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Vertical Farming: a Catalyst for Integrating Biophilic Design into Built Environment

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Vertical Farming: a Catalyst for Integrating Biophilic Design into the Built Environment

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Abstract

Could integrating vertical farming into buildings be a catalyst for promoting biophilic design? Answering this question is the aim of this study. Biophilic design (BD) focuses on human-nature connection (HNC) in the built environment (BE), and vertical farming (VF) systems provide an innovative way to integrate green spaces, natural elements, and activities related to vertical farming systems into buildings in a way that supports the goals of BD. Therefore, the study conducted a literature review on BD as an approach to HNC and extracted the goals of BD, application strategies, and elements of nature relevant to its goals. The study then addressed the concept of vertical farming and its systems, in addition to extracting the most important elements of nature that affect each system, based on the components of each system and its method of operation, in addition to comparing several vertical farming projects integrated into buildings, with a focus on the BD goals that each project seeks to achieve. Hence the term "Vertical Farming (VF) -Based Biophilic Buildings" was coined and the study then presented a SWOT analysis of this proposed term. The study concluded that integrating VF into urban buildings creates harmonious environments where nature and the BE coexist. Thus, we can create (VF) -Based Biophilic Buildings that can encourage residents' participation in natural processes, and promote health, social, and well-being goals, along with economic, environmental, and sustainability goals.

Keyword: biophilic design; vertical farming; human-nature connection; built environment; SWOT analysis.

Introduction

It is widely recognized that one of the fundamental aspects of human existence is our natural tendency to seek comfort, well-being, and mental and physical health. Biophilic design, rooted in this understanding, seeks to create environments that foster HNC by integrating natural elements, especially plants, into architectural spaces(Kellert, 2006, 2018; Zhong et al., 2023). As a deeply ingrained part of human history, farming not only provides livelihoods but also fosters a deep HNC. This connection extends beyond growing crops and raising livestock; it includes a complex web of relationships with animals, birds, and the landscape. Where several studies indicate that this relationship between humans and agriculture, animals, birds, and the surrounding environment contributes to their well-being and improves health, relaxation, boosts mood, and enhances cognitive function(Gorman, 2019; Sharma & Shyam, 2023).

As people increasingly migrate from the countryside to urban centers, turning away from agricultural practices that were historically an integral part of human life, there has been a marked disconnect and shift in the relationship between humans and nature. This disconnection can have profound psychological and neurological effects such as increased levels of stress, anxiety, and depression. Thus, as society continues to urbanize and drift away from agriculture, efforts to reconnect people with nature become increasingly important. Table 1 shows the ability of agricultural practices to support HNC.

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Table 1
The ability of agricultural practices to support human-nature connection

Agricultural practices	Supporting HNC	Ref.
Human contact with agricultural activity	– Agriculture is more than just a profession for farmers. It is a way of life closely linked to the rhythms of nature. – Participating in planting, caring for, and harvesting crops fosters a sense of purpose, self-esteem, and satisfaction	(Van Den Berg & Custers, 2011)
Relationship with Animals	– Animals play a critical role in many farmers' livelihoods and incomes. Thus, taking care of animals fosters a sense of responsibility and encourages physical activity, which improves general well-being.	(Gorman, 2019; Kues & Niemann, 2004)
Relationship with Birds	– Birds are both helpers and adversaries to farmers. Some birds help with pest control and pollination, while others harm crops and livestock, helping farmers have different experiences in nature. – Bird watching can help relax, reduce stress, and encourage feelings of peace and connection to nature.	(Sharma & Shyam, 2023; Yari, 2019)
Connection to agricultural landscape	– Agricultural landscapes provide relief from the stresses of modern life. – Spending time in natural environments and green areas can have significant physiological and psychological benefits, including lower stress levels and improved overall health.	(Milligan & Bingley, 2007)

It is clear from the previous table that the intricate web of connections between farmers, and agriculture, animals, birds, and the landscape have profound implications for their holistic health, well-being, and sustainability. Integrating plants into buildings has been shown to improve the physical and mental health of occupants as well as add aesthetic value. According to research conducted by Roger Ulrich and his co-authors, it has been demonstrated that exposure to greenery indoors can reduce stress, enhance cognitive performance, and speed up the recovery process after illness(Ulrich et al., 2008).

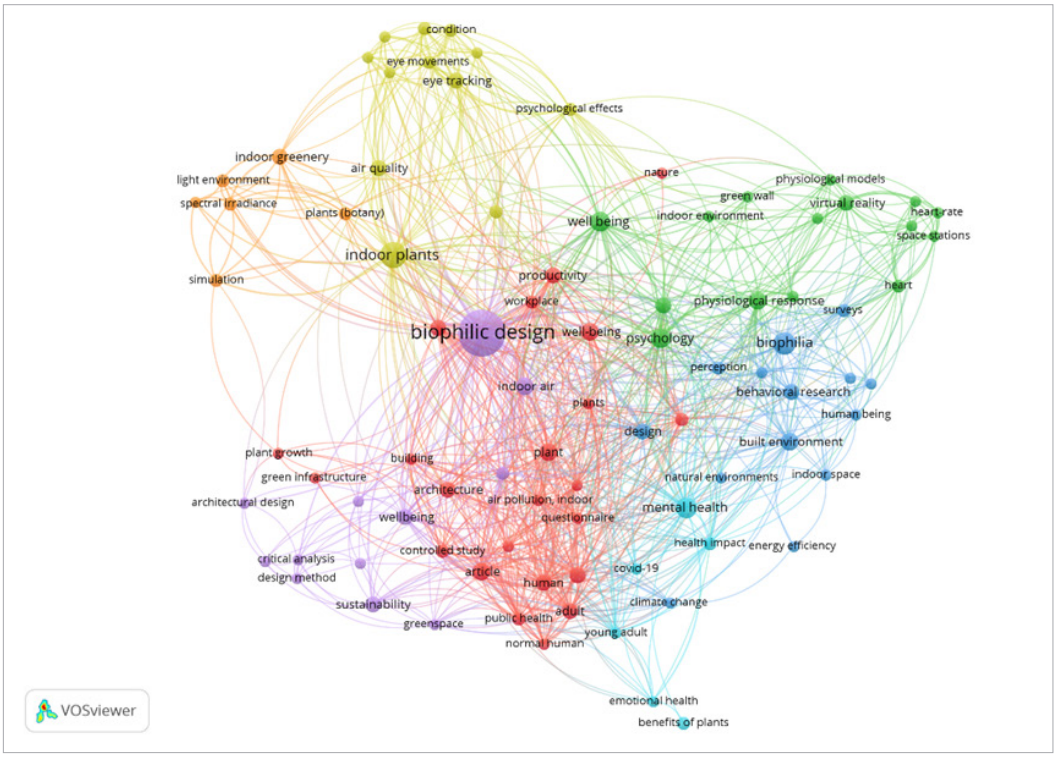
Furthermore, BD concepts are consistent with Edward O. Wilson's biophilia hypothesis, which proposes that humans have a natural attraction for nature, which when achieved, leads to overall satisfaction and productivity (Kellert & Wilson, 1993; Wilson, 1984, 1986). Therefore, designers can create an environment that promotes greater human productivity and flourishing, as well as promote healthier and more sustainable BE by adopting BD and incorporating plants into buildings(Ayuso Sanchez et al., 2018; Wijesooriya & Brambilla, 2021).

Numerous studies have shown that integrating plants into buildings has a significant impact on achieving BD and sustainability principles, while also improving occupants' well-being and mental and physical health. According to research by (Yin et al., 2018), BD elements—such as plants—have a favorable effect on reducing stress and improving cognition among building occupants. Likewise, (Hähn et al., 2021) found that employees' physical and visual access to plants in their offices and breakout areas improved their satisfaction with the workplace environment. In addition, adding plants to architectural spaces enhances energy efficiency, improves indoor air quality, and thus creates healthier indoor environments in line with sustainable design principles.

VF is a pioneering way to integrate agriculture into BE, with multiple benefits for sustainability, food production, and urban development(Shahda & Megahed, 2023). This innovative approach involves growing crops in vertically stacked layers, usually under controlled indoor conditions(Kalantari et al., 2018; Tablada & Kosorić, 2022). As cities grow and global demand for food rises, VF represents a viable alternative to producing sustainable food while reducing the environmental impact of traditional farming. So, can VF help promote BD to improve the HNC?

By searching the Scopus database on the relationship between integrating plants into buildings and achieving biophilic design principles, the "Documents" search option was used to search for publications on this topic, and under "Article title, abstract, keywords", using the keywords, using the keywords ("biophilic design" AND "plants"). Results were filtered using quick filters on databases, as follows: TITLE-ABS-KEY ("biophilic design" AND "plants") AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "SOCI") OR LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA , "ARTS") OR LIMIT-TO (SUBJAREA , "PSYC") OR LIMIT-TO (SUBJAREA, "AGRI")) as a result, 60 document results were obtained. The keywords analyzed were words that were repeated at least twice. The overlay visualization of the co-occurrence analysis of all keywords shows that the terms related to plants and agriculture are green architecture, green infrastructure, green wall, greenspace, indoor greenery, indoor plants, and plant growth. However, the term VF has not yet emerged as a term related to BD, see Fig. 1. As mentioned, VF is a new trend for integrating plants into BE, but studies have not yet addressed the expected contribution of integrating VF into BE in promoting BD principles. This, in turn, demonstrates the originality of the scope of the current research.

Fig. 1
Overlay visualization of the co-occurrence analysis of all keywords



Methodology

This study adopts a multi-method approach to investigate the extent to which the integration of VF into buildings is a catalyst for BD. The methodology involves three aspects to achieve this goal and address the research questions. First, a literature review on BD as an approach to connecting humans with nature is conducted, understanding the goals of BD, its approaches, application strategies, and elements of nature relevant to its goals in Section 3. Second, Section 4 outlines the concept of VF and its systems and investigates the most important elements of nature that affect each system, based on the components of each system and its method of operation, as well as compares several VF projects integrated into buildings, focusing on the VF systems used in each project and the BD goals that each project seeks to achieve. Third, to evaluate the concept of Vertical Farming (VF)-Based Biophilic Buildings, a SWOT analysis is presented in Section 5. Section 6 provides the conclusions. Fig. 2 illustrates the research questions and research methodology.

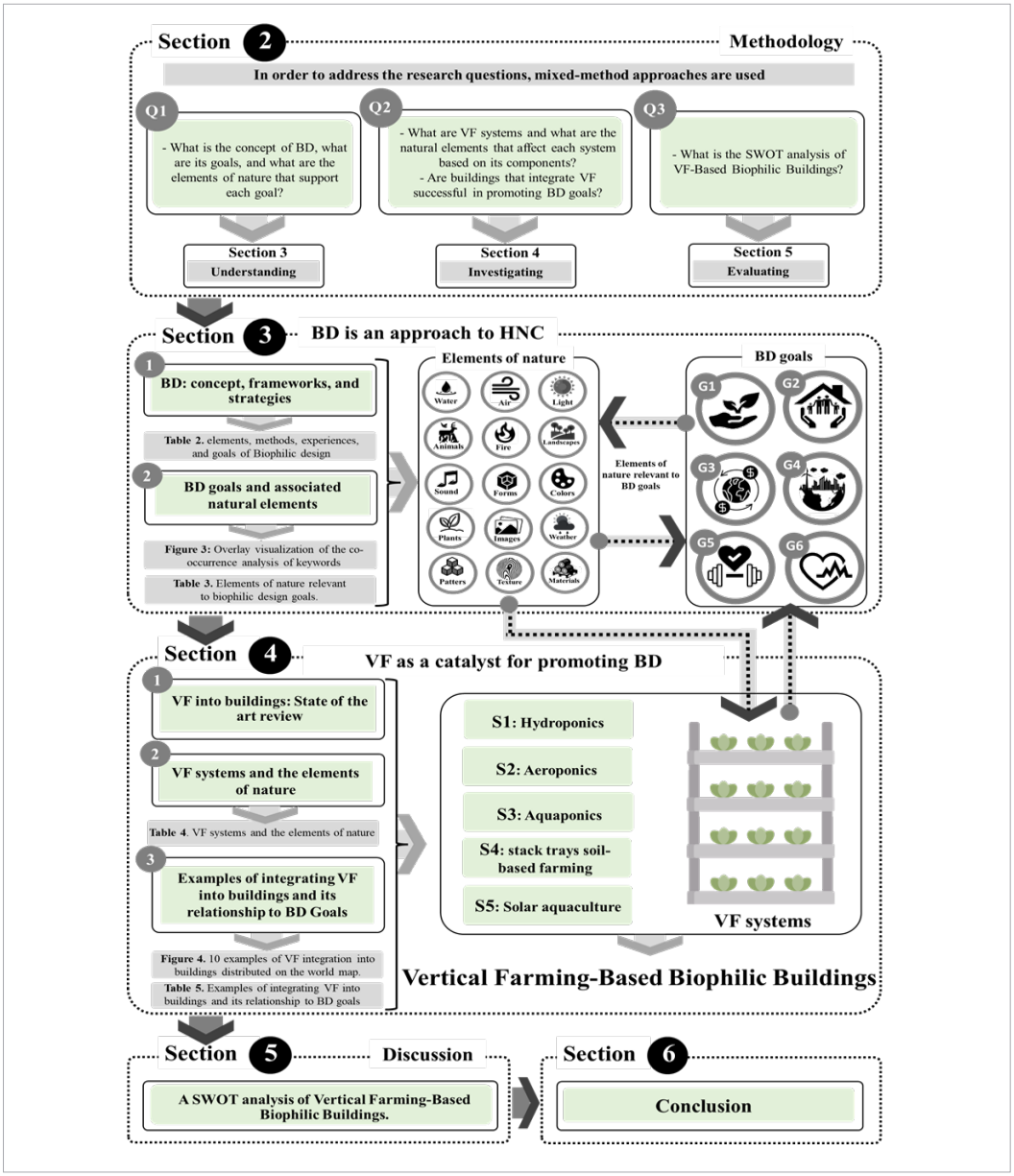


Fig. 2
Research methodology

Biophilic design is an approach to human-nature connection

Studies have repeatedly shown a positive relationship between exposure to natural environments and enhanced mood, cognitive function, and general wellness (Wijesooriya & Brambilla, 2021). Moreover, landscapes that can meet human needs elicit favorable neural and physiological responses(Browning et al., 2014). It is known that humans are naturally attracted to places with flowing water, greenery, and vegetation (Gillis & Gatersleben, 2015). Furthermore, research suggests that enhancing people's connection to nature can contribute to sustainability in the BE, emphasizing the importance of incorporating natural elements into architectural design. Unlike traditional sustainable design, which primarily focuses on energy conservation and reducing environmental footprint, biophilic development includes all aspects of sustainability with an emphasis on the relationship between humans and their surroundings(Zhong et al., 2022). It also enhances satisfaction, morale, and environmental awareness among individuals, ultimately leading to enhanced productivity(Barnaby et al., 2023).

HNC in the BE has received scholarly attention as a means of addressing the growing disconnect between humans and nature. BD has emerged as a recognized approach to bridging this gap, with scholars and practitioners introducing hypotheses, strategies, and design principles that aim to integrate natural elements into various aspects of the BE, from residential to educational and healthcare facilities (Kellert & Calabrese, 2015). The evolving interpretations of BD since 2008 underscore its importance in fostering sustainability and managing natural resources (Kellert, 2008), as well as its applicability in diverse contexts such as cities and urban planning. The concept of "Biophilic cities" has gained traction as a model for sustainable and resilient urban development (Andreucci et al., 2021). Furthermore, BD has been endorsed by organizations like the American Institute of Architects and explored for its potential in creating healthy, nature-connected learning environments(Mollazadeh & Zhu, 2021). These trends reflect a holistic approach to integrating nature into the BE.

Biophilic design: concept, frameworks, and strategies

Several frameworks have been developed to help designers understand and apply the principles of BD. Heerwagen & Hase (2001) were among the first to classify BD features, grouping natural elements into eight categories according to process, habitability, design geometry, and joyfulness(Heerwagen & Hase, 2001). A more systematic interpretation of BD was put out by Kellert (2008), who proposed two basic dimensions, six elements, and seventy-two attributes(-Kellert, 2008). Kellert & Calabrese (2015) and Browning & Ryan (2020) subsequently simplified and expanded on this interpretation(Browning & Ryan, 2020; Kellert & Calabrese, 2015; Ryan & Browning, 2020). In an effort to simplify and enhance the design process, Terrapin Bright Green has introduced a framework that focuses on the connections between nature and health. This framework evolved into fifteen patterns, one of which is "Awe" (Browning et al., 2014; Browning & Ryan, 2020). Additionally, an updated BD framework in 2022 highlighted the integration of nature into architecture to enhance sustainability, well-being, and health. It included eighteen elements and three main design approaches (Zhong et al., 2022). In 2024, a critical study of the BD frameworks proposed by researchers was presented until 2022. The study focused on separating the elements of nature used from the methods of employing these elements from the desired experiences from the intended goals of the BD (Shahda, 2024). Table 2. presents the elements, methods, experiences, and goals proposed by this study.

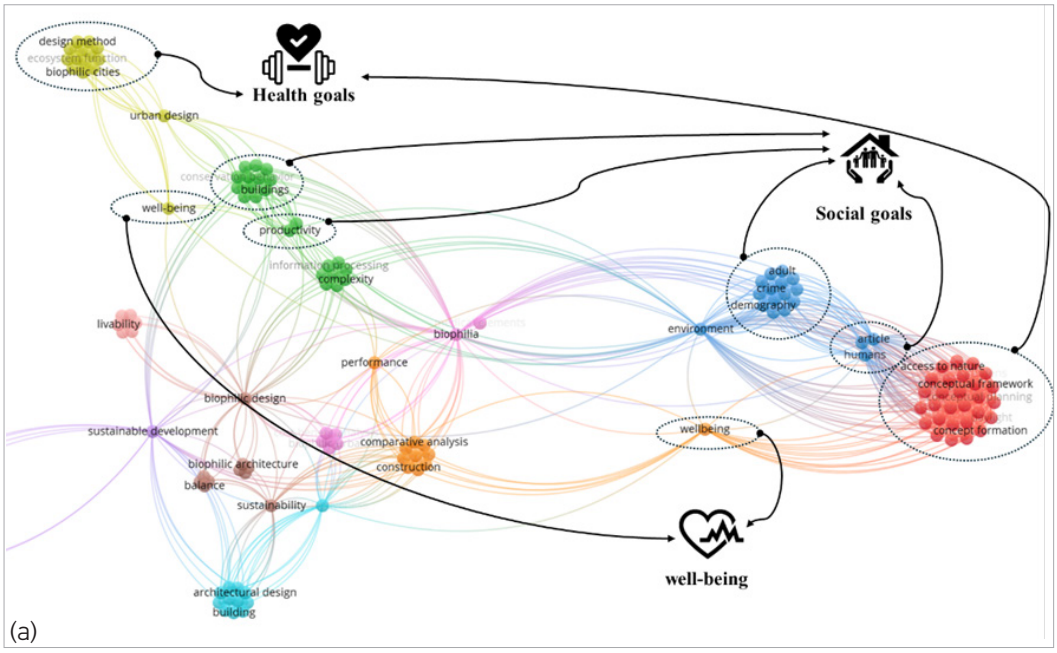
Table 2

Elements, methods, experiences, and goals of biophilic design, source adapted from (Shahda, 2024)

Elements of nature	Methods	Desired experiences	Intended goals
– Light – Air – Water – Plants – Animals – Landscapes – Weather – Fire – Images – Natural materials – Colors – Shapes and forms – Patters and geometries – Texture – **Any other elements**	– Using natural elements – Bringing natural elements – Simulating natural elements	– Connection to place – Connection of spaces – Prospect and refuge – Complexity – Mobility – Mystery – Risk/Peril – Awe – Cultural and ecological connection to the place – **Any other experiences**	– Supporting sustainability goals – Well-being – Mental and physical health – Economic benefits – Environmental benefits – Social benefits – **Any new goals**

Biophilic design goals and associated natural elements

The Scopus database was searched for documents relevant to BD goals and associated natural elements, using the 'Documents' search option, within the "Article Title, Abstract, Keywords" (goals AND benefits AND "biophilic design" OR biophilia OR "Elements of nature"). The open-source software VOSviewer was utilized to enter the collected data. It was found through the research that most of the issues raised in the current studies fall within six goals of BD. Each of the studies focuses on some elements of nature to achieve HNC. Figure 3 a, b shows the most important issues included in the current studies under each goal. Table 3. summarizes the goals that BD seeks to achieve, indicators from previous studies, and the elements of nature that are most relevant to BD and focused on to achieve each goal.



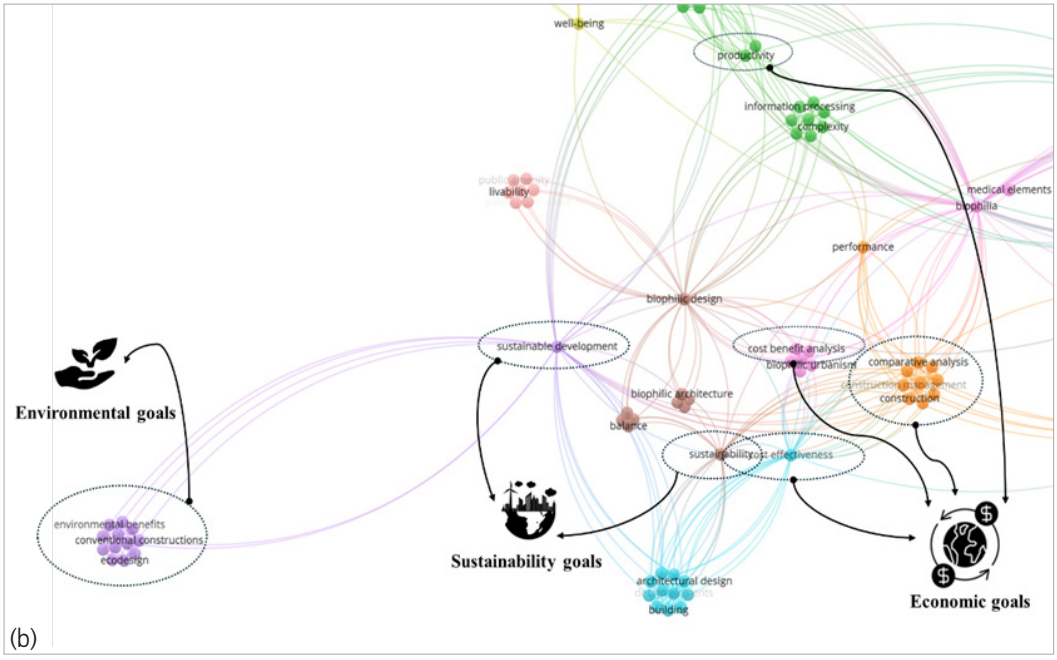


Fig. 3

a: Overlay visualization of the co-occurrence analysis of keywords related to health goals, social goals, and well-being,
b: overlay visualization of the co-occurrence analysis of keywords related to environmental goals, economic goals, and sustainability goals

Table 3
Elements of nature relevant to biophilic design goals

BD Goals		Indicators from the literature review	Examples of natural elements
	Environmental goals	– Reducing pollution and improve air quality (Aydogan et al., 2021). – Reducing energy consumption by promoting passive cooling of buildings (Africa et al., 2019). – Raising awareness of environmental issues (Boiral et al., 2019).	– Air, Plants, Daylight – Air, Daylight, Plants, Weather – Air, Plants, Daylight
	Social goals	– Reducing crime, fear, and aggression as well as increasing safety by HNC in the green area(Ceccato et al., 2020). – Encouraging social interactions(Andreucci et al., 2021).	– Daylight, Plants, Landscape – Plants, Landscape
	Economic goals	– Enabling food production (Cacique & Ou, 2022). – Boosting economic productivity(Barnaby et al., 2023). – Reducing the use of building materials(Lerner & Stopka, 2016).	– Air, Plants, Daylight – Colors, Materials, Texture – Natural materials
	Supporting sustainability goals	– Reducing energy consumption and improving building performance (Nitu et al., 2022). – Improving measurable workplace performance(Ayuso Sanchez et al., 2018). – Reducing construction costs (Ching & Shapiro, 2020). – Promoting biodiversity(Africa et al., 2019).	– Air, Daylight – Plants, Daylight – Natural materials – Plants, Animals
	Health goals	– Enhancing thermal comfort (Almusaed, 2010). – Reducing stress and providing relaxation (Yin et al., 2018). – Reducing depression and anxiety(Reeve et al., 2017). – Enhancing the healing process(Abdelaal & Soebarto, 2019).	– Air, Daylight, Plants, Landscape – Air, Daylight, Plants, Landscape – Plants, Landscape – Plants, Landscape
	Well-being	– Enhancing visual comfort and attention as well as improving aesthetics(Zhong et al., 2022) – Increasing happiness and satisfaction(Capaldi A. et al., 2014).	– Daylight, Colors, Materials, Texture, Plants

After reviewing the most important elements of nature that can be employed to enhance the goals of BD, the study aims in the following section to review the concept of VF, its techniques, and systems for integrating it into buildings, in addition to deducing the most important elements of nature that make up each system of VF, so that we can verify the potential of VF in enhancing BD.

Vertical farming as a catalyst for enhancing biophilic design

In this section, the concept of VF and its systems are introduced, in addition to investigating the most important elements of nature that affect each system, based on the components of each system and its method of operation. Several VF projects integrated into buildings are also compared, focusing on the VF systems used in each project and the BD goals each project seeks to achieve.

Vertical farming into buildings: State of the art review

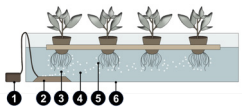
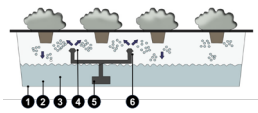
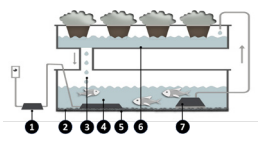
VF is an innovative method using advanced technologies to grow crops in vertically stacked layers within controlled indoor conditions (Despommier, 2010). Growing plants in trays stacked on top of each other in this innovative way increases productivity while using minimal space (Kalantari et al., 2018). This method provides a sustainable solution to problems related to urban food production by allowing fresh produce to be grown year-round close to consumers, reducing transportation emissions and enhancing food security(Al-Chalabi, 2015; Tablada & Kosorić, 2022). VF includes a variety of systems: 1) Hydroponics is a system that uses nutrient-rich water solutions instead of soil to grow plants (Al-Kodmany, 2018a). 2) Aeroponics is a system that involves suspending plants in the air and nurturing their roots with a thin mist of water and nutrients (Al-Kodmany, 2018b). 3) Soil-based VF is another system for maximizing agricultural land use. It uses traditional soil as a growing medium and stacks plants in layers (Tablada & Kosorić, 2022). 4) Aquaponics is a system that combines fish farming and plant farming, creating a symbiotic ecosystem in which fish waste fertilizes the plants and the plants purify the water for the fish (Banerjee & Adenaeuer, 2014). 5) Solar aquaculture is a system that combines fish and algae farming. Algae grow by absorbing nutrients from water, which increases the fish production rate (Al-Kodmany, 2018b).

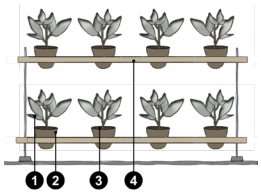
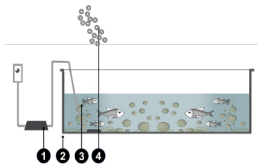
Vertical farming systems and the elements of nature

By reviewing VF systems, we find that they do not depend on the plant element only, but rather there are multiple systems that contain many elements of nature such as water, air, light, colors, and animals, see Table 4.

Table 4

Vertical farming systems and the elements of nature, source adapted from (Al-Kodmany, 2018b; Despommier, 2013; Kalantari et al., 2018; Shahda & Megahed, 2023)

VF Systems	Figure	Components	Elements of nature
S1: Hydroponics		1. Air pump 2. Air stone 3. Mineral nutrients 4. Rainwater-gray water 5. Plants roots 6. Grow tray	– Plants – Light – Air – Color
S2: Aeroponics		1. Grow tray 2. Rainwater - gray water 3. Mineral nutrients 4. Spray mist 5. Water pump 6. Spray nozzle	– Plants – Light – Air – Color
S3: Aquaponics		1. Air pump 2. Gravel beds 3. Nutrient return 4. Rainwater - gray water 5. Fish tank 6. Grow tray 7. Nutrient pump	– Plants – Light – Air – Fish

VF Systems	Figure	Components	Elements of nature
S4: stack trays soil-based VF		1. Plants 2. Container 3. Growing medium: soil 4. Growing tray: holds plants and growing media	– Plants – Light – Air – Color – Animals (bees and butterflies)
S5: Solar aquaculture		1. Green algae 2. Air stone 3. Warm water 4. Fish feeding	– Plants (Green algae) – Light – Air – Fish

By analyzing Table 4, it appears to us that all systems contain elements of nature, which are the basic components for the success of BD by bringing them into the building to achieve the desired experiences and intended goals based on the framework proposed by Shahda (2024) (Shahda, 2024).

Examples of integrating vertical farming into buildings and its relationship to biophilic design goals

After analyzing the components of VF systems and the natural elements associated with each system, it was also important to compare several VF projects integrated into buildings, focusing on the VF systems used in each project and the BD goals that each project seeks to achieve, see Table 5. The selection process of the examples was based on checking the popularity of each building through internet searches. The academic and professional experiences of the author enhanced the selection process. Many studies have adopted the principle of selecting case studies or examples based on professional experience and considered it an acceptable method (Lanzotti et al., 2018). In addition, the study focused on selecting 10 examples that varied in terms of location, building function, and construction stages. Examples included existing buildings, a building under construction, and a prototype. The study also attempted to represent most VF systems in the examples. Figure 4 shows the distribution of examples on a world map.

Fig. 4
10 examples of VF integration into buildings distributed on the world map

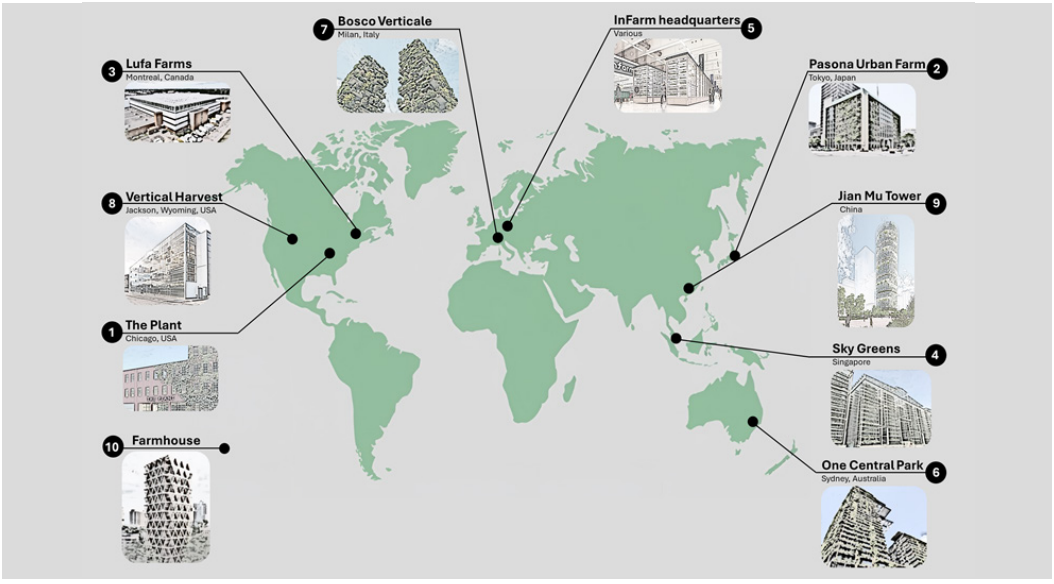


Table 5

Examples of integrating vertical farming into buildings and its relationship to Biophilic design goals, source adapted from (Al-Kodmany, 2018b; Basso et al., 2023; Chisari, 2024; Despommier, 2019; Ishween, 2021; Nouvel & Nouvel, 2014; Pasona H.Q. Tokyo, 2024; Proksch & Ianchenko, 2023; Sky Greens, 2021; Stouhi, 2021)

Project description	VF systems	Project goals	BD Goals
Name: The Plant **Location:** (Chicago, USA) **Architect:** John Edel and his team at Bubbly Dynamics LLC **Year:** 2010	Aquaponics Hydroponics	– Sustainable food production. – Convert organic waste into biogas for heating and energy production. – Create a zero-waste facility by recycling waste within a closed-loop system.	G1, G3, G4
Name: Pasona Urban Farm **Location:** Tokyo, Japan **Architect:** Kono Designs **Year:** 2010	Hydroponics Soil-Based Farming	– Integrate farming into the workplace to improve employee well-being. – Reduce the environmental footprint of food production.	G1, G2, G3, G4, G5, G6
Name: Lufa Farms **Location:** Montreal, Canada **Architect:** Mohamed Hage **Year:** 2011	Hydroponic systems inside greenhouses located on rooftops	– Provide fresh food close to consumers. – Reduce food travel distances. – Provide fresh produce year-round. – Utilize unused rooftop spaces to address food security challenges.	G1, G3, G4, G5
Name: Sky Greens **Location:** Singapore **Architect:** Jack Ng **Year:** 2012	Soil-Based Farming A new technology called "A-Go-Gro" grows vegetables in A-shaped towers, each six meters high, and each tower consists of 22 to 26 layers.	– Reduce water and energy consumption through a closed water system and improve energy efficiency. – Provide fresh local produce.	G1, G3, G4
Name: InFarm **Location:** Various locations globally **Architect:** In-house design **Year:** 2013	Modular VF Units	– Bring food production closer to consumers to ensure freshness and reduce food miles. – Reduce water use.	G1, G3, G4, G5
Name: One Central Park **Location:** Sydney, Australia **Architect:** Jean Nouvel, Patrick Blanc **Year:** 2014	Hydroponic green walls	– Create a sustainable residential and commercial building that integrates nature into the BE. – Reduce the urban heat island effect to improve air quality and enhance the aesthetic appeal of the building by creating water green walls. – To provide natural light, the heliostat system redirects sunlight to the gardens and public spaces below.	G1, G2, G3, G4, G5, G6

Project description	VF systems	Project goals	BD Goals
Name: Bosco Verticale **Location:** Milan, Italy **Architect:** Stefano Boeri **Year:** 2014	Soil-based vertical gardens	– Provide a habitat for various species of birds and insects and enhance biodiversity in BE. – Reforestation of the BE in order to absorb carbon dioxide and dust particles, produce oxygen, and improve temperature.	G1, G2, G3, G4, G5, G6
Name: Vertical Harvest **Location:** Jackson, Wyoming, USA **Architect:** GYDE Architects **Year:** 2016	Hydroponics	– Provide fresh produce to the community year-round. – Create employment opportunities for people with disabilities. – Reduce the carbon footprint of food production.	G1, G2, G3, G4, G5, G6
Name: Jian Mu Tower (Farmscraper) **Location:** Shenzhen, China. **Architect:** CRA-Carlo Ratti **Year:** Under construction	Vertical hydroponic farm	– Farm plant on a large-scale vertical hydroponic farm on the entire facade. – Achieve food self-sufficiency for the building's residents as well as enjoy the natural scenery and biodiversity in the landscape terraces. – Provide solar shading is a key function of the vertical hydroponic farm. – Enhance social interaction and well-being among office users by designing a series of indoor vertical hydroponic farms in double-height spaces.	G1, G2, G3, G4, G5, G6
Name: Farmhouse **Location:** - **Architect:** Fei and Chris Precht **Year:** Advanced prototype	Soil-based cultivation in pots. Hydroponics techniques.	– Provide residents with the opportunity to grow their own food in residential towers for consumption or sharing with their local community. – Help to reconnect physically and mentally with nature. – Equipping innovative agricultural balconies to produce plants in pots or using hydroponic techniques.	G1, G2, G3, G4, G5, G6

By analyzing the most common examples of integrating VF into buildings, we find that:

- The Plant, Sky Greens, and Lufa Farms projects seem to be able to achieve BD goals such as environmental, economic, and sustainability goals, but goals such as well-being are not expected to be achieved because these examples are primarily target food production rather than connecting building occupants to nature.
- As for the Pasona Urban Farm project, the main idea of the project was to integrate VF into work areas in order to improve well-being, as well as to educate the public about the feasibility of urban farming and sustainable food production at the educational center. Thus, this project can achieve most of the goals of BD.
- The Vertical Harvest project aims to provide job opportunities for people with disabilities in a comfortable and productive work environment, which will achieve social and health goals in addition to achieving the environmental and economic goals of BD.
- The goal of the InFarm project was to achieve scalability, i.e. adapt to different urban environments and different scales. This was done by establishing multiple branches of the project and integrating the farming units into supermarkets and restaurants. So, it seems that it is able to achieve the goals of BD such as environmental, economic, and sustainability goals, in addition to some social goals that can be achieved as a result of interacting with plants and their different colors in supermarkets and restaurants.
- One Central Park is a pioneering project for living, shopping, and entertainment in harmony with the natural world by integrating hydroponic green walls into the residential tower. Motorized mirrors mounted on the cantilever to capture sunlight and reflect it into the park area helped bring in sunlight and create a wonderful view of shadow movement. Thus, this project achieves all the goals of BD.
- The vertical forest in the Bosco Verticale project introduces biodiversity, fosters the formation of an urban ecosystem, and offers Milanese residents a constantly changing vision, with colors changing according to the season and the nature of the different plants used. Thus, the project can achieve the six goals of BD.
- Projects such as Jian Mu Tower and Farmhouse reinforce the hope of experimenting with integrating VF into buildings and the hypothesis that VF can be a catalyst for enhancing HNC and thus achieving the goals of BD, whether health, social and well-being goals, alongside economic, environmental and sustainability goals.
- According to analyzing the previous examples, the maintenance of VF in buildings involves several challenges to achieve optimal plant growth, energy and resource efficiency, wastewater management, regular maintenance of indoor environmental control systems, and achieving longevity of the VF systems, without compromising the functionality of the building in which the VF is integrated as well as taking into account the building occupants. For instance, Vertical Harvest and Pasona Urban Farm rely on a hydroponic farming system that requires regular monitoring of water management systems and insulation efficiency so that water does not leak into the building structure. A number of projects, such as Bosco Verticale and One Central Park incorporate green walls that require plant care, irrigation system checks, and biodiversity monitoring to maintain ecological benefits. In general, the maintenance of VF in buildings must balance automation and human supervision to optimize food production while reducing operational costs and without neglecting the goal of connecting the building occupants to nature and the natural processes associated with VF in buildings. It is worth noting that many studies tend to focus on studying maintenance considerations, life-cycle assessment, and the cost of integrating VF into buildings(Hatipi et al., 2025).

From the above analysis, we conclude that the ability of a building in which vertical agriculture is integrated to achieve the goals of BD depends on the project objectives from the beginning of its planning and the extent to which HNC is a primary goal of the project. As for VF, it is undoubtedly a strong incentive to enhance the experience of coexistence and HNC and thus enhance BD. However, VF must be integrated into buildings in a way that allows for enjoying nature and the promotion of biodiversity, not only for economic considerations such as achieving food security, although this is of course important. As a result, we can create **VF-based biophilic Buildings**.

Discussion on vertical farming-based biophilic buildings

The integration of VF into buildings can be a powerful catalyst for promoting BD, which focuses on reconnecting people with nature in BEs. However, there are strengths, weaknesses, opportunities, and threats that can be extracted based on a literature review and analysis of VF systems and their relationship with the elements of nature, the main factor in BD, in addition to analyzing examples of integrating VF into buildings and extracting the most important BD goals that each example achieved. Table 6 provides a SWOT analysis of VF-Based Biophilic Buildings.

Table 6
SWOT analysis of vertical farming -Based biophilic buildings

Strengths	
Enhancing human well-being and connection to nature	Integrating VF into buildings activates multiple senses. The variety of plant shapes and colors provides visual enjoyment, aromatic plants stimulate the sense of smell, and the soothing sounds of flowing irrigation systems stimulate the sense of hearing. Thus, by activating the human senses, stress is reduced, productivity is increased, and well-being is improved (Kues & Niemann, 2004; Milligan & Bingley, 2007; Van Den Berg & Custers, 2011; Zhong et al., 2022).
Biodiversity and Nature-Inspired Environments	Vegetation cover in buildings integrated with VF systems provides a variety of plant species, colors, and textures that attract insects and birds as habitats, thus increasing biodiversity in line with biophilic principles that promote visually stimulating and nature-inspired environments(Africa et al., 2019; Gorman, 2019; Sharma & Shyam, 2023).
Sustainability and resilient urban communities	VF aims to optimize resource utilization, using less water and energy and maximizing land use compared to traditional farming methods. This efficient use of resources directly supports the BD goal of integrating sustainability into the BE and enhancing the symbiotic relationship between nature and BE (Nitu et al., 2022; Zhong et al., 2022).
Local food production	Integrating VF systems into buildings can enhance food security. Using buildings to produce fresh, local food also contributes to building socially connected, participatory communities, as well as achieving food security that promotes HNC thus achieving BD principle(Tablada et al., 2020).
Physical health and Decarbonization	Integrating VF systems into buildings can reduce CO2 emissions and improve air quality, lower temperatures, increase thermal comfort, provide shading, and thus reduce energy consumption. They also purify the air and combat pollution, thus enhancing the physical health of building occupants(Kues & Niemann, 2004; Milligan & Bingley, 2007).
Psychological health	Human connection with VF, activities related to farming and monitoring the growth of plants have the greatest impact on improving the psychological health of building occupants (Sharma & Shyam, 2023; Zhong et al., 2022).
Fostering a sense of community and place	Integrating VF into buildings helps reduce "food miles" and build a community that is able to achieve food self-sufficiency. VF spaces within buildings become a place for building occupants to learn about farming and related activities, thus enhancing community resilience and promoting shared responsibility towards the environment. In addition, the participation of building occupants in farming activities and commercial activities related to the sale of produce has a profound impact on enhancing a sense of place, which is one of the most important principles of BD(Kues & Niemann, 2004; Shahda & Megahed, 2023; Yari, 2019).
Integrating natural ecosystems with architectural design	VF systems encourage architects to design buildings that adapt to natural cycles, incorporating elements such as seasonal changes in plant life or natural sunlight. This design approach is the basis for achieving the principles of BD, which aims to harmonize the BE with natural systems(Gorman, 2019; Shahda et al., 2018; Sharma & Shyam, 2023; Van Den Berg & Custers, 2011; Yari, 2019).

Weaknesses	
High initial investment cost	The high initial cost of equipment and advanced technology needed to integrate VF systems into buildings may prevent their widespread adoption. Therefore, it will not be a reliable catalyst to boost BD if the implementation cost is unavailable(Tablada et al., 2020; Tablada & Kosorić, 2022).
Technical expertise and maintenance requirements	Lack of expertise and knowledge of VF systems maintenance techniques and methods in buildings can limit the idea of integrating VF into buildings and will not be a reliable catalyst to support BD (Shahda & Megahed, 2023).
Opportunities	
Producing multi-sensory experiences	BD elements such as plants, their colors and shapes, the movement of air and water, the diversity of insects and birds, and the dynamic shadow patterns created by daylight reflections on plants- are the same elements of VF systems, and therefore the integration of these elements into the BE can be wonderful opportunities to produce multi-sensory experiences such as distinctive experiences of nature and enhance the connection to place (Gorman, 2019; Kellert, 2016; Sharma & Shyam, 2023; Van Den Berg & Custers, 2011; Yari, 2019).
Visual accessibility	The accessibility of VF space in buildings is a distinctive and attractive feature, creating scenes that mimic the mystery and dangers of the natural environment to enhance the connection to place (Gorman, 2019; Kues & Niemann, 2004; Shahda, 2024; Van Den Berg & Custers, 2011; Yari, 2019).
Wellness programs	VF can be included in wellness programs in public areas, workplaces, and residential buildings. By promoting healthier, greener surroundings, these programs can increase the attractiveness of properties (Kues & Niemann, 2004; Milligan & Bingley, 2007; Van Den Berg & Custers, 2011; Yari, 2019).
Confronting the separation of the population from nature	As the urban population outnumbers the rural population, cities face challenges related to the separation of people from nature, which may affect their physical and psychological health and performance. Therefore, integrating VF into buildings in urban areas is an opportunity to support HNC and thus enhance BD.
Sustainable development goals	Implementing the idea of integrating VF into buildings represents an opportunity to achieve many of the 17 sustainable development goals (Wijesooriya & Brambilla, 2021).
Threats	
Biophobia	Some people suffer from a fear of nature and wildlife (Biophobia), and this may pose a threat to the spread of the idea of integrating VF into buildings in order to achieve HNC and thus promote BD (White & Heerwagen, 1998).
Energy Demands and Potential for Technical Failures	The increasing energy requirements for indoor environmental control as well as the risk of technical failures in integrating VF into buildings may threaten the expansion of the idea of integrating VF into buildings to promote BD(Jenkins et al., 2014).
Return on Investment Concerns	It is difficult to predict whether VF integration projects in buildings that aim to promote BD will achieve economic feasibility, which could threaten the idea's expansion.
Laws and regulations	Building use regulations and safety standards can limit the ability to convert parts of buildings into farms. There may be a lack of supportive policies, which affects the possibility of expanding the use of VF systems in buildings.

Conclusions

The main contribution of this study is to investigate the extent to which VF is a catalyst for enhancing BD in the BE. Whereas BD focuses on HNC in the BE through architectural designs for indoor and outdoor environments, VF provides an innovative way to integrate green spaces and related activities into the BE in a practical, productive, efficient, and aesthetic way that enhances HNC thus supports the goals of BD. Therefore, the study summarized the goals of BD through a literature review, analyzed VF systems, and concluded the elements of nature that make up each system, which by bringing them into buildings can support the HNC and thus enhance the BD. The study also analyzed several examples of integrating VF into buildings and its relationship to BD goals. In addition, the term "Vertical Farming (VF) -Based Biophilic Buildings" has been coined as a result of the sequence in the study methodology. Finally, the study presented a SWOT analysis of VF-Based Biophilic Buildings.

However, the study's scope was limited by the set of projects analyzed and the BD goals derived from previous studies. Consequently, future research should focus on testing the extent to which VF contributes to each of the BD goals through experimental and numerical studies, as well as addressing the logistical and technological challenges associated with Vertical Farming (VF)-Based Biophilic Buildings. According to the study's conclusions, integrating VF into urban areas leads to harmonious environments where nature and BE coexist. In addition to improving air quality and the well-being of residents, this approach enhances biodiversity and residents' participation in natural processes. Combining VF and BD could result in Vertical Farming (VF)-Based Biophilic Buildings that are not only sustainable and resilient to environmental changes but also beneficial to human psychological and physical health as urban populations rise.

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