

Developing a Personalized Airflow System to Enhance Occupants' Well-being

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ABSTRACT

In recent years, architects have been increasingly focused on designing green, low-energy buildings that prioritize sustainability and energy efficiency. However, this emphasis on environmental considerations often overshadows the critical importance of creating indoor environments that promote the well-being, comfort, and productivity of occupants. With people in industrialized countries spending nearly 90% of their time indoors, it is imperative to shift our attention to user-centric design.

This shift becomes even more significant when we consider that office workers' salaries are about 100 times higher, per square foot, than energy costs, underscoring the need to prioritize users. Indoor environments profoundly affect physical and psychological health, cognitive abilities, and productivity through factors like thermal conditions, lighting, air quality, and noise.

Furthermore, with over 60% of the world's population projected to inhabit urban environments by 2030, it is essential to address the potential negative impacts of living in crowded, enclosed spaces, particularly in light of experiences during the COVID-19 pandemic. This has brought the user experience into sharp focus, as isolation from nature and the outside world can have adverse effects.

In response, biophilic design principles, rooted in our innate connection with nature, have gained prominence. They aim to integrate natural elements into the built environment, enhancing user comfort and performance. Airflow is a vital element in biophilic design, contributing to healthy indoor environments. This research seeks to develop an experimental system to simulate natural air movement in indoor spaces, fostering user engagement with nature and improving indoor quality.

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GENERAL AUDIENCE ABSTRACT

Architectural design has increasingly leaned towards environmentally conscious, energy-efficient structures, emphasizing sustainability. However, this has sometimes overshadowed a crucial consideration – the well-being, comfort, and productivity of occupants within indoor spaces. Given that individuals in industrialized nations spend nearly 90% of their time indoors, there's a clear need to shift towards occupant-centric design.

Moreover, the fact that the salaries of office workers per square foot far surpass associated energy costs underscores the need for user-focused design. Indoor environments significantly influence physical health, mental well-being, cognitive performance, and productivity, with factors like temperature, lighting quality, indoor air, and noise playing critical roles.

As more than 60% of the world's population is expected to reside in urban areas by 2030, understanding the potential downsides of crowded city living is essential, especially in light of the COVID-19 pandemic's effects on isolation from nature. In response, biophilic design principles, rooted in the innate human connection to the natural environment, have gained prominence. This approach integrates natural elements into the built environment to enhance user comfort and performance.

One vital element of biophilic design is airflow, which significantly contributes to creating healthier indoor spaces. In response, this research aims to develop an experimental system that simulates natural air movement within indoor environments, enhancing user engagement with the natural world and, consequently, indoor environmental quality.

Dedication

I dedicate this thesis to my great family, whose unwavering support and boundless love have been the cornerstone of my academic journey.

To my parents, for instilling in me the values of perseverance, dedication, and a thirst for knowledge. Your sacrifices and encouragement have paved the way for my success.

To my siblings, for their endless patience and understanding during my countless hours of study and research. Your belief in me has been a constant source of motivation.

To my extended family, for their constant encouragement and faith in my abilities. Your support has been a source of strength throughout this challenging endeavor.

This thesis stands as a testament to the enduring bonds of family, and I am profoundly grateful for your presence in my life.

With all my love and gratitude,

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Table of Contents

List of Tables	viii
List of Figures.....	ix
List of Abbreviations	x
1. Chapter One: Introduction	1
1.1 Overview	1
1.2 Problem Statement.....	4
1.3 Research Goal and Objectives	5
1.4 Theoretical Foundation	6
1.5 Research Significance	6
1.6 Research limitations.....	7
2. Chapter Two: Literature Review	8
2.1. Biophilia and Biophilic Design.....	8
2.1.1. The Relationship Between Biophilia and Built Form.....	8
2.1.2. Understanding Biophilia	9
2.1.3. Theory of Biophilia.....	10
2.1.4. Biophilia in Architecture.....	12
2.1.5. Experience and Attributes of Biophilic Design	15
2.1.6. Biophilic Design and the 14 Principles.....	17
2.1.7. Benefits of Biophilic Design.....	22
2.2. Biophilia and Natural Ventilation	27
2.2.1. Properties of Natural Ventilation	27
2.2.2. Benefits of Natural Ventilation.....	28
2.2.3. Challenges of Using Natural Ventilation in Biophilic Designs	30
2.3. Ventilation and Thermal Comfort	32
2.3.1. Thermal Comfort Parameters and Conditions for Human Occupancy	32
2.4. Personalized Ventilation.....	36
2.4.1. Benefits of Personalized Ventilation Unit	36
2.5. Summary.....	40
3. Chapter Three: Research Methodology	41

3.1.	Introduction.....	41
3.2.	Qualitative vs Quantitative	41
3.3.	Area of Study.....	43
3.3.1.	The Climate in Humid, Sub-Tropical Areas	44
3.3.2.	Specific Location: Blacksburg – Virginia.....	45
3.4.	Research Structure and Procedure	46
4.	<i>Expected Outcomes</i>.....	48
5.	<i>References</i>	49

List of Tables

Table 1: Biophilic Patterns and Psychological Health and Well-being (Hung, S.H. and Chang, 2021).....	24
Table 2: Biophilic Patterns and Physiological Health (Hung, S.H. and Chang, 2021)....	26
Table 3: The Research Questions and Answering Procedure (Illustrated by the Author).	47

List of Figures

Figure 2: Three Key Frameworks of Biophilic Design (Zhong et al., 2012).	22
Figure 5: The acceptable range of operative temperature and humidity for spaces that meet the criteria specified in ASHRAE Standard 55 – 2017, Section 5.2.1.1	34
Figure 6: Main Research Stages (Illustrated by the Author).	43
Figure 7: (a) United States Map, (b) Blacksburg Map.	43
Figure 8: Temperature Range for Blacksburg, (Climate Consultant).....	45
Figure 9: Wind Rose for Blacksburg, (Climate Consultant).	46

List of Abbreviations

HVAC	Heating, Ventilation, and Air-Conditioning
PV	Personalized Ventilation
CFD	Computational Fluid Dynamics
WHO	World Health Organization
SBS	Sick Building Syndrome
VOC	Volatile Organic Compounds
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
IAQ	Indoor Air Quality
MRT	Mean Radiant Temperature
VOCs	Volatile Organic Compounds
RA	System-recirculated air
FA	fresh air
COA	conditioned outdoor air

1. Chapter One: Introduction

1.1 Overview

In recent years, architects have tended to design green, low-energy buildings that reduce resource usage, preserve the environment, and achieve performance standards such as LEED. Such buildings and systems are now common as a result of much research and development. The design community has achieved great success in constructing buildings that are efficient and highly effective. However, buildings should not be designed only for sustainability, and energy efficiency. Klepeis et al. (2001) indicated that humans in industrialized countries spend nearly 90% of their time indoors. This makes sense to focus on those users, their physical and psychological health, comfort, and productivity, and design buildings and their systems to enhance and support these aspects. Also, within the corporate sector and from a financial perspective, the salaries of office workers are about 100 times higher, per square foot, than energy costs (Yin et al., 2018). This suggests that it may be worth focusing on the users more than the efficiency of the building. Therefore, it is necessary to design comfortable, healthy, and productive environments for them.

The issue of focusing on users is related to all people. The indoor design, long working hours, and stress on individuals affect short-term or long-term illnesses. This may start with losses in worker productivity and concerns for sick building syndrome (Stansfeld and Candy, 2006; Wadsworth et al., 2010). The COVID-19 pandemic, and the social changes it caused shed light on the importance of focusing on the quality of indoor environments. The pandemic shifted the focus of designers and decision-makers toward the negative impacts that indoor environments may inflict on buildings' occupants because of their isolation from nature and the outside world. Studies have shown the negative effects on the physiological and psychological aspects based on this isolation (Yin et al., 2018).

The results of studies such as this indicated that indoor environments affect users' health, cognitive abilities, and productivity. This happened through many factors, including thermal conditions, interior design, lighting, indoor air quality, noise, etc. The results of studies conducted in the United States indicate that 60% of the world's population will move to urban environments by 2030 (Habitat, 2008). This means their settlement in crowded, closed, and isolated environments may negatively affect health and wellness (Habitat, 2008). Therefore, it is necessary to design buildings in such a way as to enhance the user's connection to nature and study how to achieve this connection and the extent of its impact on occupants. Studies indicate that one effective solution may be the application of biophilic design principles (Yin et al., 2018).

In literature, the benefits of biophilic indoor environments have been predominantly shown using the biophilia hypothesis introduced by Wilson (1988). Wilson's hypothesis suggested that humans hold an inherent inclination to seek connections with nature (Wilson, 1988). The results of the study conducted by Hartig and Kahn (2016) showed that connecting to nature positively affected the physical and mental aspects of occupants, helped in recovery from surgery, reduced stress, increased productivity, and reduced mental, cardiovascular, and mortality problems. Accordingly, research related to the development of indoor environments and making them vital has developed. Biophilic design has become an approach used to integrate the built environment with nature to reach comfort and improve the performance of users (Hartig and Kahn, 2016).

Biophilic design in architecture depends on the introduction of natural elements into built environments and allowing users to communicate with nature while occupying the building. The green interior wall is the most popular method used because it provides visual comfort and improves air quality (Yin and Spengler, 2019). Despite the positive impact on users, the implementation of biophilic patterns faces several challenges. These challenges arise from identifying features that positively affect users and identifying ways to measure their effectiveness. However, the biggest challenge is keeping pace with contemporary architecture while, at the same time, addressing the shortcomings related to its lack of connection with nature (Kellert and Finnegan, 2011).

Biophilic design is an emerging trend in architecture and building design that strives to connect people with nature. This approach to design seeks to incorporate natural elements into the built environment to create a space that feels alive, vibrant, and welcoming. As part of this effort, the concept of “biophilic patterns” has been introduced, which focuses on 14 core elements that can be used to create a biophilic environment. These patterns include sunlight, natural materials, plants, views of nature, airflow, and more.

Airflow is an important element of these biophilic patterns - it is essential to providing a comfortable and healthy indoor environment. Natural ventilation is often used to improve airflow in buildings, but other techniques can be used as well. Through careful selection of windows, doors, and other features, the flow of air throughout a building can be managed to provide a more comfortable living environment. Natural ventilation is by no means the only option when it comes to improving airflow in biophilic designs.

Designers can also consider alternative forms of airflow to improve indoor environmental quality using biophilic approaches. For example, mechanical ventilation systems can be used to introduce fresh air into an indoor space while removing stale air. Heat recovery systems can also be implemented to take advantage of energy from outgoing air to reduce energy costs associated with conditioning incoming air. Additionally, air filtration systems can be used to reduce airborne pollutants in spaces by filtering out particulates and other impurities from the air. These systems can be combined with natural ventilation to achieve the best possible airflow in a biophilic design.

By incorporating elements of biophilic design, architects, and designers can create healthier and more inviting spaces. Airflow is an important aspect of this, but one should not be limited to only considering natural ventilation when designing these spaces. Instead, alternative forms of airflow should also be considered to achieve the best indoor environment. By utilizing both natural and mechanical techniques, biophilic environments can be created that are comfortable, healthy, and conducive to human

connection and engagement with nature.

For that, this research aims to develop a system to simulate natural air movement in indoor environments as a biophilic feature. This dedicated system will emulate natural air flow and its variation.

1.2 Problem Statement

Despite the benefits of mechanical ventilation systems, these systems can have negative impacts on the performance and health of building occupants due to the separation from nature and the outdoor environment (Yin and Spengler, 2019). Several studies have been published to show that adopting biophilia principles (e.g., linking buildings with nature) in building design influenced users positively (Stansfeld and Candy, 2006; Yin and Spengler, 2019). One important principle in biophilia is natural ventilation (Sanchez et al., 2018). Therefore, designers now consider opening the buildings to reconnect occupants with nature. But this approach has several limits such as:

1. Some building types do not lend themselves to natural ventilation.
2. The implementation of natural ventilation may not be an approach for some climate zones.
3. Natural ventilation may not be appropriate for certain weather conditions, or times of the day.
4. Natural ventilation is often intermittent.

If designers continue to implement closed buildings with mechanical Heating, Ventilation, and Air-Conditioning (HVAC) systems, problems associated with isolation from nature may continue to increase in the coming years. On the other hand, if architects and owners decide to open buildings and use natural ventilation, the abovementioned limits must be addressed. There is a lack of research related to the efficacy of biophilic design techniques specifically related to natural ventilation (Sanchez et al., 2018).

One solution may be to develop and redesign common HVAC systems to simulate natural ventilation while maintaining their current efficiency. Unfortunately, redesigning HVAC systems such as Variable Air Volume systems to simulate natural airflow patterns is very complex, and for this study, would require access to a functioning system for reconfiguration and control modification. Therefore, this research proposes to design and develop a localized mechanical airflow system that simulates the variability of natural airflow and may be integrated into a modular personal workstation as a strategy for the biophilic work environment. When combined with high efficiency filtration that removes airborne particles and contagions such as COVID-19 this new system can contribute to improved occupant health and wellbeing.

For that, this research will have two main questions as follows:

1. What are the characteristics of natural airflow?
2. Can a localized airflow system be designed and developed to simulate natural airflow?

1.3 Research Goal and Objectives

This research aims to design and develop a prototypical forced air system that simulates natural airflow into a modular workstation. This will help in developing healthier and more comfortable indoor spaces by changing the indoor airflow characteristics. This may be achieved by developing a biophilic localized natural airflow system that simulates natural airflow which may have positive impacts on occupants. For that, several objectives of this study were determined as follows:

1. To determine the characteristics of natural airflow based on the literature, standards, and weather data files.
2. To extend the approach of biophilic design to include a connection to nature by using localized airflow system that simulate natural airflow.
3. To setup and monitor a representative modular personal workstation and integrate a localized airflow system to understand the application of the system.

1.4 Theoretical Foundation

Phenomenology is a philosophical approach that focuses on the individual experience of a person with their environment. It examines how a person's experience influences their interpretation of their surroundings and how that interpretation affects their well-being. Phenomenology seeks to understand how people interact with objects, how the built environment interacts with the natural environment, and how people's relationship to their environment impacts their mental, physical, and emotional health.

Phenomenology and biophilic architectural designs have become important topics in modern architecture. By combining the principles of phenomenology, which focuses on the individual experience of a person in reference to the environment around them, with biophilic design, architects can create spaces that are not only environmentally friendly but also promote a sense of well-being, comfort, security, and contentment for occupants. Biophilic design implements features such as natural light, vegetation, and other elements of nature into the design, allowing occupants to enjoy the beauty and healing power of nature while using the built environment. This promotes physical, psychological, and emotional well-being, building a sense of connectedness to nature and contributing to overall health and productivity.

By incorporating biophilic design, architects can identify the motivations and needs of their clients and create environmentally friendly spaces that promote maximum well-being. This approach can be used to create spaces that are aesthetically pleasing while also offering a sense of peace and unity between occupants and their environment. Through this approach, architects have the potential to create environments that are beneficial for both occupants and the environment, allowing people to enjoy the healing power of nature.

1.5 Research Significance

This research will discuss important issues and major problems related to the negative impact of the current buildings on human health and well-being, the shortage of

application and appropriate approaches to biophilic design, and the shortage of empirical studies demonstrating the efficacy of the biophilic design. As previous studies indicated that there are many problems facing occupant health and well-being inside the buildings, some of these studies indicate that the limited application of natural ventilation is among the most important of these problems. Based on this, the significance of this research includes:

1. Extend the approach of biophilic design to include natural air movement while overcoming the limits of natural ventilation.
2. Design and development of a prototypical localized airflow system applied to an office workstation.
3. Performance evaluation of the prototypical system to determine how closely the resulting airflow patterns at the occupant location correlate with the natural airflow patterns.

1.6 Research limitations

Ultimately, this research will seek to create indoor environments that are both healthier and more comfortable. This might be accomplished by creating a biophilic localized airflow system that mimics natural airflow, which might benefit the users. For that, all variables for this research are limited to the situation in Blacksburg, Virginia.

The scope of the study is limited to the following:

1. Location: Blacksburg / Virginia.
2. Climate: Local climatic conditions in Blacksburg, Virginia.
3. Limits of the available data for analyzing the natural airflow patterns.
4. Type and characteristics of the mechanical airflow device and the control system.
5. Type and configuration for the modular personal workstation as provided by Steelcase.
6. Limits of the airflow monitoring equipment.

2. Chapter Two: Literature Review

2.1. Biophilia and Biophilic Design

2.1.1. The Relationship Between Biophilia and Built Form

Nature and humanity are closely linked. The evolution of humans has always been significantly influenced by this interaction. Since the dawn of time, mankind has relied on nature for all of their survival needs, including food, clothing, shelter, and other basic necessities. The earliest humans had close proximity to food and water supplies. They settled in naturally advantageous places where they could be protected from rivals and predators as well as the harsh weather. Large trees and caves are the oldest types of shelter. Later animal bones or tree branches were utilized to fashion an inverted V-shaped natural tent. A ring of stones or a dip in the ground was employed to firmly support that building. These rational building design principles, which mainly relied on nature, are among the earliest reliable forms of human habitation, which date back as far as 30,000 years.

Through the advancement of agriculture and trade, people became more formal and sophisticated in their living styles which could be argued to be the beginning of architecture. As permanent settlements proliferated, sturdier buildings with straight walls made of clay, stone, wood, and sun-dried bricks started to appear. The majority of these prehistoric human communities were rural. Rural societies changed and became urban ones as the surplus of production started to arise, and cities started to develop. Around 3000 BC, the earliest cities began to emerge. In these cities, people were able to live together in vast communities and support one another. From trying to create habitats apart from the natural environment, this was the pivotal moment. One of the most important shifts over the ages was the urbanization of rural areas into huge cities. At the same time, humans began producing different metals and building materials like

concrete. There was still some degree of dependence on nature while those materials were being made.

The need for buildings also increased as metropolitan regions' population densities rose during the 18th century. Huge constructions were the subject of engineering experiments. Although the buildings were formed of hefty stones and had strong, solid walls, the interiors were exceedingly dark and small. Successful experimentation with new materials like steel and glass during the "Industrial Revolution" gave rise to a whole new generation of extremely tall structures. The first high-rise structure to be supported by a steel skeleton of vertical columns and horizontal beams was the ten-story "Home Insurance Building" in Chicago. As a result of several technological advancements and social changes, the era of massive urban constructed forms like skyscrapers finally began in the 20th century (Landau and Condit, 1999). These buildings' ground-breaking construction methods ushered in a new era of huge steel and RCC skeletons that resembled glass boxes and flat, reflecting glass skins that had little to no connection to the natural environment. This surge in rapid construction was also not the best use of resources and energy because 40 to 45 percent of the world's energy and raw materials are used to construct buildings, and most crucially, their connection to the natural environment is frequently not thoroughly considered (Gottmann, 1966).

We rely on our surroundings to provide us with natural resources and to make it possible for us to form communities. Since humans are creatures of the earth, they react to its natural features, which can also be included in the built design rather than ignoring nature.

2.1.2. Understanding Biophilia

Edward O. Wilson, winner of the Pulitzer Prize, was developing views on biophilia around the same time that the World Health Organization (WHO) developed Sick Building Syndrome (SBS). He defined Biophilia as "... the innate affiliation people seek with other organisms and especially the natural world."

Throughout human evolution, we have relied on flora for food, fuel, and shelter. Being surrounded by plants and other natural components is essential to our basic life. Because of how deeply established this dependence is in human nature, biologists have given the irrational need to be around plants a name: biophilia. Wilson has also cited research that demonstrates that when given complete control over the setting of their homes and workplaces, people are drawn to locations that combine three key characteristics: being high up and overlooking the landscape, being in an area with sparsely spaced-out trees, and being close to open water, such as lakes or streams.

Over the past few years, numerous studies have demonstrated the beneficial effects of green spaces on everyone's lives and the quality of work. A great example of "bringing a city into a garden" as opposed to "garden into a city" is Singapore's "Gardens by the Bay." The Super Tree Grove's vertical gardens span 101 hectares and are 25 meters high.

2.1.3. Theory of Biophilia

Biophilia, the innate human propensity to identify with nature, is still essential to people's physical and mental health and welfare in the modern environment (Wilson, 1986; Kellert and Wilson, 1993; Kellert, 2003; Kellert, 2012). The concept of biophilia comes from an understanding of human evolution, which shows that for more than 99% of the history of our species, biology has evolved in an adaptive response to natural factors rather than pressures imposed by humans. The majority of what we take for granted today is relatively new; large-scale food production dates back only 12,000 years; cities were created 6,000 years ago; mass production of products and services started 400 years ago; and electronic technology is only around a century old. Humans did not construct or create the bio-centric universe in which the human body, mind, and senses evolved.

The term "biophilia" was first coined in 1964 by German social psychologist and psychoanalyst Eric Fromm to refer to a psychological orientation of people who are drawn to life (Fromm, 1964). The phrase was later used by biologist Edward O. Wilson, who popularized it in his book "Biophilia" published in 1984. Biophilia translates to

"love of life", where "bio" stands for life and "philia" stands for love. The description “a biological inclination to affiliate with natural systems and processes instrumental in their health and productivity” is used to describe biophilia.

Wilson claims that the term "biophilia" refers to "the connection that human beings subconsciously seek with the rest of life". He suggested that our biology may be what underlies people's strong ties to nature. The biophilia hypothesis essentially contends that modern people have an emotional affiliation with life and life-like processes and this affiliation is ingrained in our genetic structure.

According to the concept of biophilia, humans have a basic urge and predisposition to associate with other living things. It has been getting more and more support from several areas, particularly architecture. There are no known genes that affect biophilia, but it is believed that as humans have become more reliant on technology, our desire to connect with nature has diminished. According to Wilson and others, such losses in biophilia behavior could rob nature of its purpose, which would lead to a decline in human respect for the natural world.

According to one definition, biophilia is a "positive emotional attachment between humans and other living things. Innate refers to inherited traits that make up the core of human nature” and must be firmly distinguished from unfavorable or "bio phobic" reactions to natural things (Kellert and Wilson, 1993). When discussing biophilic design as a general term, one begins to examine the fundamental principles of how people interact with nature. The answer may lie in biophilic design, which links nature and the built environment to affect human behavior and well-being. The concept of biophilia has been accepted by the design community's thinkers, who have coined the phrase "biophilic design" to describe how it might be applied to environmental design (Kaplan and Kaplan, 1982).

The fields of philosophy and psychology are two that deal with the idea of biophilia. In psychology, it naturally and most significantly belongs to the field of evolutionary psychology. Some evolutionary psychologists have started to support Wilson's hypothesis that people have an innate preference for particular settings. While

presumably the result of biological evolution, they have been improved via experience and civilization. The theory contributes to the explanation of why people protect important flora and flowers near their homes, as well as domestic and wild animals, even at the cost of their own lives. In other words, our inherent enjoyment of life contributes to its maintenance.

Researchers in the fields of psychology and sociology have consistently found that people, regardless of their age or cultural background, prefer the natural environment to built environments. They have also found that people have a preference for particular types of natural environments that have characteristics that are related to our ancestors' prehistoric instincts and habitats. The work of psychologists Stephen and Rachel Kaplan has shown that people almost universally prefer pristine natural settings to artificial or developed ones (Kaplan and Kaplan, 1982).

In the first experiment, participants were shown pictures of two different environments and asked to select their favorite. In a different study, participants were asked to report how various environmental photos made them feel (Kaplan and Kaplan, 1982). The study found that subjects favored photographs of a particular kind, specifically those of natural settings, particularly those with water features, elevated terrain, and sparse trees with tall canopies. In another experiment, subjects were given pictures of several artificial surroundings and asked to select their favorite. The study found that subjects consistently preferred photos that featured more natural components including water, plants, sunlight, and views of the outdoors (Kaplan and Kaplan, 1982).

2.1.4. Biophilia in Architecture

2.1.4.1. Sick Building Syndrome (SBS)

The majority of human beings' time is spent indoors, whether they are at home, at work, or engaged in recreational pursuits. It was observed in the late 1970s that tenants in recently built homes and offices complained of vague symptoms. They were primarily referred to as "office diseases." According to a WHO assessment from 1984, concerns about poor indoor air quality may be present in up to 30% of newly constructed and

renovated buildings globally. SBS is a term coined by the WHO to describe instances in which building inhabitants have severe health issues and pain but cannot pinpoint a single ailment or cause.

SBS, to put it briefly, is a phenomenon that causes residents in airtight buildings to feel uneasy, unwell, and anxious. SBS is characterized as a "psychological and bodily suffering" that is most often associated with workplaces (Baker, 1989; Joshi, 2008). According to the United States Environmental Protection Agency (1991), the following are a few things that could be the main causes of SBS.

2.1.4.2. Chemical contaminants

Through improperly placed air intake vents, windows, and other openings, contaminants from the outside, such as pollutants from car exhaust, plumbing vents, and building exhausts (bathrooms and kitchens), can enter the space. According to Modi and Parmar (2020), by-products of combustion may enter the indoor spaces from an adjacent garage. Asbestos, dust, lead from paints, and formaldehyde can also find their way into enclosed interior areas. On the other hand, Volatile Organic Compounds (VOC) are the most prevalent indoor air pollution, coming from indoor sources. Paints, polishes, adhesives, upholstery, carpeting, machinery, produced wood items, insecticides, cleaning chemicals, etc. are the main sources of VOC. Chemical exposure is also exacerbated by environmental tobacco smoke, combustion byproducts from stoves, fireplaces, and unvented space heaters. Synthetic perfumes included in cleaning and maintenance products as well as personal care items contribute to the contamination.

2.1.4.2.1. Inadequate ventilation

The oil embargo in 1970 forced architects to create buildings that were more airtight and required less external air ventilation to conserve energy (Nsc.org, 2015). Actual airflow was lowered by the ventilation procedures to 5 cfm/person. It was discovered that this decreased intake of fresh air was insufficient to keep building occupants comfortable and in good health. Indoor air pollution is also increased by broken HVAC systems. Electromagnetic radiation

Devices that generate electromagnetic radiation, such as microwaves, televisions, and computers, ionize the air. High magnetic fields are also produced by extensive wiring without adequate grounding, which may cause cancer (Modi and Parmar, 2020).

2.1.4.3. Occupant Well-Being in Architecture

The healing component is nature. Therefore, incorporating it into everyday life and design would encourage the creation of healthy living spaces. According to Alexander (2002), a person's life is influenced by their physical surroundings, and a building's shape can have an impact on a person's ability to love, well-being, and behavior. Environments and spaces have an impact on human well-being both overtly and covertly. Special gestures have an impact on one's body and mind. The horizontals are relaxing, and the vertical proportions lift us up. Spaces are intended to invite you to stop or to allow you to move freely, depending on how they want to affect your state of mind (Alexander, 2002).

According to Day's definition in his book, health and well-being are "a state of renewal, development, and balancing relation to the world," which explains the fundamental harmony of a man's physical environment's supply of water, air, and light (Day, 2002). Natural components that are necessary for human living, such as light, water, wind, plants, stones, etc., could be included while discussing human well-being within a certain region. These components can be used in the architectural constructed form to enhance occupant well-being (Modi and Parmar, 2020).

Clean air is getting harder to find. Traffic and industrial buildings damage the air outside, whereas off-gassing from furniture, building materials, and recycled air harm the air within. The built environment is where the majority of environmental dangers start. Poor urban settings can lead to headaches, eye strain, melancholy, stress, anxiety, and even cancer (Modi and Parmar, 2020). Through the natural cycles and processes that are inherent to all living things, including humans, natural materials have the potential to bring man closer to nature (Alexander, 2002). Local use of natural resources reduces industrial processing, lowers transportation emissions, and re-establishes human interaction with the environment (Modi and Parmar, 2020).

A healthy design approach leads to a healthier living environment. Buildings would become houses of the spirit if development took a more comprehensive, holistic approach and was guided by thoughts and feelings of wellness and vitality. With this mindset in mind, new buildings would be created and existing ones would be altered to promote health and even healing (Day, 2002).

When it comes to a building's environmental and psychological effects, people occasionally do not believe they might be the cause of illness. However, residents concur that physical elements like heating, ventilation, and organic volatile substances have a significant role in the psychological, organizational, and social effects (Baker, 1989). Architectural form's psychological and emotional consequences frequently take precedence over functional considerations. Spaces can be enjoyable by relaxing and stimulating the senses. The gratification of order, diversity, rhythm, and contrast through the senses is referred to as sensual delight. It can be accomplished through a revived space quality that uses color, texture, shape, and proportion. Through powerful impressions in space, visual sensation and movement in space produce happiness (Lynch, 1981).

It appears that unhealthy buildings have a long-lasting impact on tenants, who over time develop uncontrollable and irritating behavior patterns that hinder their productivity. In healthy and enjoyable environments, inhabitants are more likely to feel at ease. SBS is not just related to the building alone. In comparison to individuals who worked in buildings without the ill building syndrome, those who worked in SBS buildings were known to have significantly higher levels of resentment, distrust, defensiveness, anxiety, and confusion (Baker, 1989).

2.1.5. Experience and Attributes of Biophilic Design

According to Wilson's approach to introducing biophilia into the human environment, "Direct Experience of Nature" is the most fundamental and successful of the three sorts of experiences. The other two are auxiliary and include artificial components. For biophilic design in the built environment, it would be most effective to choose any element of direct experience of nature (Lechner and Heating, 2009). The

attributes of "Direct Experience of Nature," as described by Kellert and Finnegan (2011), are as follows:

2.1.5.1. Air

Human comfort and productivity are affected by natural ventilation. Variations in airflow, temperature, humidity, and barometric pressure can improve the sensation of natural ventilation in the built environment. These criteria can be met by providing access to the outside, either via straightforward methods like moveable windows or through more sophisticated technology and engineering methods.

2.1.5.2. Water

Water is necessary for life, and its beneficial presence in the built environment can reduce stress, foster satisfaction, and improve performance and health. When the five senses of sight, hearing, touch, taste, and movement are combined, the water attraction can be very strong. Different design techniques, such as views of notable water features, fountains, aquariums, built wetlands, and others, might satiate the craving for touch with water. Water in the built environment is frequently most appealing when it is clean, in motion, and experience via numerous senses.

2.1.5.3. Vegetation

One of the best methods for integrating a sense of nature into the constructed environment is the use of vegetation. The presence of plants can improve comfort, physical health, performance, and productivity while reducing stress. The vegetation around constructed landscapes and buildings ought to be dense, ecologically integrated, and inclined to favor native species over invasive and exotic ones.

2.1.5.4. Animals

Throughout human history, non-human animals have played a significant role in people's experiences. However, it can be difficult to integrate it into the built environment. Through such design techniques as feeders, green roofs, gardens, aquaria, aviaries, etc., one can come into contact with animal life. Contact with animals that is

isolated and infrequent generally has minimal effect. Contact with animal life should, whenever possible, involve a variety of species and emphasize native rather than exotic animals.

2.1.5.5. Natural Landscape and Ecosystems

Plants, animals, water, soils, rocks, and geological formations are all interrelated in natural landscapes and ecosystems. People tend to favor landscapes with qualities vital to human evolution, such as wide-spreading trees, an open understory, the availability of water, forested margins, and other elements. In the built environment, self-sustaining ecosystems can be created using many architectural techniques, including artificial wetlands, grassy glades and forests, green roofs, and artificial aquatic environments. Views, observational platforms, direct engagement, and even active participation can encourage contact with natural systems.

2.1.5.6. Fire

The ability to regulate fire, which enabled the harnessing of energy beyond that of animal life and promoted the transformation of objects from one condition to another, is one of humanity's greatest achievements. Both comfort and worry can be felt being around the fire. Construction of fireplaces and hearths can create the gratifying presence of fire in the built environment (especially in cold areas), but it can also be creatively reproduced with the use of light, color, movement, and materials with different heat conductance.

2.1.6. Biophilic Design and the 14 Principles

Variables in biophilic architecture were first defined by Heerwagen and Hase (2001). Based on habitability, natural elements, process, design geometry, joy, and enticement, they assigned different natural qualities to eight criteria. Despite being a first effort, their framework showed how "natural" could be conceptualized differently in design. A few years later, the book *Biophilic Design: The Theory, Science, and Practice of Bringing Buildings to Life* was co-authored by a group of proponents of the biophilic movement (Kellert, 2008). With two fundamental dimensions, six elements, and more

than seventy contributions, Kellert (2008) offered a more methodical explanation of biophilic design in this volume.

To design biophilic buildings, Heerwagen and Gregory (2008) presented various perceivable and cognizable qualities or traits of "natural" settings. Additionally, Cramer and Browning (2008) provided three draft categories for biophilic structures. Terrapin Bright Green, a building consulting company, identified fourteen biophilic design patterns based on these three criteria (Browning et al., 2014). Similarly to this, Kellert and Calabrese (2015) condensed Kellert's (2008) original framework and suggested a new one that contains twenty-four traits divided into three categories. Later, the proponents of these two related frameworks improved and updated them (Browning and Ryan, 2020; Kellert, 2018). Recent research by Xue et al. (2019) suggested links between "environment" and human health and well-being, both from an individual and social (public health) standpoint.

In this literature review, three sample conceptual frameworks among the many biophilic design interpretations were selected to undertake a comparative analysis (Browning and Ryan, 2020; Kellert, 2008b, 2018) and presented in Figure 2. In certain significant architectural certificates, these three frameworks are frequently employed as the conceptual foundation for establishing standards about natural interaction and connection (e.g. LBC, WELL, and LEED). Much more researchers have also used them to examine biophilic design (Abdelaal and Soebarto, 2019, Aye et al., 2019, Gillis and Gatersleben, 2015, Park and Lee, 2019, Peters and D'Penna, 2020). Few studies, however, have analyzed whether the terminologies are acceptable to express "nature" in architecture more explicitly instead of adding to the ambiguity and discussing the taxonomies of "nature" in these frameworks.

The three frameworks all have the same general goal - to aid designers in comprehending and putting the idea of biophilic design into practice - but they also serve different purposes. The interpretations of Kellert (2008, 2018) are based on the biophilia theory and biophilia values taken from evolutionary psychology. In contrast, Browning and Ryan (2020) look at how biological reactions, psychological, and physiological health, and cognitive performance relate to human-nature relationships (Browning et al.,

2014). Additionally, Kellert's (2008) first framework is presented as a thorough specification of biophilic design, in which inclusion is praised. This demonstrates the developer's desire to use this idea as an all-encompassing explanation for comprehending "nature" in design. In the most recent frameworks, however, the emphasis is shifted away from the older exhaustive enumeration and toward a model that is clearer and easier to understand. It is shown in two ways: first, by the framework structure (categorizations) that was used, and second, by the elements that were included and categorized.

Key proponents recently agreed on categorizing explanations in relatively brief ways. In the beginning, Kellert (2008) used a hierarchical structure in his framework, moving from the fundamental distinction (dimensions) to subdivisions (components and characteristics). "Organic or naturalistic" dimensions are those that directly, indirectly, or symbolically resemble "natural" forms, whereas "place-based or vernacular" dimensions are those that are culturally or environmentally linked to specific places (Kellert, 2008). However, this hierarchical taxonomy occasionally leads to ambiguity because Kellert did not elaborate on the relationship between the fundamental two "dimensions" and the subsequently classed "components" and "attributes." By combining previously split "dimensions" and "elements" into three "experiences", he changed the three-level taxonomy to a two-level structure (Kellert, 2018):

1. "Direct experience of nature," which refers to "contact with basic features and characteristics of the natural environment".
2. "Indirect experience of nature," which refers to "converting empirical and objective reality into symbolic and metaphorical forms through projecting thoughts, images, and feelings,".
3. "Experience of space and place," which refers to "the spatial setting," to "consider how people manage and organize their environmental circumstances".

Similar to this, Browning and Ryan (2020) grouped different aspects of nature - physical, metaphorical/representational, and emotional - into three categories: "nature in the space," "natural analogies," and "nature of the space."

Nevertheless, the two most current frameworks still contain certain ambiguities. In terms of how it connects to touch with nature, Kellert's (2018) "sense of space and location" is difficult to comprehend. This kind comprises a variety of natural spatial features that have been labeled as "sensory aesthetic" or "survival-advantageous" (Heerwagen and Gregory, 2008; Hildebrand, 2008), in addition to the Place Attachment Theory criterion for a sense of belonging (Manzo, 2003). Instead of just experiencing the common areas and places, producing these impacts (pleasant experiences) requires specific arrangements. Therefore, a clearer expression is required. Two of the three patterns listed under the category of "natural parallels" in Browning and Ryan's (2020) framework can also be categorized into the other two categories. A physical form of "nature in the space" is a "material link with nature," while a quality or feature of "nature of the space" is "complexity and order."

Kellert (2008, 2018) typically categorizes heterogeneous nature into various categories based on qualities (concrete, simulated, emotional, or others), referring to them as "attributes." By applying a "pattern" language taken from an architectural theory book, *A Pattern Language* (Alexander et al., 1977), Browning and Ryan (2020) elaborate on the functional importance of nature in architectural design. Even though different authors use different terminology, several common aspects are present. For instance, "light," "air," and "water" are similar to "dynamic and diffuse light," "thermal and airflow variability," and "presence of water"; "weather," "changes, ages, and the patina of time," are "connection with natural systems,"; "natural shapes and forms," and "natural geometrics," are suggested as "biomorphic forms and patterns"; and "natural materials" suggested as "material connection with nature". They also concur that nature can be psychologically experienced through intentional spatial arrangements, such as creating a "prospect," "refuge," "complexity and order," or "ordered complex" (Browning and Ryan, 2020; Kellert, 2018).

Divergences can also be seen in the particular points made by various authors. Because love for "living organisms" is at the heart of biophilia theory, Kellert (2018) proposes "animals" and "plants" as two fundamental aspects separately. He also includes "fire" because it is seen to be crucial to human life. A distinctive pattern, "non-rhythmic

sensory stimuli," is defined in Browning and Ryan's (2020) framework as the "stochastic and ephemeral connection with nature that may be analyzed statistically but may not be predicted precisely". Additionally, they contain the feelings associated with certain settings, such as "mystery," "risk/peril," and one specific pattern called "awe," which is defined as "stimuli including other biophilic patterns that defy an existing frame of reference and lead to a change in perception" (Browning and Ryan, 2020).

Previous frameworks complement, confirm, correct, or improve one another. But there are a few issues, though, that could make this interpretation difficult to understand. The first is that the dichotomous expression results in overlaps between the elements. According to Browning and Ryan (2020), the 15 patterns are divided into two categories; "visual connection with nature" and "non-visual connection with nature," with the other 13 patterns being broadly covered by either category. Additionally, repeats may be seen in Kellert's (2008, 2018) classifications, such as the overlap between "information richness" and those that depict complex forms and "sensory variety" and those that give multi-sensory experiences (such as water, plants, and weather) (e.g. natural geometries and organized complexity). Additionally, only practices that have "positive environmental impacts" and improve "people's physical and mental health, productivity, and wellbeing" fall within the criteria of "biophilic design," according to the original definition (Kellert, 2008). To reduce the risk of fire, modern architecture frequently depicts "fire" in metaphorical or symbolic ways, especially in high-rise buildings. 'Non-rhythmic sensory stimuli' frequently come with the worry of evoking erratic psychological reactions and diversion. Because of this, these components do not adhere to the principles of biophilic design. According to Zhong et al., (2021), Figure 1 presented a comparison between the main three frameworks of biophilic design.

2 Dimensions, 6 Elements, and 72 Attributes of Biophilic Design (Kellert, 2008b)					
I. Organic or Naturalistic				II. Place-based or Vernacular	
1. Environmental features	2. Natural shapes and forms	3. Natural patterns and processes	4. Light and space	5. Place-based relationships	6. Evolved human-nature relationships
<ul style="list-style-type: none"> • Color • Water • Air • Sunlight • Plants • Animals • Natural materials • Views and vistas • Façade greening • Geology and landscape • Habitats and ecosystems • Fire 	<ul style="list-style-type: none"> • Botanical motifs • Tree and columnar supports • Animal (mainly vertebrate) motifs • Shells and spirals • Egg, oval, and tubular forms • Arches, vaults, domes • Shapes resisting straight lines and right angles • Simulation of natural features • Biomorphy • Geomorphology • Biomimicry 	<ul style="list-style-type: none"> • Sensory variability • Information richness • Age, change, and the patina of time • Growth and efflorescence • Central focal point • Patterned wholes • Bounded spaces • Transitional spaces • Linked series and chains • Integration of parts to wholes • Complementary contrasts • Dynamic balance and tension • Fractals • Hierarchically organized ratios and scales 	<ul style="list-style-type: none"> • Natural light • Filtered and diffused light • Light and shadow • Reflected light • Light pools • Warm light • Light as shape and form • Spaciousness • Spatial variability • Space as shape and form • Spatial harmony • Inside-outside spaces 	<ul style="list-style-type: none"> • Geographic connection to place • Historic connection to place • Ecological connection to place • Cultural connection to place • Indigenous materials • Landscape orientation • Landscape features that define building form • Landscape ecology • Integration of culture and ecology • Spirit of place • Avoiding placelessness 	<ul style="list-style-type: none"> • Prospect and refuge • Order and complexity • Curiosity and enticement • Change and metamorphosis • Security and protection • Mastery and control • Affection and attachment • Attraction and beauty • Exploration and discovery • Information and cognition • Fear and awe • Reverence and spirituality
3 Experiences and 25 Attributes of Biophilic Design (Kellert, 2018)					
1. Direct Experience of Nature		2. Indirect Experience of Nature		3. Experience of Space and Place	
<ul style="list-style-type: none"> • Light • Air • Water • Plants • Animals • Landscapes • Weather • Views • Fire 		<ul style="list-style-type: none"> • Images • Materials • Texture • Color • Shapes and forms • Information richness • Change, age and the patina of time • Natural geometries • Simulated natural light and air • Biomimicry 		<ul style="list-style-type: none"> • Prospect and refuge • Organized complexity • Mobility • Transitional spaces • Place • Integrating parts to create wholes 	
3 Categories and 15 Patterns of Biophilic Design (Browning and Ryan, 2020)					
1. Nature in the Space		2. Natural Analogues		3. Nature of the Space	
<ul style="list-style-type: none"> • Visual Connection with Nature • Non-Visual Connection with Nature • Non-Rhythmic Sensory Stimuli • Thermal & Airflow Variability • Presence of Water • Dynamic & Diffuse Light • Connection with Natural Systems 		<ul style="list-style-type: none"> • Biomorphic Forms & Patterns • Material Connection with Nature • Complexity & Order 		<ul style="list-style-type: none"> • Prospect • Refuge • Mystery • Risk/Peril • Awe 	

Figure 1: Three Key Frameworks of Biophilic Design (Zhong et al., 2012).

2.1.7. Benefits of Biophilic Design

According to White et al. (2019), spending 120 minutes in nature each week improves one's health and well-being. In general, people believe that parks and other green spaces are essential for their physical and mental well-being, particularly if they have features like paths, trees, seating, shade, and water (Lopez et al., 2020). Therefore, spending time in nature may be considered a resource for solving health issues and supporting the human ecological system, which boosts several advantages for both physical and mental health.

Since humans are a part of the biosphere and an ecosystem, it is not surprising that they have strong emotional ties to the natural world. People love savanna-like environments and have optimistic outlooks that encourage them to spend time in nature (Balling and Falk, 1982; Heerwagen et al., 1993). Wilson (1984) argued in Biophilia Hypothesis that people have a strong bond with the natural world and other living things.

Although there is a wealth of research discussing how biophilia and biophilic architecture relate to human health, a comprehensive examination of the connection between nature and health is still absent. The advantages of biophilic design were gathered from the literature to support this study and divided into two primary categories: the psychological and well-being benefits, and physiological benefits.

2.1.7.1. Biophilic Patterns and Psychological Health and Well-Being

Table 1 lists the favorable effects of biophilic designs on psychological health and well-being, including but not limited to sensations of good emotions and pleasure, attention restoration, preference, feelings of relaxation, and a reduction in aggression, among other things. Additionally, it involves enhancing cognitive performance and functionality.

Zadeh et al. (2014) found that hospital and office workers who have window views of nature and sunlight perform better and feel happier, and patients heal more quickly after surgery. In addition, a lot of the literature discussed how "direct experience with nature," or having plants in both an indoor and outdoor setting, can enhance cognitive functions and performance by enhancing communication, concentration, and productivity (Shoemaker et al., 1992; Thomsen et al., 2011; Larsen et al., 1998; Zadeh et al., 2014). According to one of the research referenced, being physically surrounded by nature not only enhances sensory perceptions and feelings of well-being but also changes states of consciousness, particularly relaxation feelings (Kjellgren and Buhrkall, 2010). According to Hung, S.H. and Chang (2021), table 1 presents the biophilic patterns and their impact on psychological health and well-being.

Table 1: Biophilic Patterns and Psychological Health and Well-being (Hung, S.H. and Chang, 2021).

	Direct experience of nature				Indirect experience of nature				Space and place				
	Visual connection to nature (Barton & Pretty, 2010; Felsten, 2009; Hartig et al., 2003; Orsega-Smith et al., 2004; Ulrich, 1984; Van den Berg & Ter Hejine, 2005; Zadeh et al., 2014)	Nonvisual connection to nature (Alvarsson et al., 2010; Koga & Iwasaki, 2013; Pheasant et al., 2010; Ratcliffe et al., 2013; Ulrich et al., 1991; Van den Berg et al., 2003)	Presence of Plant (Bringslimark et al., 2007; Dijkstra et al., 2008; Knight & Haslam, 2010; Larsen et al., 1998; Neuenhuis et al., 2014; Qin et al., 2014; Shoemaker et al., 1992; Thomsen et al., 2011)	Presence of Animals (Ratcliffe et al., 2013; Windtger et al., 2011)	Dynamic & diffuse light/season (Küller & Lindsten, 1992; Nicklas & Bailey, 1996)	Biomorphic forms & patterns (Hagerhall et al., 2004; Herzog & Bryce, 2007; Herzog & Kropscott, 2004; Joye, 2007)	Material connection with nature (Joye, 2007; Koga & Iwasaki, 2013; Lichtenfeld et al., 2012; Nyrud et al., 2014; Schatz & Bowers, 2005; Tsunetsugu et al., 2007; Reddy et al., 2012)	Presence of natural images (Beute & de Kort, 2013; Brown et al., 2013; Chang & Chen, 2005; Felsten, 2009; Herzog & Kropscott, 2004; Hunter et al., 2010; Kjellgren & Buhrkall, 2010; Lee et al., 2015; Nyrud et al., 2014; Pheasant et al., 2010; Ulrich et al., 1991; White & Gatersleben, 2011; Van den Berg et al., 2003)	Simulated natural light and air (Reddy et al., 2012)	Prospect and refuge (Gatersleben & Andrews, 2013)	Mobility & Transitional spaces (Beute & de Kort, 2013; Hartig et al., 2003; Van den Berg et al., 2003)	Place (Küller & Lindsten, 1992; Korpela et al., 2009)	Risk/Peril (Herzog & Kropscott, 2004; Herzog & Bryce, 2007)
Promoting Attention restoration	2	1 & 2		1			1	3		2		2	
Appeal aesthetic /attraction/interesting		2	2			1		2				2	
Preferences		1 & 2	2	1		1 & 2	1 & 2	3				2	2
Positively impacted attitude/Positive affects/ pleasure arousal	2	2				1	1	3		2		2	
Positive emotion/mood responses	2	1	2	1			1						
Negative mood	2							2					
Induce tranquility		2						2					
Feel relax/Restoration			2	1				2					
Low sense of fear/ Perceived fear		1 & 2						2		2			
Low anger aggression	2	2					1	2		2		2	
Low tension	2											2	
Low anxiety/stress	2	2	2	1			1 & 2	2				2	
Low depression/Sadness	2	1 & 2						2				2	
Perceived of danger	2							2		2			2
Pleasure		2					2						
effortless attention		1		1									
Psychological health		1	2						1				

	Direct experience of nature				Indirect experience of nature				Space and place				
	Visual connection to nature (Barton & Pretty, 2010; Felsten, 2009; Hartig et al., 2003; Osega-Smith et al., 2004; Ulrich, 1984; Van den Berg & Ter Heijne, 2005; Zadeh et al., 2014)	Norvisual connection to nature (Alvarsson et al., 2010; Koga & Iwasaki, 2013; Pheasant et al., 2010; Ratcliffe et al., 2013; Ulrich, 1991; Van den Berg et al., 2003)	Presence of Plant (Bringslimark et al., 2007; Dijkstra et al., 2008; Knight & Haslam, 2010; Larsen et al., 1998; Nieuwenhuis et al., 2014; Qin et al., 2014; Shoemaker et al., 1992; Thomsen et al., 2011)	Presence of Animals (Ratcliffe et al., 2013; Windhager et al., 2011)	Dynamic & diffuse light/season (Küller & Lindsten, 1992; Nicklas & Bailey, 1996)	Biomorphic forms & patterns (Hagerhall et al., 2004; Herzog & Bryce, 2007; Herzog & Kroppscott, 2004; Joye, 2007)	Material connection with nature (Joye, 2007; Koga & Iwasaki, 2013; Lichtenfeld et al., 2012; Nyrud et al., 2014; Schatz & Bowers, 2005; Tsunetsugu et al., 2007; Reddy et al., 2012)	Presence of natural images (Beute & de Kort, 2013; Brown et al., 2013; Chang & Chen, 2005; Felsten, 2009; Herzog & Kroppscott, 2004; Hunter et al., 2010; Kjellgren & Buhrkall, 2010; Lee et al., 2015; Nyrud et al., 2014; Pheasant et al., 2010; Ulrich et al., 1991; White et al., 2010; White & Gatersleben, 2011; Van den Berg et al., 2003)	Simulated natural light and air (Reddy et al., 2012)	Prospect and refuge (Gatersleben & Andrews, 2013)	Mobility & Transitional spaces (Beute & de Kort, 2013; Hartig et al., 2003; Van den Berg et al., 2003)	Place (Küller & Lindsten, 1992; Korpela et al., 2009)	Risk/Peril (Herzog & Kroppscott, 2004; Herzog & Bryce, 2007)
Overall happiness	2	2						2			2		
Familiarity	2	2									2		
Complexity								2			2		2
Fascination	1 & 2	1		1				2			2		
Being away	1 & 2							2					
Extent	1 & 2							2					
Compatibility	1 & 2							2			2		
Mystery				1		1 & 2							
Legibility						1 & 2							
Coherence													2
place attachment												2	
Improve mental engagement attentiveness								2		2			
Positive impact on cognitive performance					2		1		1				
Increase productivity			2				1		2				
Enhanced creativity							2						
Improve communication	2												
Concentration			2		2								
Social interaction	2												
Decrease sleepiness	2												
Decrease sick leave			2										

	Direct experience of nature				Indirect experience of nature				Space and place				
	Visual connection to nature (Barton & Pretty, 2010; Felsten, 2009; Hartig et al., 2003; Osega-Smith et al., 2004; Ulrich, 1984; Van den Berg & Ter Heijne, 2005; Zadeh et al., 2014)	Norvisual connection to nature (Alvarsson et al., 2010; Koga & Iwasaki, 2013; Pheasant et al., 2010; Ratcliffe et al., 2013; Ulrich, 1991; Van den Berg et al., 2003)	Presence of Plant (Bringslimark et al., 2007; Dijkstra et al., 2008; Knight & Haslam, 2010; Larsen et al., 1998; Nieuwenhuis et al., 2014; Qin et al., 2014; Shoemaker et al., 1992; Thomsen et al., 2011)	Presence of Animals (Ratcliffe et al., 2013; Windhager et al., 2011)	Dynamic & diffuse light/season (Küller & Lindsten, 1992; Nicklas & Bailey, 1996)	Biomorphic forms & patterns (Hagerhall et al., 2004; Herzog & Bryce, 2007; Herzog & Kroppscott, 2004; Joye, 2007)	Material connection with nature (Joye, 2007; Koga & Iwasaki, 2013; Lichtenfeld et al., 2012; Nyrud et al., 2014; Schatz & Bowers, 2005; Tsunetsugu et al., 2007; Reddy et al., 2012)	Presence of natural images (Beute & de Kort, 2013; Brown et al., 2013; Chang & Chen, 2005; Felsten, 2009; Herzog & Kroppscott, 2004; Hunter et al., 2010; Kjellgren & Buhrkall, 2010; Lee et al., 2015; Nyrud et al., 2014; Pheasant et al., 2010; Ulrich et al., 1991; White et al., 2010; White & Gatersleben, 2011; Van den Berg et al., 2003)	Simulated natural light and air (Reddy et al., 2012)	Prospect and refuge (Gatersleben & Andrews, 2013)	Mobility & Transitional spaces (Beute & de Kort, 2013; Hartig et al., 2003; Van den Berg et al., 2003)	Place (Küller & Lindsten, 1992; Korpela et al., 2009)	Risk/Peril (Herzog & Kroppscott, 2004; Herzog & Bryce, 2007)
State of consciousness								2					
Satisfaction (job, workplace)			2				1						
Self-esteem	2							2					
Motivation							1						
Self-confidence			2										

Note. 1 = Indicates a relationship between the biophilic patterns, even though outcomes are not yet directly supported by empirical studies; these may be influenced by biophilic patterns.

2 = Indicates a relationship between biophilic patterns and outcomes that is supported by empirical studies (< 5 papers).

3 = Indicates strong evidence of a relationship between biophilic patterns and outcomes and significant results from multiple types of research (≥ 5 papers).

An empty cell indicates that a relationship between the biophilic patterns and the outcome has not yet been determined.

2.1.7.2. Biophilic Patterns and physiological Health

According to Hung, S.H. and Chang (2021), table 2 lists the physiological effects that were discovered utilizing equipment to measure heart rate, blood pressure, cortisol levels, and other physiological markers, as well as a questionnaire designed to comprehend how the body reacts to stress. Similar results were obtained for psychological health and well-being. In addition to other advantages, stress is reduced, the heart rate and blood pressure are reduced when there are visual and non-visual links to nature, plants, and light (Hartig et al., 2003; Küller and Lindsten, 1992; Ulrich et al., 1991; Zadeh et al., 2014).

Table 2: Biophilic Patterns and Physiological Health (Hung, S.H. and Chang, 2021).

	Direct experience of nature				Indirect experience of nature			Space and place	
	Visual connection to nature (Hartig et al., 2003; Orsega-Smith et al., 2004; Zadeh et al., 2014)	Nonvisual connection to nature (Alvarsson et al., 2010; Jahncke et al., 2011; Reddy et al., 2012; Ulrich et al., 1991)	Presence of Plant (Qin et al., 2014; Thomsen et al., 2011; Ulrich, 1984)	Dynamic & diffuse light/season (Küller & Lindsten, 1992)	Material connection with nature (Joye, 2007; Koga & Iwasaki, 2013; Tsunetsugu et al., 2007)	Presence of natural images (Brown et al., 2013; Chang & Chen, 2005; Hunter et al., 2010; Kjellgren & Buhrkall, 2010; Tsunetsugu et al., 2007; Ulrich et al., 1991)	Simulated natural light and air (Reddy et al., 2012)	Prospect and refuge (Gatersleben & Andrews, 2013)	Mobility & Transitional spaces (Van den Berg et al., 2003)
Low blood pressure					2	2			
Low heart rate (BVP)	2					2		2	
SDRR						2			
Decrease in diastolic blood pressure (DBP)	2				2	2			2
Decrease in systolic blood pressure (SBP)	2				2	2			2
Frontalis muscle tension (EMG)		2				2			
Electroencephalogram (EEG)			2			2			
Less pain						2			
Reduce skin conductance level(SCL)	2	2							
Gain energy						2			
overall (Perceived) physical health	2	2	2					1	
Brain activity						1&2			
Body temperature	2								
Blood oxygen	2								
Cortisol				2					
Pulse transit time(PTT)		2		2					
Oxyhaemoglobin				2	2				

Note. 1 = Indicates a relationship between the biophilic patterns, even though outcomes are not yet directly supported by empirical studies; these may be influenced by biophilic patterns.
 2 = Indicates a relationship between biophilic patterns and outcomes that is supported by empirical studies (< 5 papers).
 An empty cell indicates that a relationship between the biophilic patterns and the outcome has not yet been determined.

2.2. Biophilia and Natural Ventilation

2.2.1. Properties of Natural Ventilation

Although there has always been natural ventilation, our buildings have developed into sophisticated heat machines. However, natural ventilation more than makes up for this lack of control with ease of use and efficiency. Currently, many technical alternatives offer substantially greater control over the flow of fresh air and thermal comfort than a simple facade opening. According to past studies (Oropeza-Perez, and Østergaard, 2014; Bienvenido-Huertas et al., 2020; Rackes et al., 2016), natural ventilation has a great potential for energy savings, especially in warmer climates. The condition of the outside air has the biggest impact on the thermal comfort restrictions of natural ventilation. Usually, these limitations only apply to air temperatures between 20 and 26 C (Axley and Emmerich, 2002).

According to Aviv et al. (2021), natural ventilation is the exchange of air between an object's interior and exterior. Wind-driven ventilation (induced by pressure differences generated by the wind blowing around the building) and "stack effect" ventilation (caused by temperature fluctuations) are two examples of natural ventilation. Natural ventilation is the process of bringing outside air inside a building. The unclean, heated air in the rooms is forced outside by the fresh air from the roof hole. This can be used without any mechanical help. It is one of the most effective methods for reducing energy use in buildings. It makes use of the wind's and buoyancy's inherent capacity to spread fresh air throughout buildings for the benefit of people. It is controlled by the pressure variations between the inside and outside of a building, or between its different sections.

Nearly all older buildings had natural ventilation. Natural ventilation has gained prominence as people have learned more about the price of energy use and its effects on the environment. Instead of the more common approach of using mechanical ventilation, this is an ideal alternative for reducing energy usage and expense, providing the permissible inner environmental condition, and maintaining a healthy and comfortable

indoor climate. Natural ventilation can be used as an alternative to HVAC units in favorable climates, saving 10%–30% of total energy use (Aviv et al., 2021).

2.2.2. Benefits of Natural Ventilation

Maintaining a healthy lifestyle is made easier by natural ventilation. For instance, the oxygen in the fresh air can raise energy levels and lower blood pressure. It aids in strengthening the immune system. Serotonin levels that are higher also boost the feeling of rejuvenation and sleep. Through a strong link to the dynamics of the environment, natural ventilation can offer a sufficient supply of breathing air, appropriate ventilation of pollutants, sufficient thermal conditioning, and humidity waste. Natural ventilation is typically chosen by designers because it reduces carbon emissions and costs less to install and maintain than fully mechanical ventilation. Additionally, it requires less maintenance, alters the expectations of the occupants, and gives them more environmental control. By providing free night cooling, this sort of ventilation lowers daytime temperatures.

In general, it is difficult to give definitive answers about the benefits and drawbacks of natural ventilation compared to mechanical systems, largely because these factors are influenced by outside factors including how a building is used and the changing temperature. Nevertheless, certain broad reasons can be provided because this subject of natural ventilation cannot be avoided. When properly installed and maintained, natural ventilation systems have several advantages over mechanical ones. Due to the use of natural forces and big openings, natural ventilation can theoretically provide a high ventilation level more cheaply. They use less energy, particularly if heating is not required. Higher levels of daylight could be provided by using well-designed systems.

The maintenance of a sustainable building environment is the other major benefit cited for natural ventilation. This argument is difficult to justify given that natural ventilation has been used for thousands of years. One factor in this is that a natural system does not require electrical energy for fans, which can account for 25% of the electrical energy used in a facility that is mechanically ventilated. There are records indicating that residents desire not to be completely cut off from the outside world and

that they wish to regulate their environment. Both of these conditions can be met by natural ventilation, but they cannot be met by a typical air conditioner. The benefit of natural ventilation is that it may provide a very high air-change level for little money and with a very simple system. Buildings with modern ventilation systems (that are modeled and operated effectively) can attain very high air-change levels by natural power, which can considerably be more in quantity than minimal ventilation needs. This is true even though the air-change rate can vary significantly.

On the other side, natural ventilation systems have several drawbacks. Natural ventilation fluctuates and is dependent on the outside climate in relation to the interior environment. Temperature differential and wind are the two driving elements that unintentionally affect the airstream rate. Natural ventilation can be challenging to manage because the airstream might be static in some places and uncomfortable and heavy in others. Lack of consistent negative pressure might cause issues with monitoring the direction of the airstream; as a result, it is dangerous to pollute hallways and adjacent rooms.

The use of particle filters is avoided through natural ventilation. Windows and vents may need to remain closed for reasons of security, culture, and temperature; in these cases, the ventilation level may be substantially lower. It only works when natural powers are available; a high ventilation level necessitates a high requirement for natural power accessibility. Normal operation of natural ventilation systems may be interrupted for a variety of reasons, including failure of doors or windows to open, equipment destruction, utility service interruption (if it is a high-tech system), inadequate modeling, improper management, or poor preservation. Natural ventilation systems typically do not perform as anticipated. Because of a lack of funding, a ventilation system's operation may be altered, increasing the risk of the transfer of airborne diseases even though the preservation cost of natural ventilation systems can be extremely low.

Natural ventilation also has the drawback of having a limited capacity to provide cooling in hot areas, especially ones that are also humid. It is important to combine this system with some sort of bearable (low-energy) cooling system for it to be acceptable in some climates. It does not require additional room for plant rooms or duct networks;

however, some locations are frequently required for stacks (chimneys, atria). The specific drawback is that mistakes made when simulating a natural system could be more challenging to correct. It's also important to be aware of other potential issues including air pollution, insect vectors, noise, and security. However, these issues can be resolved, for example, by employing improved modeling or hybrid (mixed-mode) ventilation.

2.2.3. Challenges of Using Natural Ventilation in Biophilic Designs

The present biophilic design movement was sparked by the initial biophilia hypothesis put forth by E.O. Wilson in 1984. He described biophilia as the “innately emotional affiliation of human beings to other living organisms. Innate means hereditary and hence part of ultimate human nature” (Wilson 1984). Wilson asserted that a human's need to interact with nature and natural forces is inbuilt. The built environment was the next area in which S.R. Kellert and E.O. Wilson used this idea (1993). Working in a naturally green and plant-like atmosphere was only one aspect of the concept. It was first put into practice in Kellert's recommended qualities for biophilic design (2008), in which he established the main terms, concepts, and features of the field. Kellert highlighted place-based/vernacular and organic/naturalistic as the two main dimensions. "Shapes and forms in the built environment that directly, indirectly, or symbolically reflect the inherent human affinity for nature" is referred to as having an organic dimension (Kellert 2008). "Buildings and landscapes that connect to the culture and ecology of a location or geographic area" are referred to as having a vernacular component (Kellert 2008).

This last component, as noted by Kellert, also involves a sense or spirit of place. Six major categories are then further divided into more than 70 biophilic design characteristics. There are more sophisticated qualities as well, such as sensory diversity, information richness, exploration, and discovery, or a geographic, historic, ecological, and cultural link to a place. These qualities are as basic and obvious as the presence of water, air, sunlight, plants, and animals. The environment can be an atmosphere, a process, or an experience, which is crucial for biophilic designers to comprehend. Architecture is lifeless if it does not have an atmosphere and a sense of place. If designers

want the biophilic design to be meaningful and a positive lived experience, it is vital to recognize atmospheres, ambiances, energies, mediation, and experiences.

According to Kellert's view, some clearly defined elements and traits are subject to change, while others can be improved over time. The 14 Patterns of Biophilic Design - Improving Health and Well-Being in the Built Environment by Terrapin Bright Green is one of the most recent revisions to Kellert's work. The 14 biophilic design patterns are divided into three categories: patterns inspired by nature, natural analogs, and patterns inspired by space. Another is the Biophilic Interior Design Matrix (McGee et al. 2019), which takes Kellert's work and operationalizes it for interior environments to provide designers with more concrete and understandable direction.

Kellert (2008) has discussed some of the challenges that designers have when implementing the biophilic design in real-world settings, particularly when including conceptual and abstract design elements. Many people desire clear guidelines that they can use in their designs or that can be incorporated into modeling software because the biophilic design is not always obvious in its guidelines. A holistic approach and a profound awareness of both human and non-human environmental aspects and components - their purpose and relationship that forms the overall atmosphere - are required to fully appreciate the patterns and characteristics of biophilic design. Examples include the lived experience, which is what architecture is ultimately about. Effective biophilic designers need to be extremely skilled at both rational and irrational aspects of space design. In addition to having a sense of humor, they must comprehend all aspects of space and the human experience, including mental, sensory, temporal, natural, cultural, traditional, etc. This method of approaching nature's benefits does not always align well with health-nature scientific evidence that employs a psychometric research paradigm. This can cause a disconnect, which can then be expressed as ignorance of pre-existing health-nature research or as a challenge translating biophilic attributes into design objectives that can be measured and quantified.

2.3. Ventilation and Thermal Comfort

The current ventilation systems use aim to improve the level of the environment, making it more convenient and comfortable for users. In studies conducted by Jamaludin (2014) and Haruna (2014), thermal comfort was determined as the most measure of satisfaction degree in the vacuum. On the contrary, studies conducted by Markus (1980) and Jamaludin (2014) have shown the negative impact of thermal discomfort, which may cause physical and psychological problems for users.

The idea of thermal comfort is to achieve a balanced and consistent heat exchange rate between users and their environment (Yoon, 2008). According to Jamaludin (2014) and Yoon (2008), this is achieved through several factors including the physiological, cultural, and social factors of the population, as well as environmental factors related to this study including air temperature, mean radiant temperature, relative humidity, air velocity, and turbulence intensity.

2.3.1. Thermal Comfort Parameters and Conditions for Human Occupancy

One of the main functions of ventilation is to provide thermal comfort and acceptable quality of indoor air by controlling several environmental parameters. Therefore, it is worth considering the main parameters of thermal comfort such as air temperature, operative temperature, relative humidity, air velocity, and turbulence intensity (Cui et al., 2013; Spentzou, 2015; Wigö, 2013).

2.3.1.1. Air Temperature

According to a study conducted by Yoon (2008), indoor air temperature is classified as the main parameter for measuring the degree of thermal comfort. Numerous studies on indoor air temperature and its relationship to thermal comfort have shown that reaching a vacuum temperature within the comfort zone increases the productivity and efficiency of users (Cui et al., 2013). On the other hand, thermal discomfort is closely related to the phenomenon of SBS (Seppänen et al., 2004; Kolarik et al., 2007).

2.3.1.2. Operative Temperature

According to the Chartered Institution of Building Services Engineers (CIBSE, 2006), the operative temperature considers a better and more accurate measure of thermal comfort than air temperature because it is calculated based on the air temperature and the Mean Radiant Temperature (MRT) by taking the average. It differs from the (MRT) by first taking into consideration the impact of convection and radiation in heat exchange (Spentzou, 2015; CIBSE, 2006). On the other hand, Matzarakis (2007) added that the MRT is a variable that affects the body heat exchange through radiation, so it is known as the temperature of the assumption enclosure surrounding the surface. In this case, the subject heat exchange through radiation and the environment's actual radiative are equal.

A study conducted by Walikewitz (2015) stated that because it is a variable that depends on different parameters this makes it is difficult to measure it. Due to the importance of this variable and to facilitate its handling, ASHRAE developed a model of adaptation that defined acceptable comfort zones in mechanically ventilated spaces depending on the characteristics of the space, its function, and the number of users.

Depending on the classification and assessments of ASHRAE standard 55 - 2017, figure 5 clarifies the acceptable range of operative temperature and humidity for spaces that meet the criteria specified in the ASHRAE standards Section 5.2.1.1.

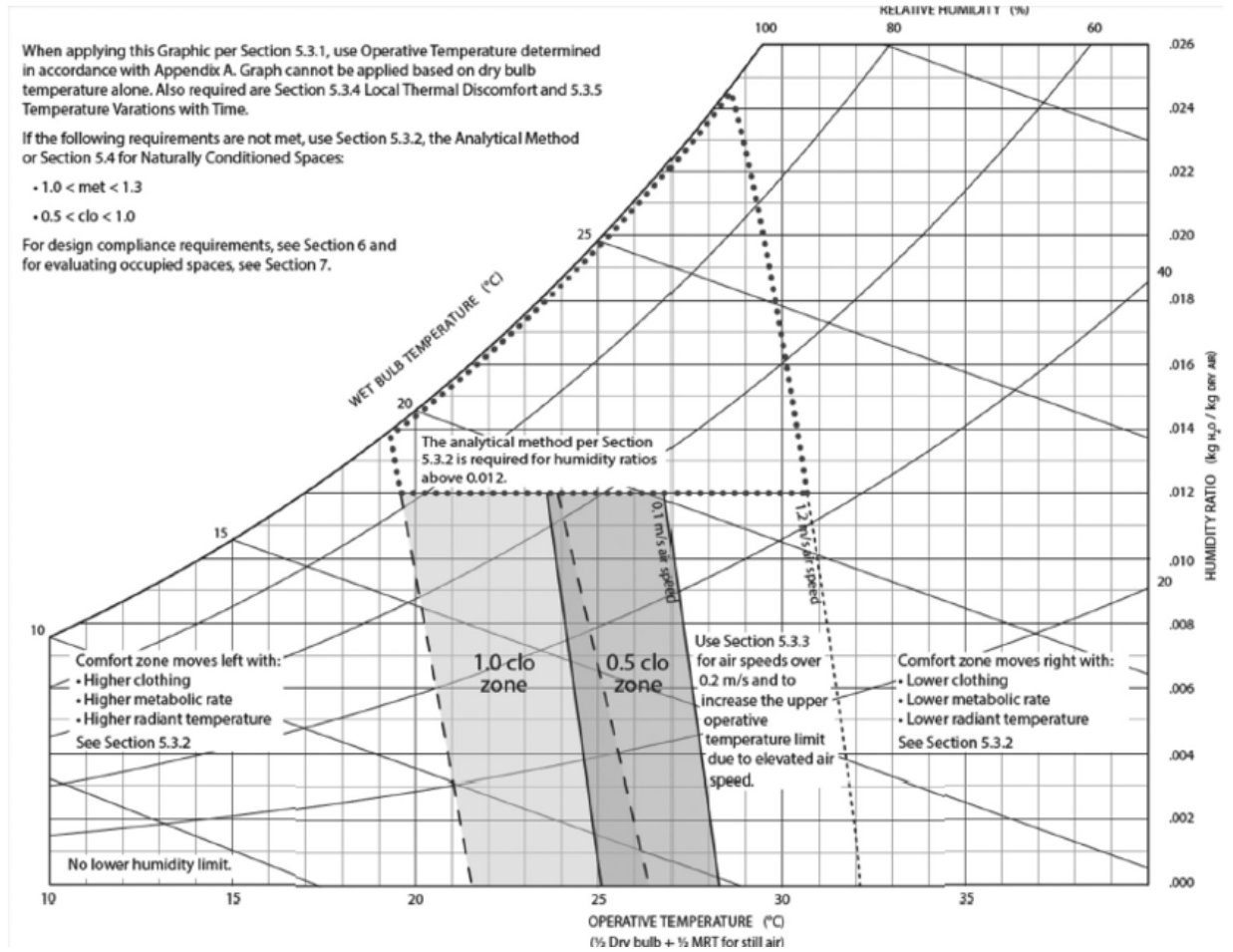


Figure 2: The acceptable range of operative temperature and humidity for spaces that meet the criteria specified in ASHRAE Standard 55 – 2017, Section 5.2.1.1

2.3.1.3. Relative Humidity

Fang (2004) argued that the importance of relative humidity lies in its ability to provide a comfortable indoor environment if appropriate humidity levels are available, and its impact on the activities of users and their sense of thermal comfort. Therefore, a study conducted by Alsmo (2014) indicated that low levels of relative humidity affect users and may cause them health problems such as dry and irritated eyes, and dryness of the outer skin of the body. Besides, the results of the studies conducted by Seppänen (2004) and Alsmo (2014) indicated that high humidity above the acceptable limit is harmful to users' health because it is an environment suitable for the multiplication of bacteria, insects, and mold.

It should be noted that obtaining a certain degree of humidity in the internal vacuum is related to the temperature of the vacuum and this is illustrated by the diagram produced by ASHRAE and shown in the previous section, figure 5. The diagram shows the relationship between operative temperature and relative humidity and indicates that relative humidity ratios should be between 30-60% according to ASHRAE standards 55-2017.

2.3.1.4. Air Velocity

The effect of air velocity on vacuum users is represented by reducing the feeling of heat by supporting the heat exchange between the body and the surrounding air through evaporation and convection, thereby enhancing the user's thermal satisfaction (Wigö, 2013). A study conducted by Spengler (2001) showed that increasing air velocity increases thermal discomfort, this phenomenon increases with increasing wind speed while decreasing it increases the feeling of thermal comfort. This has been confirmed by the standards of ASHRAE 55 - 2017 which stressed the inverse relationship between the air velocity in the vacuum and the degree of the user's thermal comfort.

2.3.1.5. Turbulence Intensity

Turbulence intensity is an important parameter in the indoor environment, allowing engineers and designers to construct a space that meets the needs of occupants. Turbulence intensity can be defined as the rate of fluctuation of air velocity inside space and it is usually expressed as a percentage of the steady-state air velocity. High turbulence intensity can lead to several problems, including reduced thermal comfort and increased energy consumption due to an increase in ventilation, making it important to quantify and measure turbulence intensity for indoor environments.

The standard for acceptable turbulence intensity in indoor environments is largely dependent on the specific use of space. To measure and analyze turbulence intensity, many different techniques have been developed. These include both real-time measurements as well as CFD simulations. Real-time techniques are generally used to measure the instantaneous air velocity at certain points within a space and these can be combined with Lagrangian or Eulerian calculation models to obtain a spatiotemporal map

of the turbulence intensity. CFD simulations are more suited for predicting the behavior of turbulence intensity before construction and design begin, as they can simulate the flow characteristics of space much more accurately.

Overall, understanding and measuring turbulence intensity is important for designing and constructing indoor environments which meet acceptable standards. Accurate measurements and computational simulations can be used to get an indication of how turbulence intensity may affect space and how this can be mitigated or managed. By doing so, engineers and designers can ensure that their designs are comfortable and safe, while also using the least amount of energy possible.

2.4. Personalized Ventilation

2.4.1. Benefits of Personalized Ventilation Unit

The PV has two key advantages over total volume air distribution: first, it has the potential to improve the quality of the air that is breathed in; and second, each occupant has been given the authority to customize and control the temperature, flow rate (local air velocity), and direction of the locally supplied personalized air in accordance with their preferences, thereby improving the conditions of their thermal comfort.

Physical measures show that using PV compared to using Total Volume ventilation (TV) significantly lowers the amount of pollution inhaled air (Bolashikov et al., 2003; Cermak and Melikov, 2003; Cermak and Melikov, 2004; Cermak et al., 2004; Faulkner et al., 1993; Faulkner et al., 1999; Faulkner et al., 2003; Melikov et al., 2002; Melikov et al., 2003; Zuo et al., 2002). Most ATDs have only been able to operate at their best when between 50 and 60 percent of the inhaled air is pure. It is now possible to boost ventilation efficacy by at least 20 times when compared to mixing ventilation because of the development of highly effective ATD that provide virtually 100% clean and cool personalized air to be inhaled by the user (Bolashikov et al., 2003; Melikov et al., 2003). When compared to mixed ventilation, the temperature of the air that is inhaled may be

lowered by up to 6 °C (in warm indoor environments), which will enhance the perceived quality of the air.

People's thermal comfort is increased by PV (Kaczmarczyk, 2003; Kaczmarczyk et al., 2004; Kaczmarczyk et al., 2002; Yang et al., 2003; Zeng et al., 2002). At room temperatures over 23 °C, the thermal environment with PV is substantially more tolerable than it is without PV. The ability to control supply airflow rate, or local air velocity, makes it evident that draught discomfort can be avoided. Although it significantly improves whole-body thermal comfort, at room air temperatures above 26 °C, the cooling capacity of the personalized flow targeting a relatively small body surface area may not be sufficient to provide some people with thermal comfort without causing draught discomfort (Sekhar et al., 2003; Yang et al., 2003).

In-depth research has been done on the interaction of flow near the breathing zone and its significance for the user's comfort in terms of temperature, perceived air quality, and cleanliness of the air they are inhaling (Bolashikov et al., 2013; Bolashikov et al., 2013; Licina et al., 2015; Licina et al., 2015; Bolashikov et al., 2017; Kierat et al., 2018). Design and positioning recommendations for the ATD, PV supply flow rate, and temperature, control of the supplied airflow's properties, and its interaction with the free convection flow already present around the human body have all been made (Bolashikov et al., 2009; Bolashikov et al., 2010; Melikov, 2015; Melikov and Dzhartov, 2013).

Compared to TV, the PV has a stronger ability to stop the spread of infection among occupants when correctly designed and implemented. The use of PV in MV-equipped rooms always shields people from the spread of infectious pathogens through the air and is superior to mixed ventilation alone (Melikov et al., 2003). However, PV encourages the mixing of room air and exhaled air in spaces with displacement ventilation (Cermak et al., 2004; Cermak et al., 2006; Melikov et al., 2003). In rooms with underfloor ventilation, a comparable effect might take place (Cermak et al., 2003; Cermak et al., 2004; Cermak et al., 2007). In practice, this could raise the danger of airborne infectious agent transmission to occupants not covered by high-efficiency PV.

A localized/personalized exhaust device was included in a different study's health-based PV performance enhancement in a mock-up healthcare clinic scenario (Junjing et al., 2014; Yang et al., 2015). A seat with integrated Personal Exhaust (PE) and PV has been proposed for use in car interior applications, and it has been tested using both human subjects and physical measures (Melikov et al., 2012; Melikov et al., 2013). The results offered unambiguous proof of the PV-PE system's efficiency in preventing airborne infections.

When using PV, there have been reports of significant energy savings in terms of energy performance. PV can give thermal comfort to users at higher room temperatures, between 25 and 27 °C, due to convective cooling of the body (Bauman et al., 1993; Kaczmarczyk et al., 2004; Melikov and Knudsen, 2007). Significant energy savings (up to 60%) are observed when PV plus MV is employed at a higher room temperature compared to TV alone (Bauman et al., 1998; Schiavon et al., 2010; Seem, 1992; Sekhar et al., 2005; Sekhar et al., 2010). In warm and humid outdoor settings, combining PV that supplies clean outdoor air with background MV based on cleaning and recirculating interior air is very energy efficient, primarily because less energy is required for dehumidifying the outside air.

At a 100% peak cooling load, the integrated PV-ACB system could save 16% of energy, and at a 25%-part cooling load, it could save as much as 42% of energy, demonstrating the system's better energy-saving potential (Sekhar and Zheng, 2018). According to Lybenova et al. (2011), when PV is combined with background MV, the air supplied to the room may be reduced by as much as 20% (and as much as 40% when the room temperature is increased by 2°C above the upper limit advised in the standards) when compared to MV alone. The supplied air was reduced by up to 80% when PV and passive chilled beams were used together.

The use of a PV unit in the home can provide occupants with numerous psychological, well-being, and physiological benefits. This type of unit is designed to provide optimal air temperature and humidity levels that are tailored to each person's

individual needs and preferences. By doing this, it effectively creates an indoor environment that is comfortable, safe, and enjoyable.

One of the primary benefits of using a PV unit is improved indoor air quality. This type of system utilizes an advanced filtration system to remove allergens, dust, pollen, smoke, and other contaminants from the air. This helps to ensure a cleaner, healthier indoor air environment, which can help to reduce the risk of respiratory illness, allergies, headaches, and eye irritation. Additionally, PV units provide improved temperature and humidity control, which can help to create a more pleasant and comfortable living atmosphere. This can be beneficial for occupants who are sensitive to hot or cold temperatures, as well as those with conditions such as arthritis or fibromyalgia that can be worsened by extremes of temperature.

Mental and emotional health benefits can also be seen when using a PV unit. The increased sense of comfort and safety that comes from having optimal temperature and humidity levels can help to reduce stress and anxiety levels. Furthermore, improved air quality can help occupants to breathe more easily, which can improve concentration, energy levels, and overall mood.

Also, the use of a PV unit can help to promote wellness by providing a better sleeping environment. Not only can this type of system help to reduce allergies and provide optimal temperature and humidity levels, but it can also help to reduce noise pollution. This can lead to more restful and restorative sleep, which can in turn help to reduce the risk of a variety of health issues such as obesity, diabetes, and heart disease.

In conclusion, there are numerous health, well-being, and wellness benefits that occupants can experience when using a PV unit. From reduced respiratory illness symptoms to improved mood and energy levels, this type of system can help to create an environment that is comforting, safe, and conducive to overall health and wellness.

2.5. Summary

In conclusion, as discussed in this chapter, the previous studies focused on developing the indoor environment and enhancing human indoor life. Researchers work hard in several disciplines to develop indoor ventilation, increase the inhaled air, improve the quality of the inhaled air, and try as much as they can to expand the comfort zone and increase the number of satisfied occupants. It is important to mention that, for achieving these goals, previous studies mainly depended on developing mechanical devices to produce steady mechanical air movement. But, none of these studies worked on using mechanical devices to produce a natural airflow. They focused on producing a steady airflow that may let occupants feel satisfied and finish their work successfully. Whereas, unfortunately, over time most of these products affected occupants negatively by separating them from the outside environment, letting them feel lazy, reducing their performance and productivity, and affecting their physiological, psychological, and well-being.

On the other hand, even when previous studies focused on developing air movement in indoor environments, they did not think about this from a biophilic point of view. Researchers mostly thought about developing the air movement for economic, industrial, commercial, and sometimes health purposes. But they did not think about improving indoor ventilation as a biophilic design. They did not think about reconnecting occupants with the outdoor environment and nature by combining the biophilic principles with the architectural designs as airflow. This is what tries to be achieved through this study. This research focuses on moving from developing mechanical air movement to developing more natural air movement and shifted the thinking from developing rigid architectural designs to developing more biophilic architectural designs that may enhance the occupants' experiences, reconnecting them to nature that may positively affect them. This research suggests developing a BLNAS as a developed biophilic system that will produce and mimic natural airflow.

3. Chapter Three: Research Methodology

3.1. Introduction

This chapter will discuss the methodology that will be adopted in conducting this study. Based on the nature of the research and its requirements, and as a broader thinking about it, the research will consist of three main phases: natural airflow characteristics phase, experimental design and setup phase, and data analysis phase. To achieve all these phases and steps qualitative and quantitative methods will be applied. For the aim of this study and its limitations, this research will primarily apply the quantitative method.

3.2. Qualitative vs Quantitative

In general, using qualitative and quantitative techniques in designing a biophilic localized natural airflow simulator (BLNAS) is an important part of creating an effective product that meets occupants' needs. Qualitative techniques involve gathering information through surveys, interviews, or focus groups to identify key features that should be included in the product design. On the other hand, quantitative techniques involve using statistical methods or computer simulations to measure performance, environmental impacts, energy efficiency, cost-effectiveness, etc. Both methods play an essential role in the design process and should be used in conjunction when creating a BLNAS.

Qualitative techniques can help designers gain a better understanding of what users would want out of a BLNAS. This kind of information is incredibly helpful in making sure the product that is created meets expectations. These techniques allow designers to gain an understanding of what features users would prefer in the product, such as noise level, airflow, and aesthetic appeal. Based on the feedback from users,

designers can make changes and improvements to the product design before it goes into production.

Quantitative techniques are also important for determining the performance and efficiency of the BLNAS. By using statistical techniques and computer simulations, designers can evaluate different factors such as air velocity, air pressure, temperature, turbulence intensity, and humidity levels, giving them an accurate understanding of how the product will interact with the environment. Additionally, a cost analysis can be used to determine how many resources and materials are needed to manufacture the product. Knowing the number of resources and costs associated with the project helps designers make better decisions once it comes time to produce the BLNAS.

Ultimately, both qualitative and quantitative techniques are necessary for the design process when creating a BLNAS. The data and information gathered through qualitative techniques can help designers understand user demand and make changes accordingly while quantitative techniques provide useful insights mainly into the performance of the product. By using both methods together, designers can create a product that meets expectations, performs well, and is cost-effective for consumers.

While this research aims to produce a prototypical biophilic natural airflow system that simulates natural airflow; to create more healthier and comfortable indoor spaces by changing the indoor airflow characteristics, this means that the new prototype should be developed, using mainly quantitative methods. The quantitative technique will be used to achieve the first and third phases which are related to determining the characteristics of natural airflow and analyzing the airflow data collected at the occupant's seat by using the TSI Hot-Wire transducer.

Based on this, figure 7 illustrates the research stages. It consists of seven main stages including introduction, literature review, methodology, data collection, experimental test setup, results and discussion, and architectural design recommendations.

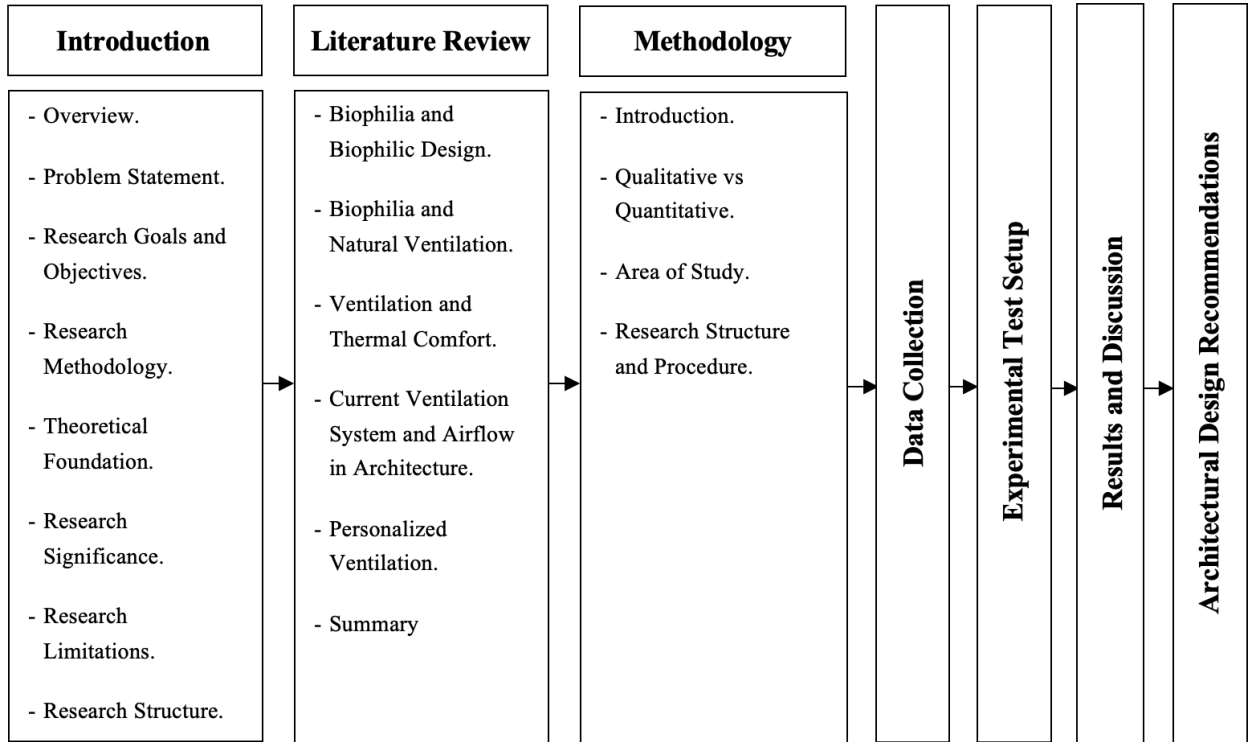


Figure 3: Main Research Stages (Illustrated by the Author).

3.3. Area of Study

Blacksburg is an incorporated town located in Montgomery County, Virginia, United States. Virginia shares the north and west borders with West Virginia, and the southern border with North Carolina and Tennessee. It is bounded by Maryland and the District of Columbia on the northeast, and Kentucky to the southwest as presented in figure 8. Blacksburg is well known for its hills, mountains, and rich valleys. Its land area is 19.77 sq mi, and according to the 2020 census, its population is 44826.

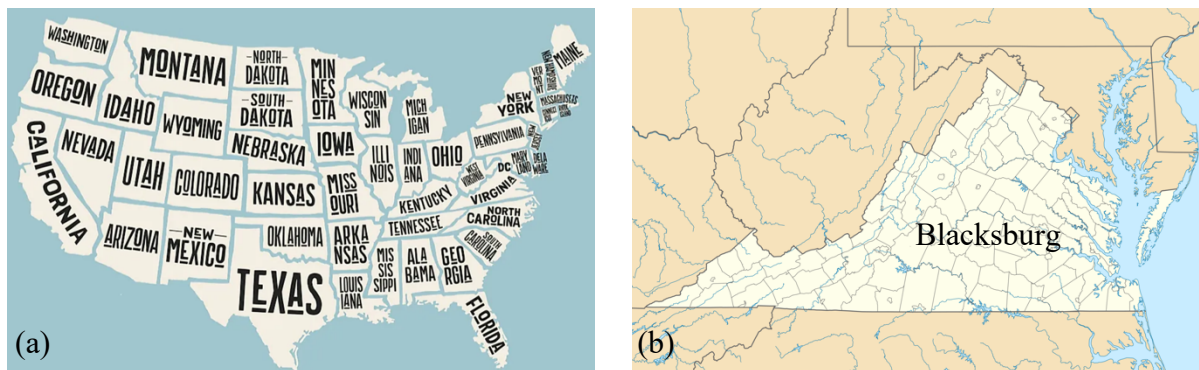


Figure 4: (a) United States Map, (b) Blacksburg Map.

3.3.1. The Climate in Humid, Sub-Tropical Areas

A climate zone characterized by hot, humid summers and cold to mild winters is known as a humid subtropical climate. These climates are typically found poleward of nearby tropical climates on the southeast side of every continent (apart from Antarctica) (Britannica.com). They are typically found between latitudes 25° and 40°. In this climate, the mean monthly temperature ranges from 0 °C (32 °F) to 18 °C (64 °F) in the coldest month to at least 22 °C (72 °F) in the warmest month (weather.gov).

A gradient between the hotter tropical climates of the southern coasts and the colder continental climates to the north and further inland exists between many subtropical climates, which tend to be found at or near coastal locations. However, in some cases, these climates also extend inland, most notably in China and the United States (tomorrow.io), where they exhibit more pronounced seasonal variations and sharper contrasts between summer and winter. Therefore, it can be claimed that the climate has slightly varied characteristics depending on whether it is placed inland or in a seaside location (weather.gov).

The American Gulf Coast and lower East Coast states, including Texas, Oklahoma, Louisiana, Arkansas, Alabama, Mississippi, Tennessee, North Carolina, South Carolina, Georgia, and Florida, have humid subtropical climates. This zone, according to Köppen's classification of climates, includes areas farther north, primarily Virginia, Kentucky, the lower elevations of West Virginia, Maryland, Delaware, Washington, D.C., New Jersey, the southeast of Pennsylvania, the majority of Connecticut, and extreme southern New York, which includes parts of Long Island and New York City. The far southern regions of Illinois, Indiana, and Ohio, as well as the central and southern parts of Kansas and Missouri, are where it is primarily found in the lower Midwest.

In this climatic zone, snowfall varies widely. Cities like New York City, Philadelphia, and Baltimore frequently get winter snowfall at the northernmost reaches of this zone. In the humid subtropical climate zone of North America, precipitation is

abundant. The wettest months are typically July or August, like in Norfolk, Cape Hatteras, Jacksonville, Charleston, South Carolina, Mobile, Alabama, and New Orleans.

3.3.2. Specific Location: Blacksburg – Virginia

Blacksburg's climate, which is cooled from the lowland areas, all of which have a humid subtropical climate, has a hot-summer humid continental climate. Although the region experiences substantially lower temperatures than areas of lower elevation at the same latitude, with only 5 days of 90 °F (32 °C) or higher highs annually, summers are humid and moderate to hot (ncei.noaa.gov). Winters are typically cool to cold, with sporadic warm spells in between with an average of 0.9 nights with lows below freezing (18 °C) (ncei.noaa.gov). The monthly mean temperature ranges from 31.9 °F (0.1 °C) in January to 71.7 °F (22.1 °C) in July. Snowfall typically occurs from December to March and averages 24.7 inches (63 cm) every season, while significant snowfall has been observed outside of those months as well. According to Climate Consultant software, figure 9 presents the temperature range for Blacksburg and figure 10 presents the wind rose.

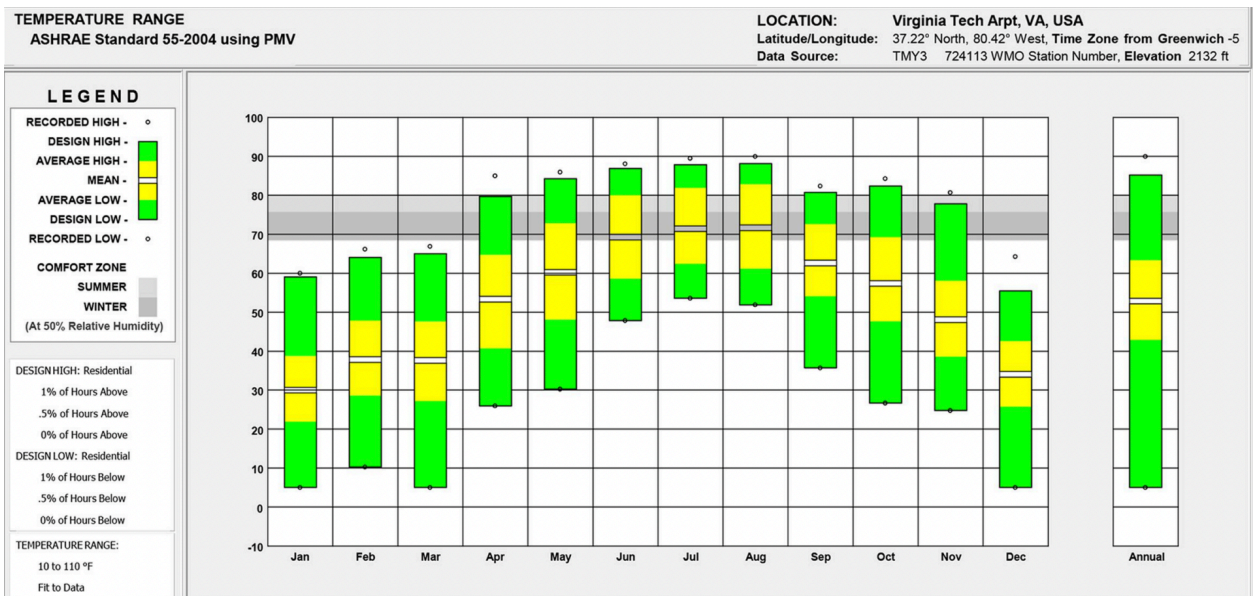


Figure 5: Temperature Range for Blacksburg, (Climate Consultant).

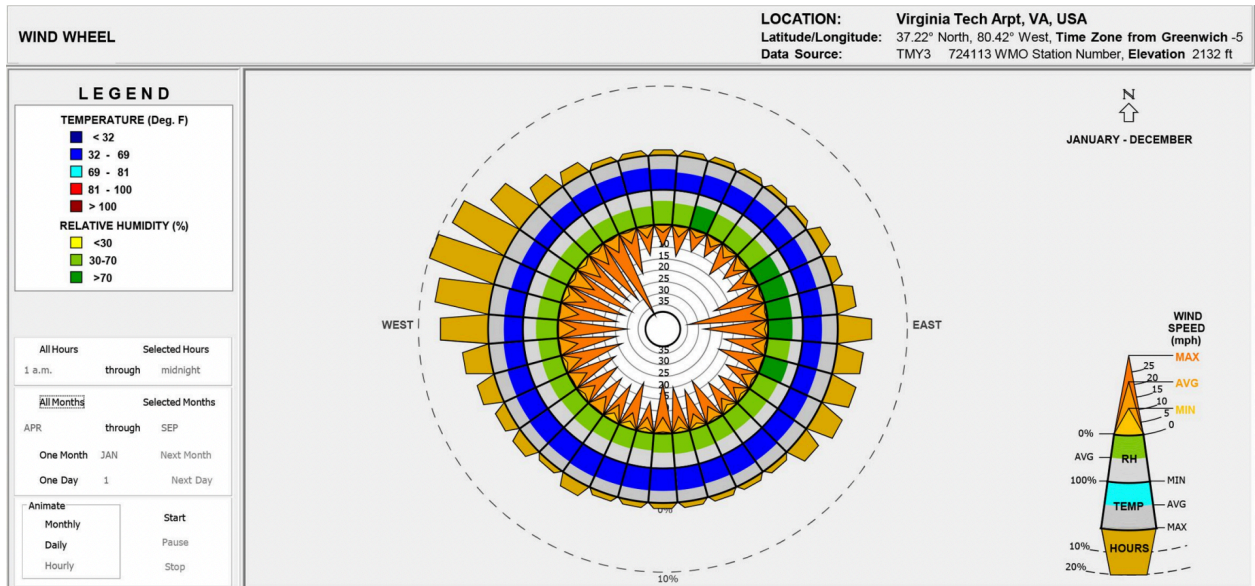


Figure 6: Wind Rose for Blacksburg, (Climate Consultant).

3.4. Research Structure and Procedure

This section explains the research structure and procedure and the steps that will move through to answer its questions and achieve its goal and objectives. Figure 11 presents a chart of the research structure and procedure. The research methodology is divided into four main phases;

1. Phase 1: Natural Airflow Characteristics.
2. Phase 2: Experimental Design and Setup.
3. Phase 3: Data Analysis.
4. Phase 4: Selection or Design of the Prototype

To answer the research questions and achieve the goals the research methodology will be divided into four main phases; the determination of natural airflow characteristics, the experimental design and setup, the data analysis, and the selection or design of the prototype.

Table 4 presents the research questions, the methodology steps that will cover it, the methods that will be used to investigate it, and its expected results.

Table 3: The Research Questions and Answering Procedure (Illustrated by the Author).

Research Question	Research Step	Method Investigation	of Expected Result
1. What are the characteristics of natural airflow?	Phase 1 Step 1 – Step 4	1. Literature. 2. Standards. 3. Typical Metrological Year (TMY). 4. Virginia Tech Airport Weather Station.	Determine the characteristics and features of natural airflow.
	Phase 2 – Step 1	Evaluate the Advantages	Determine the optimum configuration and control strategy of a localized mechanical forced airflow system and choose the device that will best meet the research goals
	Phase 2 Step 2 – Step 3	Industrial Design Process – Incorporate the Mechanical Forced Airflow Mechanism into a Modular Workstation considering the performance and appearance of the system	Incorporate the mechanical forced airflow system (prototype) into a modular workstation.
2. Can a localized mechanical forced airflow system be designed and developed to simulate natural airflow?	Phase 2 – Step 4	Logical Argumentation	Determine the indigenous and exogenous variables associated with the experimental setup and development of the prototype.
	Phase 2 – Step 4	Experimental Testing – By Setting Up the Workstation, Prototype, TSI model 8455 Hot Wire Transducer, and sensor at the occupant seating.	Design the experimental setup and record the airflow patterns data at the occupant seating. Organize, structure, and partition the collected data
	Phase 3 – Step 1	Statistical Analysis	Analyze the collected data.
	Phase 4 – Step 1	Statistical Analysis	Compare the collected data about the airflow characteristics at the location of the seated occupant with those of natural airflow from Phase one and determine the best prototype that may simulate natural airflow.

4. Expected Outcomes

The proposed study is expected to:

1. Determine the characteristics of the natural airflow based on the literature, standards, and weather data files.
2. Extend the approach of biophilic design to include a connection to nature by using localized mechanical forced airflow system that simulate natural airflow.
3. Produce more healthier and comfortable indoor spaces by changing the indoor airflow characteristics.

Produce base research for future research that may analyze the impact of the BLNAS system on users' health, wellness, and well-being.

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