INTEGRATING BIOPHILIC DESIGN IN AGRICULTURAL RESEARCH CENTERS FOR ENHANCING ENVIRONMENTAL QUALITY

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ABSTRACT

Agricultural research centers are increasingly important in supporting agricultural innovation, particularly in regions where agricultural production is closely related to local economic and environmental systems. However, research facilities are commonly discussed in terms of functional requirements, while the integration of biophilic design principles into agricultural research facilities remains insufficiently explored. Previous studies have demonstrated that biophilic strategies can improve spatial and indoor environmental quality through natural light, ventilation, vegetation, and connections with nature, but their application to agricultural research center design remains limited. This study aims to examine how biophilic design principles can be operationalized in the design of an agricultural research center through a design-based research approach. Data were collected through literature review, regulatory analysis, and site analysis, followed by design analysis, synthesis, and qualitative evaluation using four design variables: visual connection with nature, natural ventilation, inner courtyards, and thermal comfort. The findings indicate that integrating these variables into site planning, zoning, building massing, and spatial configuration can strengthen the potential for natural lighting, ventilation, thermal stability, and spatial quality. The study proposes a context-specific framework for integrating biophilic principles into agricultural research center design.

Keywords: agricultural research center, biophilic architecture, design-based research, indoor environmental quality, thermal comfort

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1. INTRODUCTION

The agricultural sector plays a strategic role in supporting national food security and regional economic growth, particularly in agrarian areas such as Indramayu Regency. The predominance of rice paddies indicates that this sector serves as the primary foundation of economic activity; however, in recent years, a decline in productivity has occurred, suggesting underlying issues within the agricultural management system. This situation calls for an innovative approach that is not only technical but also spatial and architectural. The transformation toward an innovation- and technology-based agricultural system, as outlined in the Agriculture 5.0 concept, emphasizes the importance of integrating production systems, data, and supporting infrastructure, including research facilities [1]. The development of agricultural research centers is one strategy for supporting the agricultural innovation system through the integration of research, education, and technology development. Within the framework of the innovation system, research institutions play a crucial role in promoting knowledge transfer and the development of adaptive technologies [2], [3]. Furthermore, the presence of well-planned

research facilities contributes to the effectiveness of scientific activities and the quality of research outputs [4], [5]. Therefore, the design of agricultural research centers must consider the quality of the spatial environment as a factor supporting scientific activities.

The biophilic architecture approach is relevant in this context because it emphasizes the integration of humans and nature within the built environment. This concept is based on the theory of biophilia, which states that humans have an innate tendency to connect with nature [6]. Expanded this concept into 14 design patterns that can be applied in architecture to enhance the quality of the built environment [7]. Further studies indicate that the integration of natural elements into design not only improves spatial quality but also contributes to health, comfort, and the sustainability of the built environment [8], [9].

Recent studies indicate that biophilic design can contribute to indoor environmental quality through the integration of natural lighting, ventilation, vegetation, visual connections, and other natural elements. Some studies demonstrate the relevance of biophilic design in establishing sustainable interaction between people and the built environment [8], while another studies emphasize the integration of three-dimensional green spaces as part of contemporary biophilic and sustainable design [10]. Further demonstrates the relevance of quantitative and environmental approaches in evaluating indoor environmental quality [11], while highlight the relationship between environmental conditions and occupants' environmental experience [12]. Two studies also indicate that biophilic strategies can be adapted to different building contexts [9], [13]. However, these studies predominantly address commercial, hospitality, healthcare, residential, or general institutional environments, leaving the application of biophilic principles to agricultural research facilities relatively underexplored. The relationship between the fundamental principles of biophilic architecture and their application in the built environment is illustrated in Figure 1, which provides a conceptual basis for translating biophilic principles into architectural design strategies.

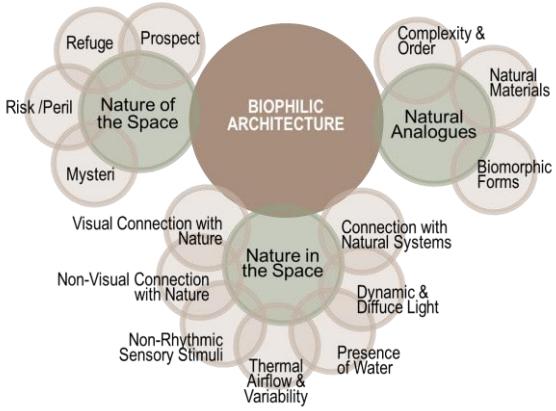

Figure 1. Conceptual Framework of Biophilic Architecture and Its Application in Architectural Design

The research problem addressed in this study is the absence of a context-specific design framework that translates biophilic principles into spatial and environmental strategies for agricultural research centers. Although agricultural research facilities require laboratories, experimental spaces, offices, learning facilities, and supporting functions, their architectural configuration is rarely discussed in relation to systematic biophilic design variables and indoor environmental quality. The problem is therefore not simply whether biophilic elements can be incorporated into an agricultural research building, but how these principles can be translated into architectural decisions concerning site orientation, spatial zoning, building configuration, natural ventilation, visual connections, inner courtyards, and thermal comfort. Addressing this problem requires an architectural research approach in which design functions as both an outcome and an instrument for testing the relationship between theoretical principles and spatial strategies. The novelty of this study lies in the operationalization of the 14 Patterns of Biophilic Design into four design variables, namely visual connection with nature, natural ventilation, inner courtyards, and thermal comfort, and their application within the specific typology of an agricultural research center. Unlike studies that primarily examine biophilic design in

commercial, residential, healthcare, or general institutional buildings, this study positions the agricultural research center as a specific architectural typology and investigates how its agrarian context can become an integral component of the biophilic design strategy. The study therefore contributes a context-specific design framework that connects site conditions, spatial programming, zoning, and biophilic strategies with indoor environmental quality. The selection of these variables is based on their alignment with biophilic design principles [7] as well as empirical evidence demonstrating their contribution to indoor environmental quality [10], [11]. Therefore, this study aims to examine how biophilic design principles can be operationalized into architectural design strategies for an agricultural research center through four variables, namely visual connection with nature, natural ventilation, inner courtyards, and thermal comfort, and to evaluate their contribution to indoor environmental quality.

2. RESEARCH METHODOLOGY

This study employs an architectural design research approach using design-based research to develop a proposed agricultural research center based on biophilic architectural principles. The study focuses on designing a new agricultural research center rather than evaluating an existing agricultural research building. The architectural design process is positioned as both a research instrument and a design outcome for investigating how theoretical principles can be translated into spatial and environmental strategies. This approach is appropriate because architectural research involves an iterative relationship between theoretical exploration, contextual analysis, design development, and evaluation. [14], [15], and [16] emphasize the integration of analytical and design processes in architectural research, while studies concerning research and laboratory facilities highlight the relationship between functional requirements, spatial organization, environmental considerations, and architectural design [4], [17]. Therefore, the design process in this study is not treated merely as the final product but as a structured research process for examining the application of biophilic principles within the specific typology of an agricultural research center.

The research was conducted through four interconnected stages: data collection and contextual exploration, design analysis and formulation of research variables, design synthesis and development, and design evaluation. Data were collected through literature review, regulatory analysis, and site analysis. The literature review examined biophilic architecture, indoor environmental quality, and the 14 Patterns of Biophilic Design as the theoretical basis for developing the research variables [7], [10], [12]. Regulatory analysis referred to National Research and Innovation Agency Regulation No. 11 of 2025 concerning the duties, functions, and organizational structure of agricultural and food research organizations to identify the functional requirements of the proposed agricultural research center [18]. Site analysis examined solar orientation, prevailing wind direction, rainfall, accessibility, views, existing vegetation, noise, surrounding land use, and other physical characteristics of the proposed site. The collected data were subsequently used to identify contextual opportunities and constraints and to establish architectural requirements for the design process.

The design analysis translated the theoretical and contextual findings into architectural requirements and four research variables: visual connection with nature, natural ventilation, inner courtyards, and thermal comfort. These variables were formulated as operational dimensions connecting the 14 Patterns of Biophilic Design with architectural decisions and indoor environmental quality [7], [10], [11], [12]. The subsequent design synthesis translated these variables into the spatial program, activity relationships, horizontal and vertical zoning, building orientation, circulation, building massing, open-space configuration, vegetation, and natural environmental strategies. The design development was conducted iteratively by relating site conditions and functional requirements to biophilic strategies. This process follows the architectural research approach in which design exploration provides a means of testing relationships between theoretical concepts, contextual evidence, and design propositions [14], [15], [16]. The resulting proposal therefore represents a research-based architectural response rather than solely a formal or aesthetic design exercise.

The final stage evaluated the proposed design qualitatively according to the four research variables. Visual connection with nature was examined through building orientation, openings, views, and relationships with the surrounding agricultural landscape. Natural ventilation was analyzed through building orientation, openings, spatial permeability, and the potential for cross-ventilation, while inner courtyards were examined as spatial elements connecting indoor spaces with vegetation, daylight, air movement, and outdoor views. Thermal comfort was assessed qualitatively through the relationship between solar exposure, shading, vegetation, natural ventilation, building massing, and spatial configuration. The evaluation examined the consistency between the proposed architectural strategies and the established biophilic variables rather than claiming quantitative measurement of environmental performance. The relationship between natural elements, spatial configuration, and indoor environmental quality is supported by previous studies [10], [11], [12]. Through these stages, the research establishes a traceable relationship between theoretical principles, contextual evidence, design variables, architectural intervention, and design evaluation, providing a basis for examining how biophilic design can contribute to the environmental and spatial quality of an agricultural research center.

3. RESULT AND DISCUSSION

3.1 Site conditions and their impact on design

The site for the agricultural research center is located in the agricultural region of Indramayu Regency, which is dominated by active rice fields. The open landscape with a wide visual horizon offers strong potential for establishing visual connections between the building and its surroundings (Figure 2). This condition forms the basis for the application of the "visual connection with nature" principle, where the building's orientation is designed to maximize views toward the surrounding agricultural fields and green open spaces.

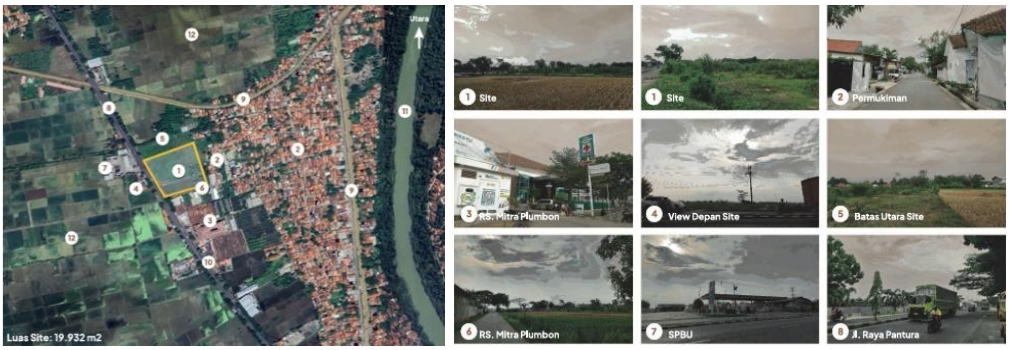

Figure 2. Site Condition & Surounding

Climate analysis indicates that the east–west solar orientation significantly influences lighting and heat control strategies. Openings on the east side are utilized to capture natural light in the morning, while the west side is controlled through the use of shading and vegetation to reduce excessive heat radiation. Additionally, the prevailing wind direction from the rice fields is utilized as the basis for implementing cross-ventilation strategies. Site conditions also reveal the presence of existing vegetation that serves as an ecological element. Vegetation is utilized as shade, a wind deflector, and a buffer against noise. Thus, the site conditions are not merely a physical backdrop but an integral part of the biophilic design strategy aimed at enhancing the environmental quality of the space. Figure 3 presents the results of the site analysis, which includes aspects of solar path, wind direction, rainfall, accessibility, views, vegetation, noise, zoning, and building massing.

This analysis was conducted to identify the site's potential and constraints that directly influence design decisions. The results of the analysis indicate that the east–west solar orientation requires a strategy for controlling solar radiation through shading and vegetation, while the prevailing wind direction is utilized to support natural ventilation. Additionally, the view and vegetation analysis reveals significant potential for applying the principle of visual connection with the surrounding agricultural landscape. Thus, the site analysis is not merely

descriptive but serves as the foundation for formulating an adaptive design response grounded in biophilic principles.

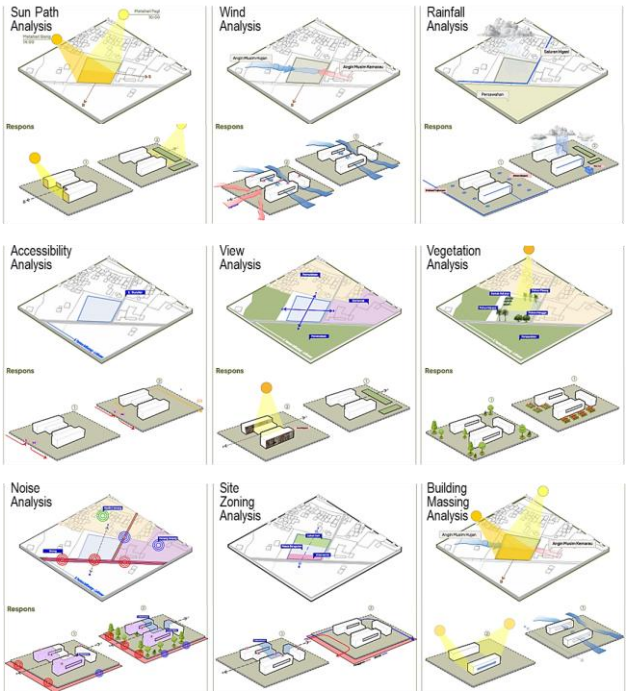

Figure 3. Site Analysis Diagram and Its Implications for Building Design

3.2 Space programming, activity, and zoning in design

The spatial program for the design of an agricultural research center is based on an activity analysis that encompasses research, education, administration, and support functions. Research activities constitute the primary function, accommodated through laboratories, researcher offices, and agricultural experimental facilities. The educational function is realized through training rooms and exhibition spaces as vehicles for knowledge dissemination. This structure aligns with the concept of research facilities that emphasize the integration of experimental spaces, workspaces, and learning spaces into a single system [4], [5], [17], [18]. Figure 4 illustrates the spatial program classification based on activity groups within the agricultural research center, comprising the research activity group, administrative activity group, supporting research activity group, and service activity group. This division indicates that the spatial program structure is systematically designed to comprehensively accommodate all research activities, ranging from core activities to supporting activities. This approach aligns with the concept of research facility planning that emphasizes the integration of functions within a single organized spatial system [4], [17]. Furthermore, this grouping of activities also supports operational efficiency and clarity of workflow within the research building [4], [17]. Thus, the spatial program structure is not only functional but also serves as the foundation for the formation of an effective spatial organization.

The spaces are organized hierarchically based on accessibility levels and functional needs. Public zones are placed in the front areas to facilitate access, while semi-public and private zones are placed further inside to maintain security and ensure concentration on research activities. Service zones are separated to support the building's operational efficiency. This approach aligns with the principles of spatial organization in complex buildings described by [4] and reinforced in studies of engineering education facilities [4], [17].

The spatial program in the design of the agricultural research center is further translated into vertical and horizontal zoning configurations. Vertical zoning illustrates the distribution of functions based on privacy levels and inter-floor relationships, where public functions are placed on the ground floor, while more private research functions are situated on upper floors. This approach aims to maintain spatial hierarchy while supporting the security and comfort of

research activities. Meanwhile, horizontal zoning illustrates the grouping of spaces based on functional proximity and spatial relationships between zones, with green open spaces serving as central elements connecting the building's various functions. This strategy aligns with spatial organization principles that emphasize functional integration and efficient spatial relationships [4].

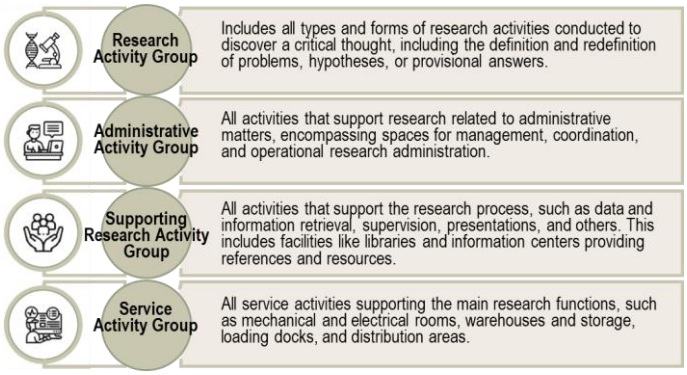

Figure 4. Spatial Program Classification Based on Activity Groups

This zoning configuration takes into account not only function but also the connection to biophilic elements. Each zone is designed to have access to natural light, ventilation, and visual connections to open spaces. This demonstrates that spatial organization directly contributes to the quality of the indoor environment, as confirmed by various studies on built environment design [8], [10], [11], [12]. Furthermore, the integration of open spaces into the zoning system reinforces the application of biophilic principles at the scale of spatial organization, rather than merely in individual architectural elements. Thus, zoning serves as a strategic tool for connecting function, spatial experience, and environmental quality in the design of an agricultural research center.

3.3 The Concept of Biophilic Architecture in Design

The concept of biophilic architecture in this design was developed based on the 14 Patterns of Biophilic Design, adapted to the context of an agricultural research center [7]. The application of these fourteen biophilic patterns, integrated into the design, serves as a strategy for comprehensively improving the quality of the built environment. In various studies, the application of biophilic principles has been shown to improve spatial quality and the experience of space through the systematic integration of natural elements [6], [8]. Furthermore, this approach is also positioned as a sustainable design strategy that simultaneously connects ecological aspects with spatial comfort [9], [11].

In the "Nature in the Space" aspect, implementation is achieved through the use of vegetation, large openings, and inner courtyards that allow natural light and air to enter. This strategy strengthens the visual and physical connection between interior spaces and the outdoor environment, which has been shown to enhance the quality of the indoor environment and user comfort [6], [13]. Empirical studies show that the direct presence of natural elements within a space can significantly improve natural lighting quality, air quality, and the perceived comfort of the space [11], [12]. Thus, the application of "Nature in the Space" elements is not merely aesthetic but also serves as a strategy to enhance the environmental performance of the space. Regarding Natural Analogues, the use of natural materials and biomorphic forms is employed to create a spatial quality that is more contextual and responsive to the environment. This approach aligns with biomimetic concepts in design, which emphasize the adaptation of natural forms and systems in architecture [19]. The use of analogies to natural forms and materials has been shown to strengthen the perception of closeness to nature and enhance the quality of users' spatial experiences [8], [9]. Furthermore, this approach also supports a more contextual integration of design with the character of the local environment.

In terms of the Nature of the Space, the spatial configuration is designed to provide experiences of openness and shelter through a combination of open and sheltered spaces. This concept has been shown to enhance the quality of the spatial experience and users' visual orientation in various biophilic studies [7], [20]. Spatial arrangements that strike a balance between openness and shelter also contribute to psychological comfort and the building's spatial quality [6], [11]. Thus, the spatial configuration serves not only a functional purpose but also as a strategy for creating a more adaptive spatial experience.

Thus, the biophilic concept in this design is not applied in isolation but as an integrated design system. To clarify the relationship between biophilic theory and the research variables used, fourteen biophilic design patterns were mapped onto four main variables: visual connection with nature, natural ventilation, inner courtyards, and thermal comfort. This mapping demonstrates that each variable serves as an operational representation of several interrelated biophilic patterns that collectively shape the quality of the built environment. Visual connection with nature encompasses patterns related to visual relationships and light dynamics, while natural ventilation encompasses patterns related to airflow and non-visual sensory stimuli. The inner courtyard variable represents spatial configurations that support spatial experience, whereas thermal comfort is enhanced through the integration of natural materials, biomorphic forms, as well as spatial complexity and regularity. Thus, this mapping serves as a conceptual foundation for linking biophilic theory with design analysis in subsequent stages (Figure 5).

Figure 5. Mapping of 14 Biophilic Design Patterns into Research Variables and Design Principles

3.4 Analysis of visual connections, natural ventilation, inner courtyards, and thermal comfort

Based on the mapping in Figure 5, the following analysis focuses on four main variables that represent the application of biophilic principles in design. The visual connection analysis indicates that the building's orientation and the configuration of its openings are designed to maximize visual connections with the agricultural landscape. This strategy aligns with the principle of visual connection in biophilic design, which contributes to enhancing the quality of the built environment [6], [7], [11]. In various studies, visual connectivity with natural elements has been shown to improve spatial quality and users' perception of comfort through more open

and contextual visual experiences [8], [9]. Furthermore, visual integration with the landscape also plays a role in reinforcing spatial orientation and clarifying the relationship between indoor and outdoor spaces in a sustainable manner [11]. Thus, the application of visual connection serves not only as an aesthetic element but as a key strategy in enhancing the quality of the built environment.

Natural ventilation is implemented through a cross-ventilation strategy that takes advantage of prevailing wind directions. The building's non-massive configuration and the use of voids allow for optimal airflow. This approach aligns with the concept of thermal and airflow variability in biophilic design, which passively enhances thermal comfort [10], [12]. Research shows that well-designed natural ventilation can improve indoor air quality and reduce reliance on mechanical systems [8], [11]. Additionally, this strategy supports energy efficiency and building sustainability through the optimal utilization of environmental potential. Thus, natural ventilation becomes a key variable in shaping the thermal and environmental quality of a space.

The integration of vegetation into the building and site design is illustrated in Figure 6, which shows the relationship between the proposed building mass and the surrounding landscape vegetation. The vegetation strategy incorporates several plant types, including Platycladus orientalis (cemara kipas), Ixora coccinea (asoka merah), Samanea saman (trembesi), palm species, Terminalia mantaly (ketapang kencana), and Mangifera indica (mango). These vegetation elements are distributed around the building and open spaces to establish visual connections with nature, provide shading, and strengthen the relationship between the building and its surrounding landscape. Thus, vegetation is treated as an integrated component of the biophilic design strategy rather than merely as a decorative landscape element.

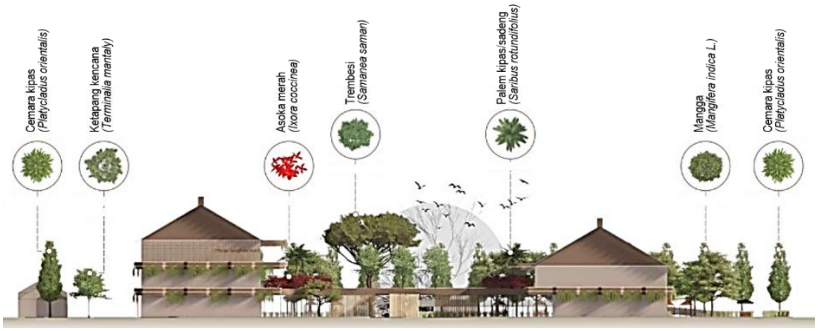

Figure 6. Building and Landscape Vegetation Design of the Agricultural Research Center

The use of an inner courtyard serves as a key element in integrating natural elements into the building. The inner courtyard functions as a source of natural light and ventilation, as well as an internal green space that simultaneously enhances the quality of the indoor environment. This concept has been widely adopted in tropical building design and has been shown to significantly improve the quality of the indoor environment [11], [21]. Other studies indicate that the presence of internal open spaces such as innercourts can improve the distribution of natural light and enhance air circulation within a building [11], [12]. Additionally, the innercourt functions as a transitional space that strengthens spatial connections between rooms. Thus, the innercourt serves as an integrative element in biophilic design strategies.

Thermal comfort is achieved through a combination of passive strategies, such as building orientation, the use of vegetation, and solar radiation control. This approach supports energy efficiency and improves the overall quality of the indoor environment. These findings are consistent with previous research showing that the integration of natural elements can enhance indoor environmental performance [10], [11], [12]. Furthermore, passive approaches in thermal design have also proven capable of creating more stable indoor conditions that are adaptive to changes in the microclimate [8], [11]. These strategies directly strengthen the relationship between architectural design and a building's environmental performance. Thus, thermal comfort is achieved not only through technology but through design integration that is responsive to the environment.

3.5 Sintesis

The synthesis indicates that biophilic variables do not operate in isolation but interact with one another to form an adaptive and integrated spatial system. Visual connection with nature plays a role in establishing spatial quality through visual links with the landscape, which reinforces spatial orientation and the user's visual experience. Natural ventilation enhances air quality and thermal comfort by optimizing natural airflow that responds to site conditions. Meanwhile, the inner courtyard serves as an integrative element that connects lighting, ventilation, and vegetation within a single sustainable spatial system. The integration of these three variables demonstrates that the quality of the built environment is shaped through the synergy of design strategies, not through the application of individual elements [7], [11].

The interaction among these variables indicates that the application of biophilic principles results in a comprehensive and measurable improvement in indoor environmental quality. Optimal natural lighting, effective ventilation, and an open, contextually responsive spatial quality are the result of the integration of systematic design strategies. Empirical studies show that the combination of visual, thermal, and ecological elements in design can significantly improve indoor environmental quality [10], [12]. Furthermore, this integration also contributes to energy efficiency and building sustainability through the optimal utilization of environmental potential [8], [11]. Thus, indoor environmental quality is not determined by a single variable, but by the dynamic relationships among these variables.

These findings reinforce the results of previous studies indicating that a biophilic approach can enhance the environmental quality of spaces through the integration of natural elements into design [6], [8], [11]. Other studies also show that the systematic application of biophilic principles can improve spatial quality, thermal comfort, and the user experience within built environments [9], [13]. This indicates that the biophilic approach holds strong relevance within the context of contemporary architectural design focused on environmental quality. Thus, the application of biophilic architectural principles in the design of an agricultural research center has proven capable of addressing research challenges while validating the formulated hypotheses. These findings also confirm that the integration of biophilic variables is an effective strategy for improving the environmental quality of spaces in research building typologies.

4. CONCLUSION AND RECOMMENDATIONS

Based on the results of the analysis and discussion, it can be concluded that the application of biophilic principles through the variables of visual connection with nature, natural ventilation, inner courtyards, and thermal comfort can significantly improve indoor environmental quality. The site's agrarian character is optimally utilized to support the design strategy, particularly in establishing visual connections with the landscape and leveraging the potential for natural ventilation. The spatial program and zoning are systematically designed to support the integration of research functions with an adaptive indoor environmental quality.

The application of biophilic concepts at the site and building scales demonstrates that the integration of natural elements serves not only as an aesthetic element but as a primary strategy in shaping spatial quality and environmental comfort. Analysis of design variables indicates that visual connections, natural ventilation, and the use of inner courtyards make a tangible contribution to improving natural lighting, air quality, and thermal stability within the spaces.

Thus, the research hypothesis stating that the application of biophilic architecture principles in the design of agricultural research centers can improve the quality of the indoor environment has been proven. This study contributes to the development of operational and context-specific biophilic design approaches for agricultural research facilities.

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