed construction even more sustainable (Muñoz et al., 2021).

1.7.4: Academic Contribution

This study contributes to the current body of knowledge by examining how 3D-printed homes perform in terms of indoor environmental quality - including air purity, thermal comfort, and sound insulation - and how these metrics compare to those of conventional buildings (Zhang et al., 2023). It also evaluates how well these homes adapt to various climate conditions, especially in regions experiencing extreme heat, cold, or humidity (Weng et al., 2020). Finally, this research explores how smart interior design can be integrated with 3D-printed structures, blending automation, energy systems, and ergonomic layouts to enhance daily living (Rekhi et al., 2022).

1.8: Scope of Study

The delimitations of this study are as follows:

- **Target:** For this research, affordable housing availability refers to the ability of people in low- and moderate-income brackets to access housing that meets their financial means without sacrificing basic needs (Kuo, 2024). This study examines how 3D Printing technology can make affordable housing more accessible by lowering construction costs, speeding up production, and improving indoor living conditions (Rekhi et al., 2022). Instead of just focusing on affordability, this research also considers whether these homes provide a good quality of life, including healthy indoor air, stable temperatures, and noise reduction (Zhang et al., 2023).
- **Location:** This research focuses on 3D Printing construction projects within the United States, specifically those designed to provide housing for low-to moderate-income

individuals and families who struggle to afford market-rate housing. The study will not examine international projects or compare affordable housing practices across different countries.

- **Time Frame:** The study focuses on recent projects from the past five years (2018-2023). It will not include older or early-stage projects that may not represent the current state of 3D Printing technology.
- **Technology:** The study looks specifically at the use of 3D Printing for building the structure of homes, such as walls and foundations. It won't explore other construction methods like modular or prefabricated housing.
- **Target Group:** The research explores how 3D Printing impacts low-income and underserved communities. It won't address the broader housing market or luxury homes.
- **Key Perspectives:** The study will mostly include insights from housing developers, architects, and environmental designers, rather than from residents or long-term occupants of 3D-printed homes.

1.9: Conclusion

This study examines how 3D Printing in construction can influence the provision of affordable housing and the indoor environment. With the housing crisis continuing to grow, 3D Printing offers a fresh solution by cutting down costs and speeding up the building process while also addressing important environmental and structural concerns. The research will focus on recent projects in the U.S. and how they might help those in need of affordable housing, especially in underserved areas. In addition, the study will explore how 3D-printed homes affect the indoor environment, such as air quality, temperature, and overall comfort, which are essential for people's health and well-being. Ultimately, this research hopes to show how 3D Printing can help shape the future of housing, creating a more sustainable and accessible way for people to live.

CHAPTER II: LITERATURE REVIEW

2.1: 3D Printing Construction Technology

3D Printing, also known as additive manufacturing, is transforming construction methods by enabling the creation of entire structures through a layer-by-layer process using advanced machines and materials. This approach is faster, more efficient, and offers greater design flexibility compared to traditional construction methods (Rekhi et al., 2022). Several techniques are commonly used in 3D Printing for construction, including extrusion-based printing, where concrete is precisely deposited through a nozzle, eliminating the need for formwork. Other methods, like binder jetting and contour crafting, further automate the process, making it possible to create walls and structural elements with minimal human labor (Weng et al., 2020).

Among various applications of 3D Printing, its use in the residential sector stands out for its potential to address the global shortage of affordable homes. Large-scale projects, such as entire neighborhoods built with 3D-printed homes, show how this technology can provide cost-effective solutions in a fraction of the time it takes with traditional methods (*5 Absurd Facts ABout the Housing Crisis*, 2020). With rising construction costs and inflation making housing even more expensive, 3D Printing offers a promising alternative (Kuo, 2024). Not only is it faster, but it also reduces waste and lowers carbon emissions, making it a more sustainable choice for the future (Muñoz et al., 2021).

Building upon this foundation, the growing adoption of 3D Printing in residential applications has paved the way for innovative housing prototypes and pilot communities worldwide. As research progresses, the focus has shifted from demonstrating technical feasibility to exploring how 3D-printed homes perform in terms of comfort, affordability, and sustainability compared to conventional construction.

2.2: 3D-Printed Homes

3D Printing is advancing home construction by providing a quicker, more affordable, and eco-friendly alternative to conventional building methods. Instead of relying on manual labor and extensive material use, this technology builds homes layer by layer using automated machinery, significantly reducing waste and speeding up the process (Rekhi et al., 2022). As housing shortages and affordability concerns continue to rise worldwide, researchers and industry leaders are increasingly looking at 3D Printing as a practical solution.

One of the most widely used methods of 3D Printing homes is extrusion-based printing, where concrete or other construction materials are precisely deposited through a robotic nozzle. This eliminates the need for traditional frameworks, cutting down on both material costs and construction time (Weng et al., 2020). Research has also highlighted the environmental benefits of this technology, as it reduces material waste and carbon emissions compared to conventional building techniques (R.-C. Zhang et al., 2023).

The housing crisis has made affordability a growing concern, and 3D Printing is emerging as a potential solution. Housing (2020) points out that the ability to construct homes quickly and at a lower cost could help address this issue. At the same time, rising labor costs and inflation have made traditional homebuilding more expensive, pushing the industry to explore alternatives like automation and digital fabrication (Kuo, 2024).

While 3D-printed homes offer significant advantages in speed, cost, and sustainability, their widespread adoption still faces practical barriers. Understanding these limitations is essential to advancing the technology from experimental demonstrations to large-scale residential applications. The following section discusses these existing challenges and areas requiring further development for successful implementation.

2.3: Challenges in Adopting 3D Printed Homes

While 3D Printing is recognized as an innovative approach to home construction, several challenges still stand in the way of its broader adoption. One key limitation is the lack of standardized building codes specific to 3D-printed structures, which creates uncertainty for builders, regulators, and policymakers (Siniavskaia, 2024). There are also ongoing concerns about the long-term durability and structural reliability of these homes, especially under varying climate conditions (Rekhi et al., 2022). In addition, the process of seamlessly integrating essential utilities - such as electrical wiring, plumbing, and HVAC systems - into printed components is still evolving (Zhang et al., 2023). Despite these obstacles, steady progress is being made. Improvements in material performance, construction automation, and design flexibility are helping to address many of these technical gaps. As the technology matures and regulations evolve, 3D-printed homes have strong potential to become a practical, sustainable, and affordable solution to meet future housing needs (Weng et al., 2020; Rekhi et al., 2022). In short, 3D-printed homes have the potential to revolutionize housing by making construction faster, cheaper, and more environmentally friendly. While some technical and regulatory challenges still need to be addressed, ongoing innovation is bringing this technology closer to widespread use. If these advancements continue, 3D Printing has the potential to play a key role in mitigating the global housing crisis.

Understanding these challenges is essential to appreciating how far 3D Printing in construction has progressed over time. Examining its historical development provides valuable context for current innovations and reveals how past breakthroughs have shaped today's advancements. The following section outlines the evolution of 3D Printing in construction, highlighting key milestones that mark its journey from experimental technology to real-world application.

2.4: History of 3D Printing in Construction

3D Printing in construction has evolved significantly over the past few decades, transforming from a concept into a viable building method. Figure 1 illustrates a timeline of key developments of 3D Printing construction from its origin, and Table 1 presents year-by-year development of 3D Printing in construction worldwide.

Figure 1

History of 3D Printing in Construction (Nampally,2025)

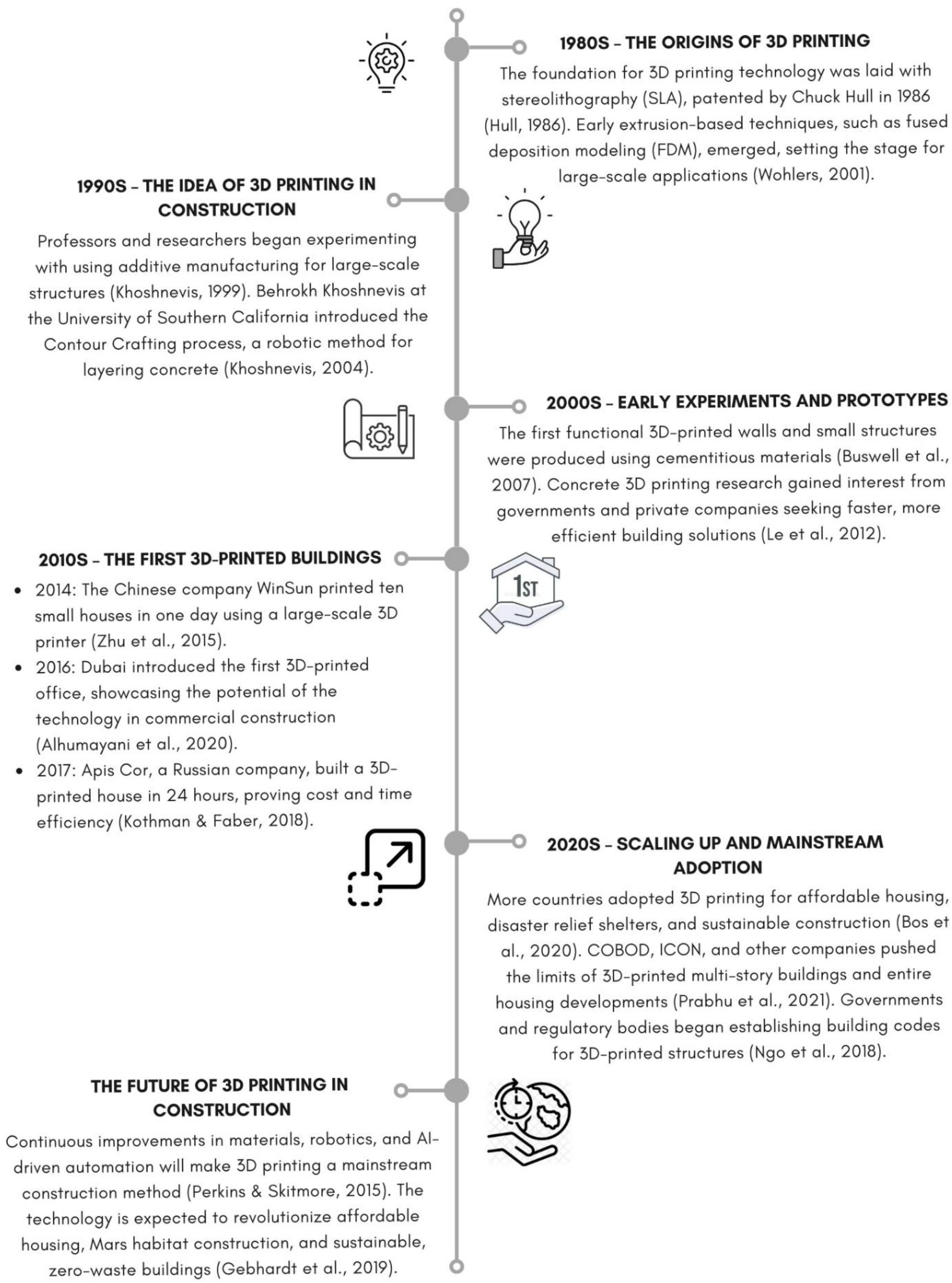


Table 1.

Year-by-Year Development of 3D Printing in Construction

2004: Contour Crafting Introduced	• Behrokh Khoshnevis developed Contour Crafting, a robotic 3D Printing method designed for construction (Rekhi et al., 2022). • This technique demonstrated the feasibility of layer-by-layer additive manufacturing for building structures, reducing labor costs and construction time.
2014: WinSun's Mass-Produced 3D-Printed Houses	• WinSun, a Chinese company, printed 10 small houses in just 24 hours using a large-scale 3D printer (Weng et al., 2020). • This marked the first large-scale demonstration of prefabricated 3D-printed concrete elements in residential construction.
2016: Apis Cor Prints a Full House in 24 Hours	• The Russian company Apis Cor successfully printed a full-scale house in 24 hours using a mobile 3D Printing system (Weng et al., 2020). • Unlike WinSun's prefabrication method, Apis Cor's approach printed the structure on-site, showing potential for more flexible applications.
2018: ICON and New Story Build the First Permitted 3D-Printed Home	• ICON and New Story built the first permitted 3D-printed home in Austin, Texas, as part of an initiative to provide affordable housing (Rekhi et al., 2022). • This project demonstrated how 3D Printing could revolutionize housing for low-income communities and disaster relief efforts.
2020: Dubai Municipality Builds the World's Largest 3D-Printed Building	• Dubai Municipality completed the world's largest 3D-printed building, a two-story structure spanning 6,900 square feet (Weng et al., 2020). • This project emphasized the feasibility of multi-story 3D Printing in commercial construction.
2021: Europe's First 3D-Printed Residential Building Completed	• Germany unveiled its first 3D-printed residential building, demonstrating that the technology could be successfully integrated into Western construction markets (Rekhi et al., 2022). • This marked a shift toward regulatory approval and mainstream acceptance of 3D-printed housing.
2022: NASA Explores 3D Printing for Space Habitats	• NASA began researching 3D-printed habitats for space exploration, particularly for Mars and Moon missions (Rekhi et al., 2022). • This initiative highlighted how 3D Printing could be used in extreme environments with limited access to traditional building materials.

Future Outlook	• Continued advancements in printing speed, material durability, and automation are expected to push 3D Printing further into mainstream residential and commercial construction (Weng et al., 2020). • The demand for sustainable and affordable housing is driving rapid adoption of 3D Printing technologies worldwide.

These milestones mark the foundation of today's construction innovation. As 3D Printing technology evolved from early prototypes to large-scale applications, it paved the way for diverse printing methods adapted to different materials and structural goals. The next section outlines the main 3D Printing techniques currently used in the construction industry.

2.5: 3D Printing Techniques in Construction

3D Printing in construction relies on several advanced techniques, each tailored to different structural and material requirements. These methods aim to reduce construction time, minimize material waste, and improve efficiency, making them particularly useful for sustainable and affordable housing projects. Table 2 shows the widely used techniques: extrusion-based printing, binder jetting, and contour crafting.

Table 2.

Techniques of 3D Printing Construction

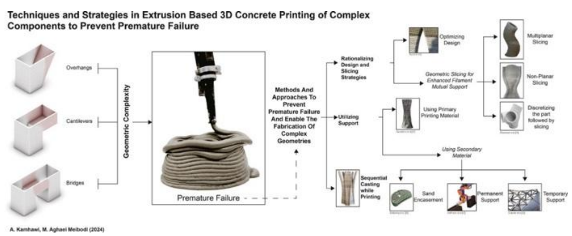
<table>
<tr><th></th><th>Extrusion-Based Printing</th><th>Binder Jetting</th><th>Contour Crafting</th></tr>
<tr><td>Description</td><td>The most widely used 3D Printing method in construction. It involves extruding construction materials - such as concrete, clay, or geopolymer mixtures - through a nozzle, layer by layer, to create walls and structural components.</td><td>A technique spraying a liquid binding agent onto a powdered material base - such as sand, gypsum, or metal powders - to form solid layers.</td><td>An automated construction method that uses robotic arms to apply layers of concrete or similar materials. Developed by Behrokh Khoshnevis, it is designed for rapid, large-scale construction (Weng et al., 2020).</td></tr>
<tr><td>Figure</td><td>

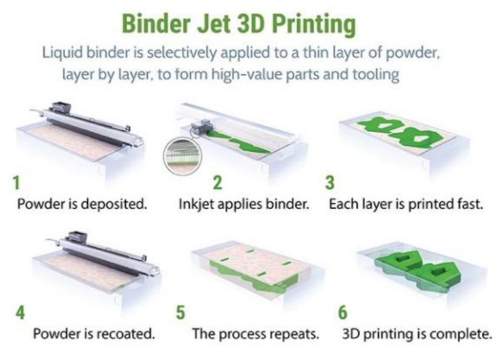
***Figure 2:** Extrusion-Based 3D Printing Construction method* (Kamhawi & Aghaei Meibodi, 2024)</td><td>

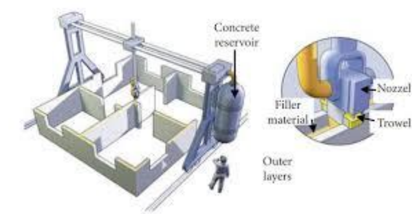
***Figure 3:** Binder Jetting 3D Printing Construction method* (3D Tech Valley, n.d.)</td><td>

***Figure 4:** Contour Crafting 3D Printing Construction method* (Rahman et al., 2020)</td></tr>
<tr><td>Process</td><td>A robotic arm or gantry system moves along a pre-programmed path, depositing the material in precise layers, gradually forming the structure.</td><td>A thin layer of powdered material is spread across the build area.
A printhead sprays a binding solution, causing the material to harden in specific areas. The process repeats layer by layer until the full structure is formed.</td><td>A robotic system moves a specialized nozzle along a predefined path. The outer shell (contour) of the building is printed first, providing a smooth and precise structure. The interior is then filled with</td></tr>
</table>

		• Excess powder is removed, and the structure may undergo post-processing for additional strength.	insulation or reinforcement materials, making it more robust.
Advantages	• Use locally available construction materials. • Reduces labor requirements and speeds up the building process. • Less material waste compared to traditional construction.	• High precision and fine detail in printed structures. • Can use various materials, including sand, ceramic, and even recyclable materials. • Works well for custom architectural designs and complex geometries.	• Significantly reduces construction time. • Uses automation, requiring minimal human labor. • Can print large-scale buildings in a single process, improving efficiency.
Application	• This method has been used by companies like ICON, Apis Cor, and WinSun to construct houses, office buildings, and emergency shelters (Muñoz et al., 2021).	• It is used for creating decorative building facades, custom molds, and non-load-bearing walls.	• Suitable for disaster relief housing, emergency shelters, and low-cost housing projects. It has also been explored for use in lunar and Martian habitat construction by NASA.
Cost Factor	• $4,000 - $10,000 per small house (depending on materials and labor costs). • Labor savings: Requires fewer workers, cutting labor costs by up to 50%.	• More expensive upfront than extrusion-based printing. • Used mainly for custom designs rather than full buildings.	• Cuts labor costs by 60-80% since most of the process is automated. • Significant material savings, reducing waste by up to 70%. • Can build a single-story home for as little as $10,000-$20,000 (compared to $150,000+ for traditional methods).

These diverse methods collectively demonstrate how 3D Printing adapts to different design and environmental needs. Understanding the techniques provides a technical foundation for comparing their efficiency and performance with traditional construction methods. The next section presents a comparative analysis between 3D-printed and conventional housing systems.

2.6: Comparison between 3D Printing and Traditional Housing

As housing prices continue to rise, 3D Printing is emerging as a promising solution for affordable homes. Organizations like ICON (*Intelligent Machines Building Humanity's Future - ICON*, n.d.) and Apis Cor (Apis Cor, 2025) are developing entire communities using 3D Printing, reducing costs and construction time dramatically (*5 Absurd Facts ABout the Housing Crisis*, 2020). In areas affected by natural disasters, 3D Printing also enables the rapid construction of shelters, providing faster relief to displaced communities (Rekhi et al., 2022).

The construction industry is undergoing a major transformation with the introduction of 3D-printed homes, offering faster, cost-effective, and sustainable alternatives to traditional building methods. While traditional construction remains dominant due to its proven reliability and regulatory acceptance, 3D Printing is gaining momentum, especially for affordable housing and disaster relief projects.

Table 3.

Comparison between 3D Printing and Traditional Housing

Factor	3D Printing Construction	Traditional Construction	Sources
Construction Period	Homes can be printed in days or weeks, significantly reducing project timelines due to automation. Some projects have been completed in less than 24 hours (Rekhi et al., 2022).	Construction can take months or years, depending on project complexity, labor availability, and supply chain delays (Weng et al., 2020).	Rekhi et al., 2022; Weng et al., 2020

Cost	30-50% cheaper due to reduced labor costs, lower material waste, and efficient production (Muñoz et al., 2021). Estimated cost per small 3D-printed house: $4,000 - $10,000.	Higher costs due to manual labor, fluctuating material prices, and waste. A traditional home costs at least $150,000, depending on location and design (Bos et al., 2020).	Muñoz et al., 2021; Bos et al., 2020
Sustainability	Reduces material waste by up to 70%, has a lower carbon footprint, and can use eco-friendly, locally sourced materials (Perkins & Skitmore, 2015).	More resource-intensive, with high energy use, significant waste generation, and a larger environmental impact (Ngo et al., 2018).	Perkins & Skitmore, 2015; Ngo et al., 2018
Customization	Easily customizable with complex, organic, or futuristic designs at little to no extra cost (Buswell et al., 2007).	Customization is complex and expensive, requiring skilled labor and additional materials and time (Zhu et al., 2015).	Buswell et al., 2007; Zhu et al., 2015
Labor Needs	Requires fewer workers (typically 2-3 operators), reducing labor costs by 50-80%. However, highly skilled personnel are needed for operating 3D printers and material preparation (Le et al., 2012).	Requires a large workforce with expertise in masonry, carpentry, plumbing, and electrical work. High dependency on manual labor leads to higher costs (Wohlers, 2001).	Le et al., 2012; Wohlers, 2001
Structural Strength	3D-printed structures can be reinforced with steel fibers, concrete admixtures, or composite materials to enhance durability (Prabhu et al., 2021). However, long-term performance is still being studied.	Traditional buildings are proven to last for decades or centuries, depending on materials and maintenance (Kothman & Faber, 2018).	Prabhu et al., 2021; Kothman & Faber, 2018
Material Use	Uses concrete, polymers, geopolymers, and recycled materials, allowing for eco-friendly and cost-effective alternatives (Alhumayani et al., 2020).	Uses wood, bricks, steel, and cement, which often involve higher costs and environmental impact (Ngo et al., 2018).	Alhumayani et al., 2020; Ngo et al., 2018
Building Regulations	Still developing worldwide, requiring new standards and	Follows well-established building codes and regulations	Bos et al., 2020;

	certifications to ensure safety and compliance (Bos et al., 2020).	that ensure safety, durability, and quality (Gebhardt et al., 2019).	Gebhardt et al., 2019
Weather Resistance	Can be engineered for extreme weather conditions but long-term durability tests are ongoing (Weng et al., 2020).	Traditional homes have a proven record for withstanding hurricanes, earthquakes, and other natural disasters (Perkins & Skitmore, 2015).	Weng et al., 2020; Perkins & Skitmore, 2015
Market Adoption	Still in early stages, with adoption limited to pilot projects and experimental housing (Rekhi et al., 2022).	Mainstream and widely accepted, with a proven track record and established market (Zhu et al., 2015).	Rekhi et al., 2022; Zhu et al., 2015

The comparison highlights how 3D Printing outperforms traditional methods as per Table 3, in terms of efficiency, cost, and environmental impact. However, practical differences in construction time, cost, and automation must be explored in detail to understand its feasibility for large-scale adoption. The following subsections examine these dimensions more closely.

2.6.1: Construction Period for 3D Printed Home

3D-printed homes are built much faster than traditional construction, with the timeframe depending on size, design, and materials.

- *Small Homes (400-600 sq. ft.) - 12* to 48 hours for the main structure (Apis Cor built a 400 sq. ft. home in 24 hours) (Weng et al., 2020).
- *Medium Homes (600-1,500 sq. ft.)* – 2 to 7 days, plus extra time for plumbing, wiring, and finishing (WinSun printed ten 650 sq. ft. homes in one day) (Muñoz et al., 2021).
- *Large Homes & Multi-Story Buildings (1,500+ sq. ft.)* – 2 to 4 weeks, requiring additional reinforcement (Dubai built a 6,900 sq. ft. 3D-printed building in two weeks) (Weng et al., 2020).

- *Entire Neighborhoods* – A few months (ICON built a 3D-printed housing community, with each home completed in 24-48 hours) (Rekhi et al., 2022).

These findings illustrate how automation reduces construction duration dramatically, positioning 3D Printing as a time-efficient alternative to conventional methods.

2.6.2: Cost of 3D-Printed Construction

According to cost analysis between 3D Printing and traditional methods, 3D Printing in construction is significantly cheaper than traditional methods due to reduced labor, material savings, and faster build times. The cost varies based on size, material type, and location, but general estimates are as follows:

- *Small Homes (400-600 sq. ft.)* Cost: $4,000 - $10,000

  Example: Apis Cor's 3D-printed home in Russia cost around $10,134 (Weng et al., 2020).

- *Medium Homes (600-1,500 sq. ft.)* Cost: $10,000 - $50,000

  Example: ICON built 500 sq. ft. homes for under $10,000 each in Mexico (Rekhi et al., 2022).

- *Large Homes & Multi-Story Buildings (1,500+ sq. ft.)* Cost: $50,000 - $200,000

  Example: A 6,900 sq. ft. Dubai Municipality building cost approximately $200,000 (Weng et al., 2020).

- *Entire Neighborhoods* Cost: $5,000 - $15,000 per home

  Example: ICON's affordable housing project in Mexico produced homes for under $10,000 each (Rekhi et al., 2022).

Table 4.

Detailed Cost Comparison

Factor	3D Printing	Traditional Construction
Home Cost	$4,000 - $50,000	$150,000+
Labor Costs	50-80% lower (2-3 workers)	High labor costs (large workforce needed)
Material Costs	30-60% less (less waste)	Expensive materials & waste
Construction Time	Days to weeks	Months to years

(Muñoz et al., 2021; Rekhi et al., 2022)

In summary, 3D Printing can cut housing costs by up to 30–50%, making it a fast, affordable, and eco-friendly alternative to traditional construction. These cost comparisons confirm that 3D Printing can reduce total housing expenses by up to 50%, strengthening its potential for affordable housing initiatives globally, as per Table 4.

2.6.3: Automation and Workforce

The primary advantage of 3D Printing in construction is automation. By relying on robotics and AI-driven systems, homes can be built with minimal human intervention, significantly reducing labor costs (Kuo, 2024). However, this shift also raises concerns about job displacement in the construction industry. While fewer manual laborers may be needed, the demand is increasing for technology-driven roles such as robotics technicians, AI programmers, and material scientists (Siniavskaia, 2024). To adapt to this evolving landscape, governments and companies must invest in upskilling initiatives and training programs to help construction workers transition into these emerging roles.

Overall, automation and digitalization are redefining the construction workforce, linking the benefits of 3D Printing not only to housing affordability but also to long-term sustainability and social transformation.

2.7: 3D-Printed Housing and Indoor Microclimate

Maintaining good indoor air quality (IAQ) is essential for human health and comfort, especially as people spend up to 90% of their time indoors. Key environmental parameters like carbon dioxide (CO_2) levels, humidity, and temperature significantly influence the indoor microclimate and overall wellbeing (EPA, 2023).

The indoor microclimate of a home - including its temperature, humidity, air movement, and air quality - greatly influences comfort, health, and energy efficiency. 3D-printed homes impact these factors through their material composition, structural design, and energy performance. Compared to traditional buildings, 3D-printed structures often offer superior thermal insulation, moisture resistance, and air quality control, creating a healthier and more comfortable indoor environment.

Innovations in 3D Printing materials, such as the use of geopolymer composites, have been shown to enhance indoor humidity regulation by passively buffering moisture, reducing reliance on mechanical systems, and lowering carbon emissions (Nature Communications, 2024). These advancements contribute to improved IAQ by maintaining optimal humidity levels, which is crucial for occupant health and building durability. Furthermore, the design flexibility of 3D Printing allows for the integration of features that promote better air circulation and natural ventilation, further enhancing the indoor environment. By addressing key aspects of the indoor microclimate, 3D-printed homes present a sustainable and health-conscious alternative to conventional construction methods.

The indoor microclimate within 3D-printed homes can be understood through its core environmental factors - temperature, humidity, air quality, and light. Each of these plays a vital role in shaping occupant comfort and energy efficiency. The following subsections examine these parameters individually to highlight how 3D Printing influences indoor environmental performance.

2.7.1: Thermal Performance & Temperature Regulation

One of the biggest advantages of 3D-printed homes is their thermal stability. Thicker printed walls provide better insulation, reducing heat loss in winter and preventing overheating in summer. Unlike traditional homes that rely on additional insulation materials, 3D-printed concrete or geopolymer layers inherently improve thermal efficiency (Weng et al., 2020).

- *Even Temperature Distribution:* Layer-by-layer printing eliminates thermal bridges (gaps where heat escapes), resulting in more stable indoor temperatures (Muñoz et al., 2021).
- *Lower Heating & Cooling Needs:* Well-insulated 3D-printed walls reduce energy consumption by up to 50%, making homes more energy-efficient (Bos et al., 2020).
- *Adaptive Climate Design:* Some 3D-printed homes incorporate passive cooling techniques like curved walls and overhangs, enhancing natural ventilation and reducing heat buildup (Rekhi et al., 2022).

2.7.2: Humidity & Moisture Control

Excess humidity in homes can lead to mold growth, poor air quality, and material deterioration. Traditional homes, especially those using wood or drywall, are more susceptible to moisture-related issues. In contrast, 3D-printed homes use water-resistant materials, improving humidity control.

- *Moisture-Resistant Materials:* Concrete and geopolymers naturally resist water absorption, reducing the risk of mold growth and structural decay (Ngo et al., 2018).
- *Seamless Walls:* Unlike bricks or drywalls, which have joints and gaps where moisture can accumulate, 3D-printed structures are monolithic, preventing water penetration (Le et al., 2012).
- *Breathability & Air Exchange:* Certain earth-based 3D-printed materials (like clay-based mixtures) allow for controlled humidity exchange, keeping the indoor air fresh and balanced (Bos et al., 2020).

2.7.3: Indoor Air Quality (IAQ), CO_2 Levels, and Ventilation

Good indoor air quality is essential for health, comfort, and day-to-day wellbeing - but it's often overlooked in housing design. Traditional homes, especially older ones, can suffer from poor ventilation, chemical-heavy materials, and loose construction. One major concern is the buildup of carbon dioxide (CO_2) - a key indicator of how well a space is ventilated. Elevated CO_2 levels can make people feel tired, sluggish, and less focused.

3D-printed homes, with their modern design and construction techniques, offer several improvements that support cleaner and healthier indoor environments.

- *Healthier Materials and Cleaner Air*

Most traditional homes are built with paints, sealants, and adhesives that release volatile organic compounds (VOCs) - chemicals that can linger in the air and impact respiratory health. In contrast, many 3D-printed homes use geopolymer or bio-based materials that emit significantly fewer VOCs, leading to a safer and fresher indoor environment (Perkins & Skitmore, 2015).

- *Built-in Ventilation through Design*

One advantage of 3D Printing is its design flexibility. Walls can be shaped or patterned to include natural airflow channels, curved forms, or openings that help promote cross-ventilation and prevent air stagnation. These passive ventilation strategies can reduce the need for mechanical systems while supporting steady CO_2 control (Rekhi et al., 2022).

- *Lower CO_2 Buildup Indoors*

CO_2 builds up quickly in enclosed, poorly ventilated spaces - especially when multiple people are present. Traditional homes with leaky windows or outdated HVAC systems often struggle to regulate this. However, 3D-printed homes, thanks to their airtight and energy-efficient construction, tend to maintain lower and more stable CO_2 levels, improving comfort and concentration for those inside (Zhang et al., 2023; EPA, 2023).

- *Fewer Irritants from Mold and Dust*

The monolithic walls in 3D-printed homes leave fewer joints or crevices where moisture, dust, and mold can collect. This makes it easier to keep the air clean and reduces exposure to common allergens - especially in humid climates or poorly ventilated spaces (Bos et al., 2020).

2.7.4: Light & Thermal Mass Effects

The ability of a material to store and release heat - known as thermal mass - affects the indoor climate. 3D-printed concrete and geopolymer materials absorb heat during the day and release it at night, naturally regulating temperature fluctuations.

- *Optimized Daylight Utilization:* 3D-printed homes can be designed with built-in skylights, curved openings, and light-optimized layouts, reducing the need for artificial lighting during the day (Muñoz et al., 2021).

- *Thermal Mass Advantage:* Thick concrete or geopolymer walls store heat in the daytime and release it at night, maintaining a stable indoor environment without over-reliance on HVAC systems (Weng et al., 2020).

These combined factors: thermal regulation, humidity balance, clean air, and light management, define the superior indoor microclimate performance of 3D-printed homes. The next section compares these parameters directly with traditional housing to highlight measurable differences in comfort and efficiency.

2.8: Comparison: 3D-Printed vs. Traditional Homes - Indoor Microclimate Factors

Table 5.

Comparison of Indoor Microclimate Factors

Factor	3D-Printed Homes	Traditional Homes	Sources
Thermal Insulation	Thick walls minimize heat loss	Requires extra insulation	Weng et al., 2020
Humidity Resistance	Water-resistant materials prevent mold	Wood & drywall absorb moisture	Bos et al., 2020
Carbon dioxide (CO_2)	Lower indoor CO_2 levels due to better air tightness and passive airflow design	Higher indoor CO_2 concentrations due to poor sealing and ventilation	Zhang et al., 2023
Indoor noise levels	Dense printed walls absorb sound, reducing indoor noise	Thinner materials and joints lead to higher indoor noise transmission	Muñoz et al., 2021; Bos et al., 2020
Air Quality (VOCs)	Ventilation & Airflow	VOCs from adhesives & paints	Perkins & Skitmore, 2015
Ventilation & Airflow	Custom designs allow better ventilation	Requires additional air circulation systems	Rekhi et al., 2022

Light & Heat Regulation	Thermal mass reduces temperature swings	Heat loss & gain requires extra energy	Muñoz et al., 2021

While this comparison outlines (Table 5) the microclimate benefits of 3D-printed homes, indoor comfort also depends heavily on acoustic quality. The following subsections explore how 3D Printing technology enhances sound insulation and overall acoustic performance.

2.8.1: Acoustic Performance: A Comparison Between 3D-Printed and Traditional Homes

When thinking about what makes a home comfortable, sound matters. Constant noise exposure, whether it's traffic outside, neighbors through thin walls, or echoes inside a room, can impact sleep, concentration, and overall wellbeing. That's why acoustic performance is a key part of indoor environmental quality (IEQ), and it's important to understand how 3D-printed homes handle sound compared to traditional ones.

In most conventional homes, soundproofing depends on materials like wood framing, drywall, and insulation. These assemblies often include air gaps, seams, and joints, which can let sound travel more easily between rooms or from outside. This is especially true in older buildings or in areas with high population density, where sound insulation may not be up to modern standards (Muñoz et al., 2021; Bos et al., 2020).

2.8.2: Monolithic Advantages of 3D-Printed Structures for Sound Insulation

3D-printed homes are built in a completely different way. Instead of using multiple layers of materials, walls are printed in thick, solid layers of concrete or geopolymer, often without any joints. This monolithic structure naturally helps block and absorb sound better. According to research, this type of wall can reduce both airborne noise (like voices or music) and impact noise (like footsteps or door slams) more effectively than standard drywall assemblies (Muñoz et al., 2021; Rekhi et al., 2022).

2.8.3: Material Properties and Their Role in Acoustic Comfort

Materials used in 3D-printed homes, such as cementitious or geopolymer composites, have naturally higher density and mass. This not only helps with temperature regulation but also plays a big role in reducing noise. Unlike timber or drywall, these materials don't vibrate as easily, meaning sound is less likely to travel between rooms or from the outdoors (Bos et al., 2020).

2.8.4: Design Flexibility in 3D Printing for Enhanced Acoustic Performance

Another advantage is design flexibility. With 3D Printing, walls can be made thicker, curved, or textured in ways that diffuse sound and minimize echoes - features that would take extra time and materials to create in traditional construction (Weng et al., 2020).

While all of these points to the acoustic potential of 3D-printed homes, more real-world studies are needed. Most research so far is either experimental or based on simulation. To fully understand how these homes perform acoustically, especially over time and in different settings, we need on-site measurements and input from people actually living in them.

With both microclimate and acoustic advantages established, understanding the measurement tools used to quantify these effects is essential. The following section outlines the instruments and methods used to evaluate indoor air quality and comfort performance.

2.9: Microclimate Measures - Comparing Indoor Air Quality Equipment

Understanding indoor environmental quality (IEQ) goes beyond theory; it requires reliable tools that can capture real-world conditions such as temperature, humidity, carbon dioxide (CO_2) levels, and ambient noise. Since people spend more than 90% of their time indoors, these parameters directly affect comfort, cognitive function, and long-term health. Choosing the right tools for measurement was, therefore, a critical step in ensuring the accuracy and relevance of the study's findings.

In selecting instruments, the review ranges from indoor air quality (IAQ) devices commonly used in research and practice. Each tool varies in scope, accuracy, portability, and data handling features. While some are highly specialized and suited for long-term laboratory installations, others are more field-friendly and designed for case studies like this one. Below is an overview of some of the leading IAQ and acoustic monitoring devices, followed by a justification of the equipment used in this study.

- *Aethair IAQ Monitor:* This device was ultimately chosen as the primary instrument for measuring indoor temperature, humidity, and CO_2 concentration. What made Aethair particularly suitable was its all-in-one sensor suite and portability. The device logs data every minute and supports wireless data export, which was especially helpful when switching between the 3D-printed and traditionally built homes during the summer field study. Its precision and user-friendly interface allowed me to monitor trends over time without interruption. One of the most valuable features of the system is its integration of artificial intelligence. As AI becomes increasingly central to today's technology landscape, the Environet platform stands out by leveraging AI to streamline data extraction. This capability allows for quick and efficient responses to specific research queries, significantly enhancing the speed and accuracy of data analysis.
- *Aranet4:* The Aranet4 is a compact CO_2 monitor popular for its simplicity and long battery life. It provides accurate spot-check measurements for CO_2 and basic climate variables like temperature and humidity. However, it lacks particulate sensing and has

limited memory, making it less suitable for extended data logging in comparative studies. For researchers who want to quickly assess ventilation in small rooms or personal spaces, Aranet4 can be a great choice, but for comprehensive monitoring, it falls short.

- *Testo 160 IAQ:* Testo 160 is a high-end, professional-grade monitor that includes CO_2, temperature, humidity, light, and pressure sensors. It is ideal for institutional buildings and long-term indoor climate evaluations. However, its cost and setup requirements (cloud-based storage and Wi-Fi infrastructure) made it less practical for field-based research. This device is more appropriate for controlled environments where higher-resolution calibration and extended precision are needed.
- *Foobot Smart Monitor:* Foobot is a commercially available, app-connected air monitor that tracks volatile organic compounds (VOCs), particulate matter, humidity, and temperature. Though marketed toward home use, its indirect estimation of CO_2 levels and lack of scientific calibration limit its use in rigorous academic studies. However, it does offer an interesting view into how non-specialist occupants perceive IAQ trends via user interfaces.
- *EXTECH SDL600 Sound Level Meter:* For measuring indoor acoustic comfort, I used the EXTECH SDL600. This device allowed me to collect precise decibel readings inside both houses at various times of day. With an accuracy of ±1.4 dB and options for A and C frequency weighting, the SDL600 met ANSI and IEC Type 2 standards, providing the level of reliability required for comparing construction types. Its SD card-based logging made post-processing straightforward.

Table 6.

Comparative Summary Table of Indoor Air Quality Equipment

Device	Parameters Measured	Accuracy / Range	Data Logging	Portability	Best Use Case
Aethair IAQ	CO_2, PM2.5, Temp, Humidity, VOCs	CO_2: ±50ppm +5%, RH: ±3%, Temp: ±0.5°C	Yes (Wireless)	High	Full-spectrum IAQ studies in field environments
Aranet4	CO_2, Temp, RH, Pressure	CO_2: ±30ppm	Limited (Bluetooth)	Very High	Spot checks; small offices or temporary usage
Testo 160 IAQ	CO_2, Temp, RH, Light, Pressure	Highly calibrated sensors	Yes (Cloud)	Moderate	Institutional buildings; lab settings
Foobot	VOCs, PM2.5, Temp, Humidity (CO_2 indirect)	Consumer-grade estimates	Yes (App)	High	Occupant experience tracking; consumer-focused applications
EXTECH SDL600	Sound levels (30–130 dB)	±1.4 dB, A/C weighting, SD logging	Yes (SD Card)	Moderate	Comparing indoor acoustic performance across spaces

The devices were selected considering the combined precision, portability, and ease of deployment (Table 6) . The Aethair IAQ Monitor offered the most balanced feature set, allowing me to capture multiple variables at once while maintaining reliability across sites. The EXTECH SDL600 was chosen specifically for its ability to measure ambient noise in a way that aligned with established residential comfort thresholds. This comparison deepens the understanding of how data collection methods influence the validity and scope of environmental studies, an insight that will be carried forward into both professional practice and future research.

These instruments provided the quantitative foundation for assessing how 3D-printed and traditional homes differ in environmental performance. The following section links these measurements to their ultimate purpose - understanding how indoor environmental quality affects user comfort and wellbeing.

2.10: User Comfort, Health, and Quality of Life

User comfort refers to the overall sense of physical and psychological satisfaction experienced by occupants within a built environment, influenced by factors such as temperature, humidity, air quality, noise, and spatial design. Table 7 shows the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and Environmental Protection Agency (EPA) guidelines, with proper minimum, maximum, and comfort ranges.

Table 7.

ASHRAE and EPA Standards for Residential Indoor Air Quality (IAQ)

Parameter	Minimum Standard	Maximum Standard	Sources
Temperature (°F)	50°F	93°F	Lyadgh. (n.d.). *ASHRAE 55-2020*. Scribd. https://www.scribd.com/document/695087734/ASHRAE-55-2020
Carbon dioxide(ppm)	600ppm	1000ppm	Atlanticei. (2021, October 15). *Ventilation for human comfort*. Atlantic Environmental Incorporated. https://www.atlenv.com/ventilation-for-human-comfort
Relative Humidity (RH)	30%RH	60%RH	(ASHRAE, 2022). *ANSI/ASHRAE Standard 62.2-2022: Ventilation and Acceptable Indoor Air Quality in Residential Buildings.* Atlanta, GA: ASHRAE.
Noise (dB)	20dB	40dB	ASHRAE. (2023). *ASHRAE Handbook – HVAC Applications, Chapter 49: Noise and Vibration Control.* Atlanta, GA: ASHRAE.

3D-printed homes offer significant improvements in comfort, health, and overall quality of life compared to traditional housing. With better insulation, lower energy consumption, and eco-friendly materials, they create a more sustainable and livable environment.

One of the key advantages of 3D-printed homes is thermal comfort. The thick, layered walls provide better insulation, helping to regulate indoor temperatures and reducing the need for excessive heating or cooling (Weng et al., 2020). Additionally, the materials used in 3D Printing, such as geopolymers and concrete composites, have superior acoustic properties, absorbing sound better than traditional drywall, which enhances indoor comfort (Muñoz et al., 2021).

Another benefit is the flexibility in design, as 3D Printing allows for customized, ergonomic layouts that promote aesthetic and functional well-being (Rekhi et al., 2022).

Health is another major consideration. Unlike traditional homes, which may contain volatile organic compounds (VOCs) from adhesives, paints, and synthetic materials, 3D-printed structures use low-VOC materials, improving indoor air quality (Bos et al., 2020). Furthermore, seamless, monolithic walls prevent moisture buildup, reducing the risk of mold growth and pest infestations, which are common in traditionally built homes with wood and drywall (Le et al., 2012).

3D-printed homes also contribute to energy efficiency and sustainability. The dense, well-insulated walls significantly reduce energy consumption, cutting heating and cooling costs by up to 50% (Weng et al., 2020). Additionally, many 3D Printing materials, such as geopolymers and recycled composites, offer lower carbon footprints, making them more environmentally friendly than conventional concrete (Bos et al., 2020).

In terms of safety and durability, 3D-printed homes are designed to withstand extreme weather conditions, including earthquakes, hurricanes, and fires (Rekhi et al., 2022). The monolithic nature of the printed walls eliminates weak joints, increasing the structural strength and reducing long-term maintenance costs.

3D-printed homes offer a healthier and safer living environment by improving air quality, enhancing comfort, and increasing structural resilience. The use of low-VOC materials, such as geopolymers and bio-based composites, reduces exposure to harmful chemicals, promoting better respiratory health (Bos et al., 2020). Additionally, moisture-resistant materials help prevent mold growth, lowering the risk of allergies and asthma (Le et al., 2012).

These homes also provide better thermal insulation, maintaining stable indoor temperatures for increased comfort and lower energy costs (Weng et al., 2020). Noise reduction is another benefit, as denser materials help create quieter living spaces, improving sleep and mental wellbeing (Muñoz et al., 2021). Structurally, monolithic designs enhance durability, offering greater resistance to earthquakes, hurricanes, and fires, ensuring long-term safety (Rekhi et al., 2022).

Overall, 3D-printed homes improve comfort, enhance indoor air quality, lower energy costs, and provide a durable and sustainable housing solution. As the technology advances, it has the potential to reshape the housing industry by making high-quality, affordable homes more accessible worldwide. With these benefits, 3D-printed housing not only provides an affordable solution but also promotes a healthier and more comfortable way of living. The findings from IAQ measurements, acoustic evaluations, and thermal assessments collectively emphasize that 3D-printed housing enhances comfort, promotes better health outcomes, and supports sustainable living. Together, these sections demonstrate that 3D Printing is not merely a construction innovation but a human-centered design advancement that directly improves quality of life.

2.11: Gap in Literature

Building upon the prior discussion on indoor microclimate and user comfort, it becomes evident that while the environmental and structural aspects of 3D-printed construction are well documented, the human-centered performance of these spaces remains insufficiently explored. Although 3D-printed construction has been widely studied in terms of its structural efficiency, cost-effectiveness, and environmental impact, limited research has examined the indoor microclimate conditions of 3D-printed homes. Critical factors such as thermal comfort, humidity control, ventilation performance, and indoor air quality remain underexplored. While existing literature acknowledges the potential of 3D Printing to enhance energy efficiency and sustainability, empirical studies assessing how these structures perform in maintaining healthy and comfortable indoor environments are scarce. Furthermore, comparative analyses between the indoor environmental quality of 3D-printed and conventionally built homes are lacking, resulting in an incomplete understanding of how this emerging technology affects occupant wellbeing.

This gap highlights the need for interdisciplinary approaches that integrate architectural design, material science, and environmental monitoring to understand how 3D-printed housing impacts everyday living conditions. Addressing this missing link is vital for evaluating the technology's real-world effectiveness, not only in affordability and sustainability but also in supporting occupant health and comfort.

Addressing this gap is essential to evaluate the viability of 3D-printed housing as a long-term solution to affordable, sustainable, and health-supportive living environments.

2.12: Conclusion

Recognizing this gap, the following section concludes the literature review by synthesizing how 3D Printing has evolved from a structural innovation into a potential solution for livable, healthy housing, and why further empirical investigation into its indoor performance is critical.

3D Printing is clearly making waves in the construction industry, offering faster build times, lower costs, and more sustainable solutions compared to traditional methods. The technology is especially promising for affordable housing, with successful projects around the world showing how entire homes and even neighborhoods, can be built quickly and efficiently. Techniques like extrusion-based printing and contour crafting are helping reshape how we think about construction. However, while the structural and economic benefits are well-covered in the research, there's still a lot we don't know about what it's like to live in a 3D-printed home. Important aspects like how well these homes regulate temperature, control humidity, ensure good air quality, and provide overall comfort haven't been studied in much detail. These indoor microclimate factors are crucial, not just for energy efficiency, but for the health and wellbeing of the people who live in them. To move this technology forward in a meaningful way, future research needs to focus more on the indoor experience of 3D-printed homes - not just how they're built, but how they feel to live in. Only then can we truly understand their potential as a long-term solution for sustainable and livable housing.

This study directly responds to that call by examining the indoor environmental conditions of a 3D-printed home in comparison to a traditional residence, analyzing real-time parameters such as temperature, humidity, CO_2 concentration, and acoustic comfort. The findings aim to bridge the existing research gap and provide empirical insights into how 3D-printed housing performs in supporting occupant comfort and wellbeing.

CHAPTER III: METHODOLOGY

3.1: Study Design

This study employs a case study to examine the performance of 3D-printed homes on indoor environmental quality (IEQ) compared to traditional homes. This study focuses on microclimate factors that are closely related to user comfort, such as temperature, humidity, carbon dioxide (CO_2) levels, and ambient noise. The research involves a comparative analysis of two distinct residential settings: a traditionally constructed home and a 3D-printed home.

During site visits, empirical data were collected using instruments Aethair IAQ Monitor to measure indoor temperature, humidity, CO_2 concentrations, and the EXTECH SDL600 sound level meter was used to record noise levels. These measurements were evaluated against established standards such as ASHRAE Standard 55 for thermal comfort, which specifies combinations of indoor thermal environmental factors and personal factors that produce acceptable thermal environmental conditions for occupants, and ASHRAE Standards 62.1 and 62.2 for ventilation and indoor air quality, which provide minimum ventilation rates and other measures intended to ensure acceptable indoor air quality and minimize adverse health effects.

By comparing the performance of the two housing types, the study aims to identify how 3D-printed homes influence IEQ in relation to conventional construction methods. The findings were expected to provide insights into the efficacy of 3D Printing technology in creating comfortable and healthy indoor environments, contributing to the discourse on sustainable and affordable housing solutions.

3.2: Procedure

The researcher approached potential case sites using the invitation letter presented in Appendix I and II. The twelve companies were initially contacted to select the 3D-printed home. The project was referred to by the COBOD International team, who have constructed the first 3D-printed house in Los Angeles, California. The case was selected due to its alignment with key study parameters, including construction size, geographic location, and building construction technique. Additionally, the project was developed by students under the Solar Decathlon Net Zero initiative, making it a strong fit for comparative analysis within the context of sustainable and affordable housing.

3.3: Research Site and Case

Two case sites were selected: a traditionally constructed home and a 3D-printed home. The two residential sites were chosen based on comparable environmental factors, as outlined in Table 5. The case study was conducted between July and September 2025, during which environmental data: temperature, humidity, carbon dioxide (CO_2), and noise levels, were systematically recorded inside and outside each unit. The collected data provides insight into the microclimate performance and user comfort of 3D-printed housing, forming the foundation for comparison with traditional residential construction.

The 3D-printed home (Site 1) is a stand-alone structure located within the Woodbury University School of Architecture campus. This site is relatively isolated from direct traffic sources, benefiting from a quieter academic environment and open surroundings. The traditional home (Site 2), located within a dense urban core, surrounded by major arterial roads and mixed-use developments. This setting exposes it to higher background noise and more variable outdoor microclimate conditions compared to the campus-based 3D-printed unit.

In terms of elevation and geographic conditions, both sites are located within the Los Angeles Basin, minimizing topographical and climatic differences. The 3D-printed home, being a single-family prototype, stands independently with no shared walls, allowing free air circulation around all sides. In contrast, the traditional residence is a studio apartment within a multi-family building, where adjacent units and limited façade exposure can affect ventilation and noise transmission.

Regarding layout and orientation, the 3D-printed home is primarily east-facing, allowing early morning sunlight and limited afternoon heat gain, while the traditional residence is north-facing, receiving diffused daylight with minimal direct solar exposure. Although the orientations differ, both maintain comparable daylight access and solar exposure levels suitable for evaluating passive comfort performance under Los Angeles summer climate.

To address weather variation, the study period from July to September reflects the city's warm, dry season, with average daytime highs between 85°F and 93°F and nighttime lows near 65°F. Minor fluctuations were recorded, with slightly higher temperatures and reduced humidity in August. Both sites were monitored under similar seasonal and climatic conditions, supported by concurrent weather data from the Climate Consultant 6.0 and BAAQMD databases, ensuring reliable comparison despite contextual differences.

3.3.1. Site – Los Angeles (Climate Data Consultant)

This research adopts a case study methodology. Climate conditions were analyzed to compare indoor and outdoor environments and evaluate user comfort. Using the Climate Consultant 6.0 application, climate data for Los Angeles, California (July - September) were examined to contextualize findings on indoor environmental quality. The analysis helped interpret thermal comfort range, solar exposure, and humidity patterns, offering an environmental context for comparing the 3D-printed and traditional residences.

Sun Chart Analysis (Los Angeles, California – July to September)

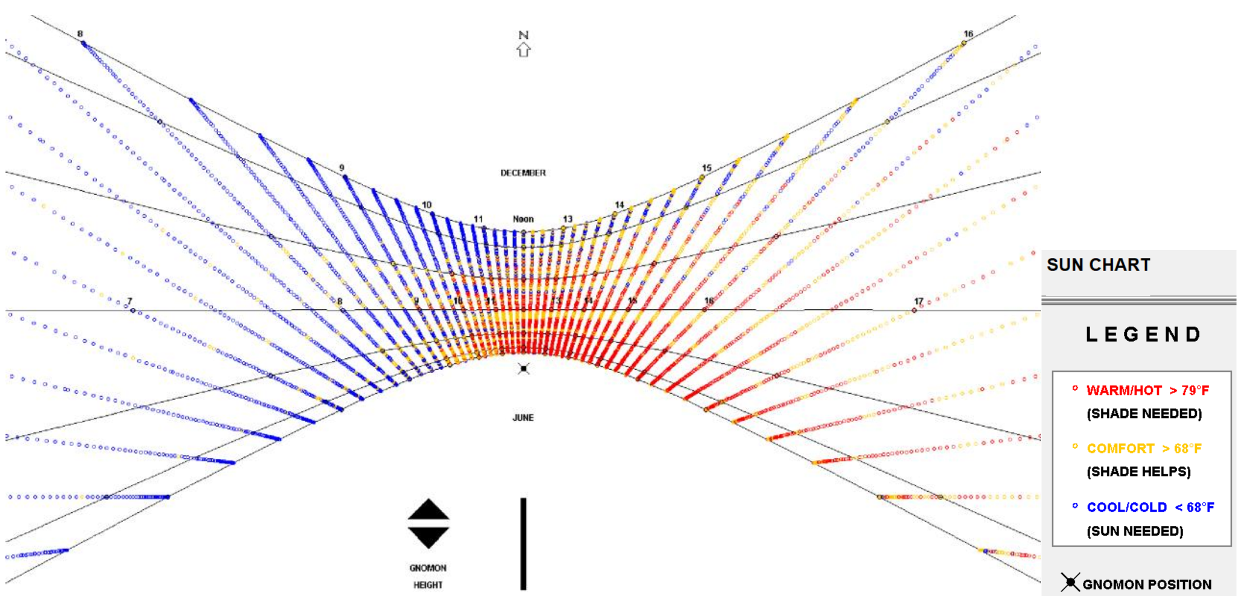
The sun chart (Figure 5) illustrates the solar path and thermal comfort zones.

- Red areas represent hot conditions (>79°F) requiring shading.
- Yellow - orange areas show moderate comfort (68 - 79°F).
- Blue areas indicate cooler periods (<68°F).

From 10 AM to 4 PM, Los Angeles experiences predominantly hot conditions, suggesting a strong need for passive shading (e.g., overhangs or fins). Mornings and evenings remain cooler, supporting daylighting and solar gain. Figure 5 highlights the importance of solar orientation and shading for energy-efficient and comfortable indoor design.

Figure 5

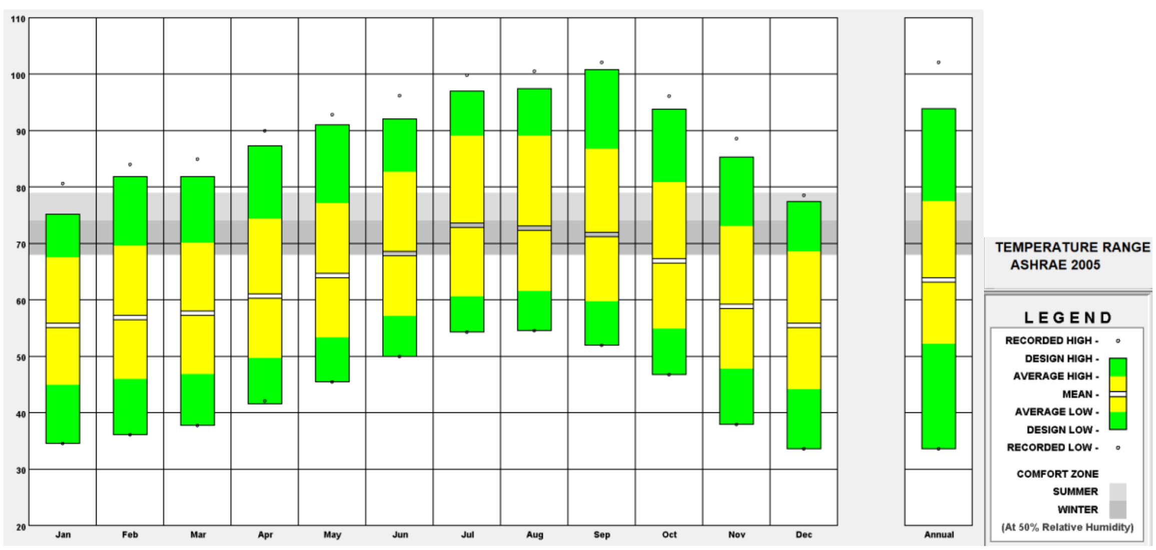
Sun Chart Analysis (*Climate Consultant 6.0) (Temperature Range Analysis (Los Angeles, California)*



The temperature range chart (Figure 6) shows monthly highs (≈85°F), lows (≈50°F), and averages within the comfort range (68 - 78°F). The warmest months (July - September) often exceed 90°F, indicating a need for cooling and shading, while winter months (45 - 55°F) suggest a need for passive heating. Los Angeles maintains a moderate climate, and comfort can be achieved with passive strategies such as shading, ventilation, and thermal mass.

Figure 6

Temperature Range Analysis (Climate Consultant 6.0) Relative Humidity Analysis (Los Angeles, California)



The relative humidity chart (Figure 6) indicates humidity levels between 40-80%, averaging near 50% RH. Midday periods show slightly drier conditions, while mornings and evenings align with comfort levels. Los Angeles generally maintains a dry climate, manageable through natural ventilation and minimal dehumidification.

Figure 7

Relative Humidity Analysis Year 2025 (Climate Consultant 6.0) Psychrometric Chart Analysis (ASHRAE 2005)

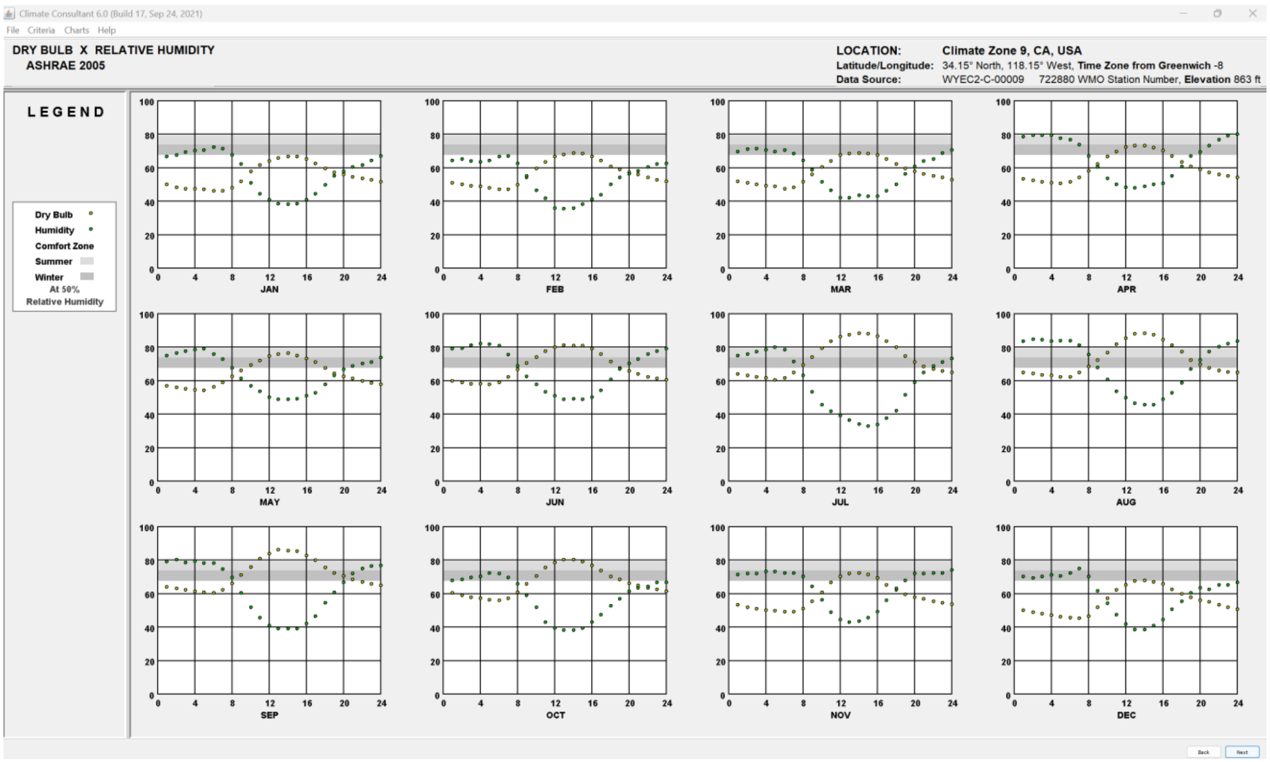
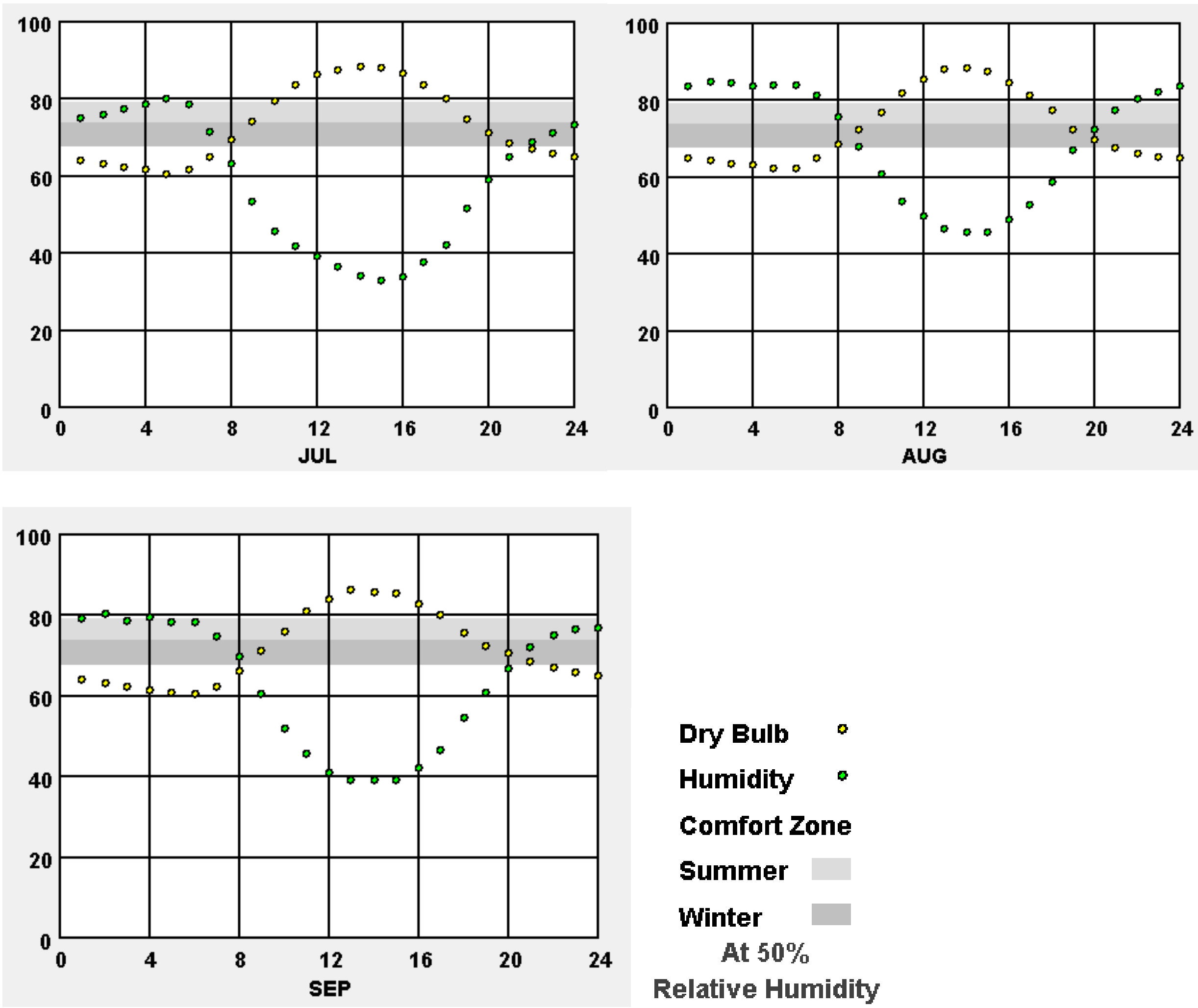


Figure 8

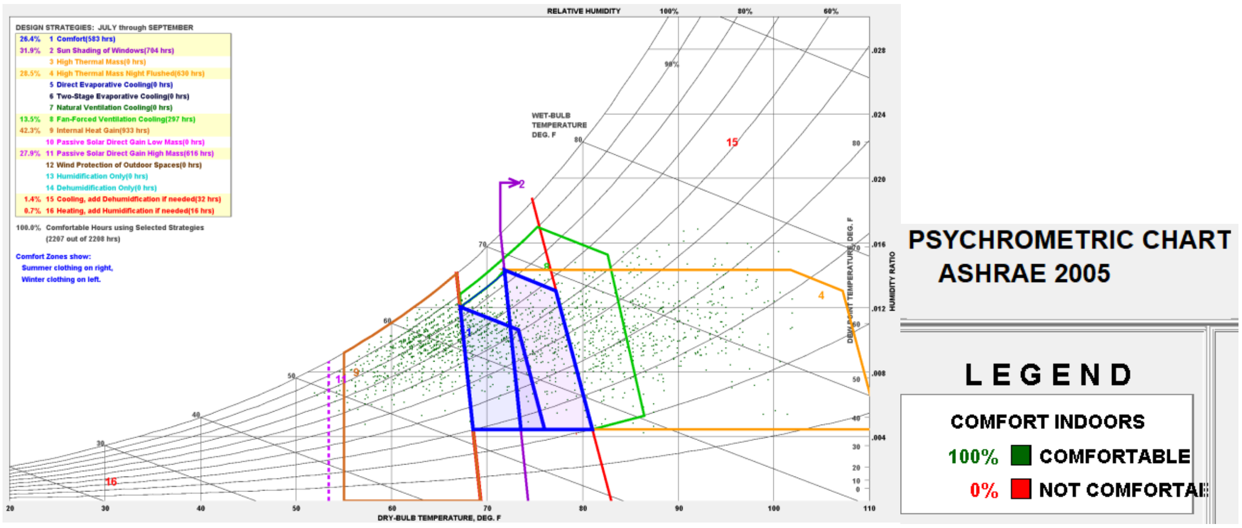
Relative Humidity Analysis Month (July - Sep 2025) (Climate Consultant 6.0) Psychrometric Chart Analysis (ASHRAE 2005)



The psychrometric chart (Figure X) shows that 38% of annual hours fall within the comfort zone, requiring no active conditioning. Suggested strategies include sun shading (27.7%), thermal mass with night ventilation (19.1%), and natural or evaporative cooling. The data indicate that Los Angeles supports passive comfort for most of the year through climate-responsive design.

Figure 9

Psychrometric Chart Analysis (*Climate Consultant 6.0) Psychrometric Chart Analysis (ASHRAE 2005)*



Outdoor air data from BAAQMD and AQICN show Good to Moderate air quality, with AQI values 35-71 and $PM_{2.5}$ levels 10-20 µg/m³.

- Monthly results: Mostly clean air, with brief moderate periods due to temperature and ozone variation.
- Weekly results: AQI below 50 through most of the period, with minor peaks (70-71) in late August and mid-September.

Overall, air quality remained stable and favorable, minimizing external effects on indoor measurements and supporting a reliable comparison between the 3D-printed and traditional homes.

Figure 10

Monthly Air Quality Index Analysis (Rainy-Day Analysis (September 18, 2025 - After Sunset to Sunrise), Weather Context)

(BAAQMD - Air Quality Data, 2025) (The World Air Quality Index project, n.d.)

South Central Bay — Monthly — 2025

Monthly	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	High AQI
Hayward	38 Ozone	42 Ozone	47 Ozone	44 Ozone	51 Ozone	38 Ozone	36 Ozone	43 Ozone	71 Ozone	71 Ozone			71 Ozone
Redwood City	58 PM2.5	41 PM2.5	59 PM2.5	38 PM2.5	53 PM2.5	53 PM2.5	26 PM2.5	41 PM2.5	57 PM2.5	34 PM2.5			59 PM2.5

Santa Clara Valley — Monthly — 2025

Monthly	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	High AQI
Gilroy	55 PM2.5	40 Ozone	52 PM2.5	45 Ozone	64 Ozone	51 PM2.5	57 PM2.5	48 Ozone	51 Ozone	49 Ozone			64 Ozone
Los Gatos	35 Ozone	43 Ozone	58 Ozone	48 Ozone	50 Ozone	42 Ozone	48 Ozone	46 Ozone	50 Ozone	48 Ozone			58 Ozone
San Jose - Jackson St.	77 PM2.5	62 PM2.5	63 PM2.5	50 PM2.5	63 PM2.5	63 PM2.5	54 PM2.5	55 PM2.5	71 Ozone	54 Ozone			77 PM2.5
San Jose - Knox Ave.	73 PM2.5	52 PM2.5	57 PM2.5	49 PM2.5	53 PM2.5	59 PM2.5	40 PM2.5	52 PM2.5	55 PM2.5	50 PM2.5			73 PM2.5
San Martin - Airport	35 Ozone	38 Ozone	43 Ozone	45 Ozone	64 Ozone	46 Ozone	48 Ozone	47 Ozone	61 Ozone	51 Ozone			64 Ozone

AQI Scale Key:

0 - 50	51 - 100	101 - 150	151 - 200	201 - 300	301 - 500	
Good	Moderate	Unhealthy for Sensitive Groups	Unhealthy	Very Unhealthy	Hazardous	learn more

Interval: Monthly | Weekly | Daily | Hourly

Figure 11

Weekly Air Quality Index Analysis (Rainy-Day Analysis (September 18, 2025 - After Sunset to Sunrise), Weather Context)

(BAAQMD - Air Quality Data, 2025) (The World Air Quality Index project, n.d.)

South Central Bay — Weekly — June - September 2025

Weekly	06/30 2025	07/07 2025	07/14 2025	07/21 2025	07/28 2025	08/04 2025	08/11 2025	08/18 2025	08/25 2025	09/01 2025	09/08 2025	09/15 2025	09/22 2025	High AQI
Hayward	37	36	28	25	25	43	30	34	36	35	26	45	71	71

Santa Clara Valley — Weekly — June - September 2025

Weekly	06/30 2025	07/07 2025	07/14 2025	07/21 2025	07/28 2025	08/04 2025	08/11 2025	08/18 2025	08/25 2025	09/01 2025	09/08 2025	09/15 2025	09/22 2025	High AQI
Gilroy	40	44	33	24	32	44	36	48	46	48	33	48	51	51
Los Gatos	40	48	40	30	33	42	37	46	40	43	29	50	45	50
San Jose - Jackson St.	39	42	34	29	31	43	34	39	37	37	29	45	71	71
San Martin - Airport	45	48	38	24	37	43	43	47	44	46	33	54	61	61

South Central Bay	Weekly												September - December 2025
Hayward	33	43	71	43	34								71
Weekly	09/29 2025	10/06 2025	10/13 2025	10/20 2025	10/27 2025	11/03 2025	11/10 2025	11/17 2025	11/24 2025	12/01 2025	12/08 2025	12/15 2025	12/22 2025	High AQI

Santa Clara Valley	Weekly												September - December 2025
Gilroy	32	42	44	49	31								49
Los Gatos	33	48	47	46	31								48
San Jose - Jackson St.	34	47	54	45	31								54
San Martin - Airport	34	44	43	51	31								51
Weekly	09/29 2025	10/06 2025	10/13 2025	10/20 2025	10/27 2025	11/03 2025	11/10 2025	11/17 2025	11/24 2025	12/01 2025	12/08 2025	12/15 2025	12/22 2025	High AQI

This page provides access to current and historical air quality and meteorological information based on measurements taken at stations in the Air District's air monitoring network. Some of the data on these pages is raw or unchecked data that may contain errors.

AQI Scale Key:

0 - 50	51 - 100	101 - 150	151 - 200	201 - 300	301 - 500
Good	Moderate	Unhealthy for Sensitive Groups	Unhealthy	Very Unhealthy	Hazardous

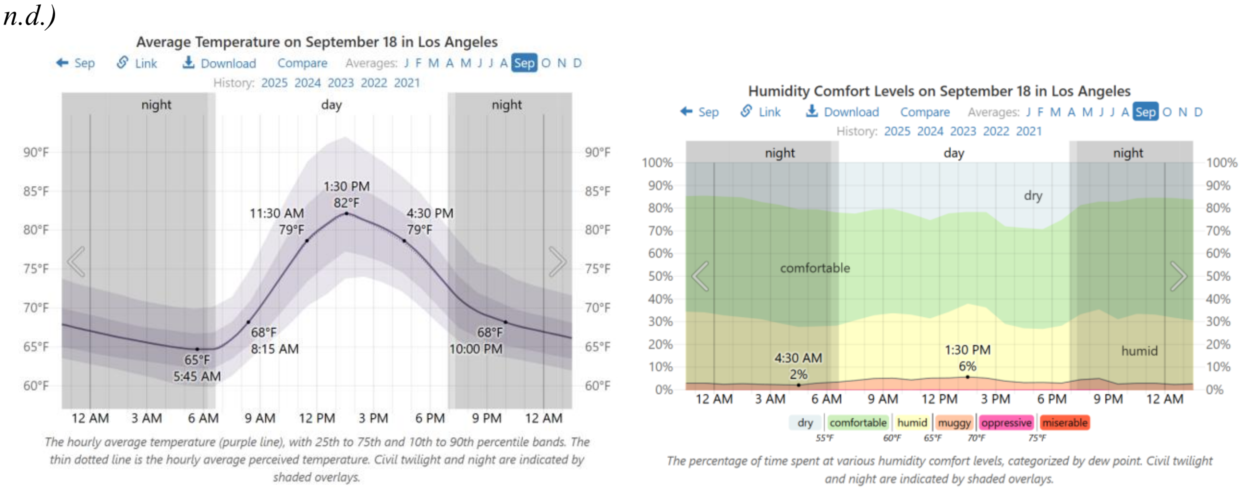
learn more

Interval: Monthly | Weekly | Daily | Hourly

Rain occurred between 9 PM (Sept 18) and 6 AM (Sept 19), peaking near 5.7% precipitation at 6 AM. Nighttime humidity rose from dry (~30%) to humid (~80%), while temperature gradually dropped from ~82 °F to ~65 °F. (Table 8, Figure 11)

Figure 12

Los Angeles, September 18 Weather, Average Temperature (California, United States) - Weather Spark, n.d.)



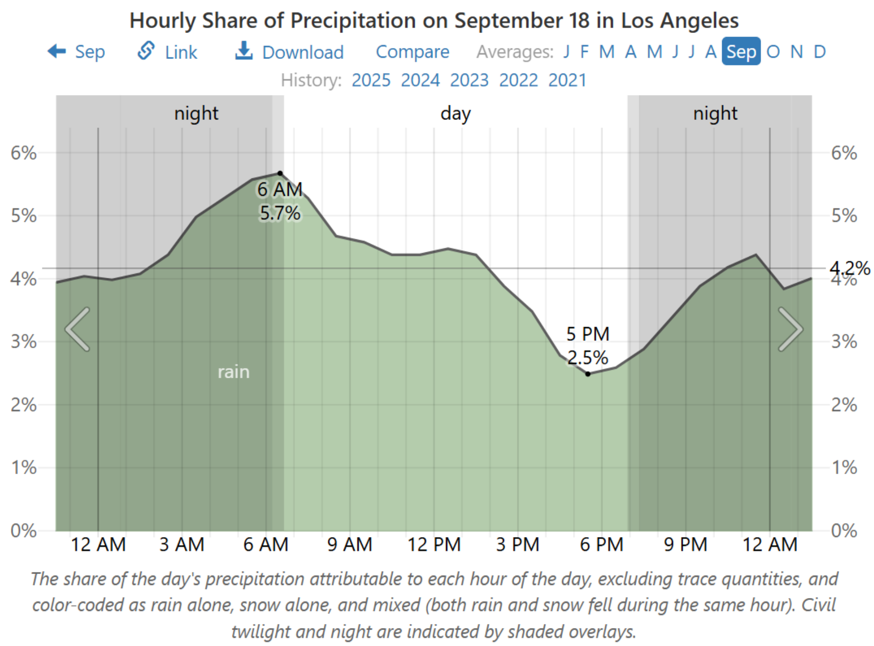


Figure 13

Aethair - Environet Data Collection_Temperature (Environet Console, 2025)

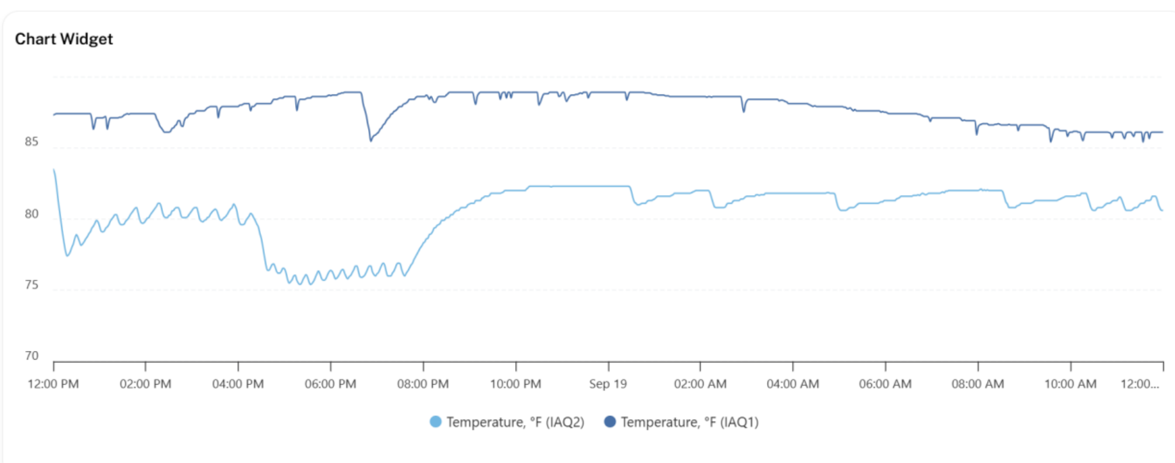


Table 8.

Rainy Temperature Analysis with 3D home, Traditional Residence, and ASHRAE

Factors	Rainy temperature LA	3D Printed	Traditional Residence	ASHRAE

	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Temperature (°F)	65 °F	82 °F	75°F	85°F	73°F	84°F	50°F	93°F
			Stable due to concrete thermal mass; slight cooling after rain onset.		More responsive to outdoor cooling and humidity rise.			

3.3.2 Case

Inclusion and Exclusion Criteria:

The inclusion criteria for the case study sites were based on climatic similarity (both located in the Los Angeles region), comparable unit size (470-477 ft²), and accessibility for instrument installation. The 3D-printed home (Site 1) was selected for its innovative construction type and relevance to emerging housing technologies, while the traditional residence (Site 2) served as a baseline model of conventional urban housing.

Exclusion criteria included any units undergoing renovation, lacking a stable power supply, or subject to irregular occupancy patterns that could affect measurement reliability. Similarly, only calibrated and functioning instruments with complete data logging capability were included in the analysis; any equipment showing sensor drift or inconsistent recording intervals was excluded.

Case 1. SolarFutures 3D-Printed Home – Burbank, California

This case study was conducted on the SolarFutures project home, a 477 ft² micro-unit located in Burbank, California, designed and constructed as part of the U.S. Department of Energy's Solar Decathlon 2024 - 2025.

The Solar Futures home is a first-of-its-kind, single-family residence in Los Angeles built with 3D-printed concrete wall elements. It was designed as a flexible, affordable, and resilient housing prototype, with the capacity to self-sustain in terms of water, power, and connectivity through integrated solar harvesting, battery storage, and rainwater/graywater reuse systems. In addition to showcasing technological innovation, the project was envisioned as a direct response to contemporary challenges such as climate change, housing affordability, and homelessness in Southern California.

This site not only allowed evaluating emerging construction technologies in practice but also reinforced the broader mission of the Solar Decathlon, to inspire innovation in sustainable design and construction while providing scalable solutions to global housing challenges.

Figure 14

Woodbury University 3d Printed House

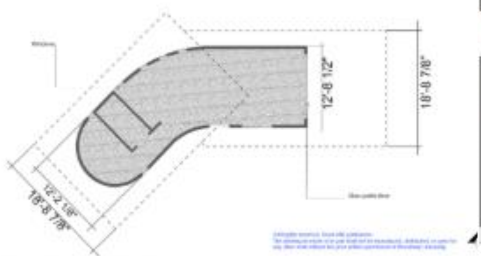
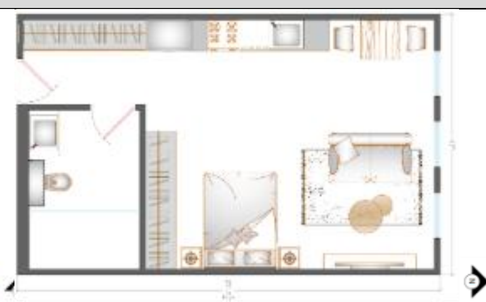
Case 2. Traditional Residence – Los Angeles, California

The comparison site is a traditional residence located in Los Angeles, CA. This site is considered comparable, as indicated in Table 9 for similarity. The unit is a studio apartment measuring approximately 470 ft², designed to accommodate a single occupant. As shown in the attached floor plan (Figure 14), the apartment integrates essential living functions within a compact footprint, including a combined bedroom and living space, a small kitchen, and a separate bathroom.

This studio apartment represents a conventional model of urban housing in Los Angeles, where space efficiency and affordability are central to residential design. Unlike the experimental and technologically advanced 3D-printed home in Site 1, this unit provides a baseline for comparison by reflecting a more traditional construction approach. This site provides a useful benchmark for evaluating user comfort in a standard housing typology against the innovative micro-unit built with 3D-printed concrete.

Table 9

Monitored Apartments – Features Tab Research Sites

	3D Printed Home*	Traditional Home
Floor Plan	 **Figure 15:** *Woodbury University 3d Printed House - Floor Plan*	 **Figure 16:** *Traditional Residence - Floor Plan*
Location	Los Angeles, California	Los Angeles, California
Floor area	477 ft²	470 ft²,
Orientation of the major opening	East	North
Number of bedrooms	0	0
Ceiling Height	9’-0” and 13’-0” as the ceiling is inclined.	9’-0”

Note:

3.4: Instrument

Indoor climate measurements were carried out at two selected residential sites during Summer 2025 (July to September), with data recorded within each house to ensure consistency. The two sites will be chosen carefully to meet the same requirements, similar area, location, and tropical climate conditions. To maintain consistency, all devices will be installed in comparable locations within each home, like bedrooms and living rooms/kitchens.

For this study, Aethair IAQ Monitor and sound level meters were used to measure indoor temperature, humidity, CO_2 levels, and noise, respectively (Table 6). Specifically, the indoor air temperature (T), relative humidity (RH), and CO_2 concentration in bedrooms and living rooms. These sensors will be placed near the outer wall.

For this study, equipment calibration and setup were performed prior to data collection to ensure accuracy and reliability. The Aethair IAQ Monitor was factory-calibrated by the manufacturer. The EXTECH SDL600 sound level meter was calibrated using the EXTECH 407766 Sound Calibrator (94 dB, 1 kHz) as per ANSI and IEC 61672-1 Type 2 standards. Calibration checks were performed both before and after field measurements to confirm instrument stability.

3.4.1: Microclimate Measures

The Aethair Indoor Air Quality (IAQ) equipment was used to capture the indoor environmental conditions that directly influence occupant comfort. Since people spend most of their time indoors, factors such as carbon dioxide (CO_2), temperature, humidity, and particulate matter play an important role in shaping both comfort and health (EPA, 2023).

This device continuously monitors the indoor microclimate every minute by measuring CO_2 levels, relative humidity, temperature, particulate matter (PM2.5/PM10), and many more.

The data collected provided a reliable basis for understanding how different construction types. For this study, the Aethair IAQ device was particularly useful because it offered a comprehensive picture of the indoor environment in real-world settings. Its portability and precision made it well-suited for comparing how a 3D-printed house and a traditional residence perform in terms of air quality and occupant comfort. (Table 10)

3.4.2: Sound Level Meter

A sound meter measures ambient noise levels to assess acoustic comfort. The EXTECH SDL600 was chosen because it provides precise and comprehensive noise level data, essential for comparing the acoustic performance of 3D-printed and traditional homes (Extech Instruments, 2011).

Table 10.

The Indoor Microclimate Portable Instruments (Zanghirella, De Carli, and Zecchin (2016)

FACTORS	AETHAIR	EXTECH SDL 600
Image	 **Figure 17:** *Aethair, n.d.*	 **Figure 18:** *ExTech SDL600: Sound Level Meter/Datalogger | FliR, n.d.*
Purpose	Records temperature, humidity, CO_2 , and particulate levels to assess indoor microclimate and occupant comfort.	While not always required, measuring noise levels can contribute to understanding the full indoor environmental quality (IEQ), especially in urban settings.
Accuracy	Temperature (TEMP): -50°F to 122°F Humidity (HUM) 20% - 85%	High accuracy ±1.4dB meets ANSI and IEC 61672-1 Type 2 standards

	CO2 Accuracy: ± (50ppm + 5% reading value)	
Data Logger	• The data is collected wirelessly and accessed through the company's online platform, *Environet*. • The website allows users to extract data in various formats, including graphs and Excel files. • Environet provides an efficient and user-friendly interface for data visualization and analysis.	• The data is stored on an in-built SD card within the device. • Retrieving the data is straightforward; by connecting the SD card to a computer, the stored files can be easily extracted for further analysis.
Other Features	Environet features real-time environmental monitoring, customizable dashboards, data export options (graphs and Excel), intelligent alerts, and device configuration controls. It supports cloud storage, secure data access, and integration through an open API for advanced analytics. AI / "Noesis GPT" analytics: automated analysis, pattern detection, faster reporting, and insight generation. It is still getting more updates for the future purposes.	EXTECH SDL 600 measures sound levels from 30 to 130 dB with ±1.4 dB accuracy. It supports A/C weighting, fast/slow response, and data logging to an SD card in Excel format. Features include a backlit LCD, Min/Max recording, programmable sampling intervals, AC output, and PC connectivity.
Relevant Research Question	Addresses **RQ 1**, focusing on CO_2 concentrations as indicators of ventilation effectiveness.	Pertinent to **RQ 2**, evaluating the impact of construction methods on indoor noise levels.

3.5: Data Collection and Analysis

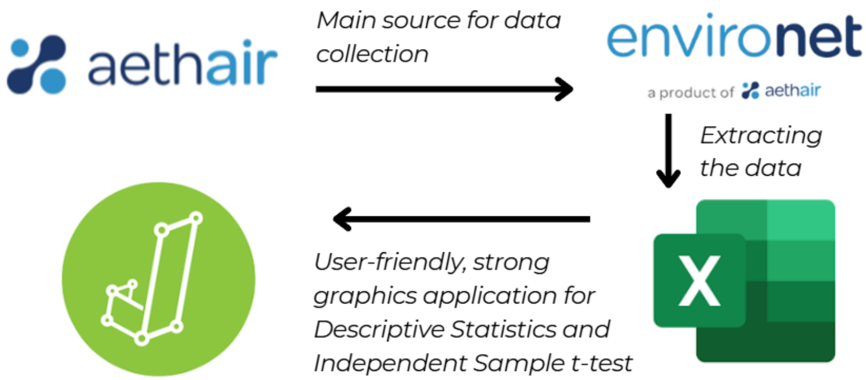
For Research Question 1, the data was collected using the Aethair Indoor Air Quality (IAQ) monitor. Once the equipment was installed at the case study site, it continuously recorded environmental parameters, which were accessed through Environet, the dedicated application for Aethair products. The data collection period was customized according to the specific duration of each case study.

The Environet platform automatically generated visual outputs such as graphs, charts, and tables for multiple indoor air quality indicators. These visualizations displayed the minimum, average, and maximum values for each measured variable. Additionally, the system provided an exportable Excel dataset containing detailed information, including the device model, serial number, description, battery status, owner, network connection, and the geolocation (pin location) of the equipment. The device recorded data at a one-minute reporting interval, ensuring high temporal resolution.

After extracting the dataset from Excel, the data were imported into JASP statistical software for descriptive statistical analysis and independent samples t-test computations to support the research findings. For statistical analysis, JASP (Version:0.95.2) was used for descriptive data analysis because it’s simple to navigate, provides clear visuals, and makes it easy to run different statistical tests. In JASP, first looked at descriptive statistics to summarize key factors like temperature, humidity, CO_2 levels, and noise. Then, used an Independent Samples T-Test to see if there were any significant differences between the two homes in terms of comfort and indoor conditions.

Figure 19.

Process of Data collection and analysis (Nampally, 2025)



3.5.1 HVAC Information

The HVAC system at Site 1 (3D-printed home) was operational during the data collection period; however, the specific temperature setpoints and operational details were not documented, making it difficult to assess its direct impact on the recorded thermal conditions.

In contrast, the traditional residence (Site 2) was occupied, with the resident maintaining thermostat settings between 77°F and 80°F, and recorded indoor temperatures ranging from 50°F to 99°F. The consistent HVAC operation likely resulted in more stable temperature and humidity values.

This difference in occupancy and HVAC use limits the direct comparability of CO_2, temperature, and humidity between the two homes. Therefore, findings should be considered exploratory, and future studies should compare occupied 3D-printed and traditional homes under controlled HVAC conditions for more accurate evaluation.

CHAPTER IV: RESULTS

During July to September, the indoor environmental quality (IEQ) of the Solar Futures 3D-printed home was studied compared to a traditionally built home. The data focused on three main parameters - temperature, relative humidity (RH), and carbon dioxide (CO_2), to understand how the units perform in supporting occupant comfort.

Overall, the traditional home demonstrated good thermal stability but showed weaknesses in ventilation, as reflected in the sharp increases in CO_2 levels. Humidity conditions were mostly comfortable but occasionally drifted to extremes. Compared to the 3D-printed house, the traditional residence performed slightly better in maintaining consistent indoor temperature, but the 3D-printed home proved more effective in sustaining healthier CO_2 levels throughout the study period. The result of the independent t-test indicated significant differences in temperature, humidity, and CO_2 level ($p < .05$) (Table 11, Table 12).

This comparison highlights the trade-offs between conventional construction and emerging technologies: while traditional housing offers predictability in thermal comfort, the 3D-printed prototype shows promise in delivering better air quality, which is equally critical for occupant health and comfort. The subsequent section elaborates on the individual factors in detail.

4.1: Indoor Microclimate Comparison (RQ 1)

The comparative analysis between the 3D-printed home and the traditional residence reveals that while both generally met ASHRAE comfort standards, their indoor microclimate behaviors differed due to material composition and occupancy.

The 3D-printed home exhibited higher thermal retention, maintaining warmer but more stable indoor temperatures and drier humidity levels owing to its concrete structure and airtight envelope. In contrast, the traditional residence showed greater humidity and CO_2 fluctuations, influenced by wood-frame construction and occupant activity.

Table 11.

Descriptive Statistics

	Temperature, °F		CO_2, ppm		Humidity, %	
	1	2	1	2	1	2
Valid	99,070	103,248	94,470	103,247	99,073	103,247
Missing	31	2	4,631	3	28	3
Mean	82.08	81.31	625.1	814.3	39.98	49.02
Std. Deviation	5.299	1.920	13.35	243.8	3.969	5.593
Minimum	61.50	66.90	624.0	609.0	29.00	33.80
Maximum	93.40	86.20	1,171	2,456	72.90	81.70

Note: 1 = 3D Printed Home, 2 = Traditional

One outlier (8.700) in the humidity dataset was removed after it was identified as an anomalous observation.

Table 12.

Independent Samples T-Test

	t	df	p	Cohen's d	SE Cohen's d
Temperature, °F	44.29	202,316	<.001[a]	0.197	0.004
CO_2, ppm	-238.28	197,715	<.001[a]	-1.073	0.005
Humidity, %	-417.80	202,318	<.001[a]	-1.858	0.006

Overall, the 3D-printed home demonstrated consistent environmental control and good air quality, though it tended toward heat buildup and low humidity during summer conditions. These findings suggest that 3D-printed construction offers strong potential for stable indoor environments, but optimizing ventilation, passive cooling, and moisture balance is essential to enhance occupant comfort and long-term performance.

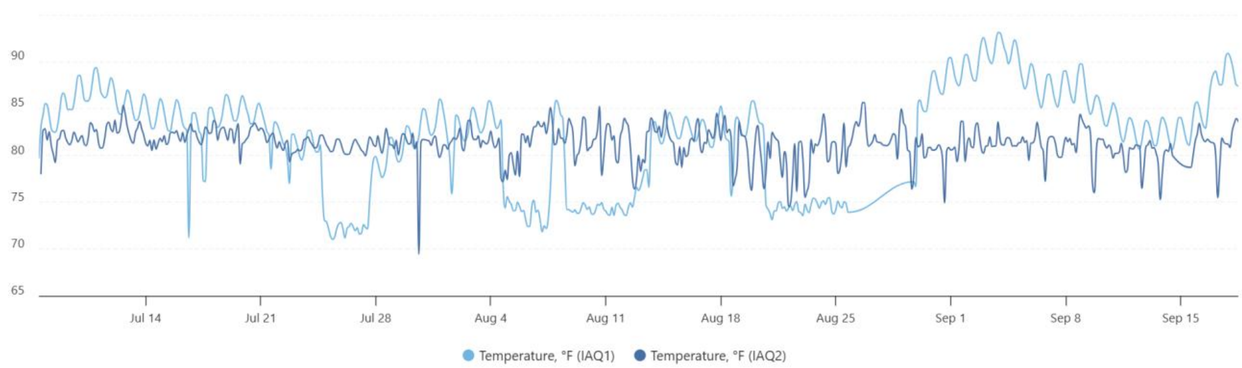
4.2: Thermal Performance (RQ 1.1)

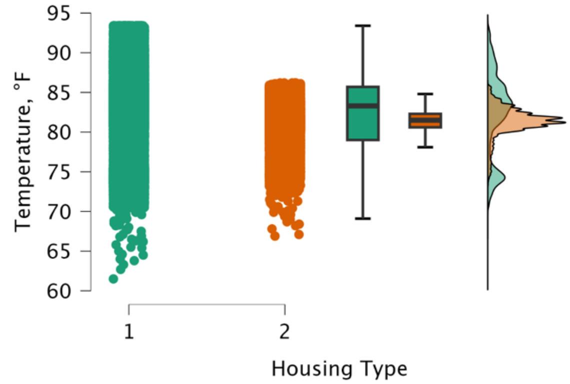
Indoor temperature in the 3D printed homes ranged from 63.3°F to 93.4°F, with an average of 82.1°F. While the average value indicates generally warm conditions, the higher peaks show that the unit experienced periods of heat buildup, which could challenge thermal comfort, particularly during the warmer Los Angeles summer days. In contrast, indoor temperatures of traditionally built home ranged from 66.9°F to 86.2°F, with an average of 81.3°F. The data shows that the traditionally built home maintained a relatively stable indoor climate, with fewer fluctuations than the 3D-printed unit.

Figure 20 highlights that while both homes followed similar daily patterns, the 3D-printed home consistently recorded higher temperature peaks. This indicates that it retained more heat and cooled down more slowly, reflecting the influence of material composition and ventilation behavior on temperature regulation.

Figure 20

Temperature difference between 3d Printed and Traditional Residence
Source: Aethair – Environet Data Collection_Temperature (Environet Console, 2025)





Comparison with ASHRAE Standard

When compared with the ASHRAE Standard 55 comfort range (50°F to 93°F, average comfort 72°F), the 3D-printed home's temperature values fall within the acceptable range, but the average and maximum readings are closer to the upper limit, suggesting a warmer indoor condition that may require cooling support for comfort (Table 13). In a traditionally built home, the temperature values also align with ASHRAE's comfort range, staying below the upper threshold of 93°F and maintaining relatively consistent thermal conditions. While still on the warmer side, these readings indicate a slightly cooler and more balanced indoor environment compared to the 3D-printed home.

Table 13

Aspects of 3D Printed Home and Traditional Residence

Aspect	3D-Printed Home	Traditional Residence
Thermal Range vs ASHRAE Standard (50°F - 93°F)	Within range but frequently near upper limit (average 82°F).	Within range and closer to mid-comfort zone (average 81°F).
Heat Retention	High - retains heat longer, reducing nighttime cooling.	Moderate - cools faster after peak heat.
Energy Efficiency	Better for stable climates, reduces the need for active heating at night.	Requires consistent HVAC adjustments due to rapid response to outdoor changes.

Comfort Implication	May feel warmer during summer; beneficial in cooler seasons.	Provides better daytime comfort but may lose heat faster overnight.
Compliance with ASHRAE Comfort Zone	Meets standard but often near the upper boundary; may need shading or ventilation improvements.	Meets standard with moderate indoor comfort across most hours.

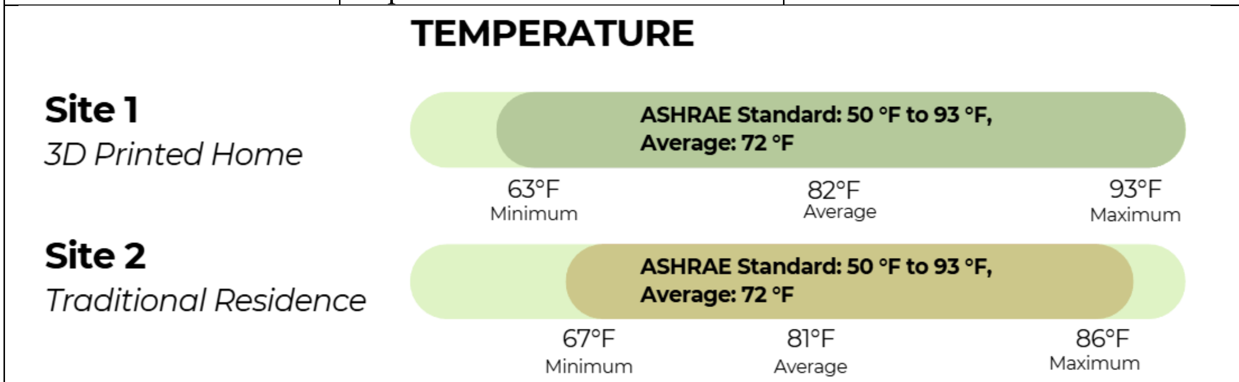


Figure 21: *Minimum, Average, and Maximum values compared with ASHRAE Standards (Nampally, 2025)*
Note: Considered the nearest value for the comparison.

The 3D-printed home's concrete-based walls possess high thermal mass, enabling the structure to absorb and store heat during the day and release it gradually at night. This contributes to a warmer average temperature but also improves temperature stability over time.

The traditional residence, built with wood-frame construction, has lower thermal mass, allowing for quicker temperature response to outdoor conditions. While this helps maintain comfort during hot days, it can also lead to faster cooling at night, requiring additional heating or insulation in cooler periods.

4.3: Humidity Control (RQ 1.2)

Relative humidity levels in the 3D-printed home ranged from 29% to 55% after removing one outlier point of 8.7%, averaging 40%. While within the ASHRAE comfort range (30-60%), occasional readings below 30% indicate dry indoor air that may cause minor discomfort. The 9%

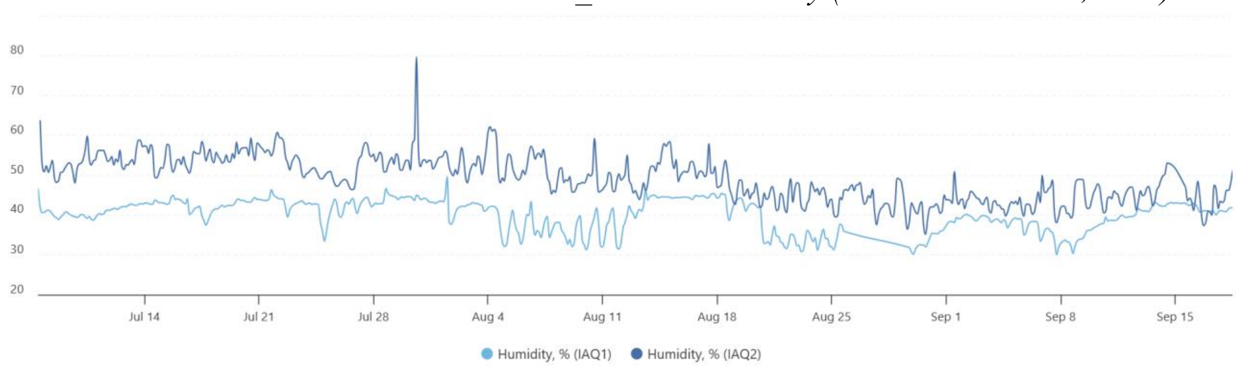
value was identified as an outlier, with the next lowest at 29%, still reflecting under-humidified conditions.

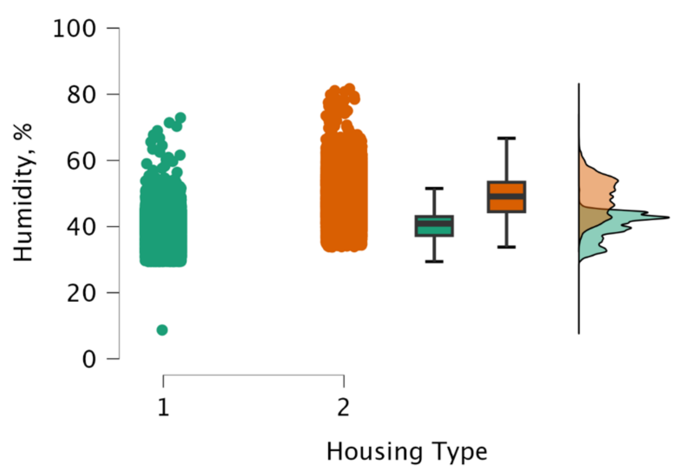
In contrast, the traditionally built residence showed humidity between 33.8% and 81.7%, averaging 49%. Although generally within the ASHRAE comfort range, values above 70% suggest occasional dampness that may affect comfort and indoor air quality.

Figure 22 shows that the 3D-printed home maintained more stable but drier humidity levels, while the traditional residence exhibited greater fluctuations influenced by occupancy and material behavior.

Figure 22

Relative Humidity difference between 3d Printed and Traditional Residence
Source: Aethair – Environet Data Collection_Relative Humidity (Environet Console, 2025)





Comparison with ASHRAE Standard

The 3D-printed home showed lower and more stable humidity levels because its concrete walls naturally controlled moisture and reduced air leaks. On the other hand, the traditional residence, made with wood framing, absorbed and released moisture more easily, causing higher and fluctuating humidity, especially since the resident was living there during data collection. This steady humidity in the 3D-printed home helps create a more comfortable and healthier space, lowering the risk of mold, protecting materials, and improving overall air quality. (Table 14)

Table 14.

Aspects of 3D Printed Home and Traditional Residence

Aspect	3D-Printed Home	Traditional Residence
Range vs ASHRAE Standard (30%-60%)	Within average range (40%), but occasional readings fall below 30%; low-humidity conditions observed.	Mostly within range, with occasional high readings > 70% RH indicating dampness.
Humidity Stability	More stable and controlled, aided by airtight construction.	Higher variation due to occupancy and porous wall materials.
Moisture Behavior	Concrete limits moisture exchange; low risk of mold or condensation.	Wood structure absorbs and releases moisture, increasing fluctuation.
Comfort Implication	Drier air may cause temporary discomfort (skin or throat dryness).	Occasionally high humidity may cause discomfort and potential surface dampness.
Building Performance Impact	Supports long-term durability and material protection; may benefit from mild humidification.	Natural balance of moisture, but higher risk of dampness and material degradation.

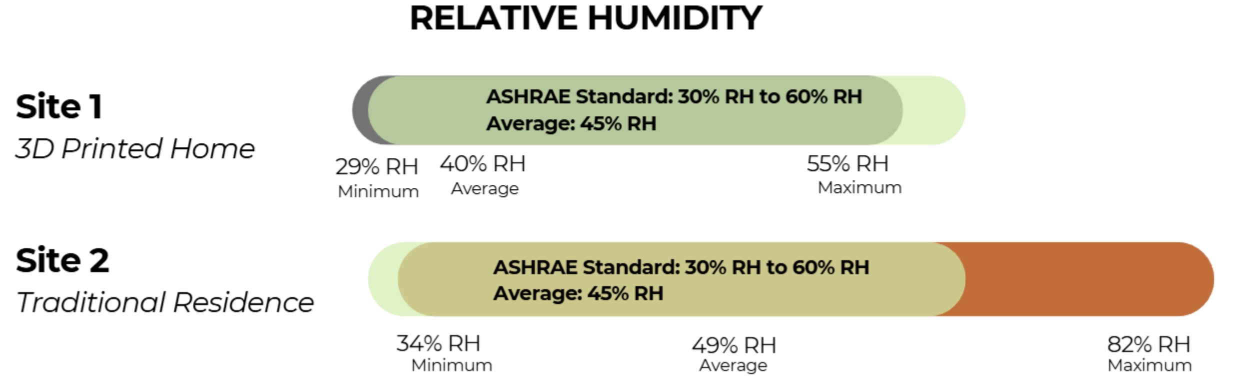


Figure 23: *Minimum, Average, and Maximum values compared with ASHRAE Standards (Nampally, 2025)*
Note: Considered the nearest value for the comparison.

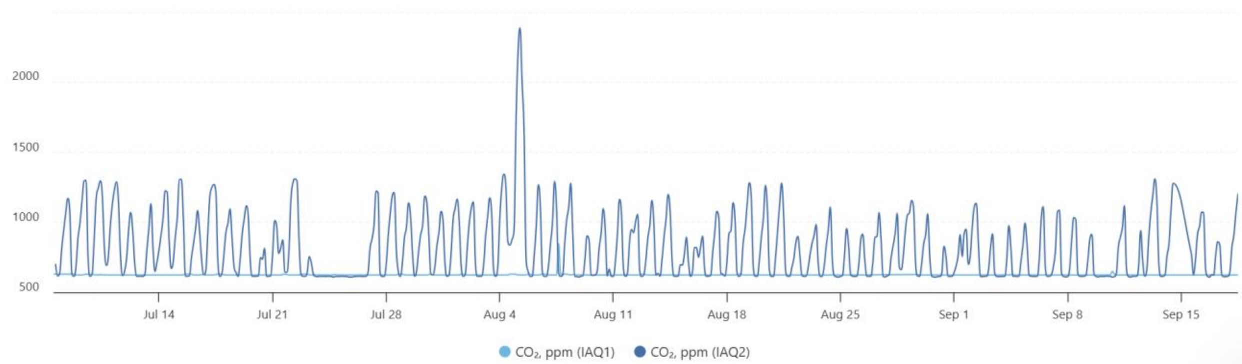
4.4: Indoor Air Quality (RQ1.3)

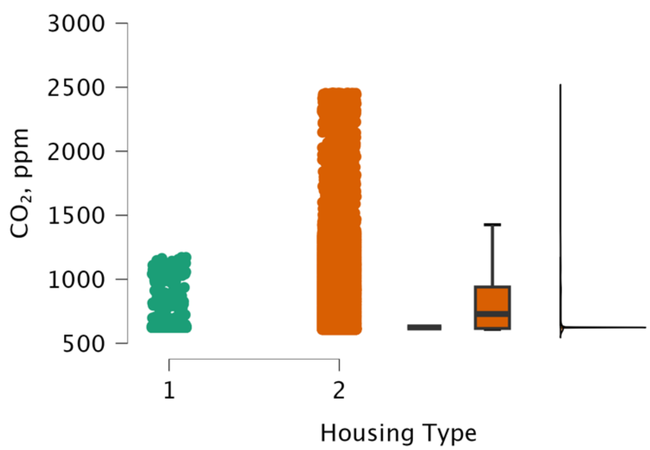
CO_2 concentrations in the 3D-printed home ranged from 624 ppm to 1171 ppm, averaging 625 ppm. These values generally fall within the ASHRAE 62.1/62.2 recommended comfort range of 600 -1000 ppm (average 800 ppm), indicating adequate ventilation and stable air quality. Occasional peaks above 1000 ppm suggest brief periods of limited airflow or reduced ventilation efficiency during data collection.

In contrast, CO_2 levels in the traditionally built residence ranged from 609 ppm to 2456 ppm, with an average of 814 ppm. While the average remains within ASHRAE comfort limits, the significant spikes exceeding 2000 ppm indicate periods of poor ventilation that may cause discomfort or reduced alertness among occupants. Compared to the 3D-printed home, the traditional residence showed greater fluctuations, reflecting the influence of human occupancy and variable ventilation behavior. (Figure 24)

Figure 24

Carbon dioxide difference between 3d Printed and Traditional Residence
Source: Aethair – Environet Data Collection_Carbon dioxide (Environet Console, 2025)





Comparison with ASHRAE Standard

The 3D-printed home showed lower and more consistent CO_2 levels because no occupants were present during the data collection period, minimizing human-induced variations. In contrast, the traditional residence, being occupied, naturally produced higher CO_2 readings due to respiration and indoor activity. The 3D-printed home's airtight concrete structure allows for better control over ventilation; however, its performance under real occupancy remains to be tested. Thus, indoor CO_2 concentrations between 1000 and 1200 ppm in sedentary spaces generally indicate acceptable satisfaction levels among occupants regarding air freshness and odor control, as noted by ASHRAE. (Table 15)

Table 15.

Aspects of 3D Printed Home and Traditional Residence

Aspect	3D-Printed Home	Traditional Residence
Range vs ASHRAE Standard (600-1000 ppm)	Mostly within range; occasional minor peaks (~1171 ppm).	Average within range, but major peaks (>2000 ppm) exceed comfort standards.
Average CO_2 Concentration	625 ppm - better baseline air quality.	814 ppm - acceptable but influenced by human presence.
Ventilation Efficiency	Stable due to controlled, airtight structure.	Variable due to occupancy and ventilation behavior.
Comfort & Health Implication	Fresh air levels maintained; occasional need for ventilation check.	Periods of stuffiness or fatigue possible at high CO_2 peaks.
Compliance with ASHRAE Guidelines	Within ASHRAE 62.1–62.2 comfort range (600–1000 ppm).	Exceeds upper limit during certain hours, indicating ventilation inefficiency.

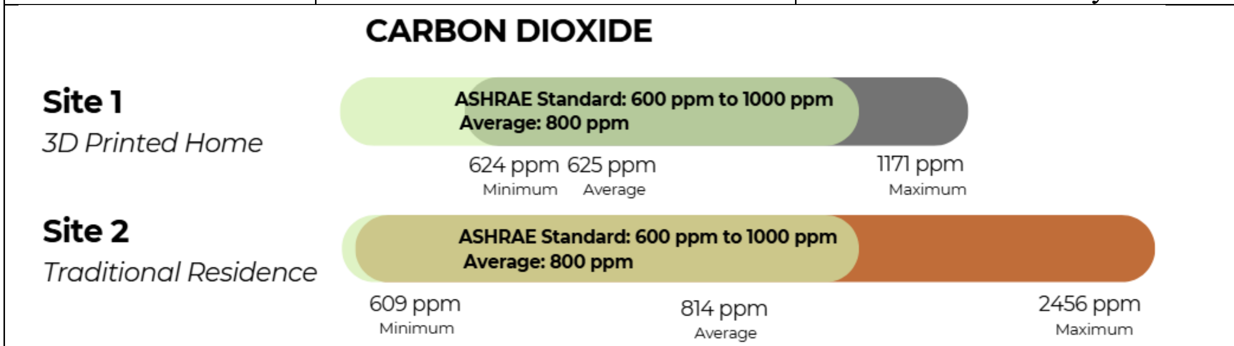


Figure 25: *Minimum, Average, and Maximum values compared with ASHRAE Standards (Nampally, 2025)*
Note: Considered the nearest value for the comparison.

4.5: Overall Data Collection from 3d Printed Site and Traditional Residence:

This case study highlights how the 3D-printed home is capable of supporting livable indoor conditions, while also pointing to areas where refinements can improve user comfort. Figure 16 shows the results from the Aethair IAQ Device from July to September, 2025. (Table 16)

Figure 26

Result from Aethair IAQ Device
Source: Aethair – Environet Data Collection_Site 1 (Environet Console, 2025)

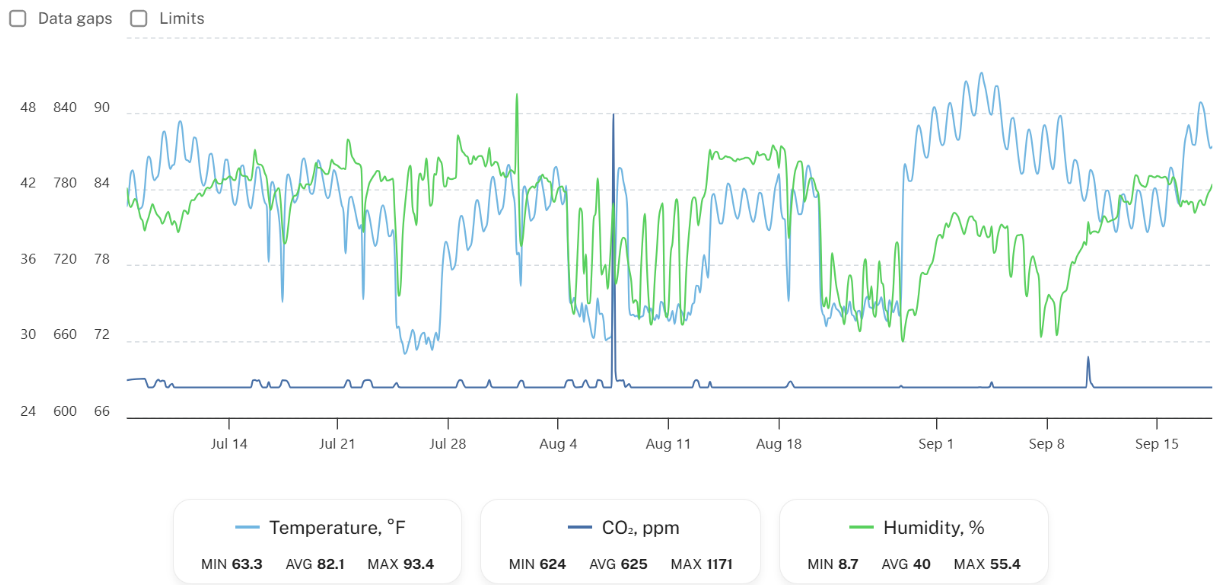


Figure 26 shows the results from Aethair IAQ Device from July to September, 2025.

Figure 27

Result from Aethair IAQ Device
Source: Aethair – Environet Data Collection_Site 2 (Environet Console, 2025)

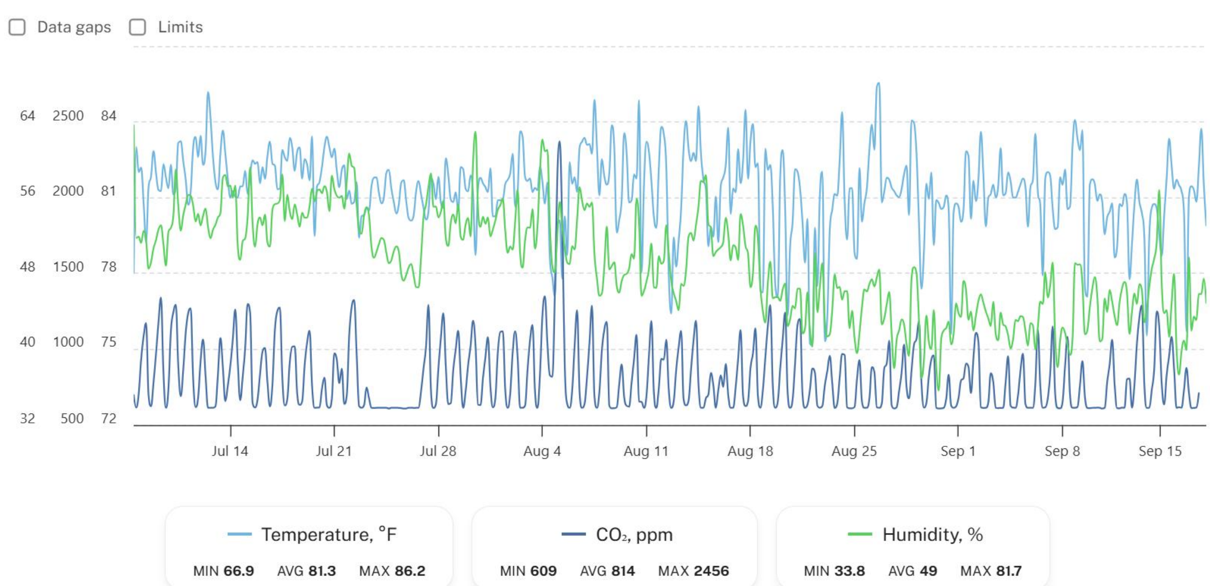


Table 16.

ASHRAE Standards vs. 3D-Printed Home and Conventional Residence

Factors	ASHRAE Standards		3D Printed Range		Conventional Residence Range	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Temperature (°F)	50°F	93°F	63°F	93°F	67°F	86°F
Carbon dioxide(ppm)	600ppm	1000ppm	624ppm	1171ppm	609ppm	2456ppm
Relative Humidity (RH)	30%RH	60%RH	29%RH	55%RH	34%RH	82%RH
Noise (dB)	20dB	40dB	33dB	37dB	34dB	41dB

Note: (°F) - Degrees Fahrenheit; (ppm) - Parts Per Million; (RH) - Relative Humidity; (dB) - Decibel

4.6: Acoustic Performance (Q2)

Table 17.

Inside Sound comparison for the 3D Printed house and Traditional Residence

	Minimum	Maximum
3D Printing	 **Figure 28:** Minimum 3d Printed home :33.1dB	 **Figure 29:** Maximum 3d Printed home :37.2 dB

Traditional	 **Figure 30:** Minimum Traditional home: 34.0 dB	 **Figure 31:** Maximum Traditional home: 41.2 dB

For the 3D-printed home, indoor noise levels ranged between 33.1 dB (minimum) and 37.2 dB (maximum). These readings remain well below the ASHRAE-recommended limit of 40 dB for residential interiors, signifying a quiet and acoustically comfortable environment. The minimal fluctuation in readings indicates strong noise insulation and material performance in blocking external and internal disturbances.

In contrast, the traditional residence exhibited noise levels between 34.0 dB (minimum) and 41.2 dB (maximum). Although the lower end suggests a calm indoor setting, the upper limit slightly exceeds the ASHRAE comfort threshold (40 dB). This implies that while generally quiet, the traditional residence may allow minor peaks of mechanical or outdoor noise to enter the space.

When compared, both housing types provide acceptable acoustic comfort (Table 17), but the 3D-printed home demonstrates superior sound insulation and greater indoor stability. The dense concrete walls of the 3D-printed structure offer natural sound absorption and reflection control, reducing airborne noise transmission more effectively than the lighter, wood-framed walls of traditional construction.

Table 18.

Comparing Inside and outside noise for 3D Printed House

	Minimum	Maximum
3D Printing House (Inside)	 **Figure 32:** Minimum 3d Printed home :33.1dB	 **Figure 33:** Maximum 3d Printed home :37.2 dB

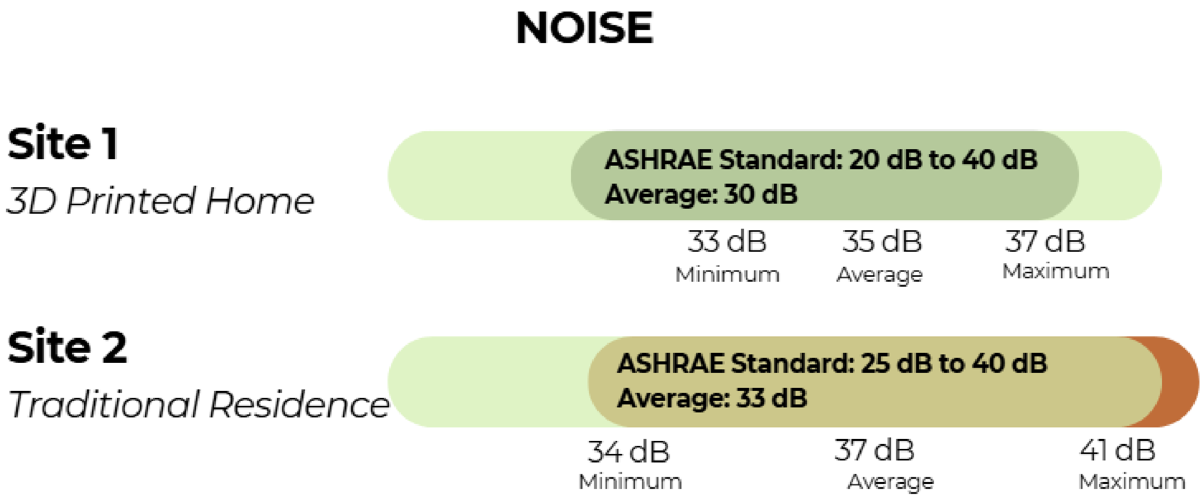
3D Printing House (Outside)	 **Figure 34:** Maximum 3d Printed home :57.6 dB	 **Figure 35:** Maximum 3d Printed home :61.8 dB

To evaluate external sound insulation, measurements were taken both inside and outside the 3D-printed home. Indoor readings ranged from 33.1 dB to 37.2 dB, while outdoor levels varied between 57.6 dB and 61.8 dB. (Table 18, Figure 36)

The difference of nearly 25 dB demonstrates the structure's strong sound attenuation capacity, effectively minimizing the impact of external environmental noise. The outdoor readings fall within acceptable limits for urban and campus environments, where moderate activity and vehicular movement are common.

These results indicate that the 3D-printed home performs exceptionally well acoustically, providing a peaceful indoor environment conducive to concentration, rest, and relaxation. The ASHRAE acoustic comfort range (≤40 dB for interiors) supports this finding, confirming that the 3D-printed structure ensures superior sound quality and occupant satisfaction

Figure 36: *Minimum, Average, and Maximum values compared with ASHRAE Standards (Nampally, 2025)*
Note: Considered the nearest value for the comparison.



The 3D-printed home maintained quieter and more consistent noise levels than the traditional residence, staying well within ASHRAE's indoor comfort range. This performance stems from the dense, monolithic concrete walls used in additive construction, which offer enhanced sound insulation and vibration damping. Conversely, the traditional residence exhibited slightly higher peaks, reflecting its lighter framing system and greater susceptibility to environmental or mechanical sound transmission.

CHAPTER V – DISCUSSION

5.1. Discussion Summaries

RQ1: **How do 3D-printed homes influence indoor microclimate conditions compared to conventional construction methods?**

The overall findings show that 3D-printed homes maintain more stable indoor environmental conditions than traditional residences, particularly in temperature, humidity, and air quality. The solid, monolithic walls and high thermal mass of 3D-printed materials showed effectiveness in reducing daily fluctuations, improve air tightness, and support consistent comfort levels. Compared with conventional construction, the 3D-printed unit demonstrated stronger control of internal climate factors, staying within ASHRAE and EPA comfort ranges throughout the study period.

These outcomes confirm that 3D Printing technology supports better energy performance, moisture regulation, and occupant well-being, making it a promising approach for sustainable housing applications.

RQ1.1: How does the thermal performance (indoor temperature regulation) of 3D-printed homes differ from that of traditionally constructed homes?

The 3D-printed home exhibited greater heat retention and higher indoor temperature stability, primarily due to the concrete material's thermal mass. While both homes met ASHRAE comfort thresholds (50°F - 93°F), the 3D-printed unit tended to stay warmer, averaging between 63°F - 93°F, while the traditional home maintained slightly cooler and more balanced daily temperatures, closer to the ASHRAE midpoint of 82°F.

Interpretation:

- The 3D-printed home shows higher heat retention, likely resulting from its dense concrete structure and thermal inertia.
- The traditional residence maintained better daily thermal balance, offering a closer alignment with ASHRAE comfort midpoints.
- Both sites remained within comfort limits, though the 3D-printed home's elevated temperatures suggest that passive cooling, shading devices, or enhanced ventilation would improve summer comfort.
- The thermal mass benefits of 3D-printed walls are advantageous in cooler climates but may present challenges in warmer regions without adequate airflow.
- Overall, construction material and wall design significantly influence indoor temperature stability, user comfort, and energy efficiency within ASHRAE-defined thermal conditions.

RQ1.2: In what ways does the indoor humidity level in 3D-printed homes differ from that in conventional homes, especially regarding comfort and moisture control?

The 3D-printed home maintained consistent indoor humidity levels, averaging between 29 - 55% RH, while the traditional home showed more variation, ranging from 34 - 82% RH. The airtight and water-resistant concrete structure of the 3D-printed home limited moisture intrusion, whereas the traditional residence's porous materials allowed higher fluctuation, particularly during rainy periods.

Interpretation:

- The 3D-printed home sustained steady but slightly drier conditions due to reduced moisture exchange through its sealed concrete walls.
- The traditional residence displayed more variation in humidity linked to occupant activity and material porosity.
- Stable humidity in 3D-printed homes enhances both comfort and material durability, though occasional dryness could occur in extended warm periods.
- Traditional structures offer a more natural moisture balance but face higher risks of dampness and mold.
- Both homes remained within ASHRAE's 30 - 60% comfort range, underscoring how material composition and airtightness influence indoor moisture behavior and comfort performance.

RQ1.3: How does the indoor air quality in 3D-printed homes, measured by CO_2 level, differ from that in conventionally built homes?

The 3D-printed home recorded lower and more consistent CO_2 levels (624-1171 ppm), compared to the traditional residence, which periodically rose above (609-2456 ppm) during occupancy. These findings indicate that airtight design and passive ventilation integration in the 3D-printed home supported more stable air quality and lower pollutant accumulation.

Interpretation:

- The 3D-printed home maintained cleaner baseline air quality with minimal CO_2 fluctuations, likely aided by limited occupancy and sealed construction.
- The traditional home exhibited higher CO_2 spikes due to occupant activity and inconsistent ventilation patterns.
- The 3D-printed home's design inherently supports stable IAQ performance, though further testing under occupied conditions would provide a more comprehensive picture.
- Effective ventilation management is crucial in both building types to ensure long-term air quality.
- Compared to ASHRAE guidelines, both homes maintained CO_2 levels below the 1000 ppm limit, but the traditional unit exceeded comfort thresholds more often, emphasizing the role of ventilation design and monitoring in occupant health.

RQ2: To what extent do 3D-printed homes impact indoor noise levels relative to traditional homes?

The 3D-printed home achieved superior acoustic comfort, maintaining sound levels between 33 - 37 dB, compared to 34 - 41 dB in the traditional residence. The dense, joint-free walls effectively blocked external and internal noise transmission, resulting in a quieter and more stable acoustic environment.

Interpretation:

- The 3D-printed home consistently maintained lower indoor noise levels than the traditional residence.
- Its thick concrete structure offered excellent sound insulation, reducing outdoor and mechanical noise infiltration.
- The traditional unit experienced slightly higher peaks but remained within ASHRAE's 20 - 40 dB comfort range.
- **Pros:** Enhanced privacy, reduced disturbances, and improved acoustic comfort in the 3D-printed home.
- **Cons:** Hard reflective surfaces may create minor echo effects if not treated with absorptive finishes.
- Overall, the 3D-printed home demonstrated strong compliance with ASHRAE acoustic standards, confirming its potential to provide both affordability and improved livability through superior noise control and indoor calmness.

5.2. Limitations

While this study provides valuable insights into the indoor microclimate and environmental comfort of 3D-printed housing compared to traditional construction, several limitations should be acknowledged. In terms of occupancy variation, the 3D-printed home was unoccupied during data collection, while the traditional residence was inhabited. This difference likely influenced humidity, CO_2 levels, and noise readings, limiting the direct comparability of ventilation and activity-related impacts. With respect to short monitoring duration, measurements were taken primarily between July and September, representing warm summer season conditions in Los Angeles, California. Longer monitoring across multiple seasons would better capture year-round performance and thermal behavior. Regarding the limited sample size, this study examined only one 3D-printed home and one traditional residence, which limits the generalizability of the findings. To strengthen future research, a broader sample including multiple homes across varied climatic zones and construction types should be considered to capture more representative and comparable results. Clarifying that this research is limited to one 3D-printed home and one traditional home highlights the need for expanded sampling in future studies. In relation to sensor and calibration factors, minor discrepancies in sensor calibration or placement may have affected localized readings, particularly for humidity and sound.

Considering external environmental influences, outdoor factors such as traffic noise, surrounding vegetation, and weather fluctuations may have introduced variability not fully controlled in this study. In terms of equipment errors, since the case study sites were located in California, occasional technical glitches made it difficult to coordinate with on-site representatives in real time. As a result, some minute-by-minute data points were lost due to intermittent network connectivity issues. Regarding occupancy influence, it is important to note that the 3D printed home was unoccupied during the research period, whereas the traditionally built home was inhabited. As the traditional residence was occupied, the resident's personal comfort preferences likely influenced temperature regulation and HVAC usage. Additionally, the presence of a functional kitchen in the unit may have contributed to fluctuations in CO_2 levels during cooking activities. In contrast, the 3D-printed house served as a demonstration project where individuals visited intermittently but did not reside, resulting in minimal human influence on indoor environmental variations. Despite these constraints, the findings establish a foundational understanding of how material composition and design strategies in 3D-printed housing affect indoor comfort, guiding future research toward larger, long-term, and occupant-inclusive assessments.

5.3. Future Study

Several areas can be explored further to deepen the understanding of how 3D-printed homes perform compared to traditional construction in real-life conditions. With respect to including occupied 3D-printed homes, future studies should focus on units that are actually lived in so that human activities, HVAC usage, and daily routines influencing temperature, humidity, and CO_2 levels can be captured. In terms of year-round monitoring, future research should extend across different seasons to identify how thermal comfort and energy performance vary throughout the year. Regarding a larger and more diverse sample, expanding the study to include multiple 3D-printed and traditional homes across different regions and at different stages of their lifespan (for instance, one constructed five years ago, another built two years ago, and a recently completed unit) would strengthen comparisons and show how building age and material aging influence indoor environmental performance over time. Future research can be strengthened by comparing 5 -10 homes across varied climatic zones and construction types to generate more robust and representative results. In relation to improved data collection systems, integrating advanced, cloud-based sensors can minimize data loss caused by network interruptions and improve the precision and continuity of environmental monitoring.

Considering linking energy and comfort, future research should connect indoor comfort data with energy use by assessing HVAC efficiency, passive cooling effectiveness, and the potential energy savings of 3D-printed materials. Regarding acoustic and material testing, further investigation into the sound absorption and acoustic insulation properties of 3D-printed concrete could confirm its long-term potential for improving indoor comfort and noise control. In terms of occupant feedback and comfort perception, combining quantitative measurements with user surveys can offer a more holistic understanding of how residents actually feel and experience comfort, air quality, and livability in 3D-printed homes. With respect to an alternative data collection approach, future studies could incorporate small-scale box prototypes equipped with indoor microclimate monitors, allowing controlled testing conditions and more extensive comparative data on temperature, humidity, CO_2, and thermal behavior. In line with an expanded future direction, these limitations emphasize the need for long-term, multi-season monitoring, larger sample sizes, controlled prototype testing, and occupant-inclusive assessments to support deeper scientific understanding. In conclusion, future studies should adopt a more occupant-centered and long-term approach, capturing both technical data and human experience to understand how 3D-printed construction can evolve into a sustainable, comfortable, and practical housing solution for diverse climates and communities.

CHAPTER VI – CONCLUSION

This research explored how 3D-printed homes perform in terms of indoor microclimate and user comfort when compared to traditionally constructed residences. Using data collected through Aethair Indoor Air Quality (IAQ) equipment and analyzed with the Environet application, the study examined temperature, humidity, carbon dioxide (CO_2) levels, and noise to understand how construction methods and materials influence the indoor environment. The findings were compared against ASHRAE standards to assess overall comfort performance.

Overall, the results indicate that the 3D-printed home maintained stable and consistent indoor conditions, demonstrating the potential of this construction method in achieving comfortable living environments.

- The CO_2 levels largely stayed within acceptable limits, suggesting good ventilation and air quality.
- Humidity levels were generally balanced but tended to be slightly drier, indicating the need for improved moisture regulation.
- The temperature readings showed higher heat retention in the 3D-printed home due to its concrete structure and thermal mass, which helped stabilize indoor conditions but also led to warmer peaks during the summer period.

In comparison, the traditional residence showed greater variation in humidity and CO_2 levels, influenced by occupancy and wood-frame materials, but maintained slightly cooler temperatures overall.

The acoustic analysis further emphasized the benefits of 3D-printed construction. The solid concrete walls effectively reduced outdoor noise, providing a quieter and calmer indoor environment compared to the traditional home. This demonstrates that 3D-printed housing not only supports goals of affordability and sustainability, but can also improve everyday comfort, privacy, and livability.

However, a few limitations were noted during the study. The difference in occupancy between the two sites, the short monitoring duration, and data collected during a single season restrict the generalization of the findings. These factors highlight the need for extended, year-round monitoring and studies involving occupied 3D-printed homes to gain a more complete understanding of their performance.

In conclusion, this research shows that 3D-printed homes hold strong potential as a sustainable and comfortable housing solution. With continued development and integration of passive cooling, ventilation control, and humidity management, they can meet and in some aspects exceed, traditional construction standards. As the technology continues to evolve, 3D-printed construction can play an important role in addressing housing challenges by creating affordable, resilient, and environmentally responsive homes that enhance the quality of life for future communities.

"3D Printing will change the way we build, the way we live, and the way we think about architecture - creating homes that enhance comfort, indoor environmental quality, and sustainable living."

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Appendix I. Invitation to Collaborate – 3D Printed Home

CHRISTOPHER C. GIBBS
COLLEGE OF ARCHITECTURE
The UNIVERSITY of OKLAHOMA

Date: 05/21/2025

Dear COBOD Team,

Subject: Request for Case Study Collaboration – The Impact of 3D Printing Construction on Affordable Housing, Indoor Microclimate and User Comfort.

My name is Keerthana Nampally, and I am currently pursuing my Master's degree in Interior Design at the University of Oklahoma. I am conducting a thesis research titled: **"The Impact of 3D Printing Construction on Affordable Housing, Indoor Microclimate and User Comfort."**

I am investigating the potential of 3D-printed construction as a solution for affordable housing, with a specific focus on how it affects indoor microclimate conditions and user comfort. Given your company's leadership in the field of 3D-printed housing, I am writing to respectfully request your support in conducting a **case study** on your residential projects.

If granted permission, I would visit your site to collect indoor environmental quality (IEQ) data as proposed below. I have summarized the key components for your consideration:

Research Questions

- **RQ1:** In what ways do 3D-printed homes influence indoor microclimate conditions compared to conventional construction?
- **RQ2:** How do 3D-printed homes impact indoor noise levels relative to traditionally built homes?

Proposed Timeline

I intend to conduct the initial site visit in **the mid weeks of May 2025 or early weeks of June 2025** to capture data during the early summer season. A second visit to remove the equipment is

Figure 37: *Request for Case Study Collaboration – 3D Printed Home Page:1 (Nampally, 2025)*

tentatively planned for **the mid weeks of August 2025** or **the early weeks of September 2025**. I am flexible with the schedule and willing to adjust based on your availability.

Measurements to Be Collected

I will collect indoor temperature, humidity, CO_2 levels, sound levels, following ASHRAE and EPA indoor environmental standards. Data will be collected using professional-grade portable equipment, and no physical modifications or disruptions will be made to the home.

Preferred Site

Extrusion-based 3D concrete printing method with special focus on thermal mass, insulation strategies, and interior wall finishes that influence environmental comfort. One 3D printed home newly built, and another same/similar 3D printed home built 2 years or earlier.

Oklahoma and Texas regions are prioritized for proximity, These are preferred sites, but I am open to other technologies and locations if available.

Purpose and Benefits

This research aims to strengthen our understanding of how 3D-printed housing can serve as a sustainable, affordable, and healthy alternative for residential living. The findings will be shared with you upon completion and can potentially enhance your performance narratives and project documentation.

I would be honored to include your project as a case study in my thesis and sincerely hope for the opportunity to collaborate. Please feel free to reach out with any questions or clarifications. I am available at your convenience to discuss this further.

Thank you for your time and consideration.

Warm regards,
Keerthana Nampally
Master's Student | Interior Design
University of Oklahoma

Thesis Chair: **Prof. Yeji Yi** | yeji.yi@ou.edu

Figure 38: *Request for Case Study Collaboration – 3D Printed Home Page:2 (Nampally, 2025)*

Appendix II. Invitation to Collaborate – Traditional Home

CHRISTOPHER C. GIBBS
COLLEGE OF ARCHITECTURE
The UNIVERSITY *of* OKLAHOMA

Date: 06/06/2025

Dear Resident,

Subject: Request for Case Study Collaboration – The Impact of 3D Printing Construction on Affordable Housing, Indoor Microclimate and User Comfort.

My name is Keerthana Nampally, and I am currently pursuing my Master's degree in Interior Design at the University of Oklahoma. I am conducting a thesis research titled: **"The Impact of 3D Printing Construction on Affordable Housing, Indoor Microclimate and User Comfort."**

I am investigating the potential of 3D-printed construction as a solution for affordable housing, with a specific focus on how it affects indoor microclimate conditions and user comfort. I am writing to respectfully request your support in including your home as a case study in my research.

If granted permission, I would visit your site to collect indoor environmental quality (IEQ) data as proposed below. I have summarized the key components for your consideration:

Research Questions

- **RQ1:** In what ways do 3D-printed homes influence indoor microclimate conditions compared to conventional construction?
- **RQ2:** How do 3D-printed homes impact indoor noise levels relative to traditionally built homes?

Proposed Timeline

I intend to conduct the initial site visit in **June 2025** to install an IEQ measurement device. A second visit to remove the device is tentatively planned for **September 2025**. Alternatively, we

Figure 39: *Request for Case Study Collaboration – Traditional Home Page:1 (Nampally, 2025)*

can consider shipping the device rather than visiting if you prefer. I am flexible with the schedule and willing to adjust based on your availability.

Measurements to Be Collected

I will collect indoor temperature, humidity, CO_2 levels, sound levels, following ASHRAE and EPA indoor environmental standards. Data will be collected using professional-grade portable equipment, and no physical modifications or disruptions will be made to the home.

I will also need some basic information about your home, such as square footage, ceiling height, number of rooms and windows, and other relevant layout details.

Purpose and Benefits

This research aims to strengthen our understanding of how different construction methods can offer a sustainable, affordable, and healthy alternative for residential living. Your participation may also contribute to advancing best practices in future homebuilding construction.

I would be honored to include your site in my thesis and sincerely hope for the opportunity to collaborate. Please feel free to reach out with any questions or clarifications. I am available at your convenience to discuss this further.

Thank you for your time and consideration.

Warm regards,
Keerthana Nampally
Master's Student | Interior Design
University of Oklahoma

Thesis Chair: **Prof. Yeji Yi** | yeji.yi@ou.edu

Figure 40: *Request for Case Study Collaboration – Traditional Home Page:2 (Nampally, 2025)*

Appendix III. Equipment

CHRISTOPHER C. GIBBS
COLLEGE OF ARCHITECTURE
The UNIVERSITY of OKLAHOMA

Equipment Loan

Please review the information regarding the equipment loan condition and sign if you agree.

Owner - University of Oklahoma:

Contact Person: ______________________________

Address: ______________________________

City: ____________ **State:** ____________ **Zip:** ____________

Phone: ____________ **E-mail:** ______________________________

Case Study Representative:

Contact Person: ______________________________

Address: ______________________________

City: ____________ **State:** ____________ **Zip:** ____________

E-mail: ______________________________

Equipment Identification

Description of each item (including serial #)	Cost / Value

Transportation

1. Who will pay charges for transportation, including transit insurance, to the borrower location specified above?
   [ ] **Owner (University)** [ ] **Borrower**
2. Who will be responsible for the transportation charges, including transit risk insurance, when equipment is returned to the owner - University of Oklahoma Norman campus?
   [ ] **Owner (University)** [ ] **Borrower**
3. [ ] **Return Opt-1:**
   The borrower will be packing the equipment, and they will be shipping it to the Owner. (Through the Postal Service)

   [ ] **Return Opt-2:**
   The Owner will be visiting there, and picking the equipment.

Period of Loan

From: ______________________ **Through:** ______________________

Agreement

I understand and agree that the owner lend the identified equipment to the borrower for the loan period through transportation as indicated above. The equipment should be returned without any damages and loss. This agreement may be terminated at the request of either party.

Owner Signature: ______________________ **Date:** ____________

Owner Printed Name: ______________________________

Borrower Signature: ______________________ **Date:** ____________

Borrower Printed Name: ______________________________

Copies to: (after approval) Lender, Department, Equipment Management

Page 1 of 1

Figure 41: *Request for Equipment Loan from the University of Oklahoma (University of Oklahoma, 2025)*

Appendix IV. Volunteer Participation Consent/Waiver & Release

WOODBURY
UNIVERSITY
FOUNDED IN 1884

Human Resources/Risk Management

VOLUNTEER PARTICIPATION
INFORMED CONSENT/WAIVER & RELEASE

PARTICIPANT'S NAME: Keerthana Nampally

EVENT: (Describe the event/locations and dates):
Research with IAQ data for Master's Thesis

In consideration of the acceptance of my voluntary participation in the above ~~event~~/activity, I hereby waive, release and discharge any and all claims for damages for death, personal injury or property damage which I may have, or which may hereafter accrue to me, against the Woodbury University as a result of my participation in this activity.

This release is intended to discharge the Woodbury University and their trustees, officers, administrators, faculty, event vendors, third party participants, other employees and volunteers from and against any and all liability arising out of or connected in any way with my participation in the event/activity, even though that liability may arise out of negligence or carelessness on the part of the University or persons mentioned above.

I understand that participation in this event will include a great deal of physical activity. I further understand that accidents and injuries can arise out of this activity; knowing the risk, nevertheless, I hereby agree to assume those risks and to release and to hold harmless the University and persons mentioned above.

It is further understood and agreed that this waiver, release and assumption of risks is to be binding on my heirs and assigns.

Participant Signature: [signature] **Date:** 07/07/2025

WU Witness: [signature] **Date:** 7/7/25

If participant is under 18 years of age, parent or guardian must read and sign the following:
This release, its significance, and assumption of risk have been explained to and are understood by the minor.

Parent or Guardian Signature: ____________________ **Date:** ____________________

Figure 42: *Volunteer Participation from Woodbury University (Woodbury University, 2025)*

This form was completed as part of Woodbury University's Risk Management process to permit equipment use for data collection. ***IRB approval was not required****, as the study did not involve human subjects; the form served solely as a safety and equipment use acknowledgment.*