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# Evaluation of the Kahramanmaraş Sütçü İmam University Garden Landscape Design in the EXPO 2023 Onikişubat/Kahramanmaraş Country Gardens Area in Terms of Implementation and Post-EXPO Use

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**Abstract**

*This study was carried out to evaluate the country gardens area created within the scope of EXPO 2023 Onikişubat/Kahramanmaraş (EXPO 2023), specifically focusing on the Kahramanmaraş Sütçü İmam University (KSU) garden. First, the landscape design and implementation process of the area were examined, and then the current use status of the site was evaluated through field observations conducted in 2025 and 2026. Within the scope of the field studies, the use status, maintenance level, structural elements, and plant materials of the area were examined and documented through site photographs. The findings showed that the general EXPO area is actively used, while the country gardens section remains idle in terms of use, maintenance, and management. Most structural elements remained in place, although partial deterioration was observed, while planted areas deteriorated due to insufficient maintenance. As a result of the study, it was revealed that post-event use and maintenance processes are important for the sustainability of EXPO areas.*

***Keywords:*** *EXPO 2023, Country Gardens, Landscape Design, Post-Use Evaluation, KSU.*

# EXPO 2023 Onikişubat/Kahramanmaraş Ülke Bahçeleri Alanında Kahramanmaraş Sütçü İmam Üniversitesi Bahçesi Peyzaj Tasarımının Uygulama ve EXPO Sonrası Kullanım Açısından Değerlendirilmesi

**Öz**

*Bu çalışma, EXPO 2023 Onikişubat/Kahramanmaraş (EXPO 2023) kapsamında oluşturulan ülke bahçeleri alanını, Kahramanmaraş Sütçü İmam Üniversitesi (KSÜ) bahçesi özelinde değerlendirmek amacıyla gerçekleştirilmiştir. Çalışmada, öncelikle alanda uygulanan peyzaj tasarımı ve uygulama süreci incelenmiş, ardından 2025 ve 2026 yıllarında gerçekleştirilen arazi gözlemleri ile alanın mevcut kullanım durumu değerlendirilmiştir. Arazi çalışmaları kapsamında alanın kullanım durumu, bakım düzeyi, yapısal ve bitkisel elemanlar incelenmiş ve saha fotoğrafları ile belgelenmiştir. Elde edilen bulgular, EXPO alanının genel olarak aktif kullanıldığını, ancak ülke bahçeleri bölümünün kullanım, bakım ve yönetim açısından atıl kaldığını göstermiştir. Yapısal elemanların büyük bölümü yerinde kalmış olmakla birlikte kısmi bozulmaların bulunduğu, bitkisel alanlarda ise bakım eksikliğine bağlı bozulmaların oluştuğu belirlenmiştir. Çalışma sonucunda, EXPO alanlarının sürdürülebilirliğinde etkinlik sonrası kullanım ve bakım süreçlerinin önemli olduğu ortaya konulmuştur.*

***Anahtar kelimeler:*** *EXPO 2023, Ülke Bahçeleri, Peyzaj Tasarımı, Kullanım Sonrası Değerlendirme, KSÜ.*

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## 1. Introduction

EXPOs are large-scale international events that attract broad audiences. They stimulate economic activity in host cities, promote cultural values, and support the development and reorganization of urban spaces. They also provide a platform for countries to present their scientific, technological, and cultural achievements and facilitate knowledge exchange among societies (Kaya & Erbaş, 2022; Nichols, 1966). Horticultural EXPOs contribute to landscape architecture by supporting the development of urban green spaces and presenting landscape approaches shaped by different cultural traditions.

Although EXPOs are temporary events, they are generally expected to produce lasting effects on their host cities. The concept of "event legacy" refers to the physical and social assets that remain after an event has ended (Moggi et al., 2025). The continuity of these assets depends on effective planning, maintenance, and management. A major concern is whether the spaces developed for mega-events remain functional after the event period (Deng et al., 2016). Previous studies have shown that EXPO sites may lose their intended functions over time and fail to achieve their planned post-event use. Despite their role in promoting urban development, their subsequent use and spatial transformation often remain below initial expectations (Minner et al., 2022). Post-event use and management therefore need to be incorporated into EXPO planning from the outset.

Country gardens are designed to represent the cultural identity and spatial traditions of participating countries. They allow countries to express their identity through landscape design and provide visitors with opportunities to experience different landscape concepts (Koch, 2024). In addition to their exhibition function, these gardens may contribute to the provision of public open spaces and the transformation of urban environments (Ballester, 2014).

The long-term use of gardens and landscape areas developed for EXPOs requires design decisions that account for post-event maintenance and management. A country gardens zone containing gardens associated with different countries was established as part of EXPO 2023 Onikişubat/Kahramanmaraş. This study evaluates this zone, with particular emphasis on the Kahramanmaraş Sütçü İmam University (KSU) garden, according to its design, implementation, and post-EXPO use. The landscape design and implementation stages were examined, and field observations were conducted in 2025 and 2026 to assess the current condition of the site. The assessment focused on current use, maintenance practices, and the condition of built and plant components. The findings were used to determine how design and implementation decisions affected the subsequent use and maintenance of the garden.

## 2. Material and Method

### 2.1. Material

The study area is located in the country gardens section of the EXPO 2023 site in Onikişubat district, Kahramanmaraş. The EXPO site is located approximately 15 km west of the city centre along the Kayseri highway. It lies near the Ceyhan River, Sır Dam, Kılavuzlu Dam, Menzelet Dam, and the Kılavuzlu recreation area. The Kahramanmaraş Organized Industrial Zone is located west of the site.

The EXPO 2023 site covers approximately 789,000 m². The country gardens section covers approximately 170,000 m² and contains plots ranging from 250 to 1,000 m². The KSU garden occupies one of these plots and covers 354.45 m². Figure 1 shows the general location of the study area, and Figure 2 shows the boundaries of the KSU garden.

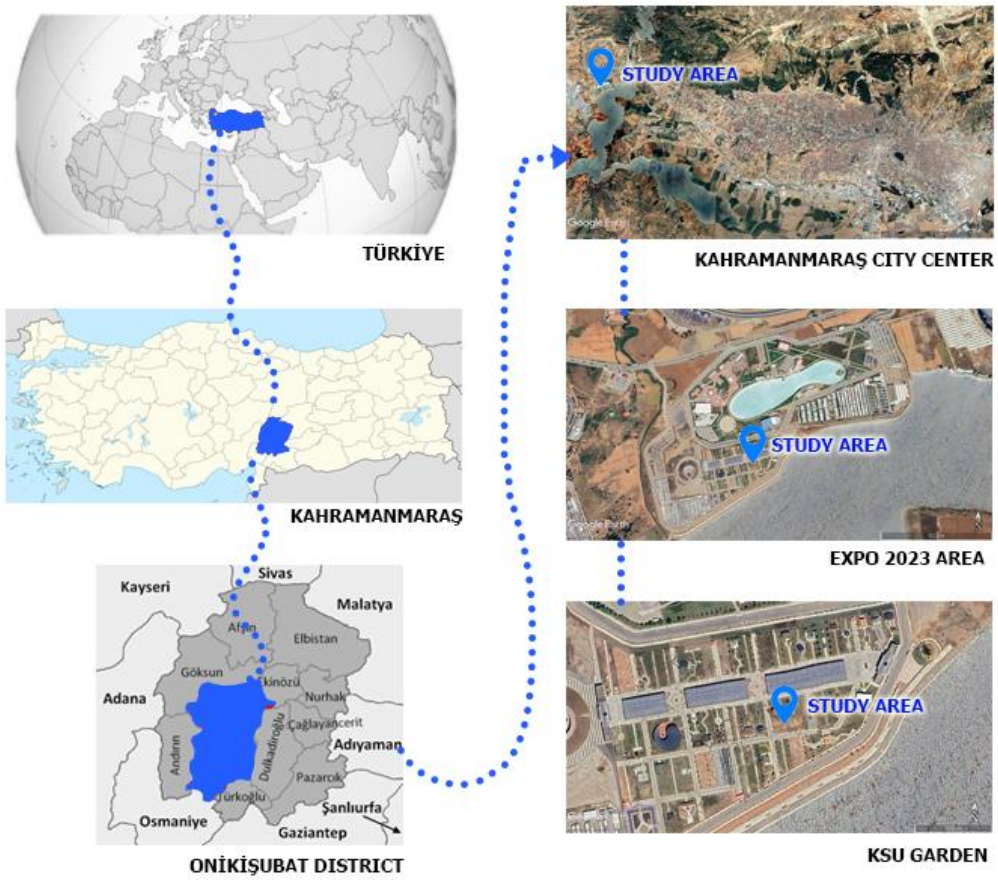



**Figure 1.** Location of the study area (adapted by the author using Google Earth (2026), D-maps (n.d.))




**Figure 2.** Study area boundary (adapted by the author using Google Earth (2026))

## 2.2. Method

The study evaluated the design, implementation, and post-EXPO use of the country gardens section, with the KSU garden selected for detailed assessment. An initial field observation was conducted immediately after the opening of EXPO 2023 in October 2023 to document the implemented condition of the garden. Subsequent field observations were conducted in May 2025, October 2025, and May 2026 to assess changes in use, maintenance, and physical condition over time.

The implemented landscape design was examined according to its spatial organization, circulation system, site furniture, structural components, and planting arrangement. The condition recorded immediately after the opening was compared with the final design project to identify preserved,

modified, and omitted design decisions. Later observations were compared with the post-opening condition to determine changes occurring during the post-EXPO period.

The current condition of the site was assessed under eight categories: general use, accessibility, urban furniture, structural components, infrastructure, trees and shrubs, lawn areas, and groundcover plants. Each category was evaluated through field observations and photographic documentation.

A three-point scale was used to classify the condition of each category. Components that had lost their function were assigned a score of 1, partially deteriorated components were assigned a score of 2, and preserved components were assigned a score of 3. To ensure consistency, the same category definitions and scoring criteria were applied during all field visits, and the assessments were cross-checked using dated field photographs and field notes.

## 3. Findings and Discussion

The assessment covered the implemented landscape design, changes made during construction, post-EXPO use, maintenance, built components, and vegetation condition of the KSU garden.

### 3.1. KSU garden landscape design and post-implementation status

The landscape design project for the KSU garden was prepared by Tuğluer & Kısakürek (2023). The project was revised several times during the design stage. The 6 February 2023 Kahramanmaraş earthquakes delayed the opening of EXPO 2023 and created uncertainty regarding the implementation schedule. After the opening date was announced as 14 October 2023, the project was simplified to accommodate the limited construction period.

The final project included a reception area representing the university at the entrance and a main circulation axis extending through the centre of the garden. Seating areas and site furniture were positioned around this axis. Andesite and concrete paving materials formed the main hard surfaces, while planting areas defined the spatial boundaries.

The main axis organized pedestrian circulation and connected the different sections of the garden. Trees, shrubs, lawn areas, and groundcover plants were combined to form the planting composition. Figure 3 presents the revised landscape design project, and Figure 4 presents the dimensioned plan.



**Figure 3.** EXPO 2023, KSU garden: Revised landscape design project following the February 6, 2023 Kahramanmaraş earthquakes (Tuğluer & Kısakürek, 2023)

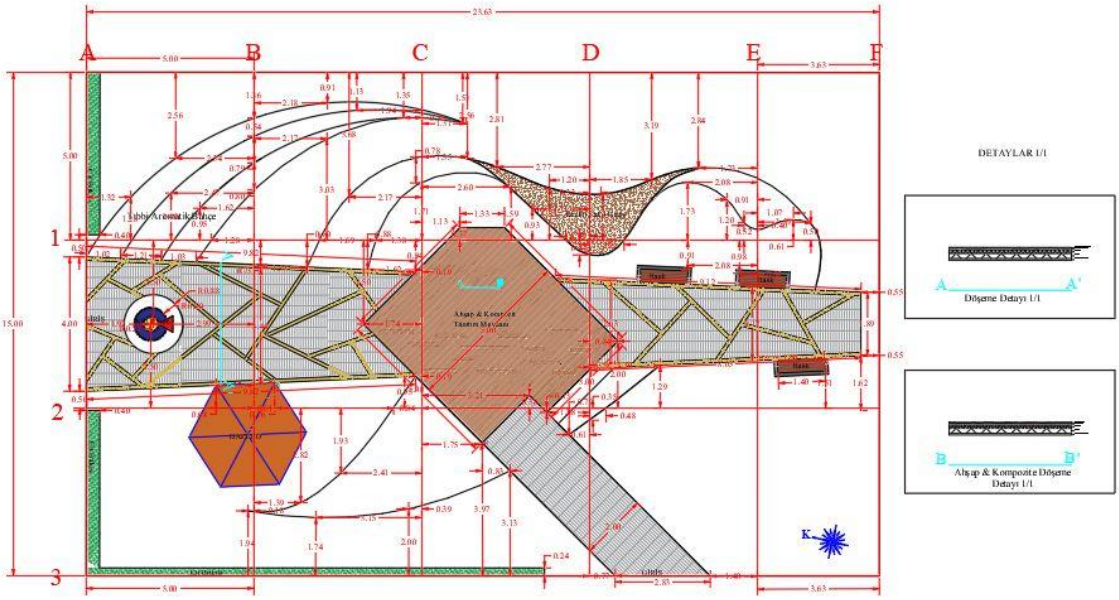



**Figure 4.** EXPO 2023, KSU garden landscape design project, dimensioned plan (Tuğluer & Kısakürek, 2023)

The implementation largely preserved the main design concept. The central axis and general spatial organization were maintained. However, the connection path planned for the adjacent plot was omitted because a connection between the two plots could not be established.

Surface patterns were created by varying the spacing and orientation of the paving units. Plant materials were supplied from the inventories of the KSU Construction Works Department and Onikişubat Municipality. The boundaries of the planting areas were preserved, but the number and diversity of plants were lower than those specified in the original design (Figure 5).



**Figure 5.** Post-opening images of the EXPO 2023 KSU garden (Tuğluer, 2023)

### 3.2. Evaluation of The Current Status of The Area

Field observations conducted in 2025 and 2026 revealed that while the EXPO area was generally actively used, the country gardens section remained idle and not actively utilized. It was observed that there was no security or control at the entrance to the country gardens, and the shuttle vehicles at the entrance were parked and left unused. Similarly, the KSU garden was found to be lacking maintenance, control, and use (Figure 7).

In terms of infrastructure, the lighting systems were found to be operational, but it could not be determined whether the irrigation system was being used regularly. Upon examination of structural elements, it was determined that the KSU logo at the entrance was missing, and there were deformations in places on the pavement and pedestrian walkways. However, some structural elements, such as the gazebo used as a gathering area and seating unit, were still in place, but had become dysfunctional due to the area's lack of use (Figures 8 and 9).

Upon examination of the plant elements, it was determined that no maintenance had been carried out and the plants were largely left unattended. Some of the tree and shrub groups were still alive, while some individuals showed signs of drying and mortality. It was determined that the lawn areas were neglected, partially dried and weakened. Observations made during the spring revealed that the lawn areas and ground cover plants were heavily overgrown with weeds reaching approximately 1 meter in height (Figures 8 and 9). This clearly indicates a lack of regular maintenance in the area. An evaluation graph and table showing the use status of the area are given in Table 1 and Figure 6.

**Table 1.** Current Use Status Assessment of the EXPO 2023 Country Gardens and KSU Garden Area (2025–2026)

| Functions | Current Use Status | Scores |
|---|---|---|
| General use condition of the area | Lost its function | 1 |
| Accessibility within the area | Lost its function | 1 |
| Urban furniture elements | Preserved | 3 |
| Structural elements | Partially deteriorated | 2 |
| Infrastructure | Partially deteriorated | 2 |
| Trees and shrubs | Partially deteriorated | 2 |
| Lawn areas | Lost its function | 1 |
| Groundcover plants | Partially deteriorated | 2 |
| **Overall assessment** | **14/24 points;** **mean = 1.75/3; performance = 58.33%** | |

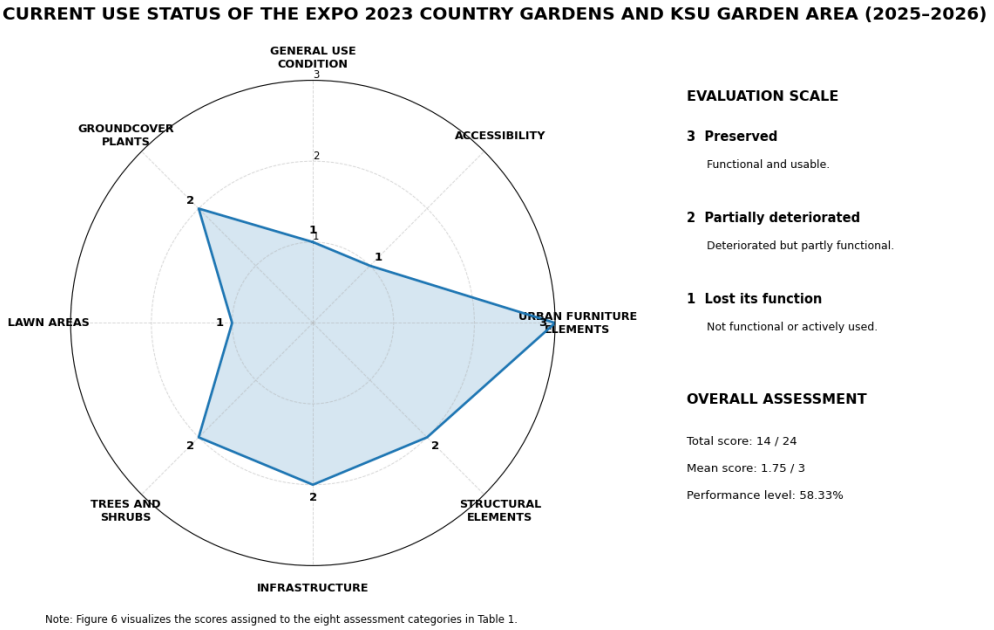



**Figure 6**. Performance of the current use status of the EXPO 2023 country gardens and KSU garden area (Tuğluer, 2026b)




**Figure 7.** Images of the entrance and plaza section of the EXPO 2023 country gardens (Tuğluer, 2025; 2026a)



**Figure 8.** Current status of the EXPO 2023 KSU garden during the summer–autumn period of 2025 (Tuğluer, 2025)



**Figure 9.** Current status of the EXPO 2023 KSU garden during the spring period of 2026 (Tuğluer, 2026a)

The assessment produced a total score of 14 out of 24, a mean score of 1.75 out of 3, and an overall performance level of 58.33%. These values indicate partial deterioration rather than complete functional loss. Most physical components remain in place, but general use, accessibility, and lawn areas have lost their intended functions. Structural elements, infrastructure, trees and shrubs, and groundcover plants were assessed as partially deteriorated, while urban furniture was preserved. Completion of the design and construction therefore did not ensure sustained use. Accessibility, maintenance, visitor-oriented functions, and effective management determine whether a public landscape remains active. Horticultural EXPOs are intended to facilitate interaction with nature, generate social benefits, and support continued public use (Chen et al., 2025). However, the country gardens section, particularly the KSU garden, no longer provides the experience envisioned in the original design, although the wider EXPO 2023 site remains active. Çakır (2023) organized the Şehit Ömer Halisdemir Square design around local needs through accessible circulation, gathering and seating areas, recreational facilities, and service functions. This comparison shows that accessible design and functional diversity support public use, but their benefits cannot be sustained without continued operation and maintenance.

Previous studies have reported that visitor numbers and levels of use often decline after EXPO events (Yang et al., 2021). Although EXPOs contribute to the physical and spatial development of host cities (Batuhan, 2020), these benefits diminish when long-term use and management are not sustained. EXPO sites may also create an architectural and structural legacy, but the continuity of this legacy depends on regular use, maintenance, and management (Polat & Tezcan, 2023). The Kirazlıdere Glass Observation Deck provides a contrasting example. Çakır & Tekin (2025) reported that controlled access, year-round maintenance, social facilities, lighting, and clear spatial organization supported intensive visitor use and a positive user experience. At EXPO 2023, the main site remained active and

maintained, whereas the country gardens section was unused and neglected. Visitor activity was concentrated in maintained areas and declined markedly in sections without regular upkeep.

EXPOs generate economic, social, and spatial benefits for host cities during the event period. Preserving these benefits requires post-event use scenarios to be defined during the planning stage (Güven & Suna, 2022). Infrastructure alone cannot sustain site functionality without users, maintenance, and active management. The long-term performance of EXPO sites depends on their post-event functions and integration into the urban system as well as their design and implementation. Reuse and urban integration influence the long-term performance of these large-scale investments (Gao, 2020). The current condition of the country gardens section shows how an implemented landscape design can lose its function when continued use is not supported.

The design and implementation of the KSU garden were completed, but use, maintenance, and management were not sustained. Insufficient maintenance and the absence of access control reduced site functionality and visitor presence. The comparison with previous studies confirms that the success of landscape design depends on accessible and diverse functions, continued use, regular maintenance, and long-term management.

## 4. Conclusion and Suggestions

This study evaluated the design, implementation, and post-EXPO use of the country gardens section and the KSU garden at EXPO 2023. The design was largely implemented, but use, maintenance, and management activities were not sustained after the event. The main EXPO site remained active, whereas the country gardens section was unused.

Most structural components remained in place. However, insufficient maintenance reduced the visual and functional quality of the planted areas. Lawn and groundcover areas lost much of their original function, and some trees and shrubs showed drying, decline, or mortality.

The operational lighting system showed that part of the infrastructure remained functional. Nevertheless, the presence of infrastructure did not support active use in the absence of maintenance, access control, management, and visitor-oriented functions.

Post-event use scenarios should be defined during the planning stage of EXPO projects. The country gardens section requires regular maintenance, controlled access, active management, and new functions that attract visitors. Reuse strategies should connect the area with the main EXPO site and the surrounding urban structure.

Future EXPO projects should include long-term operation, maintenance, and management plans before implementation. These plans should identify the responsible institutions, required resources, maintenance schedules, access arrangements, and functions that will support continued public use after the event.

## Acknowledgments and Information Note

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The article complies with national and international research and publication ethics. Ethics Committee approval was not required for the study.

## Author Contribution and Conflict of Interest Disclosure Information

The article was written by a single author. There is no conflict of interest.

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# Methodological Analysis of Color Research in the Built Environment

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**Abstract**

*Color in the built environment is a fundamental environmental variable that directly shapes human psychology, physiology, and spatial perception processes. Based on an original quantitative matrix compiled from 54 empirical articles published between 1990 and 2025, this study analyzes the methodological evolution and structural patterns of research examining color parameters in the built environment over the past thirty-five years. Within the scope of the collected dataset, descriptive frequency and multiple-response cross-tabulation analyses were conducted using SPSS.The findings reveal a significant chronological acceleration in color studies, heavily concentrated on educational and office typologies. Methodologically, a structural transition is documented from traditional full-scale mock-ups toward immersive virtual reality environments, accompanied by a shift from subjective psychological scales to objective neurophysiological measurements such as EEG. Statistical analysis confirms that user-oriented emotional and affective dimensions represent a time-independent, dominant core outcome, whereas spatial perception and direct behavioral variables constitute chronic literature gaps. Finally, a widespread reporting omission regarding international color standardization systems is identified, undermining methodological replicability in environmental design.*

***Keywords:*** *Color Research, Built Environment, Empirical Research Methods, Methodological Analysis, Color Effects.*

# Yapılı Çevre Renk Araştırmalarında Kullanılan Yöntemlerin Analizi

**Öz**

*Yapılı çevrede renk, insan psikolojisi, fizyolojisi ve mekânsal algı süreçlerini doğrudan biçimlendiren temel bir çevresel değişkendir. Bu çalışma, 1990–2025 yılları arasında yayınlanmış 54 ampirik makaleden derlenen özgün bir nicel matris üzerinden, yapılı çevrede renk parametrelerini inceleyen araştırmaların son otuz beş yıllık metodolojik evrimini ve yapısal örüntülerini analiz etmektedir. Toplanan veri seti kapsamında SPSS ortamında betimsel frekans ve çoklu tepki çapraz analizleri yürütülmüştür. Bulgular, renk çalışmalarında kronolojik olarak bir ivmelenme olduğunu ve bu çalışmaların ağırlıklı olarak eğitim ve ofis tipolojilerinde yoğunlaştığını ortaya koymaktadır. Metodolojik açıdan, geleneksel tam ölçekli deneysel odalardan (mock-up) sanal gerçeklik ortamlarına doğru yapısal bir geçiş belgelenmiş, bu sürece öznel psikolojik ölçeklerden EEG gibi nesnel nörofizyolojik ölçümlere doğru bir kayma eşlik etmiştir. İstatistiki analizler, kullanıcı odaklı duyuşsal ve duygusal boyutların dönemlerden bağımsız, baskın bir temel sonuç olduğunu, mekansal algı ve doğrudan davranışsal değişkenlerin ise kronik literatür boşlukları oluşturduğunu göstermektedir. Son olarak, uluslararası renk standardizasyon sistemlerine ilişkin yaygın bir raporlama eksikliği tespit edilmiş olup, bu durum çevresel tasarımda metodolojik tekrarlanabilirliği zayıflatmaktadır.*

***Anahtar kelimeler:*** *Renk Araştırmaları, Yapılı Çevre, Deneysel Araştırma Yöntemleri, Metedolojik Analiz, Renk Etkisi.*

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## 1. Introduction

Sommer (1969) emphasized the reciprocal relationship between humans and the built environment, arguing that individuals shape their living environments according to their needs and aspirations, while the transformed physical environment, in turn, plays a decisive role in shaping human perceptions, attitudes, and behavioral patterns. Among the various components of the built environment, color is undoubtedly one of the most influential. The remarkable ability of the human visual system to discriminate approximately 2.5 million different color shades (Linhares et al., 2008) enhances the potential of color to create unique, dynamic, and multilayered effects on architectural surfaces and within three-dimensional spaces.

Color is a dynamic phenomenon that encompasses multifaceted functions across both the physical and psychological dimensions of human experience, serving as a signifier and a mechanism of impact across a broad spectrum ranging from visual value generation to wayfinding, the shaping of affective states to cognitive focus, and the appreciation of spatial quality to human behavior (Elliot&Maier, 2014; Valdez & Mehrabian, 1994). Color, which enhances spatial diversity, facilitates the differentiation of architectural elements, and highlights specific areas, serves as a fundamental instrument in constructing the intended atmosphere and mood within a design. (Güneş & Olguntürk, 2020; Jaglarz, 2024).

In this context, research on color effects spans a broad and interdisciplinary literature encompassing many fields such as psychology, neurophysiology, architecture, and interior design (Hurlbert & Ling, 2007; Elliot & Maier, 2014). Drawing from diverse scientific methods, these studies start from different fundamental questions and utilize different techniques and conceptual tools (Anter & Billger, 2010). One of the most dynamic domains where this interdisciplinary theoretical framework materializes and directly intersects with human experience is architectural interiors. When abstract color theories at the macro scale are translated into the interior scale, wall surfaces in particular transform into environmental stimuli, becoming objects of rational empirical research. At this point, the 'contextual role' of color in interior color research comes to the fore as a critical distinction in terms of empirical validity. Because a color experience within an architectural context with a specific function (office, classroom, hospital room, etc.) produces different results than an isolated color stimulus in a laboratory environment. Therefore, the individual's exposure to environmental colors possessing a specific context directly directs their psychological well-being, mood, attention level, and spatial performance (Aksoy & Hidayetoğlu, 2019; Jonauskaite & Mohr, 2025). Indeed, in current interior-oriented empirical studies, the role of color is handled multi-dimensionally, and besides the affective relationships and behavioral orientations of color on human attitudes, its direct somatic effects on neurophysiological processes such as blood pressure, heart rate, and brain activities are comprehensively documented (Küller et al., 2006; Al-Ayashi et al., 2016; Llinares et al., 2021; Bower et al., 2022; Liu et al., 2022).

### 1.1. Historical Development of Color Research in the Built Environment

The empirical investigation of the effects of color stimuli on human psychology and physiology has a well-established experimental history spanning for over 100 years. Féré (1885; 1887) pioneered the field by conducting the first quantitative studies explicitly examining the influence of color on psychological and physiological functioning. Subsequently, Baldwin (1893) investigated how color stimuli elicited fundamental motor responses during early childhood, while Cohn (1894) carried out some of the earliest quantitative experiments exploring the positive and negative emotional responses evoked by different colors.

Early psychological studies on color perception and affective meanings are theoretically grounded in Wundt's (1897) dimensions of responses to stimuli, namely "pleasure, tension, and inhibition." These conceptual categories later provided a foundation for experimental research demonstrating that human judgments and environmental experiences are organized along the "pleasure, arousal, and dominance" (PAD) framework (Mehrabian & Russell, 1974). Eysenck (1941), in turn, documented this early historical accumulation of knowledge by presenting a comprehensive literature review spanning approximately forty to fifty years of experimental research and incorporating over 20,000 ratings.

Studies on the effects of environmental color have developed in parallel with the effects of space and environmental evaluations on people. Pressey (1921) found that there was no difference in the responses of warm and cold colors on the autonomic nervous system, whereas luminance increased performance speed. Guilford & Smith (1959), who examined the experimental background of color perception and preferences, were the first researchers to systematically study hue, value, and chroma parameters in order to measure affective component. Despite Guilford's approach, much of the color research conducted until 2010–2015 focused primarily on "hue," the most dominant dimension of color. However, current research proves that value (lightness) and saturation (chroma) also play equally critical roles in modifying psychological and physiological responses to environmental conditions, and that color effects can only be understood through the multiple interaction of these three dimensions (Elliot & Maier, 2014; Duyan & Işık, 2022; Liu, 2022; Duyan & Şener, 2025).

Since the second half of the 20th century onwards, measurement tools have diversified, and with the development of the Semantic Differential Scale by Osgood et al. (1957), interior colors have begun to be analyzed multi-dimensionally within this framework. Utilizing the Semantic Differential Scale (SDS), Sivik (1969) revealed the relationships between the perceptual dimensions of colors and their associative meanings. Similarly, Hogg (1969) employed the SDS to measure user perception in interiors, defining the dimensions of *dynamism, spatial quality, emotional tone, evaluation*, and *complexity.* During the same period, Inui (1969) advanced the empirical study of interior color by systematically documenting color characteristics in diverse interior environments, including hospitals, schools, hotels, cinemas, and residential spaces, using the Munsell system and subjective evaluations of color schemes. Küller (1972), on the other hand, developed new descriptive dimensions for evaluating environment and space through factor analysis. Tikkanen (1976) investigated the effects of color changes in school environments on students' emotions.Ruttenberg (1988) defended the role of color on environmental atmosphere and emotional balance, while Willumsen (1988) conceptualized the spatial effect of color at three levels as information/communication, emotional response, and aesthetic perception.

These pioneering researches presented in a chronological flow clearly show that the effects of the color stimulus on human psychology and physiology do not consist of a uni-dimensional preference norm, rather, they are shaped in a multi-layered structure hosting perceptual, cognitive, and somatic processes together. Therefore, grasping these versatile effects created by color components in the built environment on the user within a holistic theoretical framework prepares an appropriate ground for the examination of integrated 'attitude' models, which is one of the fundamental areas of environmental psychology.

### 1.2. Attitudes Towards Environmental Color Stimuli

Research in the field of interior environmental perception clearly demonstrates that spaces are not merely passive physical backdrops, rather, they function as active environmental stimuli capable of directly influencing users' behaviors, emotional states, and cognitive processes (Mehrabian & Russell, 1974; Evans, 2003; Bower et al., 2022). According to the Mehrabian and Russell (M-R) model developed within this framework, stimuli originating from the physical environment (such as color, light, and texture) play a central role in generating emotional states that, in turn, shape individuals' behavioral intentions, specifically approach or avoidance responses.

Human responses to the built environment and particularly to color stimuli as one of its most dominant components are conceptually framed within the attitude construct in social psychology and environmental psychology literature. "Attitude" is defined as a learned evaluative and response tendency toward a specific object, person, institution, or event. Environmental attitudes, in turn, refer to psychological orientations through which components of the built environment are perceived and evaluated as either positive or negative (Milfont & Duckitt, 2010). According to the "*Tripartite Model of Attitudes"* developed by theorists such as Allport (1954), Rosenberg & Hovland (1960), Hilgard (1980), and Ajzen (1993), responses to a stimulus are examined across three primary dimensions: affective, cognitive, and behavioral.

*"The affective component"* encompasses the emotional reactions an individual experiences toward color stimuli, such as liking or disliking, feelings of comfort, anxiety, and similar responses. For example, it is well documented that warm colors with high saturation tend to evoke feelings of arousal, alertness, and discomfort, whereas cool colors such as blue and green are associated with calmness, coolness, and relaxation (Küller et al., 2009; Siamionava et al., 2018; Büker & Kaynakçı Elinç, 2023). "*The cognitive component"* involves an individual's thoughts, perceptions, and mental evaluations of color stimuli, and it directly influences processes such as concentration, attention, and task performance. In the context of educational environments, cognitive capacity refers to students' ways of perceiving lectures, maintaining attention, and processing memory and comprehension (Dzulkifli & Mustafar, 2013). "*The behavioral component"* refers to actions performed within a space as a result of color stimuli, as well as performance outcomes and decisions to prefer or avoid a given environment.

A wide variety of experimental setups have been constructed in the literature of architecture, interior design, and psychology to measure these attitudes. The Semantic Differential Scale, developed by Charles E. Osgood and colleagues, has been widely used to quantitatively measure both the affective and cognitive dimensions of perception through bipolar adjective pairs (Osgood et al., 1957). In studies conducted along these lines, researchers have resorted to diverse data collection instruments and spatial simulation methods to evaluate user attitudes. For instance, in investigations carried out within full-scale (mock-up) experimental offices and workspaces, Ainsworth et al. (1993) examined job performance, anxiety, and arousal levels through standard office tests and psychological scales, while Kwallek et al. (1996) explored the effects of wall colors on mood and performance, and Stone & English (1998) alongside Stone (2001) researched the role of red and blue walls calibrated on reading comprehension success and spatial satisfaction. Similarly utilizing full-scale experimental spaces, Read et al. (1999) revealed the impact of different wall colors on the collaborative behaviors of children aged 3–5 in a preschool play environment through systematic video observations, whereas Küller et al. (2009) validated the emotional effects of office colors on users in a full-scale experimental room (mock-up) using neurophysiological methods such as pioneering EEG and ECG measurements. Wang & Russ (2008) examined the relationship between students' classroom wall color preferences and personality types by applying 15 different colors to the walls of a computer-simulated classroom, whereas Baytin et al. (2005), who conducted their study in-situ experiment, applied 32 different colors to the walls of an architectural studio on a weekly basis and monitored changes in students' performance and attention levels. Yıldırım et al. (2007) measured perceptual responses to wall color in a cafe-pastry shop atmosphere using the Semantic Differential Scale, and Genschow et al. (2015) analyzed the effect of Baker-Miller pink on prisoners' aggression levels in a real-world prison field study using institutional staff observation logs.

With the integration of neurophysiological methods, the relationships between color stimuli and somatic responses have been established on a more objective empirical basis. Consequently, physiological indicators such as autonomic nervous system activity, galvanic skin response (GSR), heart rate (ECG), electroencephalography (EEG) and respiratory rate have been increasingly employed to assess the effects of color stimuli (Al-Ayashi, 2016; Jacobs & Hustmyer, 1974).

Today, the influence of color in interior design is considered a significant variable that shapes a user's attitude towards the built environment through factors such as comfort, satisfaction, perceived spatial quality, and behavioral tendencies (purchasing, approach, etc.) (Bellizzi & Hite, 1992). Beyond the Tripartite Model of Attitudes, it is also methodologically important to distinguish two constructs that are frequently examined in the literature: "color preference" and "the effects of color on spatial perception". Color preference represents an individual's subjective evaluation of, satisfaction with, and aesthetic appreciation for a particular color stimulus or spatial color composition. As such, it can be regarded as an affective construct that reflects the pleasure dimension of emotional responses (Ou et al., 2004). On the other hand, spatial perception, which encompasses the optical and geometric effects of color within a space, refers to the cognitive capacity through which individuals process and interpret physical spatial attributes such as depth, spaciousness, width, and height based on visual

information. From this perspective, spatial perception can be conceptualized as a fundamentally cognitive process and a mechanism of spatial evaluation within the field of environmental psychology (Aksoy & Hidayetoğlu, 2019). Accordingly, empirical research on color typically treats color preference as an affective–aesthetic outcome, whereas changes in spatial perception are regarded as cognitive–spatial functions, thereby providing a comprehensive framework for understanding users' attitudes toward the built environment.

### 1.3. Aim and Scope of the Study

Despite the existence of a rich literature investigating the effects of colors on human reactions, these studies exibit a very large diversity and a fragmented structure from a methodological perspective. Researchers utilize controlled laboratory experiments, questionnaire-based field researches, full-scale mock-ups, and in recent years, digital simulation techniques extending from computer visualizations to immersive virtual reality (VR) environments. Although this methodological diversity enriches the field, it causes a lack of standardization in the operational definitions of colors (differences between color systems such as NCS, Munsell), the control level of environmental variables such as data collection tools (psychometric scales, performance tasks, or neurophysiological tools). This state of affairs restricts the comparability and generalizability of the findings (Elliot & Maier, 2014).

An examination of the existing literature reveals that reviews have predominantly been conducted from thematic perspectives, such as color-emotion relationships, functional spatial interactions, or general historical contexts (Savavibool & Moorapun, 2017; Elliot & Maier, 2007; Elliot, 2019; Coutinho & Akbay, 2023; Jonauskaite & Mohr, 2025). However, systematic reviews that comprehensively classify the strengths and limitations of the methodological approaches, data collection instruments, and spatial representation techniques used in built environment color research have not yet matured, leaving a gap in the literature with a methodological framework waiting to be clarified. Addressed in this direction, this study aims to fill this methodological gap by examining it through a structural lens, thereby contributing to the literature by providing a holistic guide for future empirical research.

The main objective of this study is to classify, compare, and analyze the methodological trends of data collection tools, spatial color presentation environments, and spatial functions used in empirical research methods examining the effect of color in the built environment. The historical progression of interior color research indicates that, with technological advancements, it has evolved from simple effect measurements towards more rational and multi-dimensional measurements. Accordingly, the study covers works published between the years 1990 and 2025 a period characterized by the qualitative and quantitative development of research techniques and accelerated scientific production conducted strictly within the contexts of diverse spatial functions (office, education, commercial, residential, etc.). The classification matrix has been constructed according to the attitudes of users (affective, behavioral, cognitive), the data collection tools utilized (task completion, psychometric scales, neurophysiological measurements), and spatial color representation methods (real space, mock-up, computer-aided visualization, virtual reality).

Since the focus of this research is on the methods employed in studies on the effects of interior colors, user-derived personal and demographic variables such as gender, occupation, and cultural background, which are frequently encountered in empirical studies, were excluded from the scope of this study. With this in mind, rather than a direct comparison of the quantitative results of the studies examined, this study aims to provide a structural analysis of the methodological designs, simulation techniques, and data collection tools applied.

## 2. Material and Method

This study investigates the methodological evolution and structural patterns of empirical color research in the built environment over a specific thirty-five-year period (1990–2025). A comprehensive literature review was conducted using databases such as Scopus, Web of Science (WoS), and Google Scholar. The search utilized the following keyword combinations: "color in interior space", "environmental color perception", "color effect", "color psychology built environment", "color and user behavior", and "color perception".In the first stage, publications retrieved from the databases

were screened, and only studies employing experimental designs were retained. In the second stage, each study was assessed to determine whether it investigated user perception, attitudes, or performance within a physical or simulated interior environment. Ultimately, 54 original research articles that met the inclusion and exclusion criteria and focused on different spatial functions and empirical measurement methods were included in the final dataset.To analyze the structural trends within this dataset, an original quantitative coding and matrix system was developed. The methodological characteristics of the selected 54 articles—including spatial functions, presentation formats, measured dependent variables, and data collection instruments—were transformed into standardized categorical data. This compiled matrix was then transferred to SPSS software to perform advanced quantitative evaluation. Descriptive frequency analyses were conducted to map chronological shifts, and multi-response crosstabulation (multiple response analysis) combined with Pearson Chi-Square ($\chi^2$) independence tests was executed to detect statistically significant correlations between historical periods, spatial mediums, and investigated user outcomes (Figure 1).

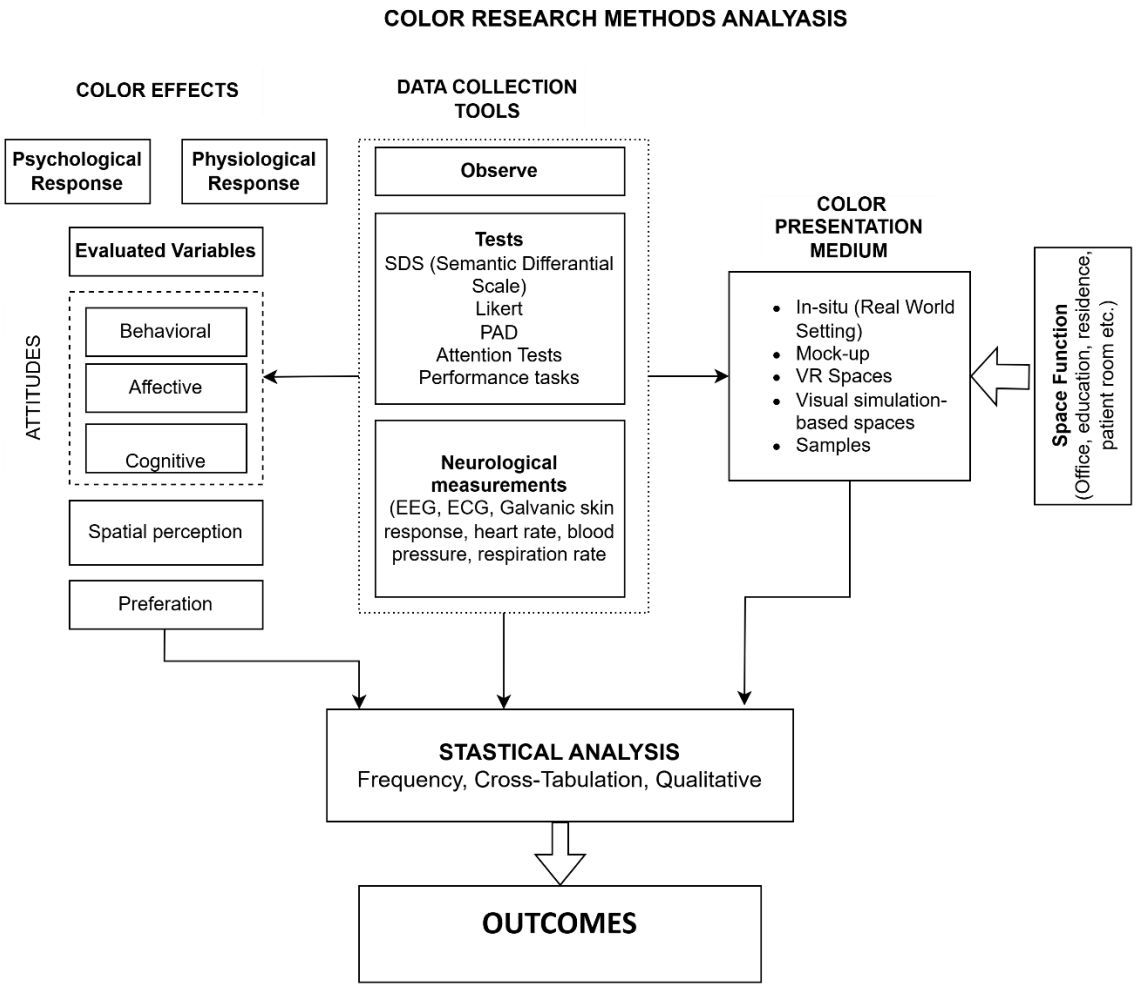



**Figure 1.** Conceptual framework of methodological trends and variables in built environment color Research analysis (Created by the author)

### 2.1. Spatial Color Evaluation and Presentation Methods

Experimental methods in color research are designed to isolate causal relationships between color stimuli as independent variables and human responses as dependent variables under controlled environments. The selected studies implement these approaches across four primary presentation mediums:

*In Situ (Field Studies / Real-World Settings):* Conducted in real-world settings to examine the natural interaction between users and spatial colors. While offering the highest ecological validity, its presence

is relatively limited in the dataset due to operational challenges in controlling ambient lighting and environmental parameters.

*Mock-Up and Controlled Laboratory Settings:* Studies where researchers systematically manipulate color attributes (hue, value, chroma) in standardized physical spaces or color booths while holding confounding variables (CCT, CRI, acoustics, air quality) constant.

*Visual Simulation-Based Environments and Virtual Reality (VR):* Digital 3D modeling (e.g., 3ds Max) where color schemes are applied to virtual surfaces. Participants experience these environments via screen projections or immersive VR headsets, simulating spatial presence and real-time movement.

*Isolated Color Samples and Standardized Color Charts (Swatches):* Studies relying on physical color chips or standardized systems (e.g., Munsell, NCS, RAL) associated with contextual, cognitively imagined spatial scenarios.

### 2.2. Data Collection Instruments

The data collection instruments analyzed within the research matrix are categorized based on the subjectivity/objectivity of the measured user responses and the targeted psychological or physical dimensions:

#### 2.2.1. Affective measurement methods (affective measurements: mood, emotion, and color preference)

Structured psychometric instruments are commonly employed to measure users' subjective evaluations, psychological attitudes, and preferences toward specific interior color conditions.

**Semantic Differential Scale (SDS):** Participants rate color conditions using bipolar adjective pairs (e.g., Warm–Cool, Spacious–Confined) on 5- or 7-point scales to transform semantic spatial dimensions into quantitative data (Osgood et al.; 1957).

**Likert Scales:** These consist of structured statements designed to measure users' levels of agreement regarding color preference, perceived spatial comfort, and environmental experience, ranging from *"strongly disagree"* to *"strongly agree."*

**Emotional Response and Mood Scales (PAD and Profile-Based Instruments):** Standardized instruments including the PAD (Pleasure–Arousal–Dominance) emotional state model, (Mehrabian & Russell; 1974), POMS (Profile of Mood States), and choice-oriented ranking tests to capture affective fluctuations across different spatial functions.

**Color Preference and Choice-Oriented Measures:** These are ranking or preference tests that identify users' aesthetic preference patterns and emotional associations by determining which color or color composition they associate with specific spatial functions (e.g., hospitals, residential settings, or workplaces).

#### 2.2.2. Performance-oriented methods (task performance and attention)

Attention Tests and Task Performance methods are designed to measure the effects of color stimuli on individuals' cognitive capacity. Participants are asked to complete tasks such as attention tests, reading comprehension exercises, visual search tasks, proofreading, or standardized office-related tasks in controlled colored environments. Objective performance outcomes are then assessed, including concentration levels, error rates, and task completion speed.

#### 2.2.3. Behavior-oriented methods (behavioral observations)

This approach investigates users' natural behavioral patterns in existing environments characterized by specific color schemes. For example, the impact of wall colors on customers' dwell time in retail spaces or the effects of color on concentration duration in educational settings can be identified through direct observation or video analysis conducted in ways that minimize observer effects. By capturing behavior as it occurs in real-world contexts, observational studies provide valuable insights into the practical and behavioral consequences of color applications in spatial environments.

#### 2.2.4. Neurophysiological Methods (Neurological and Physiological Measurements)

These are advanced laboratory-based methods that measure the involuntary, objective, and biological responses of the human nervous system to color stimuli, with the aim of eliminating potential response biases in self-report measures (e.g., social desirability bias).

- EEG (Electroencephalography): During exposure to specific color compositions, brainwave activity (alpha, beta, theta, and delta) is recorded in real time using electrodes placed on the scalp.
- ECG (Electrocardiogram) and Heart Rate Variability (HRV): This method analyzes fluctuations in cardiac rhythm and HRV parameters to measure the direct effects of color tones on the autonomic nervous system, particularly the balance between sympathetic and parasympathetic activity. It provides objective physiological datasets related to anxiety, arousal, or relaxation states elicited by different colors.
- Blood Pressure and Pulse Measurements: Participants' blood pressure and real-time pulse rates are recorded either during exposure to spatial environments designed with specific color schemes or immediately after exposure to color stimuli. This method provides objective and direct physiological data to verify the effects of color on arousal or relaxation through hemodynamic responses of the cardiovascular system.
- Galvanic Skin Response (GSR): By monitoring instantaneous changes in skin conductance, the GSR method is used to record emotional arousal and stress levels induced by color stimuli through sweat gland activity, providing real-time and objective measurements of autonomic nervous system responses.

## 3. Findings and Discussion

Following preliminary screening conducted through database searches, the abstracts and full texts of approximately 180 studies were reviewed. In line with the inclusion and exclusion criteria, a total of 54 empirical studies were included in the qualitative and quantitative synthesis. Considering the chronological distribution of the articles within the scope of the review (1990–2025), a marked acceleration in publication frequency has been observed particularly after 2010. This trend indicates a growing body of empirical research focusing on the effects of built environment components and spatial color parameters on user experience.

To describe the methodological boundaries, variable networks, and data collection instruments of color-focused research in the built environment, two main tables were constructed. Accordingly, the methodological distribution matrix of the 54 empirical studies classified according to spatial typology, mode of presentation, and dependent variable groups in a chronological framework is presented in Table 1 (Methodological Distribution Matrix). In addition, detailed parametric information of these studies, including sample sizes, specific color/lighting parameters tested, and data collection instruments used, is synthesized in Table 2 (Data Extraction Table).

**Table 1.** Methodological Distribution Matrix of the 54 Reviewed Empirical Articles by Typology, Medium, and Variables (Chronological Order)

| Authors | Year | Function Typology | Presentation Medium | | | | | Evaluated Variables | | | | | Data Collection Instruments | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Affective | | Cognitive | | | | | | | |
| | | | In-situ (Real World Setting) | Mock-Up | VR Spaces | Visual simulation-based spaces | Samples | Behavioral | Preference | Mood, Well-being, Emotional States | Spatial Perception | Attention, Performance, Arousal | Observe | SDS (Semantic Differential Scale) | Likert | Attention Tests, Task performance | Neurological measurements | Survey/ Other Tests |
| Kwallek & Lewis | 1990 | Office | | ● | | | | | | ● | | | | | | | | ● |
| Ainsworth et al. | 1993 | Office | | ● | | | | | | ● | | ● | | | | ● | | ● |
| Kwallek et al. | 1996 | Office | | ● | | | | | ● | ● | | ● | | | ● | ● | | ● |
| Stone & English | 1998 | Office | | | | | | | | ● | | ● | | | | ● | | |
| Read et al. | 1999 | Education | | ● | | | | ● | | | | | ● | | | | | ● |
| Stone | 2001 | Office | | ● | | | | | | ● | | ● | | | | ● | | ● |
| Babin et al. | 2003 | Shopping | | | | | ● | ● | | ● | | | | | ● | | | ● |
| Edge | 2003 | Patient room | ● | | | | | | | ● | | | | | | | | ● |
| Baytin et al. | 2005 | Education | ● | | | | | | ● | ● | | ● | | ● | | ● | | ● |
| Yıldırım et al. | 2007 | Shop | ● | | | | | | | ● | ● | | | ● | | | | |
| Kwallek et al. | 2007 | Office | | ● | | | | | | | | ● | | | | ● | | ● |
| Manav | 2007 | Residence | | | | | ● | | ● | ● | | | | | | | | ● |
| Dijkstra et al. | 2008 | Patient room | | | | ● | | | | ● | | | | | | | | ● |
| Küller et al. | 2009 | Office | | ● | | | | | | ● | | ● | | ● | | ● | ● | |
| Kamaruzzaman & Zawawi | 2010 | Office | | | | | ● | | ● | ● | | | | | | | | ● |
| Yıldırım et al. | 2011 | Living room | | | | ● | | | | ● | ● | | | ● | | | | |
| Yıldırım et al. | 2012 | Hairdressing Salon | | | | ● | | | | ● | | | | ● | | | | |
| Öztürk et al. | 2012 | Office | | ● | | | | | | ● | | ● | | ● | | ● | | |
| Jalil et al. | 2013 | Education | | | | | ● | | ● | | | ● | | | ● | | | |
| Park J. | 2013 | Livig room | | ● | | | | | ● | ● | | | | | | | | ● |
| Bakker et al. | 2013 | Office | ● | | | | | | | ● | ● | ● | | | | ● | | ● |
| Genschow et al. | 2015 | Prison cell | ● | | | | | ● | | ● | | | ● | | ● | | | ● |
| Yıldırım et al. | 2015 | Education | | | | ● | | | | ● | | | | ● | | | | |
| Tantanatewin & Inkarojrit | 2016 | Bank Sub-branch | | | | ● | | | | ● | ● | | | ● | | | | |
| Duyan & Unver | 2016 | Education | ● | | | | | ● | | ● | | ● | ● | ● | ● | ● | | ● |
| Al-Ayash et al. | 2016 | Education | | ● | | | | | | ● | | ● | | | | | ● | ● |
| Çağatay & Hidayetoğlu | 2016 | Education | ● | | | | | | | ● | ● | | | ● | | | | |
| Savavibool & Moorapun | 2017 | Office | | | | ● | | | | ● | ● | | | ● | | | | |
| Müezzinoğlu | 2018 | Education | ● | | | | | | | | ● | | | | | ● | | |
| Siamionava et al. | 2018 | Contexless | | | ● | | | | | ● | | | | | | | | ● |
| von Castell et al. | 2018 | Contexless | | ● | | | | | | ● | | ● | | | | ● | | ● |
| Yıldırım et al. | 2019 | Education | | | ● | | | | | ● | ● | | | ● | | | | |
| Güneş & Olguntürk | 2020 | Living room | | ● | | ● | | | | ● | | | | | | | | ● |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cha et al. | 2020 | Contexless | | | ● | | | | ● | | ● | | ● | | ● | ● | ● |
| Pourbagher et al. | 2020 | Education | | | | ● | | | ● | | ● | | | ● | | | ● |
| Ulusot et al. | 2020 | Bedroom | | ● | | | ● | | ● | ● | | | | | | | ● |
| Baper et al. | 2021 | Education | | | | | ● | | ● | ● | | | | | | | ● |
| Lipson-Simith et al. | 2021 | Living room, Hospital, Contexless | | | ● | | | | ● | ● | | | | | | | ● |
| Llinares et al. | 2021 | Education | | | | ● | | | | | | ● | | | ● | ● | ● |
| Bower et al. | 2022 | Contexless | | ● | ● | | | | | ● | | | | | | ● | ● |
| Liu *et al* | 2022 | Education | | | ● | | | | | ● | | ● | | | | ● | ● |
| Duyan & Ünver | 2022 | Education | ● | | | | | ● | ● | ● | ● | ● | ● | ● | ● | | |
| Oh & Park | 2022 | Contexless | | ● | | | | | | ● | | | | ● | ● | ● | |
| Xu et al. | 2022 | Hotel room | | | ● | | | | ● | ● | | | | ● | | | ● |
| Akbay & Demirbaş | 2023 | Contexless/ Library | | | | ● | | | | ● | | | | | ● | | ● |
| Weijs et al. | 2023 | Contexless | | ● | | | | | | ● | | ● | | | | ● | ● |
| Duyan & Işık | 2024 | Education | | | | ● | | | | ● | ● | ● | | ● | ● | | ● |
| Ulusoy | 2024 | Bedroom | | | | ● | | | | ● | | | | | | | ● |
| Sun et al. | 2024 | Education | ● | | | | | | | ● | ● | | | | ● | | ● |
| Aydoğdu | 2024 | Patient room | | | | ● | | | ● | ● | ● | | | ● | ● | | ● |
| Duyan & Şener | 2025 | Home-office | | | | ● | | | | ● | ● | ● | | ● | ● | | ● |
| Yüksektepe & Küçükkılıç | 2025 | Patient room | | | ● | | | | ● | ● | | | | | ● | | ● |
| Bölükbaşı & Uç | 2025 | Patient room | | | ● | | | | | ● | | | | | ● | | ● |
| Hendi & Mazaherian | 2025 | Therapy room | | | ● | | | | | ● | | | | | | | ● |

**Table 2.** Detailed Data Extraction and Parametric Overview of the Reviewed Studies: Sample Sizes, Color Systems, and Measurement Instruments

| | Author (s)/ Year | Functional Typology | Stimulus Presentation Mode | Dependent Variables (Outcomes) | Veri Toplama Araçları | Tested Colours | Color System | Participants |
|---|---|---|---|---|---|---|---|---|
| 1 | Kwallek & Lewis (1990) | Office | Full scale Mock-up | *Affective* | Profile of Mood States(POMS) | Red, green, white | Munsell | 222 |
| 2 | Ainsworth et al. (1993) | Office | Full scale Mock-up | *Affective and cognitive (arousal level )* | State Anxiety Inventory, Multiple Affect Adjective Check List (MAACL), office task. | Red, Blue-Green, White | | 36 Adults |
| 3 | Kwallek et al. (1996) | Office | Full scale Mock-up | *Preference, affective, cognitive (task performance)* | POMS (Profile of Mood States), self-report fo preferation | Nine schemes featuring red, blue, and white, including their different value and saturation tones. | Munsell | 94 Adults |
| 4 | Stone & English (1998) | Office | Mock-up | Preference, Affective, Cognitive (task performance) | Multiple Affect Adjective Check List (MAACL), | Red, blue | Munsell | 112 participants |
| 5 | Read et al. (1999) | Education | Mock-up | Behavioral | Parten's Social Participation Scale | Purple, blue, green, Yellow, orange and red | Munsell | Children (3-5 Aged) |
| 6 | Stone (2001) | Learning environment | Mock-up | Preference, Affective, Cognitive (task performance) | Multiple Affect Adjective Check List (MAACL), performance tasks, surveys | Red, blue | | 26 male, 32 female |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 7 | Babin et al. (2003) | Shop | Samples | *Affective* | Likert | Hot and cold colors, blue, orange | | 141 |
| 8 | Edge (2003) | Patient room | In-situ | *Affective* | | Purple, green, orange, beige | | 19 female, 20 male, 26-89 (Aged) |
| 9 | Baytin et al. (2005) | Education | In-situ | *Affective, attention* | State-Trait Anxiety Inventory | Purple, green, orange, beige | | 19 female, 20 male (39 participants) |
| 10 | Yıldırım et al. (2007) | Shop | In-situ | *Affective, Perception* | SDS | Yellow, purple | | 250 |
| 11 | Kwallek et al. (2007) | Office | Mock-up | *Cognitive (Performance)* | Performance tasks, Eysenck Personality Inventory, PAD, (QMSSA) | White, red, blue-green | | 67 female, 23 male (90 participants) |
| 12 | Manav (2007) | Residence | Samples | Affective, preference | Frequency | 41 colors | | 50 (30 female, 20 male) |
| 13 | Dijkstra et al. (2008) | Patient room | Visualization | Affective | Stress Arousal Checklist | orange, green | | 38 male, 51 female |
| 14 | Küller et al. (2009) | Office | | Affective, *Cognitive (Performance)* | EEG, | Red, blue, Comlexity | | Ex.1. 6 female, 6 male (17-28), Ex.2. 17 female, 8 male (20-31), Ex. 3. 20 female, 20 male (21-62) |
| 15 | Kamaruzzaman & Zawawi (2010) | Office | Samples | Affective | Questionaire | Blue, yellow, grey | | **50** |
| 16 | Yıldırım et al., (2011) | Living Room | Visualization | Affective | SDS | Red, blue | Lab | 150 |
| 17 | Yıldırım (2012) | Hairdressing | Digital Visualization | Affective | SDS | Cream, lilac, orange | | 70 participants (30-60 Aged) |
| 18 | Öztürk et al. (2012) | Office | Mock-up | Affective | Clerical tasks, SDS | Yellow, grey | NCS | 60 participants |
| 19 | Jalil et al. (2013) | Learning environment | Samples | Affective/ Preferation | Likert | Red, blue,green, pink, purple, brown, orange, yellow, white, black, grey | Munsell | 798 (19-27 Aged) |
| 20 | Park (2013) | Living Room | Mock-up (1/2 scaled) | Affective/ Preferation | Preference | 45 colors | Munsell | Children (37-11 Aged) 63 participants |
| 21 | Bakker et al. (2013) | Office | In-situ | Affective, perceive, performance | Questionaire | Red and Blue | | 52 (26-52 Aged) |
| 22 | Genschow et al. (2015) | Prison cell | Field Experiment / In-situ | Behavioral | Observe | Baker_Miller Pink | | 59 Adults (19-46 Aged) |
| 23 | Yıldırım et al. (2015) | Education | Visualization | Affective | SDS | Cream, blue, pink | | Male s |
| 24 | Tantanatewin & Inkarojrit (2016) | Bank sub-branch | Visualization | Affective | SDS | Yellow-orange, grey-white | | 144 |
| 25 | Duyan & Unver (2016) | Learning envronment | In-Situ | Attention | Attention test | Red, Yellow, Green, Blue, Purple | Munsell | 8-9 aged |
| 26 | Al-Ayashi et al. (2016) | Learning envronment | Mock-up | Affective, ccognitive | SAT comprehension test, neurophysiological tests | Red, yellow, blue | NCS | 24 |
| 27 | Çağatay & Hidayetoğlu (2016) | Education | In-situ | Affective | SDS | Cream, blue, green | RGB | 939 male (15-19 Aged) |
| 28 | Savavibool & Moorapun (2017) | Office | Visualization | Affective, perception | SDS, questionnaire | Blue, complexity, neutral | | 80 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 29 | Müezzinoğlu (2018) | Education | In-situ | Affective, Cognitive, perception | SDS, Performance, attention tests | Yellow, blue, neutral | Munsell | 80female, 80 male (160) |
| 30 | Siamionava et al. (2018) | Hotel room | VR | Affective, perceive | PAD | Red, blue | | 76 female, 63 male (139) |
| 31 | von Castell et al. (2018) | Contexless | Mock-up | Affective, performance | LMT (Lern- und Merkfähigkeitstest), self assestment | Pink, red, blue, white | | 170 |
| 32 | Yıldırım et al. (2019) | Education/ Classroom | VR | Affective | SDS | Light/medium red, light/ medium blue, grey | NCS, RGB | 113 Adults |
| 33 | Güneş & Olguntürk (2020) | Living room | Visualization | Affective | Emotion matching | Red, green, blue, grey | RGB | 180 (90 female, 90 male) (17-26) |
| 34 | Cha et al. (2020) | Contexless | VR | Affective , cognitive | SDS, SAT, neurophysiological tests | Red, green, blue, white | | 55 |
| 35 | Pourbagher et al. (2020) | Education/ Classroom | Visualization | Affective, Attention | Likert | Green, blue, red, yellow, white | | 275 (20-24 Aged) |
| 36 | Ulusoy et al. (2020) | Bedroom | Mock-up | Affevtive, preference | Questionnaire | 42 colors | Munsell | 20 Adults |
| 37 | Baper et al. (2021) | Education | Samples | Affevtive, preference | Questionnaire | Yellow, green, blue, purple, white, and black, grey | Munsell | 36 female, 29 male (65) |
| 38 | Lipson-Smith et al. (2021) | Living room, hospital, contexless | VR | Affective, preferation | | 40 colors | | 745 |
| 39 | Llinares et al. (2021) | Education | Visuliation | Attention, performance | EKG, EEG, heart rate | 24 colors | | 160 |
| 40 | Bower et al., (2022) | Contexless | Mock-up/ VR (HMD) | Cognitive | EKG, respiratory belt transducer, SCR finger plate electrodes | Blue, white | | 18-55 Aged (18 Adults) |
| 41 | Liu et al. (2022) | Education | VR | Affective, attention | EEG, ECG | Yellow, red, white, blue, and green, while | RGB | 30 |
| 42 | Duyan & Unver (2022) | Education/ Classroom | In-situ | Cognitive | Attention test (Bourdon) | 5R 7/8 Red, 5YR 7/8 Orange, 5Y 7/8 | Munsell | 8-9 aged (43 Children) |
| 43 | Oh & Park (2022) | Contexless | Mock-up | Affective | | 12 green, blue colors | | 24 (9 m, 15 f) |
| 44 | Xu et al. (2022). | Hotel room | VR | Affective | Questionnaire | Yellow, blue, grey | | 112 |
| 45 | Akbay & Demirbaş (2023) | Contexless | Visualization | Affective | International Personality Item Pool (IPIP) | Black, grey, white, Yellow, orange, red, pink, Purple, black, blue, and green | NCS | 37 female, 18 male (18-36 Aged) |
| 46 | Weijs et al. (2023) | Contexless | Mock-up | Affectice, Arousal | Self assestment, GSR | Red, blue | | 60 (39 female, 21 male) |
| 47 | Duyan & Işık (2024) | Education | Visualization | Affective, perceiving | SDS | Red, blue-green, purple | Munsell | 52 (24 female, 28 male) |
| 48 | Ulusoy (2024) | Bedroom | Visualization | Affective, preferetion | | Purple, brown, orange, yellow, blue, green, pink, red | | 100 |
| 49 | Sun et al. (2024) | Education | In-situ | Affective | PANAS-C | Hot (red, yellow), cold (blue, green) | | 123 |
| 50 | Aydoğdu (2024) | Patient room | Visualization (In-situ) | Affective, ppreference | SDS, Likert | Light-medium, saturated (Red, green- | Munsell | 69 (43 female, 26 male), 18-65 Aged |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | yellow, blue, Purple), grey, white (14 Colors) | | |
| 51 | Duyan &Şener (2025) | Office | Visualization | Affective, perceiving | SDS | Light-saturated-dark (Red, red-purple, blue, green-yellow), (12 Colors) | Munsell | 51 (24 female, 27 male) |
| 52 | Yüksektepe & Küçükkılıç Özcan (2025) | Patient room | VR | Affective, preference | SDS, Likert | Light, very slightly saturated-light, slightly saturated-light, moderately saturated (Red, Yellow, green, blue, Purple) neutral (16 colors) | Munsell | 70 |
| 53 | Bölükbaşı & Uç (2025) | Patient room | VR | Affective | PAD | Orange, blue | RGB | 41 female-39 male, 18-67 Aged |
| 54 | Hendi & Mazaherian (2025) | Therapy room | VR | Affective | Self-Assessment Manikin (SAM), PAD | 17 colors | | 57 |

All data were analyzed using descriptive and inferential statistical methods in the SPSS program. Initially, descriptive frequency analyses were performed to determine the distribution of categorical variables. Subsequently, the relationships between parameters were evaluated using the Crosstabs tool, complemented by a qualitative content analysis to systematically categorize the non-numerical methodological insights extracted from the articles. The conceptual schema for the study's analysis is shown in Figure 2.

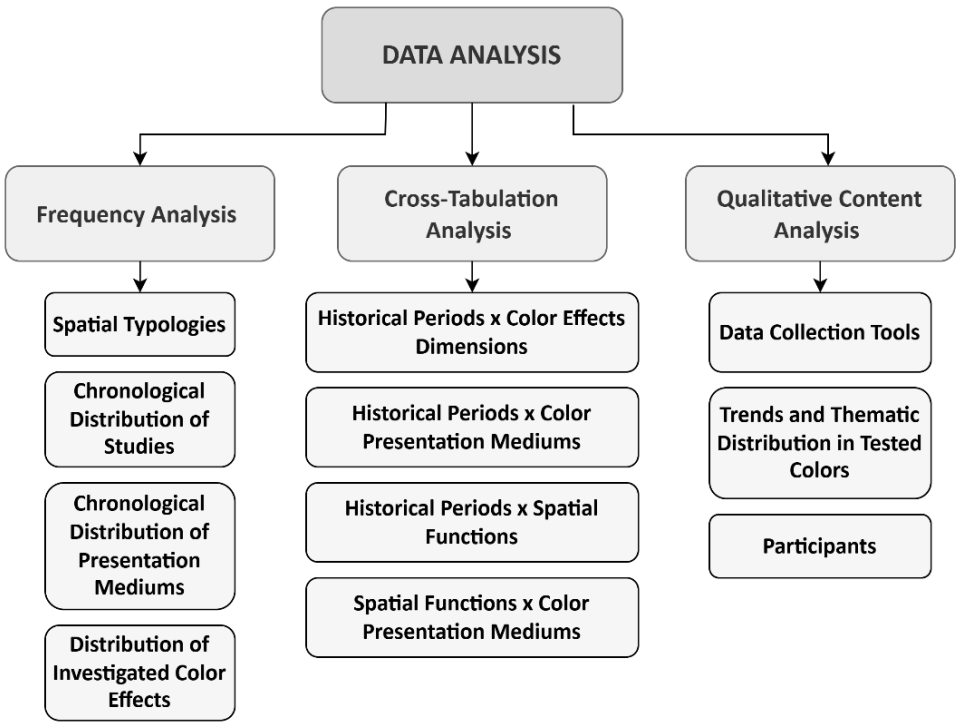



**Figure 2.** Conceptual schema of data analysis (Created by the author)

### 3.1. Frequency Analysis

Descriptive frequency analyses were conducted to reveal the general methodological structure, temporal trends, and architectural functions focused on by empirical research examining color parameters in the built environment. Accordingly, the publication years, spatial typologies, color presentation environments, and tested dependent variable dimensions of the 54 studies included in the systematic review were structured using frequency (f) and percentage (%) distributions calculated via SPSS software.

#### 3.1.1. Spatial typologies

Across the 54 analyzed empirical studies, it was observed that the research tends to concentrate on specific spatial typologies. Notably, the most heavily investigated functions are clustered around Educational ($29.6\%$) and Office environments ($22.2\%$). These are followed respectively by Context-Independent experimental setups ($13.0\%$), Residential settings ($11.1\%$) (e.g., living rooms and bedrooms), and Patient rooms ($9.3\%$). In contrast, studies conducted in more specialized Environments such as bank branches, hotel rooms, therapy rooms, hair salons, and prison cells remain highly limited in number and are aggregated under the 'Other' category ($14.8\%$). This distribution demonstrates that color research in the built environment is predominantly focused on learning and work-related contexts, highlighting significant research gaps in environments associated with more diverse user profiles and specialized functions (Table 3).

#### 3.1.2. Chronological distribution of studies

The 54 analyzed studies were categorized into a total of 7 periods consisting of 5-year intervals to accurately reflect the 35-year temporal span. The distribution pattern reveals that environmental color research remained highly limited during the early periods of 1990–1995 ($3.7\%, f = 2$) and 1996–2000 ($5.6\%, f = 3$) (Table 3). Descriptive analysis verifies that the primary turning point and growth momentum of the literature initiated after 2016 ($f = 13, 24.1\%$), reaching its peak in the final period (2021–2025) with 18 studies ($33.3\%$).

**Table 3.** Frequency analysis of chronological periods, spatial functions, and color presentation mediums.

| Varables | Category | Frequency (f) | Percentage (%) |
|---|---|---|---|
| Publication year | 1990-1995 | 2 | 3,7 |
| | 1996-2000 | 3 | 5,6 |
| | 2001-2005 | 4 | 7,4 |
| | 2006-2010 | 6 | 11,1 |
| | 2011-2015 | 8 | 14,8 |
| | 2016-2020 | 13 | 24,1 |
| | 2021-2025 | 18 | 33,3 |
| Spatal function | Education | 16 | 29,6 |
| | Office | 12 | 22,2 |
| | Contexless | 7 | 13 |
| | Residence | 6 | 11,1 |
| | Patient Room | 5 | 9,3 |
| | Others (Hair dressing salon, shop, bank branch, etc.) | 8 | 14,8 |
| Color presentation Medium | Mock-up | 15 | 27,8 |
| | Visualization | 14 | 25,9 |
| | In-situ | 11 | 20,4 |
| | VR (Virtual reality) | 9 | 16,7 |
| | Samples | 5 | 9,3 |
| **Total** | | **54** | **100** |

### 3.1.3. Chronological Distribution of Presentation Mediums

An investigation of the color presentation mediums used in the analyzed studies reveals that early research was predominantly conducted in in-situ environments ($f = 11,\ 20.4\%$) and full-scale experimental settings (Mock-ups, $27.8\%$). With the advancement of computer-based visualization techniques, two-dimensional digital representations became increasingly prevalent ($f = 14, 25.9\%$), and in recent years, the utilization of Virtual Reality (VR) applications has reached a remarkable level ($f = 9, 16.7\%,$ ) (Bölükbaşı & Uç, 2025; Bower et al., 2022; Cha et al., 2020; Hendi & Mazaherian, 2025; Liu et al., 2022; Xu et al., 2022; Yüksektepe & Küçükkılıç, 2025).

VR has become a vital component of contemporary research by replacing the cost and control limitations of in-situ studies with an immersive experience comparable to mock-up accuracy (Heydarian et al., 2015). Additionally, some studies directly utilized standardized color charts/swatches (Samples, $9.3\%, f = 5$) for evaluation purposes (Table 3). Overall, this trend clearly demonstrates a methodological-technological shift toward increasing experimental control and the sense of immersion in environmental color research (Babin et al., 2003; Jalil et al., 2013; Manav, 2007).

### 3.1.4. Distribution of Investigated Color Effects

The analysis of the psychological and perceptual effect types investigated in the analyzed studies reveals that the vast majority of research conducted in architectural environments ($f$ = 48, 88.9%) focuses on affective effects, including mood, psychological comfort, and semantic evaluations. This is followed respectively by cognitive effects ($f = 18, 33.3\%$) and color preferences ($f = 12, 22.2\%$). In contrast, empirical studies investigating the effects of color on spatial perception ($f = 7,\ 13.0\%$) and direct user behavior ($f = 3, 5.6\%$) are determined to remain highly limited in the literature (Table 4).

To identify the dimensions in which the included studies address color parameters and the psychophysical outcomes they focus on, a Multiple Response Frequencies analysis was conducted using the SPSS statistical software. Within the scope of the analysis, a dichotomous variable set was defined, taking into account that a single study could simultaneously investigate multiple dependent variables or effects.

**Table 4.** Frequency distribution of investigated color effects.

| Color Effects Dimensions | Frequency (n) | Usage rate Percentage (%)* |
|---|---|---|
| Emotional/Affective | 48 | 88,9 |
| Cognitive | 18 | 33,3 |
| Color Preference | 12 | 22,2 |
| Spatial Perception | 7 | 13 |
| Behavioral | 3 | 5,6 |
| **Total Responses** | **88** | **163** |

*Because a multiple response analysis was applied, the sum of percentages exceeds $100\%$, and the total number of responses exceeds the total number of articles ($N = 54 < 88$). Percentages were calculated based on the total number of articles.

The analysis results indicate that articles could test more than one effect simultaneously. According to the obtained multiple response frequency distributions, emotional and affective effects represent by far the most heavily focused area in architectural color studies, with a dominant rate of $88.9\%$. Affective effects are followed by cognitive effects with a frequency of $33.3\%$ and direct color preferences with $22.2\%$. On the other hand, the spatial/volumetric effects of color on spatial perception ($13.0\%$) and its direct behavioral outcomes ($5.6\%$) have been found to be investigated to a highly limited extent in the literature (Babin et al., 2003; Duyan & Unver, 2016; Genschow et al., 2015; Read et al., 1999). The operational difficulty of observing or measuring individuals' direct physical behaviors (e.g., purchasing behavior, spatial dwell time, and social interaction) in response to color, compared to administering standard questionnaires, has created a relative research gap in the literature.

The distribution of color effect parameters demonstrates that architectural color research heavily concentrates on users' emotional states and perceptual responses; however, the behavioral and spatial simulation dimensions of color still constitute a significant research gap waiting to be addressed in the literature.

### 3.2. Cross-Tabulation Analysis of Methodological Parameters

To reveal the structural and methodological relationships, historical trends, and patterns among the 54 empirical studies included in the analysis, two-way crosstabulation analyses were conducted. Within this scope, the projections of chronological processes (historical periods) on the measured dimensions of color effects, preferred spatial functions, and utilized color presentation mediums were examined. Additionally, to decode the methodological correlations and tendencies between spatial functions and color presentation mediums, Chi-Square ($\chi^2$) independence tests between categorical variables were executed. These multidimensional analyses present the 35-year methodological transformation of the color literature, the dominant trends in the field, and potential research gaps for future studies within a holistic framework.

#### 3.2.1. Cross-tabulation analysis of historical periods and color effects dimensions

Multiple Response Crosstabulation, conducted to determine which empirical outcomes are measured on users and the historical trends of these measurements over time in built environment color research, reveals the multidimensional structure of the literature (Table 5, Figure 3). It was found that a total of 88 impact dimensions were tested in 54 independent scientific publications included in the review. It was observed that the studies performed an average of 1.63 different impact measurements per article, and due to this experimental diversity, the overall usage rate reached 163.0% of the total number of articles.

A holistic examination of the last 35 years reveals that affective effects have consistently been the primary focus of research. Of the 54 studies included in the review, 88.9% (f = 48) examined the effects of color on human psychology, mood, and psychological comfort. In particular, affective outcomes formed the empirical basis in 92.3% (f=12) of the 13 empirical studies published between 2016-2020 and in 88.9% (f=16) of the 18 articles in the most recent period, 2021-2025. Pearson Chi-Square analysis confirms that the research trend of affective effects does not show a statistically significant difference between periods ($\chi^2$=2.607, df=6, p=0.856). This proves that the affective dimension has always been a focal point in the literature, regardless of the historical process.

Cognitive effects, which examine the influence of color parameters on work and learning performance, concentration, and attention, were investigated in 33.3% of the reviewed studies (f = 18). A period-based analysis showed that cognitive effects accounted for 50.0% of the studies (f = 1) during the 1990–1995 period. As the volume of the literature expanded, this proportion remained relatively stable, reaching 30.8% (f = 4) in 2016–2020 and 33.3% (f = 6) in 2021–2025. No statistically significant association was found between publication period and the frequency with which cognitive effects were investigated ($\chi^2$ = 3.851, df = 6, $p$ = 0.697).

Color preference was examined in 22.2% of the reviewed studies (f = 12). A temporal analysis indicated that color preference was investigated in 66.7% of the studies (f = 2) during the 1996–2000 period, whereas this proportion declined to 22.2% (f = 4) in the most recent period (2021–2025). However, no statistically significant association was identified between publication period and the selection of color preference as an empirical dependent variable ($\chi^2$ = 5.607, df = 6, $p$ = 0.469).

Spatial perception, which encompasses studies examining three-dimensional spatial boundaries, perceived depth, volumetric illusions, and the perception of ceilings and walls, accounted for 13.0% of the reviewed studies ($f$ = 7). The most notable increase in research on spatial perception was observed during the 2016–2020 period, when digital representations and three-dimensional modeling became increasingly prevalent, with 30.8% of the studies published during this period ($f$ = 4) focusing on this topic. In the most recent period (2021–2025), this proportion declined to 11.1% ($f$ = 2). No statistically significant association was found between publication period and the distribution of studies investigating spatial perception ($\chi^2$ = 7.639, df = 6, $p$ = 0.266).

Behavioral effects, which examine the direct influence of color on users' behavior, represented only 5.6% of the reviewed studies (f = 3), making them the least investigated research domain over the past 35 years. Historically, behavioral effects were examined only sporadically, appearing in the 1996–2000 ($f$ = 1, 33.3%), 2011–2015 (f = 1, 12.5%), and 2021–2025 ($f$ = 1, 5.6%) periods. No statistically significant association was identified between publication period and the frequency with which behavioral effects were investigated ($\chi^2$ = 6.618, df = 6, $p$ = 0.358). This finding suggests a persistent and time-independent research gap, likely attributable to the methodological challenges associated with measuring individuals' direct behavioral responses to color.

**Table 5.** Distribution of color effects in built environment research by years (1990–2025)

| Periods | Totaly Researchs (N) | Affective Effect n (%) | Cognitive Effect n (%) | Color Preference n (%) | Spatial Perceive n (%) | Behavioral Effect n (%) |
|---|---|---|---|---|---|---|
| **1990-1995** | **2** | 2 (%100,0) | 1 (%50,0) | 0 (%0,0) | 0 (%0,0) | 0 (%0,0) |
| **1996-2000** | **3** | 3 (%100,0) | 2(%66,7) | 2 (%66,7) | 0 (%0,0) | 1 (%33,3) |
| **2001-2005** | **4** | 3 (%75,0) | 2 (%50,0) | 1 (%25,0) | 0 (%0,0) | 0 (%0,0) |
| **2006-2010** | **6** | 5 (%83,3) | 2 (%33,3) | 1 (%16,7) | 0 (%0,0) | 0 (%0,0) |
| **2011-2015** | **8** | 7 (%87,5) | 1 (%12,5) | 2 (%25,0) | 1 (%12,5) | 1 (%12,5) |
| **2016-2020** | **13** | 12 (%92,3) | 4 (%30,8) | 2 (%15,4) | 4 (%30,8) | 0 (%0,0) |
| **2021-2025** | **18** | 16 (%88,9) | 6 (%33,3) | 4(%22,2) | 2 (%11,1) | 1 (%5,6) |
| **Totaly** | **54** | **48 (%88,9)** | **18 (%33,3)** | **12 (%22,2)** | **7 (%13)** | **3(%5,6)** |

*Because a multiple response analysis was applied, the sum of percentages exceeds 100%, and the total number of responses exceeds the total number of articles ($N = 54 < 88$). Percentages were calculated based on the total number of articles.

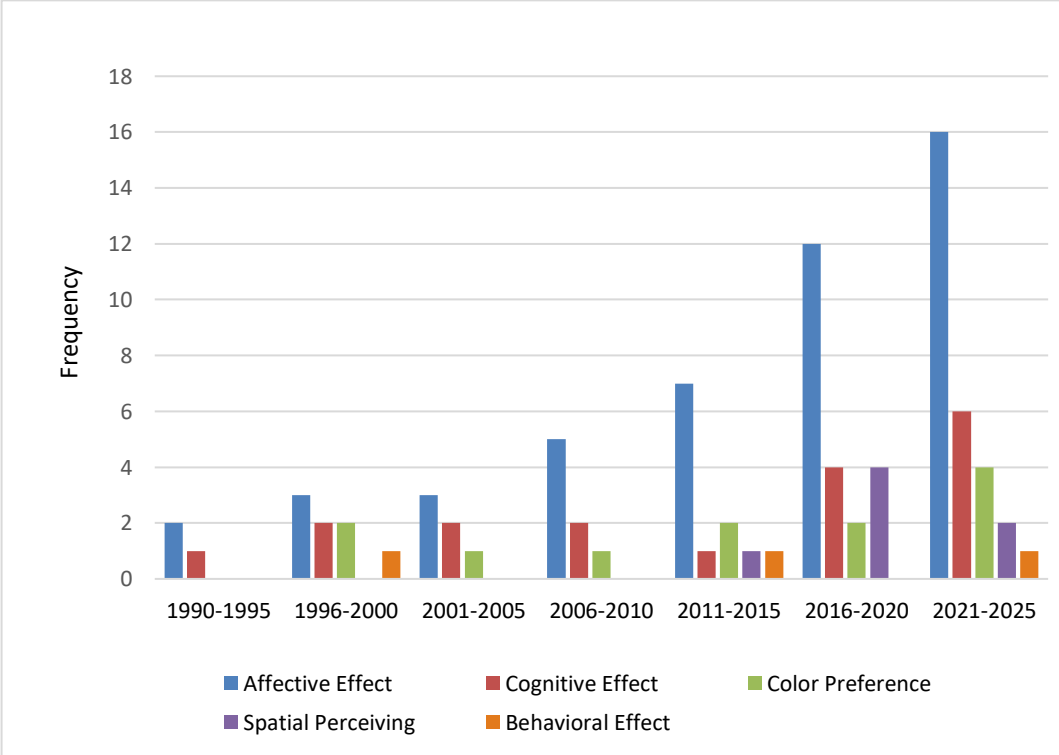



**Figure 3.** Distribution of investigated color effects in built environment research by years (1990–2025) (Created by the author)

### 3.2.2. Cross-tabulation analysis of historical periods and color presentation mediums

A Pearson's chi-square test was conducted to examine the relationship between historical periods and the color presentation mediums employed in empirical studies. The results indicated no statistically significant categorical association between the two variables ($\chi^2 = 33.237,\ df = 24,\ p = 0.099,\ V = 0.392$). Although the overall association did not reach the conventional level of statistical significance ($p \leq 0.05$), the obtained Cramer's *V* value (0.392) indicates a moderate effect size, suggesting a meaningful methodological trend. This finding implies that the relatively small sample size (N = 54) may have limited the statistical power of the chi-square test, preventing the association from reaching statistical significance despite the presence of practically meaningful temporal patterns. An examination of the period-specific frequency distributions and row and column percentages reveals a clear methodological transition toward digital color presentation environments over time (Table 6).

During the 1990–1995 period, all studies (100.0%, f = 2) employed mock-up environments. Similarly, mock-up methods were used in 66.7% (f = 2) of the studies published between 1996 and 2000 and in 50.0% (f = 2) of those published during 2001–2005. These findings reflect the methodological constraints of the early research period, when immersive digital simulation technologies such as virtual reality (VR) were either unavailable or not sufficiently accessible for experimental applications. Consequently, researchers relied primarily on full-scale physical mock-ups and controlled laboratory settings to investigate the effects of color parameters. Despite the subsequent emergence of digital technologies, the mock-up approach has maintained a stable presence throughout the study period.

In-situ studies conducted in real architectural environments also represented a consistently employed research method across the reviewed literature. Their temporal distribution demonstrates relatively stable usage throughout the intermediate periods, accounting for 33.3% of the studies in 1996–2000, 25.0% in 2001–2005, 37.5% in 2011–2015, and 23.1% in 2016–2020. These findings indicate that field-based investigations remained an important methodological approach for evaluating users' responses to color in environmental settings.

The visualization approach, encompassing two-dimensional digital images, rendered scenes, and computer-generated visualizations, first emerged in the literature during the 2006–2010 period, representing 33.3% of the studies published during that interval. Its adoption increased substantially over time, accounting for 38.9% (f = 7) of the studies published between 2021 and 2025, thereby becoming one of the two most frequently employed color presentation methods. This trend suggests that continuous improvements in rendering technologies, display quality, and screen calibration have encouraged researchers to adopt flexible digital visualization techniques while reducing the cost and logistical complexity associated with constructing physical experimental environments.

The introduction of virtual reality (VR) marked the most notable methodological transformation in recent years. No VR-based color presentation studies were identified before 2016. However, VR accounted for 23.1% (f = 3) of the studies conducted during the 2016–2020 period and increased further to 33.3% (f = 6) in 2021–2025, making it one of the two most frequently adopted presentation methods in the most recent period.

Conversely, the proportion of in-situ studies declined markedly, decreasing from 37.5% during 2011–2015 to only 11.1% in the 2021–2025 period. This shift indicates that contemporary researchers increasingly favor digital presentation environments, particularly visualization techniques and VR, over physical field experiments or mock-up settings because of their advantages in experimental control, flexibility, cost efficiency, and the ability to standardize environmental conditions across participants.

**Table 6.** Distribution and Trends in Color Presentation Media by Period

| Publication Year | In-situ f (%) | Mock-up f (%) | Visualization f (%) | VR f (%) | Samples f (%) | Total f (%) |
|---|---|---|---|---|---|---|
| 1990-1995 | 0 (0,0%) | 2 (100,0%) | 0 (0,0%) | 0 (0,0%) | 0 (0,0%) | 2 (3,7%) |
| 1996-2000 | 0 (0,0%) | 3 (100,0%) | 0 (0,0%) | 0 (0,0%) | 0 (0,0%) | 3(5,6)% |
| 2001-2005 | 2 (50,0%) | 1(25,0%) | 0 (0,0%) | 0 (0,0%) | 1 (25,0%) | 4 (7,4%) |
| 2006-2010 | 1 (16,7%) | 1 (16,7%) | 2 (33,3%) | 0 (0,0%) | 2 (33,3%) | 6 (11,1%) |
| 2011-2015 | 3 (37,5%) | 2 (25,0%) | 2 (25,0%) | 0 (0,0%) | 1 (12,5%) | 8 (14,8%) |
| 2016-2020 | 3 (23,1%) | 3 (23,1%) | 3 (23,1%) | 3 (23,1%) | 1 (7,7%) | 13 (24,1%) |
| 2021-2025 | 2 (11,1%) | 3 (16,7%) | 7 (38,9%) | 6 (33,3%) | 0 (0,0%) | 18 (33,3%) |
| Total (f) | 11 | 15 | 14 | 9 | 5 | 54 |
| General Rate (%) | 20,40% | 27,80% | 25,90% | 16,70% | 9,30% | 100,00% |

### 3.2.3. Cross-tabulation analysis of historical periods and spatial functions

To examine the historical development and temporal trends of the spatial functions (typologies) investigated in color research, cross-tabulation and chi-square analyses were conducted between publication periods (grouped into five-year intervals) and spatial function categories.

The statistical analyses yielded a Pearson's chi-square value*, $\chi^2$= 62,619, (df = 60, p = 0.383),* and a Cramer's *V* of 0.440. Although these results indicate no statistically significant categorical association between publication period and spatial function ($p > 0.05$), the *Linear-by-Linear Association* statistic was statistically significant ($\chi^2 = 6.701$, $p = 0.010$). This finding demonstrates a significant linear temporal trend, indicating that the types and diversity of spatial functions investigated have changed systematically over time rather than by chance. The Cramer's *V* value (0.440) further suggests that this structural trend represents a moderate-to-strong association.

The frequency distribution of the 54 reviewed studies across publication periods (1990–1995: 2; 1996–2000: 3; 2001–2005: 4; 2006–2010: 6; 2011–2015: 8; 2016–2020: 13; 2021–2025: 18) demonstrates a substantial expansion of the literature during the last decade, with 57.4% of all studies published after 2015. Accompanying this growth, notable shifts in the spatial typologies investigated were observed (Table 7). Office environments dominated the early literature, accounting for 100.0% of the studies published during 1990–1995 ($f = 2$), 66.7% during 1996–2000 ($f = 2$), and 50.0% during 2006–2010 ($f = 3$). These findings suggest that early color research primarily focused on optimizing workplace productivity, computer-based work performance, visual comfort, and environmental stress within office settings.

Educational environments constituted the largest spatial category in the overall dataset, representing 29.6% of the reviewed studies (f = 16). However, their temporal distribution reveals that 12 of these 16 studies (75.0%) were published after 2015, with six studies (46.2%) conducted during 2016–2020 and another six studies (33.3%) during 2021–2025. This pattern confirms that, over the past decade, the relationship between color, lighting, and environmental comfort in learner-centered educational environments has become a major focus of research, reflecting the growing emphasis on active learning, flexible educational spaces, and student well-being.

**Table 7.** Distribution of Spatial Functions by Period

| Periods | Office (n) | Education (n) | Residence (n) | Patient Room (n) | Contexless (n) | Other Functions * (n) | Period Total (N / %) |
|---|---|---|---|---|---|---|---|
| **1990-1995** | 2 (100%) | 0 (0,0%) | 0 (0,0%) | 0 (0,0%) | 0 (0,0%) | 0 (0,0%) | **2** (%3,7) |
| **1996-2000** | 2 (66,6%) | 1 (33,3%) | 0 (0,0%) | 0 (0,0%) | 0 (0,0%) | 0 (0,0%) | **3** (%5,6) |
| **2001-2005** | 1 (25,0%) | 1 (25,0%) | 0 (0,0%) | 0 (0,0%) | 0 (0,0%) | 2 (50,0%) | **4** (%7,4) |
| **2006-2010** | 3 (50%) | 0 (0,0%) | 1 (16,7%) | 1 (16,7%) | 0 (0,0%) | 1 (16,7%) | **6** (%11,1) |
| **2011-2015** | 2 (25%) | 2 (25%) | 2 (25%) | 0 (0,0%) | 0 (0,0%) | 2 (25%) | **8** *(%14,8)* |
| **2016-2020** | 1 (7,7%) | 6 (46,2%) | 2 (15,4%) | 0 (0,0%) | 3 (23,1%) | 1 (7,7%) | **13** *(%24,1)* |
| **2021-2025** | 1 (5,6%) | 6 (33,3%) | 1 (5,6%) | 4 (22,2%) | 4 (22,2%) | 2 (11,2%) | **18** *(%33,3)* |
| **Total (n / %)** | **12** *(%22,2)* | **16** *(%29,6)* | **6** *(%11,1)* | **5** *(%9,3)* | **7** *(%13,0)* | **8** *(%14,8)* | **54** *(%100,0)* |

Other Functions*: Hairdressing, Shop, Prison cell, Hotel room, Library

Of the five studies investigating patient rooms included in the dataset, 80.0% (*f* = 4) were published during the most recent period (2021–2025), representing 22.2% of the studies conducted within that period. This marked increase may be interpreted as reflecting the growing influence of healing environments, evidence-based design, and post-pandemic design approaches emphasizing user health and well-being within the field of environment–behavior research.

Whereas the early literature focused primarily on a limited range of spatial typologies, such as offices, educational environments, and retail spaces, studies published after 2015 expanded to include more specialized settings, including hotel rooms, libraries, and prison cells. One of the most notable findings is that 57.1% (*f* = 4) of the seven *contexless* studies were published during the 2021–2025 period. This trend suggests that recent advances in digital technologies, particularly virtual reality (VR), have enabled researchers to isolate spatial variables and conduct more controlled experiments focusing directly on the fundamental effects of color parameters, independent of specific architectural contexts.

### 3.2.4. Cross-Tabulation Analysis of Spatial Functions and Color Presentation Mediums

To examine the relationship between spatial functions (spatial typologies) and the color presentation mediums used to deliver color stimuli to participants, a cross-tabulation analysis and Pearson's chi-square test of independence were conducted on the 54 empirical studies included in this review. The results revealed a statistically significant association between the spatial function investigated and the color presentation medium employed ($\chi^2 = 56.630$, df = 40, p = 0.042, Cramer's V = 0.512). Since the p-value was below the conventional significance threshold ($p < 0.05$), the findings indicate that the selection of color presentation mediums varies systematically according to the spatial typology being investigated rather than occurring by chance.

An examination of the overall distribution of spatial functions and presentation mediums shows that the literature has primarily focused on educational environments (29.6%) and office environments (22.2%). Regarding presentation methods, mock-up environments (27.8%) and visualization techniques (25.9%) were the most frequently employed approaches.

Among the 12 studies focusing on office environments, more than half (58.3%) used mock-up environments, consisting of full-scale physical models or controlled laboratory settings, to present color stimuli. Furthermore, 46.7% of all mock-up studies (15 studies in total) were conducted in office settings. This pattern may be explained by the fact that office-based color research frequently investigates long-term cognitive performance, concentration, and productivity, which require highly

controlled experimental conditions. Full-scale physical environments minimize potential confounding factors associated with digital displays, such as color distortion and screen flicker, thereby providing a more natural and reliable representation of color.

Educational environments exhibited the greatest methodological diversity, encompassing 16 studies employing multiple presentation mediums. Of these, 37.5% were conducted as in-situ experiments in real educational settings, while 31.3% employed visualization techniques. More than half (54.5%) of the 11 in-situ studies in the dataset were carried out in educational environments. The widespread use of field experiments in schools and university classrooms is likely attributable to the ease of accessing participants, existing lighting systems, and authentic learning environments, making these settings particularly suitable for evaluating users' responses to color under real-world conditions.

A clear preference for digital simulation techniques was observed in spatial typologies with more restricted accessibility, particularly residential environments (6 studies) and patient rooms (5 studies). Half of the residential studies (50.0%) employed visualization techniques, whereas studies involving patient rooms relied equally on visualization (40.0%) and virtual reality (VR) (40.0%). In healthcare settings, where infection control, patient safety, and psychological well-being are critical considerations, the logistical and ethical constraints associated with physical interventions through in-situ experiments or mock-up environments appear to have encouraged researchers to adopt digital presentation methods capable of evaluating alternative color schemes under highly controlled conditions without disrupting clinical environments (Table 8).

**Tablo 8.** Distribution of Color Presentation Mediums According to Spatial Functions

| Function | In-situ (n) | Mock-up (n) | Visualization (n) | VR (n) | Samples (n) | Total Function (N / %) |
|---|---|---|---|---|---|---|
| **Education** | 6 | 3 | 5 | 1 | 1 | **16** *(%29,6)* |
| **Office** | 0 | 7 | 3 | 1 | 1 | **12** *(%22,2)* |
| **Contexless** | 0 | 3 | 0 | 4 | 0 | **7** *(%13,0)* |
| **Residence** | 1 | 0 | 3 | 0 | 2 | **6** *(%11,1)* |
| **Hasta Odası** | 1 | 0 | 2 | 2 | 0 | **5** *(%9,3)* |
| **Other Functions*** | 3 | 2 | 1 | 1 | 1 | **8** *(%14,8)* |
| **Toplam (n / %)** | **11** *(%20,4)* | **15** *(%27,8)* | **14** *(%25,9)* | **9** *(%16,7)* | **5** *(%9,3)* | **54** *(%100,0)* |

Other Functions*: Hairdressing, Shop, Prison cell, Hotel room, Library

Virtual Reality (VR) was used in 57.1% of the 7 “Context-Free” studies, which did not define a specific spatial function and aimed to isolate the direct abstract psychological/emotional effects of color. Nearly half (44.4%) of the total 9 VR studies fall into this category. This data confirms the flexibility that VR technology offers researchers in creating isolated laboratory environments stripped of spatial cues, where external stimuli are completely controlled.

### 3.3. Qualitative Content Analysis

Due to the high diversity of color variations in the studies, the combined use of heterogeneous systems based on verbal (e.g., “hot/cold,” “complexity”) or numerical criteria instead of standard codes, and the fact that data collection tools varied depending on the measured variables, it was not possible to create a quantitative matrix in SPSS. To overcome this methodological limitation and gain a holistic view of the structural trends in literature, the parameters of the 54 studies included in the research were subjected to qualitative content analysis. Accordingly, systematic thematic coding was performed based on color stimulus characteristics, the color systems used, data collection tools, and participant profiles.

### 3.3.1. Data collection tools

The data collection instruments employed to assess users' responses to color varied according to the empirical depth of the studies, the dependent variables investigated, and the historical evolution of research methodologies. Across the reviewed literature, the Semantic Differential Scale (SDS) emerged as the most frequently used instrument. In particular, studies by Yıldırım et al. (2007), Yıldırım et al. (2011), Yıldırım et al. (2012), Yıldırım et al. (2019), Duyan & Unver (2016), Duyan & Işık (2024), Duyan & Şener (2025), Öztürk (2012), Tantanatewin & Inkarojrit (2016), and Müezzinoğlu (2018) adopted the SDS as the primary tool for evaluating users' perceptions of color, spatial impressions, and affective responses. In addition, several standardized psychological assessment instruments were employed to measure mood and emotional states, including the Profile of Mood States (POMS) (Kwallek & Lewis, 1990; Kwallek et al., 1996), the Multiple Affect Adjective Check List (MAACL) (Ainsworth et al., 1993; Stone & English, 1998; Stone, 2001), the Pleasure–Arousal–Dominance (PAD) scale (Siamionava et al., 2018; Bölükbaşı & Uç, 2025; Hendi & Mazaherian, 2025), and the Positive and Negative Affect Schedule for Children (PANAS-C) (Sun et al., 2024).

Studies investigating the effects of color on cognitive outcomes, such as work performance, learning, and concentration, relied on objective performance measures in addition to self-reported assessments. To evaluate attention, learning, and cognitive performance, researchers employed instruments including the Bourdon Attention Test (Duyan & Ünver, 2022), the Lern- und Merkfähigkeitstest (LMT) (von Castell et al., 2018), Scholastic Assessment Test (SAT) comprehension tasks (Al-Ayashi et al., 2016; Cha et al., 2020), and a variety of clerical and office-based performance tasks (Ainsworth et al., 1993; Kwallek et al., 2007).

In recent years, advanced physiological measurement technologies capable of capturing participants' immediate and involuntary responses have become increasingly integrated into color research. Küller et al. (2016), Llinares et al. (2021), and Liu et al. (2022) employed electroencephalography (EEG) and electrocardiography (ECG) to record brain activity and cardiac responses. Similarly, Bower et al. (2022) combined ECG with a respiratory belt transducer and skin conductance response (SCR) finger electrodes, whereas Weijs et al. (2023) utilized galvanic skin response (GSR) sensors to monitor autonomic nervous system activity. The integration of these neurophysiological measurement techniques has enabled researchers to obtain objective indicators of individuals' responses to color, complementing traditional self-report measures and reducing reliance on subjective evaluations.

The relatively small number of studies examining the influence of color on users' observable behavior and social interaction primarily relied on observational methodologies. Read et al. (1999), for example, employed the Parten Social Participation Scale to code children's social behaviors in play environments. Likewise, Duyan and Ünver used a structured teacher observation form to document the behavioral responses of primary school children aged 8–9 years under different classroom wall color conditions. Similarly, Genschow et al. (2015), who investigated the effects of color in prison cells, validated their findings through structured behavioral observation.

### 3.3.2. Characteristics of Tested Color Stimuli

The characteristics of the color stimuli employed in empirical studies have changed over time. A qualitative examination of the reviewed literature reveals clear trends in color selection, the number of colors tested, and the methods used to specify color stimuli.

From the early years of the literature to the present, most researchers have favored primary and contrasting color combinations in laboratory and digital experimental settings in order to reduce experimental complexity. In particular, the red–blue color pair, either alone or combined with green and white, has remained one of the most frequently employed color schemes (e.g., Kwallek & Lewis, 1990; Stone & English, 1998; Bakker et al., 2013; Weijs et al., 2023).

In contrast, several studies adopted substantially larger color sets to capture users' responses across a broader range of color stimuli. Manav (2007) and Park (2013) investigated 41 and 45 colors, respectively, while Ulusoy (2020) evaluated 42 colors and Lipson-Smith et al. (2021) employed 40 colors to maximize visual diversity within the experimental environment. More recent studies have

continued this trend by utilizing multiple color stimuli, including Aydoğdu (2024) with 14 colors, Yüksektepe & Küçükkılıç (2025) with 16 colors, and Hendi & Mazaherian (2025) with 17 colors.

The reviewed studies also demonstrate increasing attention to specifying colors not only by their common names but also according to their hue, value, and chroma. For example, Kwallek et al. (1996) evaluated nine color schemes composed of different shades of red, blue, and white, whereas Duyan & Ünver (2022) specified color stimuli using precise Munsell notations, such as 5R 7/8 Red and 5Y 7/8 Yellow. Similarly, Yüksektepe & Küçükkılıç (2025), Duyan & Işık (2024), and Duyan & Şener (2025) systematically classified color stimuli according to variations in hue, value, and chroma before presenting them to participants.

The qualitative analysis further reveals a lack of methodological consistency in the standardization of color stimuli across empirical studies. The Munsell Color System constitutes the most widely adopted and scientifically established framework for defining hue, value, and chroma in environment–behavior research (Kwallek & Lewis, 1990; Stone & English, 1998; Duyan & Ünver, 2022; Aydoğdu, 2024; Duyan & Şener, 2025; Yüksektepe & Küçükkılıç, 2025). However, several studies employed the Natural Color System (NCS) (Öztürk, 2012; Al-Ayashi et al., 2016; Akbay & Demirbaş, 2023), while the increasing use of digital visualization and virtual reality technologies has led to the adoption of RGB color specifications in screen-based experiments (Çağatay & Hidayetoğlu, 2016; Cha et al., 2020; Bölükbaşı & Uç, 2025). Nevertheless, a considerable proportion of the 54 reviewed studies did not report any internationally recognized color specification system (e.g., Munsell, NCS, or RAL). This lack of technical reporting represents a notable methodological limitation that restricts the reproducibility and comparability of empirical color research.

### 3.3.3. Sample characteristics and participant profiles

Sample characteristics constitute a fundamental methodological component of empirical color research, as they directly influence the reliability, generalizability, and contextual relevance of research findings. The reviewed studies exhibit considerable diversity in terms of sample size, age groups, and demographic characteristics. Nevertheless, participant selection appears to vary according to the research setting, spatial function, and experimental methodology employed, while also revealing several consistent methodological patterns across the literature.

Sample sizes ranged from laboratory-based micro-samples consisting of only 18 participants (Bower et al., 2022) to large-scale studies involving as many as 939 participants (Çağatay & Hidayetoğlu, 2016). Studies employing digital visualization and computer-based presentation techniques generally achieved substantially larger sample sizes than those conducted in controlled physical environments. For example, Jalil et al. (2013) recruited 798 participants, whereas Pourbagher et al. (2020) included 275 participants. Despite this variability, the majority of empirical studies employed sample sizes ranging between 50 and 150 participants to ensure adequate experimental control while maintaining manageable data collection procedures (e.g., Dijkstra et al., 2008 [89 participants]; Yıldırım, 2012 [70 participants]; Savavibool & Moorapun, 2017 [80 participants]; Duyan & Işık, 2024 [52 participants]; Aydoğdu, 2024 [69 participants]).

With regard to participant profiles, the reviewed literature predominantly relied on university students and adult participants. However, the age composition of the samples varied according to the spatial function and target user group under investigation. For example, Read et al. (1999) examined children aged 3–5 years in studies of educational environments, whereas Duyan & Ünver (2016, 2022) investigated the responses of primary school children aged 8–9 years to different classroom color conditions. In contrast, Edge (2003), who examined patient rooms in healthcare settings, included participants ranging in age from 26 to 89 years, thereby encompassing older adults as well. Furthermore, many recent studies have sought to maintain a balanced representation of female and male participants, reflecting an increasing emphasis on demographic balance to enhance the empirical validity and representativeness of research findings.

## 4. Conclusion and Suggestions

This study systematically reviewed 54 empirical studies on color in the built environment published between 1990 and 2025, providing a comprehensive overview of the methodological development of the field over the past 35 years. Unlike previous review studies, which primarily summarize empirical findings, the present study focused exclusively on the methodological characteristics of the reviewed research. The selected studies were systematically analyzed and compared in terms of spatial functions, types of effects investigated, color presentation media, data collection instruments, color specification systems, and participant characteristics. Accordingly, this study presents a comprehensive methodological framework that illustrates the historical evolution of empirical color research in the built environment.

The findings indicate a substantial increase in the number of empirical color studies over the last decade, accompanied by considerable methodological diversification driven by advances in digital technologies. Nevertheless, the fundamental research directions have remained relatively consistent over time. Most studies have focused on the effects of color on mood, psychological comfort, and spatial perception, whereas investigations addressing behavioral responses remain remarkably limited. This finding suggests that significant research gaps still exist, particularly regarding the cognitive and, more importantly, the behavioral effects of color within built environments.

From the perspective of spatial functions, early studies predominantly focused on office environments, whereas educational settings have emerged as the most extensively investigated spatial typology in recent years. Furthermore, the increasing inclusion of specialized settings, such as patient rooms, hotel rooms, libraries, and contextless experimental environments, reflects the growing interdisciplinary and user-centered nature of color research.

One of the most notable methodological transformations identified in this review concerns the evolution of color presentation media. While early studies primarily relied on physical mock-up environments and in-situ experiments, recent research has increasingly adopted computer-based visualizations and, particularly, virtual reality (VR) technologies. The enhanced experimental control, flexibility, cost-effectiveness, and standardized testing conditions offered by digital presentation media have encouraged researchers to adopt these approaches more frequently. Parallel to this development, the integration of neurophysiological measurement techniques—including electroencephalography (EEG), electrocardiography (ECG), and galvanic skin response (GSR)—has enabled researchers to objectively assess participants' physiological responses alongside conventional subjective evaluations.

Despite these methodological advances, the reviewed studies also revealed several important methodological limitations. In particular, the absence of internationally recognized color specification systems (e.g., Munsell, NCS, or RAL), insufficient reporting of lighting conditions, and the inadequate description of the technical properties of color stimuli in a considerable number of studies limit both the reproducibility and the comparability of empirical findings. Likewise, the predominance of university students and young adults as research participants restricts the generalizability of existing findings to broader user populations and different age groups.

Based on these findings, future empirical studies should adopt internationally recognized color specification systems and report not only hue but also value and chroma as essential attributes of color stimuli. In addition, systematically documenting technical parameters such as illuminance levels, correlated color temperature (CCT), color rendering index (CRI), screen calibration, and other characteristics of the experimental environment is recommended to enhance methodological rigor and facilitate replication. Future research would also benefit from placing greater emphasis on behavioral responses to color, validating findings obtained in virtual reality environments through comparisons with real-world settings, integrating neurophysiological measurements with subjective assessment scales, and recruiting more diverse participant samples representing children, older adults, and other user groups.

In conclusion, this study systematically analyzed the methodological characteristics and historical evolution of empirical color research in the built environment. By synthesizing methodological trends across spatial functions, investigated effect types, color presentation media, data collection instruments, color specification systems, and participant characteristics, the study provides a comprehensive methodological framework for the field. This framework is expected to serve as a valuable reference for the design of future empirical color studies and to promote more standardized, comparable, and reproducible research in the built environment.

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The article complies with national and international research and publication ethics. Ethics Committee approval was not required for the study.

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This study was written by a single author. There is no conflict of interest.

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# Adaptive Facade Systems: An Evaluation of Design Scales and System Principles

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**Abstract**

*This study investigates adaptive facade systems as innovative architectural solutions that enhance building energy efficiency and occupant comfort in response to changing environmental conditions. By employing a literature review methodology, the research identifies key adaptive facade types—such as active, kinetic, smart, interactive, and biomimetic—and examines their classification, control mechanisms, and material characteristics. Particular attention is given to the environmental parameters (solar radiation, wind, humidity, and noise) that influence facade performance and the control parameters (thermal comfort, visual comfort, indoor air quality, acoustic comfort, and energy generation) that adaptive facades are designed to optimize. The study also categorizes adaptation methods as static or dynamic and highlights control strategies as intrinsic or extrinsic. Findings demonstrate that adaptive facades, through smart materials and responsive technologies, represent an integrated design approach that aligns energy efficiency with environmental responsiveness. The study provides a theoretical foundation for further research and application in performance-based, sustainable architecture.*

***Keywords:*** *Adaptive Facade, Dynamic Envelope, Climate Responsiveness, Smart Building.*

# Adaptif Cephe Sistemleri: Tasarım Ölçekleri ve Sistem Prensipleri Üzerine Bir Değerlendirme

**Öz**

*Bu çalışma, değişen çevresel koşullara yanıt verebilen ve böylece yapıların enerji verimliliğini ve kullanıcı konforunu artıran yenilikçi mimari çözümler olarak adaptif cephe sistemlerini incelemektedir. Literatür taraması yöntemiyle yürütülen araştırmada; aktif, kinetik, akıllı, etkileşimli ve biyomimetik gibi temel adaptif cephe türleri belirlenmiş, bu sistemlerin sınıflandırma biçimleri, kontrol mekanizmaları ve malzeme özellikleri analiz edilmiştir. Güneş ışınımı, rüzgâr, nem ve ses gibi fiziksel çevresel parametrelerin cephe performansı üzerindeki etkilerine ve bu etkileri optimize etmeyi amaçlayan kontrol parametrelerine (termal konfor, görsel konfor, iç hava kalitesi, akustik konfor ve enerji üretimi) odaklanılmıştır. Adaptasyon yöntemleri statik ve dinamik; kontrol stratejileri ise içsel ve dışsal olarak sınıflandırılmıştır. Çalışmanın bulguları, akıllı malzemeler ve duyarlı teknolojiler yoluyla adaptif cephelerin çevresel koşullara uyum sağlayan, enerji verimli ve entegre tasarım yaklaşımları sunduğunu ortaya koymaktadır. Bu çalışma, sürdürülebilir ve performansa dayalı mimarlık bağlamında kuramsal bir temel sunmaktadır.*

***Anahtar kelimeler:*** *Adaptif Cephe, Dinamik Kabuk, İklim Duyarlılığı, Akıllı Bina.*

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## 1. Introduction

Contemporary architectural design is increasingly defined by the need to address multifaceted challenges that extend well beyond traditional notions of aesthetics and function. In an era marked by rapid urbanization, global warming, rising energy consumption, and the depletion of natural resources, the built environment plays a critical role in shaping the sustainability agenda. Buildings account for a significant proportion of global energy use and carbon emissions, making it imperative that architects and designers examine innovative strategies to reduce environmental effect while enhancing indoor comfort (Wigginton & Harris, 2002; Loonen et al., 2015). In this context, the building envelope has come to be viewed not simply as a protective outer shell but as a dynamic, responsive interface that mediates the relationship between the interior environment and external climatic conditions. This shift in perspective has led to the emergence of adaptive facade systems, which are designed to respond to changing environmental stimuli—such as solar radiation, wind, humidity, temperature, and daylight—in real time. These systems enable buildings to operate more efficiently by adjusting their physical or functional characteristics according to external conditions, often through kinetic, smart, or interactive mechanisms (Romano et al., 2018).

Adaptive facades serve a dual purpose. On one hand, they improve the energy performance of buildings by regulating heat gain and loss, managing solar exposure, and supporting natural ventilation. On the other hand, they contribute to occupant well-being by enhancing visual, thermal, and acoustic comfort. Through the integration of smart materials, automated controls, sensors, actuators, and responsive geometries, these systems embody a convergence of architecture, engineering, and environmental science. As Aelenei et al. (2018) suggest, adaptive facades represent a paradigm shift in architectural practice—one that emphasizes performance-based, responsive, and intelligent design over static, prescriptive solutions. However, the successful implementation of adaptive facade systems is contingent upon a comprehensive understanding of their typologies, control principles, material properties, and the specific environmental parameters they are intended to address. Technological innovation alone is insufficient without an integrated design approach that considers the physical context, user needs, operational logic, and energy goals. Moreover, the architectural integration of such systems requires critical consideration of scale, adaptability, aesthetics, and long-term functionality.

This study aims to investigate adaptive facade systems through a holistic and multi-scalar perspective, focusing on their classification, functional components, control strategies, and interaction with environmental variables. In particular, the research seeks to examine how adaptive facades can respond effectively to physical environmental factors—such as solar radiation, wind, humidity, and noise—while simultaneously enhancing energy efficiency and occupant comfort. By analyzing both the theoretical system and real-world applications, this study contributes to the growing discourse on high-performance architecture and the role of responsive systems in the design of sustainable buildings.

## 2. Material and Method

This study was conducted with the aim of establishing a conceptual system for adaptive facade systems and evaluating their classification schemes, relationships with environmental parameters, and control strategies through a holistic approach. Within the scope of the research, one of the qualitative research methods, the literature review, was employed. A literature review is a research method that enables the systematic examination of previously conducted academic studies on a specific topic and the structuring of the existing body of knowledge through analysis and interpretation. In this context, theoretical approaches to adaptive facade systems, technical classifications, system components, environmental interaction strategies, and material-based applications were compiled from written sources and analyzed through a content-oriented perspective.

During the research process, both national and international publications were systematically reviewed, including academic journal articles, theses, conference proceedings, book chapters, and reports related to the subject. Various academic databases, digital libraries, and scholarly search engines were utilized during the scanning phase. The collected sources were categorized according to

themes aligned with the research questions and were evaluated within a coherent theoretical structure. Through this method, key approaches and trends in the existing literature were identified, and the characteristics of different facade types along with their adaptive strategies in response to environmental conditions were systematically revealed. Thus, the theoretical foundation of the study was strengthened, providing a solid basis for the analyses presented in the subsequent sections.

## 3. Findings and Discussion

### 3.1. Types of Adaptive Facades

In the literature, adaptive facade systems are categorized into various subtypes such as active facades, kinetic facades, intelligent facades, interactive facades, and biomimetic facades (Romano et al., 2018; Aelenei et al., 2018; Engin, 2022). These subcategories represent key criteria for defining a facade's adaptability potential. Adaptive facades, which are expected to respond to changing environmental conditions, demonstrate varying adaptation capabilities and methods depending on their inherent facade characteristics. An adaptive facade system can be designed based on the properties of a single facade type, or it can be developed as a hybrid system incorporating multiple characteristics from different facade categories. For example, the adaptive facade of the Campus Kolding building in Denmark represents a hybrid adaptive system. Thanks to its components and integrated technological features, this facade exhibits the combined functions of a kinetic, interactive, and responsive facade (Aelenei et al., 2018).

#### 3.1.1. Active facades

Active facade systems are designed to help minimize the building's energy consumption while ensuring optimal indoor comfort conditions. These systems include facade components that can easily integrate with external environmental conditions. In response to changing environmental stimuli, active facades are capable of continuously controlling their formal or chemical deformations, either through automated control mechanisms or manual user input, depending on the needs of the occupants (Ruitenbeek, 2016; Ochoa & Capeluto, 2008; Romano et al., 2018). The responsiveness and activeness of these systems can be enhanced through the integration of smart sensors, automation technologies, and data analysis networks, which enable more precise environmental adaptation and energy efficiency as seen in Figure 1.

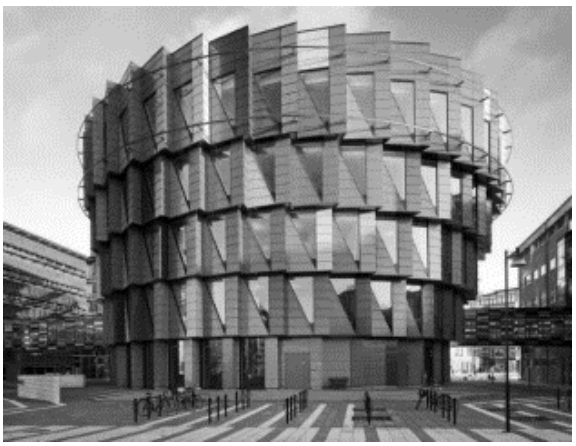


**Figure 1.** Kuggen Building's Active Facade (Sweden-Gothenburg, 2011) (Kuggen/Wingårdh Arkitektkontor, 2012)

#### 3.1.2. Kinetic (dynamic) facades

Although the origins of kinetic facades—systems that incorporate movable facade elements programmed to respond to climatic or other environmental factors—can be traced back in architectural history, their integration with advanced technology is relatively recent (Ibrahim & Alibaba, 2019). These facades, often referred to as dynamic facades, are capable of altering their size, shape, orientation, or openings in response to physical parameters such as light, humidity, temperature, and wind (Kensek & Hansanuwat, 2011).

As shown in Figure 2, the ability of these systems to transform their form contributes significantly to improving indoor comfort conditions, while also helping to prevent energy losses and reduce energy-related operational costs within the building.



**Figure 2.** Carabanchel Social Housing's Kinetic Facade (Spain-Madrid, 2007) (Carabanchel Housing / Foreign Office Architects, 2008)

### 3.1.3. Interactive facades

The term interactive facade generally refers to technological or responsive elements embedded in a building's exterior that are capable of engaging with users or reacting to external stimuli. Interactive facade systems are typically designed to respond to various environmental changes or external inputs, and often require user engagement to operate (Velikov & Thün, 2013; Loonen et al., 2013).

These systems may incorporate technological components such as motion sensors or touch-sensitive interfaces, allowing the facade to temporarily alter its features based on user interaction as depicted in Figure 3. While supporting improvements in the building's energy performance, interactive facades also aim to enhance user participation and engagement with the architectural environment (Romano et al., 2018).



**Figure 3.** Cyclebowl Expo Interactive Facade (Germany, 2000) (Atelier Brückner, 2024)

### 3.1.4. Intelligent (smart) facades

Smart facade systems aim to enhance the building's energy efficiency through the integration of advanced technological components into the building envelope. These systems commonly include sensors, control mechanisms, automated lighting, and ventilation systems (Wigginton & Harris, 2002). By monitoring variables such as sunlight, temperature, air quality, and energy consumption, intelligent facades enable buildings to respond more sensitively and efficiently to changing environmental conditions.

In addition to artificial intelligence and computer-based technologies, smart facade designs often incorporate phase-changing smart materials and photovoltaic panels, which contribute to both passive and active energy strategies (Esgil & Yamaçlı, 2023).

### 3.1.5. Biomimetic facades

The term biomimetic, derived from the Greek words "bios" (life) and "mimesis" (imitation), was introduced by Frosch and Gallopoulos (1989) and refers to the use of biological and natural systems as sources of inspiration in design (Uç, 2023). Biomimetic facades, designed by emulating the structural and functional characteristics of nature, aim to enhance various comfort parameters such as thermal regulation, ventilation, light transmission, and acoustic performance. These facades represent a design concept that contributes to energy efficiency by integrating principles observed in living or natural systems (Zari & Storey, 2007). Through this nature-inspired approach, biomimetic facades provide sustainable solutions that harmonize with environmental conditions.

## 3.2. System Principles in Adaptive Facades

### 3.2.1. Environmental and control parameters influencing adaptive facade design

Environmental factors such as solar radiation, wind, sound, and humidity/precipitation present in a building's external environment are considered key physical parameters that significantly effect both indoor comfort and building performance. These physical environmental parameters have the potential to directly influence structural efficiency and interior environmental quality. In response to these external variables, a range of control parameters have been identified that mediate the interaction between the environment and the building (Loonen et al., 2015). These control parameters emerge as factors affecting visual, acoustic, thermal comfort, indoor air quality, and on-site energy production, all of which are critical to the holistic performance of adaptive facade systems (Belek & Yamaçlı, 2023). The accurate analysis of physical environmental parameters shaped by a building's geographical location plays a critical role in minimizing structural energy losses while also enabling the fulfillment of necessary control parameters within the interior space (Manioğlu, 2011). For example, the position and angle of solar incidence at a specific location affect both visual and thermal comfort conditions, and at the same time, solar energy can be utilized for on-site energy generation. When photovoltaic technologies are integrated into the facade, interaction with sunlight enables energy production through the building envelope (Voigt et al., 2023).

Wind is another physical environmental parameter that influences both thermal comfort and indoor air quality. When incorporated into adaptive facades, various elements can harness wind to generate kinetic energy, contributing to the energy demands of the building.Humidity levels in the outdoor environment directly affect thermal comfort and indoor air quality. High humidity levels may hinder evaporation processes, causing undesirable overheating in the interior. Additionally, excess humidity can negatively effect air freshness, reducing the quality of the indoor atmosphere. Another significant parameter is sound, which affects acoustic comfort. To prevent the transmission of unwanted external noise and to ensure a comfortable acoustic environment, adaptive facade designs can be developed to act as buffers (Başarır & Altun, 2017).

In this context, the main control parameters expected to be addressed by adaptive facade systems include visual comfort, thermal comfort, indoor air quality, acoustic performance, and energy production (Loonen et al., 2015). Adaptive facades have the capability to respond to these environmental parameters in real-time, allowing them to dynamically optimize performance in relation to varying external conditions (Romano et al., 2018).

### 3.2.2. Scales of adaptation

Adaptive facade systems consist of various architectural elements capable of modifying their characteristics to respond to changing environmental conditions (Ferguson et al., 2007). Sensitivity to external environmental factors can be achieved at different scales, including facade materials, individual components, or the entire facade system (Aelenei et al., 2018) (Table 1). These elements can function independently, or multiple adaptive components may be integrated simultaneously in hybrid adaptive facade systems. The selection of adaptive facade materials plays a crucial role in the interaction between the building and its environment and contributes significantly to the building's overall performance. A review of existing applications indicates that smart materials are often employed to achieve material-scale adaptability in adaptive facade systems (Looman, 2017). These

materials are designed to detect structural and environmental variations and respond accordingly to provide appropriate conditions within the interior space (Kroschwitz, 1992). Among the most commonly used smart materials in adaptive facade applications are photochromic, thermochromic, and electrochromic glasses (Oral & Karakoç, 2015). These materials can autonomously modify their optical and thermal properties in response to external stimuli such as light, heat, or electricity and revert to their original state. For instance, photochromic glass changes its color based on the UV intensity of incident light, helping to prevent glare and unwanted lighting conditions in the interior space (Ritter, 2007).

Thermochromic glass, unlike photochromic materials, responds primarily to the heat energy carried by sunlight. When exposed to solar radiation, it traps the heat and alters its optical properties through specific chemical reactions (Addington & Schodek, 2005). Electrochromic glass, on the other hand, requires an electric current to control its transparency level. This type of glass can be used in facade systems to provide dynamic climate control, significantly improving energy efficiency (Topal & Arpacıoğlu, 2020). In addition to smart materials, elements such as adaptive sun-shading devices, light shelves, photovoltaic panels, and wind turbines can also be integrated into facades. These components, often referred to as smart facade elements, are widely used to enhance energy performance and indoor environmental quality (Oral & Karakoç, 2015). Whether integrated in a static or dynamic manner, these components are capable of reacting to environmental stimuli to improve building performance (Çiftçi & Arpacıoğlu, 2021).

Through single- or double-skin facade systems, it is also possible to achieve adaptive functionality at the system scale without necessarily integrating specific adaptive components. For example, the adaptive facade of the Institut du Monde Arabe in Paris was designed with intrinsic adaptability, without the need for additional adaptive elements (Engin, 2022). The facade consists of a single layer that is perceptible from both the interior and the exterior, effectively responding to changing environmental conditions.

**Table 1.** Adaptation Scales and Functional Strategies in Adaptive Facade Design

| Adaptation Scale | Description | Examples | Functionality |
|---|---|---|---|
| **Material Scale** | Materials that autonomously respond to environmental stimuli | -Photochromic glass<br>-Thermochromic glass<br>- Electrochromic glass | Alters optical/thermal properties in response to light, temperature, or electricity |
| **Component Scale** | Individual building elements with responsive or kinetic capabilities | -Operable louvers<br>-Light shelves<br>- PV panels<br>- Wind turbines | Regulates daylight, ventilation, solar gain, and energy generation |
| **System Scale** | Entire facade system designed with integrated adaptive performance | - Double-skin facades<br>- Smart curtain wall systems<br>- Institut du Monde Arabe facade | Provides holistic environmental control (visual, thermal, acoustic, air quality, energy use) |
| **Hybrid Integration** | Combination of multiple adaptation strategies and elements across different scales | - Mixed use of smart materials and kinetic devices<br>- Responsive facades with sensors + AI integration | Enhances dynamic adaptability and performance efficiency through multi-layered feedback systems |

### 3.2.3. Adaptation methods

Adaptivity in facade systems can occur through two primary approaches: static or dynamic adaptation (Oral & Karakoç, 2015; Megahed, 2017) (Table 2). In static adaptive facades, the facade or its components remain in a fixed position relative to their original state while still responding to external environmental conditions. This type of adaptation is particularly evident in facade systems that integrate adaptive materials at the material scale. On the other hand, dynamic adaptive facades incorporate movable architectural components designed to respond actively to changing external conditions. These components may operate individually or collectively and exhibit kinetic behavior at micro or macro scales (Aelenei et al., 2018). At the macro scale, kinetic adaptability involves the movement of facade elements or entire systems through actions such as sliding, folding, rotating, or scaling (Moloney, 2011).In contrast, micro-scale movement is typically associated with material-level deformation, where morphological changes in smart materials lead to responsiveness (Loonen et al., 2013; Aelenei et al., 2018). When such materials are used across the whole facade, the entire system can exhibit micro-scale adaptive motion.

**Table 2.** Adaptation Method in Adaptive Facades

| Adaptation Method | Features | Examples |
|---|---|---|
| **Static Adaptation** | - No moving parts<br>- Material-based response<br>- Low energy consumption<br>- Typically occurs at the micro scale | Thermochromic glass, photochromic materials, phase-change materials |
| **Dynamic Adaptation** | - Involves physical movement<br>- Kinetic systems at micro or macro scale<br>- Can be controlled by automation systems<br>- May require energy input | Movable sunshades, foldable panels, rotating facade components |

### 3.2.4. Control Techniques in adaptive facades

Adaptive facades respond to external stimuli through integrated control systems. These systems are responsible for processing environmental data, activating system components, adapting to external conditions, and executing responsive operations (Moloney, 2011). The control techniques employed in adaptive facades can utilize both active and passive technologies (Tabadkani et al., 2020). In facades using passive control techniques, the system analyzes and responds to external environmental conditions independently, without the need for additional components or energy. In contrast, active control techniques require a combination of components and technological tools to facilitate and manage this adaptation.

There are two primary control strategies in adaptive facades: external (extrinsic) and internal (intrinsic) control systems (Velasco et al., 2015). The extrinsic control system represents an active control technique, consisting of sensors and actuators that are operated through automation and require energy input (Belek & Yamaçlı, 2023). These systems can only function through user input and typically utilize processors, data networks, and software to detect environmental variables and transmit them to a central control unit (Figure 4). However, these systems are usually designed to respond to predefined scenarios, which limits their adaptability to unpredictable changes in the physical environment (Loonen et al., 2013).

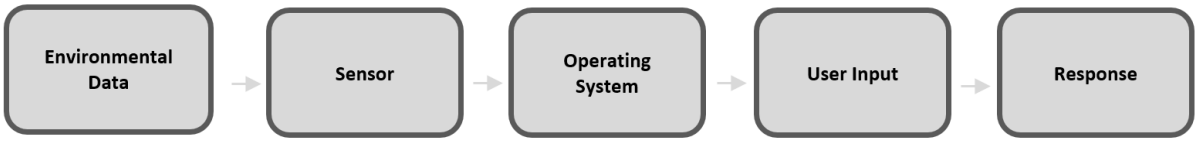



**Figure 4.** Data collection and response generation process in extrinsic control systems (Fox & Yeh, 2000)

On the other hand, intrinsic control systems operate with a much simpler mechanism. These systems do not require any external hardware, as they function based on inherent material or system

properties (Fox & Yeh, 2000). Moreover, intrinsic systems do not consume energy for adaptation, making them self-sufficient. They can perceive environmental stimuli and respond accordingly without intermediaries (Figure 5). Their flexibility allows for real-time adjustment to unanticipated conditions, enhancing their ability to adapt compared to extrinsic systems. When reviewing real-world adaptive facade applications, it is evident that intrinsic control techniques are more commonly preferred than extrinsic ones due to their greater adaptability and lower energy demand (Ghamari & Asefi, 2010).

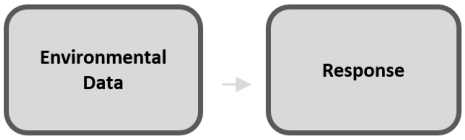



**Figure 5.** Data collection and response generation process in intrinsic control systems (Fox & Yeh, 2000)

## 4. Conclusion and Suggestions

In contemporary architectural discourse, sustainability, energy efficiency, and user comfort have evolved beyond conventional design concerns to redefine the role and function of the building envelope. Within this system, adaptive facade systems have emerged as dynamic and responsive architectural solutions capable of interacting with environmental variables and altering their physical or functional attributes in real time. Unlike static, passive envelopes, adaptive facades contribute not only to the reduction of energy consumption but also to the enhancement of occupant comfort, environmental responsiveness, and performance flexibility throughout the building's lifecycle.The findings of this study, based on an extensive literature review, reveal that adaptive facades are classified into various categories—including active, kinetic, interactive, smart, and biomimetic types—each defined by its mechanisms of environmental adaptation. These typologies represent a spectrum of responses to climatic stimuli, with some systems operating through singular technological strategies, while others function as hybrid solutions that integrate multiple adaptive features simultaneously. The increasing prevalence of hybrid systems indicates a growing tendency toward multi-functional, layered facade approaches in high-performance architectural design.

The successful response of adaptive facades to environmental inputs is largely dependent on the accurate analysis of physical environmental parameters—such as solar radiation, wind, humidity, and noise—and their correlation with critical control parameters, including visual comfort, thermal comfort, indoor air quality, acoustic performance, and energy production. The integration of smart materials (such as photochromic, thermochromic, and electrochromic glazing) and intelligent systems (sensors, actuators, and automation software) facilitates a continuous and optimized interaction between the building and its environment. These technologies enable the facade to function as a dynamic environmental interface, improving both performance and responsiveness. Furthermore, the control techniques employed in adaptive facades—categorized as either intrinsic or extrinsic—play a decisive role in determining the system's responsiveness, energy consumption, and sustainability potential. Intrinsic control strategies, which operate autonomously without external hardware or energy input, have proven particularly advantageous in terms of adaptability and energy efficiency. Their inherent ability to sense and respond to environmental stimuli allows for greater flexibility in addressing unforeseen conditions, making them increasingly preferred in practical applications.

Ultimately, adaptive facade systems signify a paradigm shift in architectural practice—one that reimagines the facade not as a static protective shell but as an active, intelligent, and performative mediator between indoor and outdoor environments. However, their successful implementation demands more than technological sophistication; it requires an integrated design approach that synthesizes contextual analysis, user behavior, climatic data, operational strategies, and architectural coherence. Interdisciplinary collaboration, holistic planning, and life-cycle-oriented design methodologies are essential to realizing the full potential of adaptive facades as a cornerstone of sustainable architecture. In this regard, further in-depth theoretical and practical investigations into adaptive facades are critical for advancing climate-responsive and energy-efficient architectural practices in the built environment of the future.

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The article complies with national and international research and publication ethics. Ethics Committee approval was not required for the study.

**Author Contribution and Conflict of Interest Disclosure Information**

The article was written by a single author. There is no conflict of interest.

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**Research Article**

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# Design of a Low-Cost, Hand-Operated Centrifuge with Real-Time Monitoring

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**Abstract**

*This study has developed a modular centrifuge system that is portable, low-cost and does not require electricity. It can be produced using 3D printing technology. The project aims to provide an economical, energy-independent solution for separating biological and chemical samples, particularly in environments where access to electricity is limited or laboratory infrastructure is inadequate. Findings obtained from the experiments suggest that the centrifuge can generate sufficient centrifugal force for basic separation processes at laboratory level, producing results consistent with the 2000×g range specified in the literature. The developed centrifuge supports the 'frugal science' approach due to its low production cost, modular structure, lack of energy requirements and ease of replication via 3D printing.*

***Keywords:*** *3D Printing Technology, Arduino-Based Systems, Low-Cost Design, Manually Operated Mechanisms, Real-Time Measurement.*

# Düşük Maliyetli, Elektriksiz Çalışan ve Gerçek Zamanlı Ölçüm Yapabilen bir Santrifüj Tasarımı

**Öz**

*Bu çalışmayla, elektrik gerektirmeyen, taşınabilir, düşük maliyetli ve 3B baskı teknolojisiyle üretilebilen modüler bir santrifüj sistemi geliştirilmiştir. Projenin amacı, özellikle elektrik erişiminin sınırlı olduğu veya laboratuvar altyapısının yetersiz bulunduğu ortamlarda biyolojik ve kimyasal numunelerin ayrıştırılmasını sağlayabilecek, enerji bağımsız, ekonomik bir çözüm sunmaktır. Deneyler sonucunda elde edilen bulgular, cihazın laboratuvar düzeyinde temel ayırma işlemleri için yeterli merkezkaç kuvveti üretebildiğini ve literatürde belirtilen 2000×g aralığıyla uyumlu sonuçlar verdiğini göstermiştir. Geliştirilen santrifüj, düşük üretim maliyeti, modüler yapısı, enerji gereksinimi bulunmaması ve 3B baskı ile kolaylıkla çoğaltılabilir olması sayesinde "tutumlu bilim" (frugal science) yaklaşımını desteklemektedir.*

***Anahtar kelimeler:*** *3B Baskı Teknolojisi, Arduino Tabanlı Sistemler, Düşük Maliyetli Tasarım, Elle Çalıştırılan Mekanizmalar, Gerçek Zamanlı Ölçüm.*

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## 1. Introduction

A centrifuge is a device that uses centrifugal force to separate substances of different densities within liquids (Sule et al., 2019). A common tool in laboratories, centrifuges play an important role in processes such as separating plasma from blood samples, detecting pathogens in biological fluids and isolating DNA (Haque et al., 2022).

Centrifugation involves spinning a sample around an axis to increase the gravitational field strength. This creates a relative centrifugal force (RCF), also known as 'g' force, which pulls cells and other particles towards the position farthest from the centre of rotation. RCF is proportional to the square of the rotor speed and radial distance, and can be calculated using the following equation (Haque et al., 2022) (Eq. 1).

$$RCF = 1.118 \times 10^{-5} \times \overline{r} \times \omega^2 \qquad \text{(Equation 1)}$$

Here, $\overline{r}$ is the average radial distance of the sample in the tube (in centimetres) and ω is the rotor speed (in revolutions per minute, RPM). The radial dimensions of the centrifuge tubes are given in Figure 1.

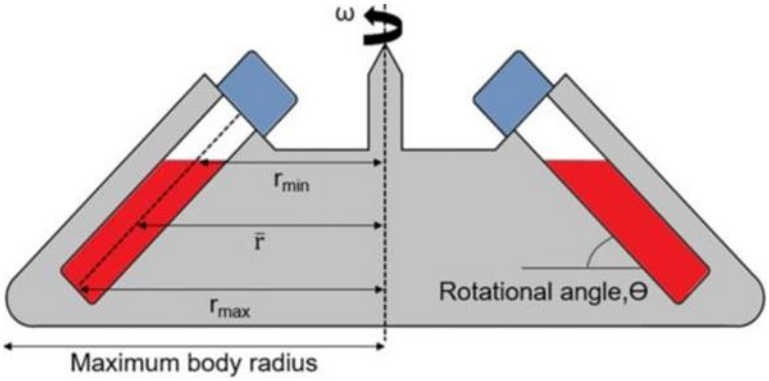



**Figure 1.** Schematic representation and radial dimensions of centrifuge tubes on a fixed-angle adapter (Haque et al., 2022)

From Equation 1, we can see that the RCF increases with rotor speed and distance from the axis. However, to achieve the highest RCF value, it is necessary to consider not only these two parameters, but also factors such as the moment of inertia, torque and aerodynamic drag. Changes in rotor geometry increase motor torque, leading to a decrease in rotational speed due to the inverse proportion between torque and speed. Since RCF is proportional to the square of the speed, a decrease in rotor speed significantly reduces separation efficiency. Therefore, centrifuge design must strike a balance between radial distance and speed. While increasing the radial distance raises the RCF, the rotational speed may decrease due to increased inertial moment and aerodynamic drag. In this study, the speed parameter was prioritised due to its square relationship with RCF, and the system was designed to be lightweight, compact and efficient. In addition, the rotational angle is an important factor in the separation process. As high-angle rotors tend to produce more compact pellet formation, 45° fixed-angle rotors are commonly favoured in commercial systems (Haque et al., 2022).

Unlike commercial centrifuges, the system developed in this study allows the tubes to move to a 0° position parallel to the radial distance during centrifugation. This ensures that the centrifugal force acts entirely in a horizontal direction. The ability of this innovative design to increase pellet formation speed and improve separation efficiency has been investigated.

Traditional centrifuges typically operate under fixed laboratory conditions and rely on electrical power. They are also high-cost devices (Byagathvalli et al., 2019). With a capacity of 20–100 tubes, these devices have rotor diameters ranging from 20–40 cm and weigh an average of 120 kg.

In weight. Prices start at 1,500 US dollars. Although smaller microcentrifuge models are available, these are generally limited to samples with a volume of less than 1.5 ml and are not compatible with clinical tubes (Haque et al., 2022).

Around 14% of the global population — approximately 1.1 billion people — still lack access to electricity. Even in areas where electricity is available, frequent power outages can disrupt laboratory work. In Nigeria, for example, prolonged power outages force many laboratories to use generators, which leads to high costs and an adverse environmental impact. To overcome these issues, alternative manually operated centrifuge systems have been developed. These include paper centrifuges (paperfuges), salad spinner-based centrifuges and egg beater-based centrifuges. However, Sule et al. (2019) found that these systems cannot provide sufficient durability and efficiency for high-volume samples.

In recent years, open-source and low-cost scientific devices have grown in popularity within the scientific community. Components produced using 3D printing technology are used in applications such as chemical mixing, optical testing, measuring water quality, and microfluidic systems. This technology enables the development of economical, customisable, modular solutions (Sule et al., 2019).

One of the most notable studies in this area is the 'Paperfuge' project, which was developed by Manu Prakash and his team at Stanford University. Inspired by a toy pinwheel, this motorless centrifuge costs only 20 pence to produce and can reach speeds of 125,000 RPM when powered by humans. The Paperfuge has brought innovation to diagnostic processes in areas with limited resources by performing basic biological procedures such as separating blood from plasma (Bhamla et al., 2017).

Similarly, the '3B-Fuge', developed by Byagathvalli et al. (2019), can be produced on a 3D printer for less than 1 USD and can reach speeds of 6,000 RPM (approximately 2,000 g). These are successful examples of the 'frugal science' approach that has emerged in recent years, aiming to make scientific devices more accessible, portable and affordable. The proliferation of 3D printing technology has also enabled the quick, cheap and practical production of such devices (Byagathvalli et al., 2019).

This study begins with the premise that centrifuges, which are widely used in laboratories, are expensive, require electricity and are not portable. This limits scientific research, particularly in rural areas and schools with limited resources. Where access to electricity is limited, there is a need for an economical, accessible solution that can enable the separation of biological samples.

The aim of this study is therefore to develop a prototype centrifuge that can be produced using 3D printing technology. This centrifuge should have a modular structure, be low-cost and be manually operable. The prototype is intended to measure speed in real time via an Arduino microcontroller and operate independently of energy sources.

This will result in the creation of a portable, innovative and sustainable laboratory tool for researchers and students, thereby increasing access to scientific tools and promoting the adoption of a frugal science approach.

## 2. Material and Method

Within the scope of this project, a prototype of a manually operated, low-cost, portable centrifuge that does not require electricity has been developed. The system can be produced modularly using 3D printing technology and measures speed in real time using an Arduino microcontroller. This innovative centrifuge is intended to facilitate biological analyses in rural areas and laboratories with limited resources.

### 2.1. Materials and Equipment Used

The materials used in the production of the device are listed below;

PLA filament (UZARAS 1.75 mm White PLA Plus™ Filament); Arduino infrared sensor (Easy Electronics 2-piece IR); Arduino LCD screen (SANEC Arduino 2x16 LCD Screen (I2C Module)); Pin-separable jumper cable; 10 mm diameter x 3 mm neodymium magnet (NdFeB magnet); 8 pieces; One each of:

- 20 cm iron rod with an 8 mm diameter;
- 10 cm iron rod with an 8 mm diameter;
- 08 cm iron rod with an 8 mm diameter;

8 pieces of bearing (608zz) with an 8 mm inner diameter; 300 mm x 150 mm x 3 mm transparent plexiglass sheet; M3 x 5 mm bolt and nut. The material cost analysis is shown in Table 1.

**Table 1**. Material cost analysis (Created by the authors)

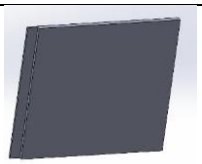
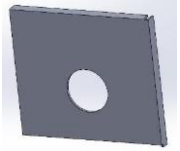
| Material Name | Aim of Use | Quantity | Unit Price | Total Cost |
|---|---|---|---|---|
| **PLA Filament** | Body and gear production with a 3D printer | 0.4 Kg | 300 TL/Kg | **120 TL** |
| **Arduino Nano (Clone)** | Speed measurement and data processing | 1 Piece | 120 TL | **120 TL** |
| **LCD Screen (16x2 I2C)** | Instantaneous display of RPM value | 1 Piece | 50 TL | **50 TL** |
| **PIR Sensor** | Detection of number of revolutions | 2 Piece | 25 TL | **25 TL** |
| **Bearing (608zz)** | Reducing friction and rotational movement | 8 Piece | 15 TL | **120 TL** |
| **Neodymium Magnet** | Sensor trigger | 8 Piece | 10 TL | **80 TL** |
| **Connecting Elements** | Assembly (Screws, Nuts, Washers, etc.) | 1 Package | 35 TL | **35 TL** |
| **TOTAL** | | | | **550 TL** |

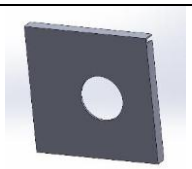
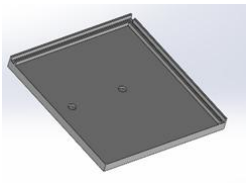
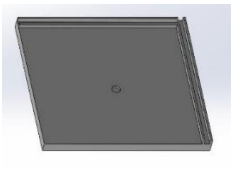
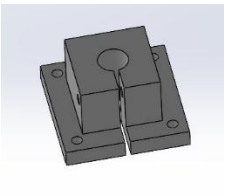
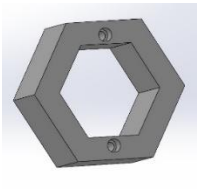
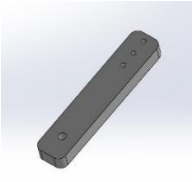
The equipment used consists of a 3D printer (Creality Ender 3 Pro), a microcontroller, (Arduino UNO) and a digital Laser RPM Tachometer (TLS Robotik DT-2234C).

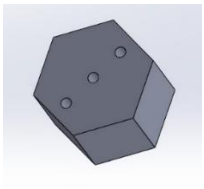
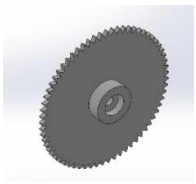
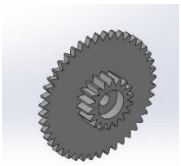
### 2.2. Modelling and Printing Process

All of the 3D-printed components of the centrifuge were designed using SolidWorks software in a 3D modelling (CAD) environment and manufactured using fused deposition modelling (FDM) technology. The printing processes were carried out using a Creality Ender 3 Pro 3D printer. Polylactic acid (PLA)-based UZARAS 1.75 mm White PLA Plus™ filament was used to produce the centrifuge's main components. All parts were prepared using standard printing parameters via Ultimaker Cura 15 slicing software and transferred to the printer. Table 2 presents the basic components of the designed centrifuge and information about the function of each component.

**Table 2**. List of the main components of the modular centrifuge produced using 3D printing technology (Created by the authors)

| Components | Quantity | Role | The Appearance of Components |
|---|---|---|---|
| Segment 1 | 1 | Left rear wall |  |
| Segment 2 | 1 | Right rear wall |  |
| Segment 3 | 1 | Left ceiling |  |

| | | | |
|---|---|---|---|
| Segment 4 | 1 | Right ceiling |  |
| Segment 5 | 1 | Right side wall |  |
| Segment 6 | 1 | Left side wall |  |
| Segment 7 | 1 | Bottom right base |  |
| Segment 8 | 1 | Bottom left base |  |
| Segment 9 | 3 | Shaft holder |  |
| Segment 10 | 1 | Hexagonal nut |  |
| Segment 11 | 1 | Centrifuge rotating arm |  |
| Segment 12 | 1 | Centrifuge rotating arm extension |  |

| | | | |
|---|---|---|---|
| Segment 13 | 1 | Hexagonal rotating arm |  |
| Segment 14 | 2 | Rotating roller |  |
| Segment 15 | 1 | Sample rotating roller |  |
| Segment 16 | 1 | 64-tooth disc (150 mm diameter) |  |
| Segment 17 | 2 | 44, 18-tooth compound disc (100 mm and 40 mm diameter) |  |
| Segment 18 | 1 | Sample holder table |  |
| Segment 19 | 1 | Sample holder tray cover |  |
| Segment 20 | 12 | Sample ring (rotor) |  |

### 2.3. RPM Meter (Tachometer)

An Arduino-based tachometer system has been designed to monitor the rotation speed (RPM) of samples in a modular centrifuge in real time.This system consists of three main components: a sensor module (Arduino Infrared Sensor (Easy Electronics 2 Pcs IR)), an Arduino UNO microcontroller, and an LCD screen (SANEC Arduino 2x16 LCD Screen (with I2C Module)).The sensor detects signals from the rotor's rotational movement and transmits them to the Arduino board. The data processed by the Arduino is then displayed as RPM values on the LCD screen.The connection layout of the tachometer system are presented in Figure 2, and circuit diagram of the tachometer system are presented in Figure 3.

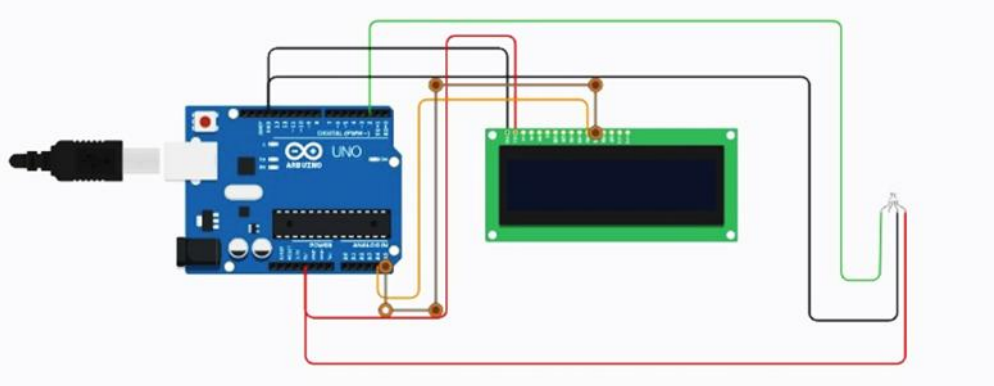



**Figure 2.** Connection diagram of the RPM (tachometer) system.This is a circuit diagram showing the physical layout of the connections between the Arduino UNO board, the LCD screen, and the sensor module.This system allows for real-time measurement of the centrifuge's rotation speed (RPM) (Created by the authors)

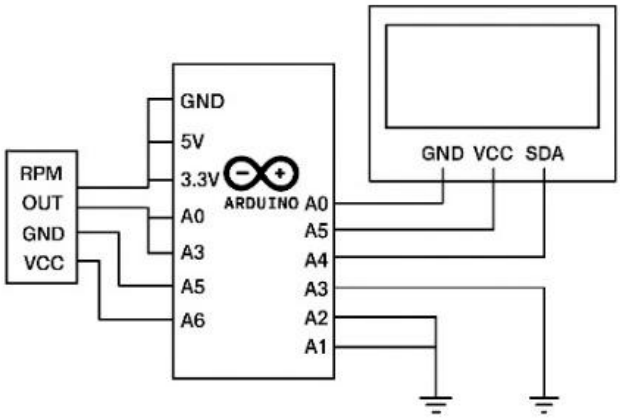



**Figure 3.** Circuit diagram of an RPM (tachometer) system.This is a technical drawing showing the electronic connections of the basic components (Arduino UNO, LCD screen, and sensor module) used in a tachometer system.This diagram illustrates the system's circuit-level setup and the data flow between the measurement components (Created by the authors)

Special software has been developed to enable the Arduino-based tachometer to measure the rotational speed (RPM) of the centrifuge rotor in real time.This software calculates the number of revolutions per minute over a specific time interval by counting the digital signals received from the sensor and displays the resulting value on an LCD screen.The primary goal of the code is to accurately and reliably measure rotational speed while also enabling the system to respond quickly to instantaneous changes.The code section is based on the code found in the forum post titled "Arduino IR Tacho" ("Arduino IR Tacho", 2022).The software code for the tachometer system is given in Figure 4.

```
#include<LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd (0x27, 16.2);//
float value=0;
float rev=0;
int rpm;
int oldtime=0;
int newtime;
void isr() //interrupt service routine
{
rev++;
}
void setup()
{
lcd.begin();
lcd.clear();
lcd.backlight();
attachInterrupt(digitalPinToInterrupt(2),isr,RISING);}
void loop()
{
delay(1000);
detachInterrupt(0);//detaches the interrupt
newtime=millis()-oldtime;//finds the time
int wings = 1;// no of wings of rotating object, for disc object use 1 with white
tape on one side
int RPMnew = rev/wings;//here we used fan which has 3 wings
rpm=RPMnew*(60000/newtime);//calculates rpm
oldtime=millis();//saves the current time
lcd.clear();
lcd.setCursor(0,0);
lcd.print("___TACHOMETER___");
lcd.setCursor(0,1);
lcd.print(rpm);
lcd.print("RPM");
lcd.print(" ");
lcd.setCursor(8,1);
lcd.print(rev);
lcd.print(" rev");
lcd.print(" ");
rev=0;
attachInterrupt(digitalPinToInterrupt(2),isr,RISING);

}
```

**Figure 4.** Software code for an Arduino-based RPM measuring system ("Arduino IR Tacho", 2022).The figure shows the program flow that enables reading sensor signals, using timer functions, and displaying the measured RPM values on the LCD (Created by the authors)

### 2.4. Centrifuge Assembly

The modular centrifuge that was designed was assembled by combining the components modeled in a CAD environment.The assembly process was carried out in four main stages: rotor system, drive mechanism, fuselage components, and cover system.

First, the motor and gear system that provide the basic movement of the centrifuge were placed on the lower platform and axial alignment was performed.Next, gears are mounted to connect the rotor

shaft to the motor shaft, providing rotational transmission.The sample carrier rotor and tube holders are fixed to the upper platform, ensuring stable placement of the samples.

The centrifuge body consists of modular panels produced using 3D printing.These panels are assembled to hold the lower and upper platforms together, after which the protective side covers and front panel are secured.In the final stage, the electronic components (tachometer sensor, LCD screen, Arduino board) were installed and the wiring was completed.Finally, the system was enclosed with transparent plexiglass.Figure 5 shows the assembled mechanical components of the centrifuge and their assembly sequence, while Figure 6 shows the fully assembled version.

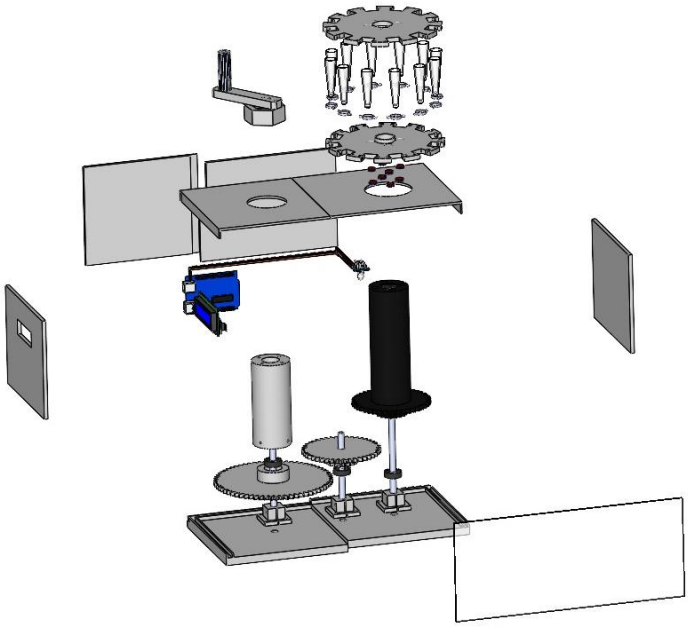


**Figure 5.** Exploded 3D view showing the assembly stages of the modular centrifuge.The figure schematically shows the assembly sequence and positions of the centrifuge's rotor, gear system, motor, housing panels, and sample carrier components (Created by the authors)

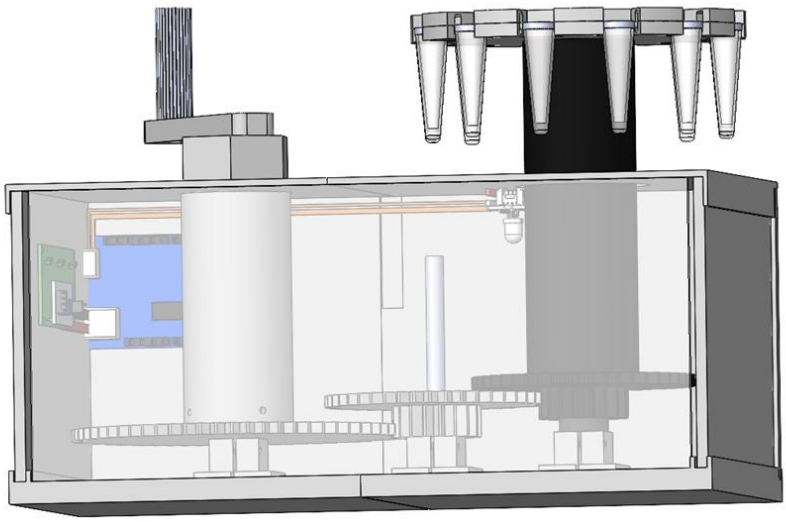


**Figure 6.** 3D view of the assembled modular centrifuge (310 x 155 x 135 mm) (Created by the authors)

### 2.5. RPM Calculation of the Gear System of a Modular Centrifuge

The gear system of the modular centrifuge, which generates the centrifugal force necessary for pellet formation of the samples, is positioned as shown in Figure 7.

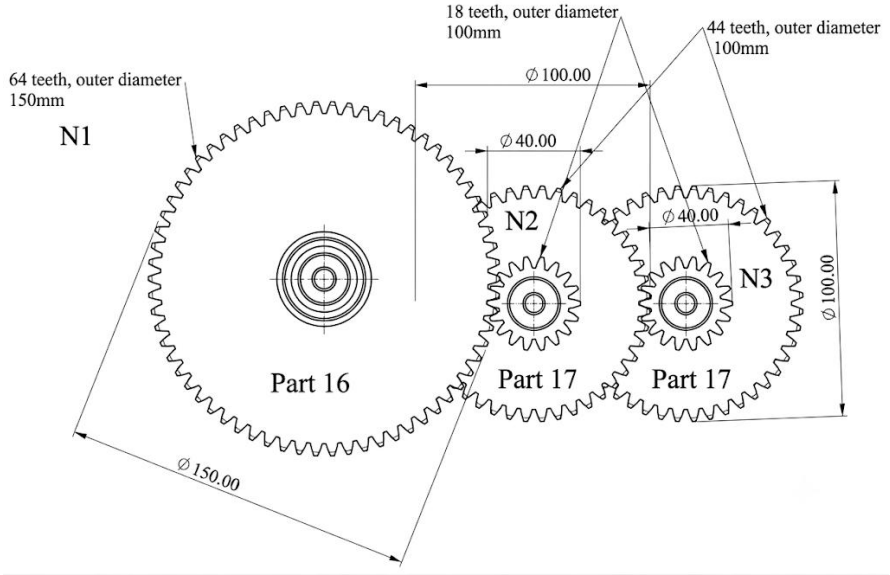



**Figure 7.** Diagram showing the layout of the gear system of a modular centrifuge (Created by the authors)

The RPM output of the gear system of the modular centrifuge has been theoretically calculated using the following formula. Number of teeth: (Eq. 2)

$$N_1 = 64, N_{2a} = 18, N_{2b} = 44, N_3 = 18 \quad \text{(Equation 2)}$$

When the first gear is rotated one full turn (revolutions per second), the rotation of the last gear is found as follows.$\Delta\theta_1 = 1\Delta\theta_3$

The basic relationship between two gears (for gear pair A–B) (Eq. 3):

$$\omega_A N_A = -\omega_B N_B \Longrightarrow \frac{\omega_A}{\omega_B} = -\frac{N_B}{N_A} \quad \text{(Equation 3)}$$

And since angular velocity and angular displacement (number of rotations) are directly proportional, the same ratio applies to the number of rotations (Eq. 4):

$$\frac{\Delta\theta_A}{\Delta\theta_B} = -\frac{N_B}{N_A} \quad \text{(Equation 4)}$$

In the system, since the two teeth of the second combined gear are on the same shaft and similarly Accordingly (Eq. 5): $\omega_{2a} = \omega_{2b} = \omega_2 \Delta\theta_{2a} = \Delta\theta_{2b} = \Delta\theta_2$

$$\Delta\theta_2 = -\frac{N_1}{N_{2a}}\ \Delta\theta_1 \quad \text{(Equation 5)}$$

and (Eq. 6),

$$\Delta\theta_3 = -\frac{N_{2b}}{N_3}\ \Delta\theta_2 \quad \text{(Equation 6)}$$

Since two minus signs cancel each other out (two contacts = two changes of direction), for magnitüde (Eq. 7):

$$\boxed{\Delta\theta_3 = \frac{N_1}{N_{2a}} \cdot \frac{N_{2b}}{N_3}\ \Delta\theta_1} \quad \text{(Equation 7)}$$

The formula above shows how many revolutions N3 makes in one second if N1 makes one revolution in one second.To obtain the standard 1 revolution/min result of N3 to which the samples are attached, the result of Equation 7 is multiplied by 60 (1 min = 60 s) to find the RPM value.

To test the accuracy of the modular centrifuge's RPM measurement system, the device's measurements were compared with those of a tachometer (TLS Robotik DT-2234C Digital Laser RPM Tachometer).

### 2.6. Modular Centrifuge Testing Method

To evaluate the performance of the developed modular centrifuge, experimental applications were carried out on two different sample types: one biological and one chemical.A solution of Saccharomyces cerevisiae (yeast) was used as the biological sample, and a saturated calcium carbonate (CaCO3) solution (0.5 M, 100 mL) was used as the chemical sample.

Both sample types were distributed in equal volumes (2 mL) into Eppendorf tubes, and care was taken to maintain rotor balance.During the experiments, the rotational speed of the 64-toothed rotor was adjusted to one full revolution per second and its multiples, and the sedimentation behavior of the samples was observed at different RPM values.

In the yeast solution, the time it took for cells to gather at the bottom was used as the evaluation criterion, while in the CaCO3 solution, the rate of decomposition of solid particles was used.Thus, the device's ability to perform effective separation on both live biological samples and chemical solutions was investigated.

To test the accuracy of the modular centrifuge's RPM measurement system, the device's measurements were compared with those of a tachometer (TLS Robotik DT-2234C Digital Laser RPM Tachometer).In addition, parallel experiments were conducted with a commercial laboratory centrifuge (ISOLAB Refrigerated Centrifuge) to evaluate the overall performance of the device.

## 3. Findings and Discussion

The modular centrifuge, which forms the basis of the project, was first designed in a three-dimensional (3D) modeling (CAD) environment using SolidWorks software, 2022 version. The components, whose design has been completed, were manufactured using fused deposition modeling (FDM) technology, and all parts are listed in detail in Table 2.After assembling the mechanical components, the electronic elements such as the tachometer sensor, LCD screen, and Arduino board were installed, and the wiring was completed, resulting in the final assembly of the system as shown in Figure 8.

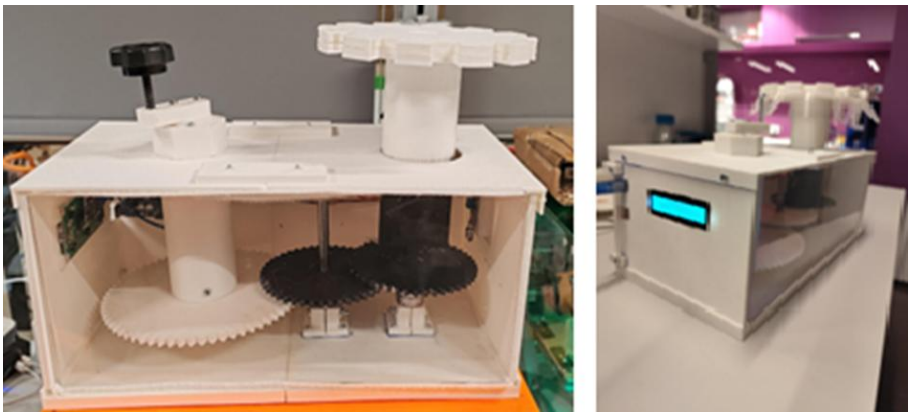


**Figure 8.** The modular centrifuge assembled and ready for use (Created by the authors)

A working video of the modular centrifuge shown in Figure 8, in its ready-to-use state, has been uploaded to the system with the file name “2204-A project report attachment.mp4”, a size of 8.094 KB and the “mp4” extension.

### 3.1. Theoretical and Experimental Calculation

According to the formula given in Equation 7; If we substitute the number of teeth in the system consisting of parts 16 and 17 (rotation):$\Delta\theta_1 = 1$

$$\Delta\theta_3 = \frac{64}{18} \cdot \frac{44}{18} \cdot 1 = \frac{2816}{324} = \frac{704}{81} \text{ rotatıon} \approx 8.6913580247 \text{ rotatıon/second}$$

According to this result, the 64-tooth gear (N1, Part) attached to the turning handle16) When rotated 1 turn per second, N3 (Part17) It has been calculated that the wheel rotates 8,691 revolutions per second.

In centrifuge systems, the rotational speed is usually expressed in RPM (repeats per minute), so this value is converted as follows:

$$8.691 \text{ revolutions/second} \times 60 = 521.46 \text{ RPM}$$

Therefore, theoretically, the system's output speed has been calculated as 521.46 RPM.

During the experimental studies, an Arduino-based tachometer integrated into a modular centrifuge was used for real-time speed measurement.Measurements revealed that the system rotated at an average speed of 572 RPM (see Figure 9). Similar results were also measured with a tachometer (TLS Robotics DT-2234C Digital Laser RPM Tachometer).

This result shows that a value quite close to the theoretical calculation was obtained and that the mechanical efficiency of the system is high.

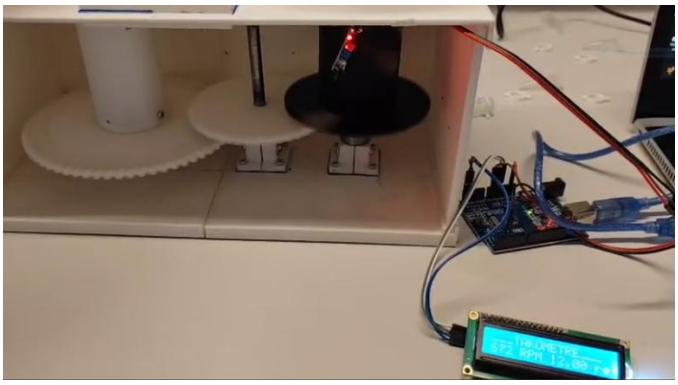


**Figure 9.** Experimental measurement with an Arduino-based tachometer integrated into a modular centrifuge (Created by the authors)

### 3.2. Testing the Modular Centrifuge on Samples

The performance of the developed modular centrifuge system was evaluated on two different sample types: one chemical and one biological.A saturated calcium carbonate (CaCO3) solution (0.5 M, 100 mL) was used as a chemical sample, and a yeast (Saccharomyces cerevisiae) suspension was used as a biological sample.2.0 mL samples were taken from each sample, placed in Eppendorf tubes, and centrifuged at approximately 2,000 RPM for 5 minutes.Centrifugation was performed at room temperature (approximately 25 °C).

In the CaCO3 solution (Figure 10-A), a homogeneous white suspension was observed before centrifugation.After the process (see Figure 10-B), a dense white pellet formed at the bottom of the tube, while the clear supernatant phase became visible at the top.This result demonstrates that the system can effectively precipitate solid particles in the solution.

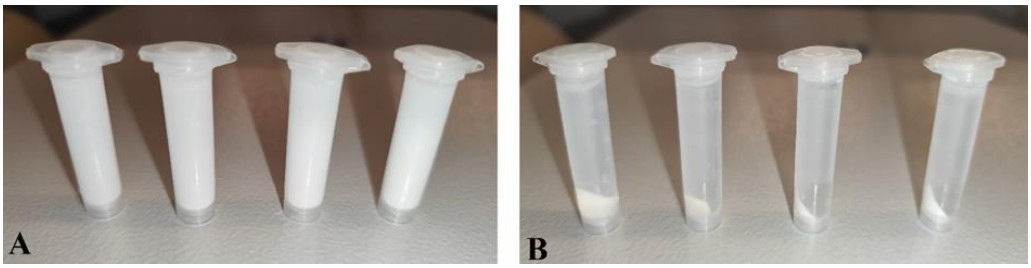



**Figure 10.** Pre-centrifugation of saturated calcium carbonate (CaCO3) solution (A) and after the developed modular centrifuge (B) image.After centrifugation, white pellets formed at the bottom of the tubes and a clear supernatant phase formed at the top (Created by the authors)

Similarly, a cloudy and homogeneous mixture was observed in the yeast suspension before centrifugation (see Figure 11-A), a light beige yeast pellet formed at the bottom of the tube after centrifugation (see Figure 11-B), and the upper phase became clear.This indicates that the system can also successfully precipitate biological cell suspensions.

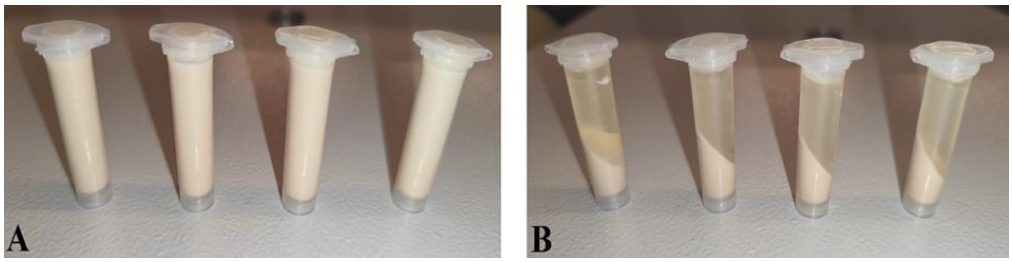



**Figure 11.** Pre-centrifugation of yeast (Saccharomyces cerevisiae) suspension (A) and after the developed modular centrifuge (B) image.After centrifugation, light beige yeast pellets formed at the bottom of the tube, while the liquid phase was observed to have separated in the upper phase (Created by the authors)

Before the centrifugation process(A) and thereafter(B) The images taken visually demonstrate the separation performance of the modular centrifuge.

**4. Conclusion and Suggestions**

Within the scope of this project, a modular, low-cost, and manually operated centrifuge prototype that can be produced using 3D printing technology has been successfully designed and manufactured.The project stems from the need to develop an energy-independent system capable of separating biological and chemical samples in regions with limited access to electricity.The designed device is capable of real-time speed measurement via an Arduino microcontroller, allowing the system's rotational performance to be monitored in real time.

The system uses an Arduino-based microcontroller to measure the speed in real time and display it to the user as RPM on an LCD screen. All components of the centrifuge were produced using PLA filament in a 3D printer, and the total cost of the assembled system was found to be 550 TL. Experimental tests revealed that the system could reach an average range of 1710–2280 RPM, effectively precipitating yeast (Saccharomyces cerevisiae) and calcium carbonate ($CaCO_3$) solutions at these values.

As a result of the experimental studies, it was determined that the system has 64 gears connected to the crank handle, N1 (Part).16) When rotated 1 turn per second, N3 (Part17) that its wheel rotates 8,691 revolutions per second;It has been calculated that it can reach speeds of approximately 570 RPM per minute.

When the N1 component of the centrifuge is rotated at 3-4 revolutions per second, the modular centrifuge reaches a speed of 1710 – 2280 RPM, as measured by an Arduino microcontroller and a tachometer (TLS Robotics DT-2234C Digital Laser RPM Tachometer).These results show that the Arduino-based RPM meter integrated into the modular centrifuge provides accurate and real-time results.It has been observed that successful precipitation (pellet) formation is achieved in Saccharomyces cerevisiae (yeast) and CaCO3 solutions at this rate.In both examples, the formation of dense and compact pellets at the bottom of the tubes after centrifugation demonstrates that the centrifugal force generated by the system is sufficient for laboratory-level separation processes.In the literature, it is reported that ~2000–3000×g (3–5 minutes) range is generally used in cell harvesting protocols for Saccharomyces cerevisiae (Brown et al., 2017; Loock et al., 2023).However, successful sedimentation has also been reported in chemical solutions containing particles such as CaCO3 at similar rate ranges (Sabri et al., 2016).These findings demonstrate that the modular centrifuge developed within the scope of this project can be effectively used in multi-purpose laboratory experiments.

The device's key advantages include not requiring any power, being 3D-printed, having interchangeable (modular) parts, and having a very low production cost.With open source systems in the literature (Bhamla et al., 2017; Byagathvalli et al., 2019; Sule et al., 2019). Compared to Haque et al. (2022), this study offers a unique contribution in terms of integrating both a mechanical system and an electronic measurement module.They stated that the ability to produce low-cost centrifuges through 3D printing strengthens applied learning in engineering education.This situation shows that the developed system can be evaluated not only as a scientific tool but also as an educational tool.

The N1/N3 ratio used in the centrifuge's gear mechanism enabled the manual input movement to be accelerated by 8.6 times, allowing for efficient torque transfer.In addition, the device called “Mobilefuge” developed by Bhupathi and Devarapu (2021) presents an open-source design of a 3D-printed centrifuge that is cost-effective, simple, stable, safe, robust, consumes less power, and can therefore be operated even from mobile phones (Bhupathi and Devarapu, 2021).In this project, the modular centrifuge developed is manually operated, so it requires very little electrical energy.Therefore, this project, in line with the concept of frugal science, aims to create a user-friendly device that does not require energy.

The PLA-based biopolymer material used in the production of the device supports a sustainable engineering approach with its environmentally friendly and recyclable properties.Thanks to the design flexibility offered by 3D printing technology, the system can be easily rescaled for different rotor sizes or sample volumes.In this respect, the project serves as a parallel example to efforts on the localization of sustainable laboratory technologies.

An examination of the production cost of the developed modular centrifuge revealed that the entire system could be realized with a relatively low budget.The total cost of all components used in the production of the prototype, including 3D printing filaments, the Arduino UNO microcontroller board, the infrared (IR) sensor module, the LCD screen unit, the mil, and neodymium magnets, was approximately 550 TL.This figure represents only a small fraction of the cost of commercial laboratory centrifuges (approximately 2–3%), demonstrating that the system successfully meets its goal of being a “low-cost engineering solution”.

It is believed that the developed prototype could be a practical educational tool used in science and biology laboratories, especially in rural or resource-constrained schools, for teaching fundamental physics concepts such as the relationship between "mechanical energy and centrifugal force".All the findings indicate that the developed modular centrifuge can be effectively used not only in educational settings but also in low-resource laboratory applications such as field research, microbiological preliminary tests, and water quality analyses.Therefore, the system is considered a portable, accessible, and economical scientific instrument.The SWOT analysis of the study is shown in Table 3.

**Table 3:** SWOT analysis

| **STRENGTHS** | **WEAKNESSES** |
|---|---|
| **1.** Cost Advantage: While commercial centrifuges cost around 60,000 TL, this prototype can be produced at a very low cost of 550 TL (Frugal Science).<br>**2.** Energy Independence:It can operate entirely manually without needing to be connected to the electrical grid (an advantage for disaster areas and rural regions).<br>**3.** Real-Time Data (Critical Power):Unlike its competitors (Paperfuge, etc.), it allows the instantaneous RPM speed to be displayed on the LCD screen thanks to the Arduino and sensor, ensuring standardization.<br>**4.** Repairability & Modularity:The parts can be 3D printed and interchangeable anywhere. | **1.** Human Factors and Fatigue:Manual turning systems can cause physical fatigue in the operator and make it difficult to maintain a constant speed during prolonged operations.<br>**2.** Speed Limit:The achieved speed of 2280 RPM may be insufficient for advanced molecular biology studies requiring very high speeds (such as DNA/RNA isolation).<br>**3.** Material Strength:PLA material has lower long-term resistance to heat and mechanical stress compared to other industrial plastics. |
| **OPPORTUNITIES** | **THREATS** |
| **1.** Educational Kit Potential:It can be used as a "STEM Education Kit" in schools to teach the working principles of centrifuges. | **1.** Raw Material Supply:Logistical problems that may arise in rural areas regarding the supply of electronic components such as filament or Arduino. |

| STRENGTHS | WEAKNESSES |
|---|---|
| **2.** Mobile Health Services:It can be used in mobile health screenings in African countries without electricity or in war/disaster zones.<br>**3.** Technology Integration: The system has the potential to be converted into a hybrid (both manual and electric) configuration with the addition of a simple battery or solar panel module. | **2.** Alternative Simple Solutions:"Salad dryers" or very simple "string systems" are creating competition at a lower cost (but not at a metric level).<br>**3.** Calibration Needs:Sensors can become dusty or shifted over time, increasing the risk of measurement errors. |

In conclusion, this project;By integrating 3D printing technology, open-source hardware, and mechanical design principles, a domestically produced, accessible, and sustainable laboratory tool has been created.This system is capable of supporting scientific research in regions with limited access to laboratory infrastructure, and serves as a concrete example of the "science everywhere" concept.Future studies are proposed to increase the system's speed capacity, add automatic timer and data logging modules, optimize the rotor geometry, and adapt all components for domestic production.With these improvements, the device's usability can be expanded into different fields such as biotechnology, environmental engineering, and educational technologies. Furthermore, the system can be considered an educational tool that encourages applied learning in engineering and science education.

The modular centrifuge system developed in this project has demonstrated that basic separation processes can be performed in non-laboratory environments thanks to its low cost and portable design.Various improvements can be made in the future to enhance the system's performance and adapt it to different applications.Increasing rotational speed by optimizing rotor geometry and gear ratios will allow for the generation of higher centrifugal forces, thereby expanding its usability in advanced biotechnological applications such as DNA isolation, protein precipitation, or microparticle separation.In addition to a manual turning mechanism, integrating pedal or spring-based power transmission systems can increase turning continuity while reducing the operators physical effort.

Furthermore, by adding temperature, time, and vibration sensors to the Arduino-based electronic system, a digital interface can be developed that automatically records the parameters of the centrifugation process.This system will therefore make significant contributions to data analysis and experimental reproducibility in both educational and research settings.Besides 3D printing, using injection molding or bioplastic materials can enhance the device's durability and environmental sustainability.

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The article complies with national and international research and publication ethics. Ethics Committee approval was not required for the study.

**Author Contribution and Conflict of Interest Declaration Information**

All authors contributed equally to the article. There is no conflict of interest.

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# Three-Dimensional Concrete Printing Technology and Bridge Applications: A Critical Review

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**Abstract**

*This study examines the contributions of three-dimensional (3D) concrete printing technology to architectural practice and evaluates its potential use in bridge construction. Drawing on the existing literature, the advantages and limitations of 3D concrete printing relative to conventional construction methods; particularly in terms of speed, labour requirements, and material efficiency are discussed. Ten bridge structures built with 3D concrete printing between 2017 and 2025 are analysed in terms of equipment, reinforcement strategy, structural span, cross-section geometry, concrete type, and production method. Through paired comparisons of formally and methodologically related bridges, the study traces the year-by-year development of robotic and additive production. The findings highlight the technological advantages, current limitations, and future development opportunities of 3D concrete printing in pedestrian and bicycle bridge infrastructure, offering guidance for integrating this innovative method into architectural technology and education.*

***Keywords:*** *3D Concrete Printing, Bridge Construction, Additive Manufacturing.*

# Üç Boyutlu Beton Yazdırma Teknolojisi ve Köprü Uygulamaları: Eleştirel Değerlendirme

**Öz**

*Bu çalışmada üç boyutlu (3B) beton yazdırma teknolojisinin mimari pratiğe katkıları incelenmekte ve köprü inşasında kullanım potansiyeli değerlendirilmektedir. 3B beton yazdırma; hız, iş gücü gereksinimi ve malzeme verimliliği açısından literatürdeki bulgulara dayanarak avantaj ve sınırlılıkları değerlendirilmiştir. 2017–2025 yılları arasında 3B beton yazdırma ile inşa edilen on köprü yapısı; ekipman, donatı stratejisi, açıklık, kesit geometrisi, beton türü ve üretim yöntemi açısından analiz edilmiştir. Biçimsel ve yöntemsel olarak ilişkili köprülerin eşleştirilmiş karşılaştırmaları yoluyla, robotik ve eklemeli üretimin yıllar içindeki gelişimi izlenmiştir. Elde edilen bulgular, yaya ve bisiklet köprüsü 3B beton yazdırmanın teknolojik avantajlarını, mevcut sınırlılıklarını ve gelecekteki gelişim olanaklarını ortaya koyarak bu yenilikçi yöntemin mimarlık teknolojisi ve eğitimiyle bütünleştirilmesine yönelik yol gösterici değerlendirmeler sunmaktadır.*

***Anahtar Kelimeler:*** *3B Beton Yazdırma, Köprü İnşası, Eklemeli İmalat.*

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## 1. Introduction

Three-dimensional (3D) printing technology is defined as the process of forming an object by depositing material layer by layer (El-Sayegh et al., 2020). Unlike conventional shaping methods—in which material is removed or carved away to obtain the desired form—3D printing builds the object by extruding successive layers through a nozzle until the final geometry is achieved. This fundamental difference is illustrated in Figure 1.

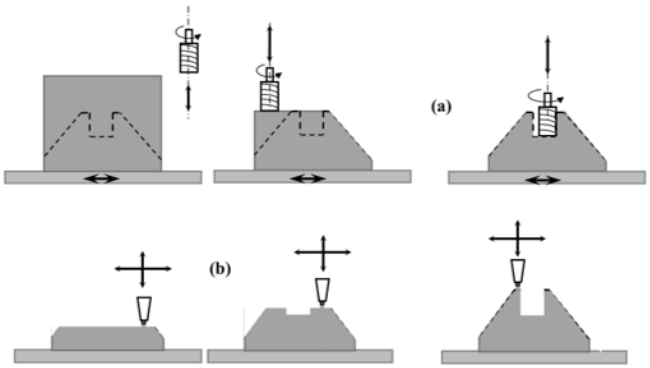



**Figure 1.** Conventional subtractive manufacturing (a) and additive manufacturing through 3D printing (b) (El-Sayegh et al., 2020)

In recent years, 3D concrete printing technology has been tested in a variety of applications, including single-storey buildings, urban furniture, shell structures, and various pavilions. However, the use of this construction system at the structural scale of bridges is still in its early stages (Zhang & Sanjayan, 2025).

Compared with single-storey buildings or pavilions, bridges require considerably higher mechanical performance and durability, since they must safely carry not only their own dead load but also continuously changing live loads. Dynamic loads such as vehicular and pedestrian traffic generate vibration, oscillation, and fatigue effects associated with repeated stresses; therefore, long-term fatigue resistance is a critical part of the design. In addition, because bridges are exposed to continuously varying dynamic effects such as wind loads, seismic movements, and thermal expansion and contraction, they also require special engineering solutions in terms of aerodynamic stability and seismic performance. Owing to open-air exposure, corrosion resistance, waterproofing, regular maintenance, and long service-life planning are also decisive design factors; in pedestrian bridges in particular, the vibration comfort and user safety arising from live loads must additionally be taken into account. When bridges developed and implemented to meet all these structural requirements are examined, the examples across the 2017–2025 spectrum contribute significantly to understanding the development of 3D concrete printing technology over the years. While the bridges built to date serve pedestrian and bicycle traffic, they have not yet been used for vehicular traffic.

3D concrete printing technology offers many significant advantages, including flexibility of on-site or off-site production, more efficient material use compared with conventional construction methods (El-Sayegh et al., 2020; Allouzi et al., 2020; Wang et al., 2020), greater geometric freedom that allows complex designs (Al Jassmi et al., 2018), faster production processes (Jagoda et al., 2020), cost-effective application without the need for formwork (De Schutter et al.,2018), improved sustainability through reduced waste, on-site occupational safety, and a reduction in the required labour force (Bhooshan et al., 2022).

Nevertheless, this technology also has certain limitations: longer production times (García-Alvarado et al., 2021), high overall cost (El-Sayegh et al., 2020; Ahmed et al., 2022), the requirement for specialised printing material such as rheological and stiffening (El-Sayegh et al., 2020; Ahmed et al., 2022; Salet et al., 2018, De Schutter et al.,2018), and the risk of job losses due to the reduced need for workers (El-Sayegh et al., 2020).

The growing interest in 3D-printed bridges has recently been accompanied by review studies that approach the field from different disciplinary perspectives. Zhang & Sanjayan (2025), for instance,

review 3D concrete printing and digital fabrication technologies for bridge construction by classifying them into process categories—extrusion-based, particle-based, and shotcrete-based printing, and digital casting—with an emphasis on concrete-handling and nozzle-based mixing technologies, that is, from a primarily material- and process-engineering standpoint. The present study differs from such category-based reviews in both perspective and method: rather than organising the discussion around printing-process categories, it adopts a project-based, case-oriented approach centred on realised bridges, and evaluates them from the standpoint of architectural design, production strategy, and integration with architectural education. In addition, by comparing formally and methodologically related bridge pairs across successive years, it aims to make the developmental trajectory of the technology explicit—an analytical emphasis that complements, rather than overlaps with, process-oriented engineering reviews.

Within this framework, the aim of this study is to examine ten bridges built with 3D concrete printing technology between 2017 and 2025, to compare them across a consistent set of criteria, and thereby to provide guidance for integrating the technology into architectural practice and education.

### 1.1. Overview of 3D Concrete Printing Technology: The 3D Concrete Printing Process and Equipment

The printing process can be carried out on-site or off-site, and the equipment used in production can vary considerably. As shown in Figure 2, this equipment may include Cartesian systems, cylindrical systems, suspended systems, articulated mechanisms, robotic arms, gantry cranes, and frame-mounted setups.

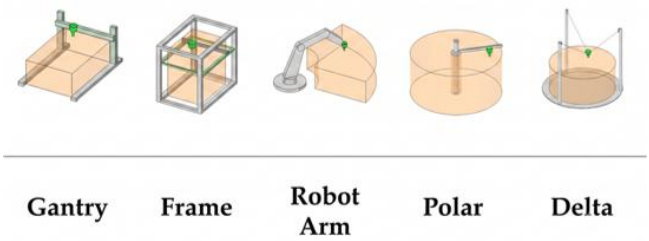



**Figure 2.** Hardware and tools used in printing (Cao et al., 2022)

3D printing technology can be applied through different methods, the most common of which are the following:

- Contour Crafting – A gantry-based system in which a print head guided by CAD data deposits concrete material in successive layers to form the desired geometry (Khoshnevis, 2004) shown in Figure 3 (left).
- Concrete Printing – Similar to contour crafting, but generally using high-performance concrete; the material is extruded layer by layer through a nozzle (El-Sayegh et al., 2020) shown in Figure 3 (right).

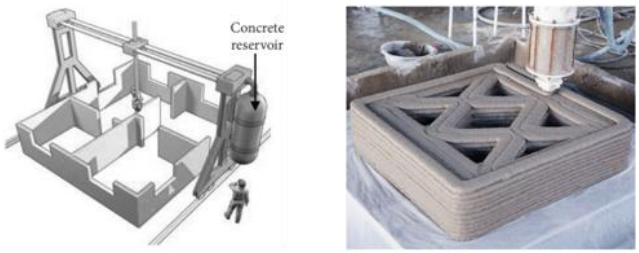



**Figure 3.** Contour crafting (left) and the concrete printing process (right) (Allouzi et al., 2020); concrete printing of a Tsinghua Bridge element (Xu et al., 2020)

- Selective Binder (Cement) Activation (SPI, SCA) – Layers in a powder bed are selectively solidified using a liquid binder to obtain a three-dimensional object (Lowke et al. 2018). The unused powder can be reused, while the printed component is cleaned and removed from the system (Talke et al., 2019) shown in Figure 4(left).
- Binder Jetting –This process originated in metal manufacturing and produces a solid form by selectively jetting a bonding agent over a bed of powder or sand, layer upon layer (García-Alvarado

et al., 2021). Is best known construction-scale version D-Shape, was created by Enrico Dini and can reach build dimentions of 6 × 6 × 6 m (Al Jassmi et al., 2018) shown in Figure 4(middle).

- Shotcrete 3D Printing – This method derives from wet-mix sprayed concrete. The structural element is built up as compressed air drives succesive layers of fine-grained concrete or cement mortar through the nozzle (Rennen et al., 2023) shown in Figure 4(right).



**Figure 4.** Post-printing cleaning in selective cement activation, printing with Binder Jetting (D-Shape), and production with the shotcrete spraying technique (Talke et al., 2019; Jakupović, 2016; Rennen et al., 2023).

## 2. Material and Method

This study is a critical review based on the examination of bridge structures produced with 3D concrete printing technology. Within the scope of this study, all bridge structures produced using 3D concrete printing technology since the emergence of the method were identified and examined. A literature and project-report search was conducted covering the period from 2017—the year in which the first 3D-printed bridge was realised—to 2025. The search was carried out using keywords such as "3D printed bridge," "3D concrete printing bridge," "additive manufacturing bridge," and "robotic concrete printing bridge" in academic databases (e.g., Scopus, Web of Science, Google Scholar) as well as official project reports and institutional publications. All identified structures satisfying the following criteria were included:

- the structure is a bridge (serving pedestrian, bicycle, or vehicular traffic) rather than a building, pavilion, or other typology;
- the primary load-bearing elements were produced through 3D concrete/mortar printing; and
- sufficient technical documentation—such as a peer-reviewed publication, official project report, or detailed conference paper—was available regarding the production method, materials, and structural dimensions.

As a result of this process, ten bridges built between 2017 and 2025 were identified as constituting the complete set of documented 3D-printed concrete bridges to date, and were included in this study. This comprehensive scope allows the developmental trajectory of the technology to be traced without the risk of selective omission.Each bridge was analysed on the basis of project reports and peer-reviewed publications in terms of four main axes:

1. the production method and equipment used,
2. cross-section geometry, reinforcement condition, and number of unit elements,
3. concrete type and strength, and
4. location, span, and function.

The data obtained were organised into comparative tables, and bridges that are formally and methodologically related were further evaluated through paired comparisons in order to trace the development of the method over time.

## 3. Findings and Discussion

### 3.1. Technical Insights from previous studies on Reinforcement and Cross-Section Strategies

In a study on 3D printing (Cao et al., 2022), it was reported that the robotic arm remains the most widely used system among different printing methods. However, the same study emphasised that delta and circular systems have higher setup costs, whereas frame and gantry systems are more widely

preferred owing to their lower costs, easy installation, and simple maintenance requirements. Building on these technological differences, Figure 5 presents various wall-printing patterns and their reinforced versions. Furthermore, studies on extrusion-based printing have focused on overcoming interlayer weakness by integrating continuous reinforcement during the deposition process. Research has demonstrated that utilizing a custom-designed nozzle to simultaneously embed steel reinforcing mesh into the extruded concrete filament effectively provides structural continuity across layers and significantly enhances flexural performance (Marchment & Sanjayan, 2020).

The study showed that adding reinforcement increases structural strength but lengthens the production time compared with unreinforced printing. The main filament-deposition patterns observed in practice are the simple layout, the parallel-lattice layout, the filled parallel layout, and the hollow parallel layout; these walls can further be strengthened with horizontal, vertical, or densified bar-reinforcement configurations (García-Alvarado et al., 2021).

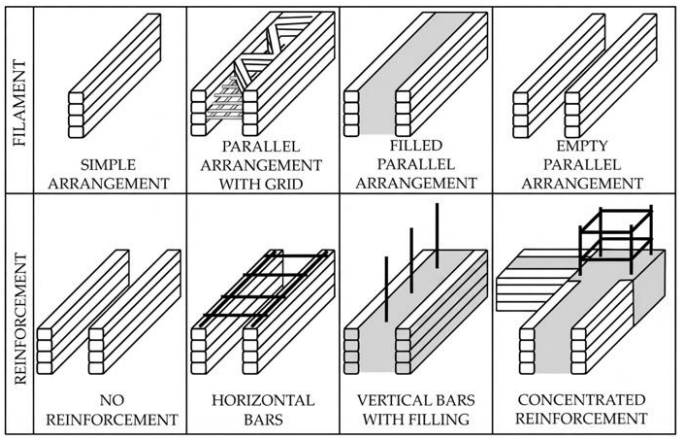



**Figure 5.** Wall types produced through 3D printing and the reinforcement methods of these walls (García-Alvarado et al., 2021)

In addition, the hollow-section design approach, which aims to increase material efficiency, allows structurally safe production even without the use of reinforcement. Figure 6 shows the different hollow sections that can be applied to achieve this effect. Unlike conventional construction methods, 3D concrete printing deposits only the required amount of material, and when combined with hollow-section strategies it offers significant material savings in terms of both structural efficiency and weight reduction (Wang et al., 2020).

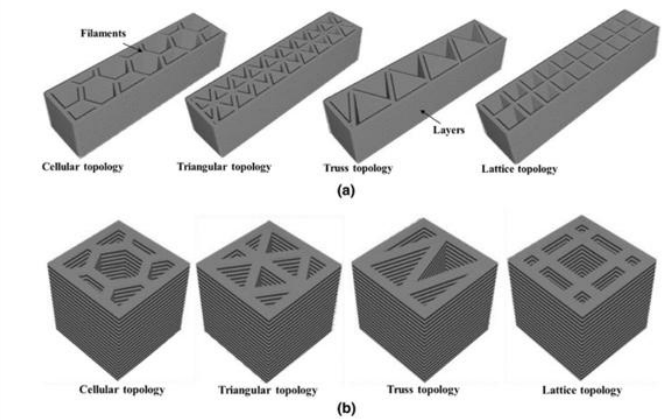



**Figure 6**. Hollow cross-section forms (Adapted from Wang et al., 2020)

### 3.2. Case Analysis of 3D-Printed Bridges

In this section, the ten bridges produced with 3D concrete printing technology and examined in this study are introduced. Table 1 presents an overview of these bridges, summarising their location, year of construction, function, total length, and maximum span. As shown in the table, the bridges span a

construction period from 2017 to 2024 and range considerably in scale, from 4 m research prototypes to full-scale structures exceeding 20 m in length.

**Table 1.** Summary of bridge location, year, function, length, and span data (Pons-Valladares et al., 2023; Salet et al., 2018; Vantyghem et al., 2020; Xu et al., 2020; Bhooshan et al., 2022; Yang et al., 2024; Ahmed et al., 2022; Dell'Endice et al., 2024; Rennen et al., 2023)

| Bridge | Location | Year | Function | Bridge Lenght | Max.Span |
|---|---|---|---|---|---|
| **IAAC** Bridge | Madrid, Spain | 2017 | Pedestrian | 12 m | 12 m |
| Gemert Bridge | The Netherlands | 2017 | Pedestrian + bicycle | 8 m | 6.5 m |
| Vertico Bridge | Belgium | 2020 | Pedestrian | 4 m | 4 m |
| Baoshan (Tsinghua) Bridge | Shanghai, China | 2019 | Pedestrian | 23.6 m | 14.4 m |
| Striatus Bridge | Venice, Italy | 2021 | Pedestrian + bicycle | 16.6 m | 16.6 m |
| Xiang Phoenix Bridge | Shanghai, China | 2021 | Pedestrian | 9.5 m | 6 m |
| Nijmegen Bridge | The Netherlands | 2021 | Pedestrian + bicycle | 29 m | 6.5 m |
| Phoenix Bridge | Lyon, France | 2023 | Pedestrian + bicycle | 18 m | 16 m |
| Knitcrete & Shotcrete Bridge | Germany | 2023 | Pedestrian | 4.5 m | 4 m |
| External-cable reinforced bridge | China – Australia | 2024 | Pedestrian | 4 m | 4 m |

Each example is presented with a detailed description of its technical characteristics and construction process. Key data such as the year of construction, structural dimensions, production method, material properties, and assembly process are provided in order to establish a clear and descriptive basis for the subsequent comparative analysis.

### 3.2.1. IAAC 3D-Printed Bridge / Madrid, Spain / 2017

According to the report of the Institute for Advanced Architecture of Catalonia, this bridge is the first application of 3D printing technology in the field of civil engineering. The bridge is 12 m long and 1.75 m wide (Pons-Valladares et al., 2023) shown in Figure 7.



**Figure 7.** IAAC pedestrian bridge, Madrid (Adapted from IAAC, 2017)

Built using micro-reinforced concrete, the structure minimises both material use and waste while maintaining structural performance. The project was implemented in Alcobendas Park in the Castilla-La Mancha region of Madrid, Spain. With its parametric design, the bridge was produced using the D-Shape robotic concrete printing process. Production took 45 days, and the bridge consists of eight U-shaped segments (Figure 8), each cast in a production chamber with steel-reinforced mortar and cured with the aid of heat.

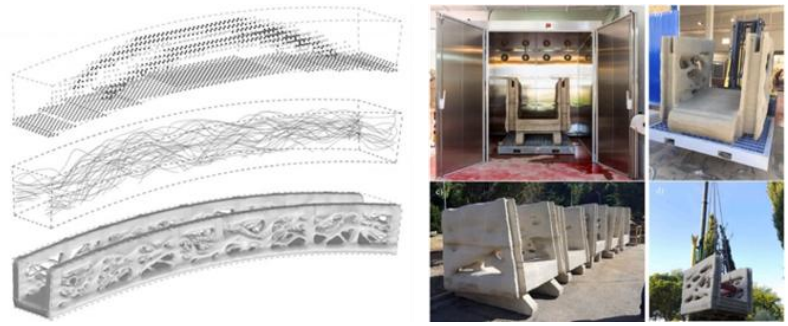


**Figure 8** Design development image; (right) curing device and unit components (Pons-Valladares et al., 2023)

Temporary steel girders were used during construction to support assembly (Pons-Valladares et al., 2023). Figure 9 shows the temporary steel support system and the form of the bridge composed of eight parts. Each bridge part measures 2 × 2 × 2 m (Pons-Valladares et al., 2023); this size limitation was determined in order to obtain the highest efficiency from the method used.




**Figure 9.** Segmented bridge structure and the temporary steel supports below (Pons-Valladares et al., 2023)

### 3.2.2. Gemert Bicycle and Pedestrian Bridge / The Netherlands / 2017

This bicycle and pedestrian bridge, located in the village of Gemert in the Netherlands, crosses a small canal (Figure 10) according to the project report (Salet et al., 2018). It is 6.5 m long and 3.5 m wide. Each structural unit was produced with a gantry-type 3D printer and, after printing, was rotated 90 degrees and assembled through the combination of pre-tensioned and post-tensioned tendons (Figure 11) (Salet et al., 2018).



**Figure 10** Gemert bicycle and pedestrian bridge, The Netherlands (Salet et al., 2018)

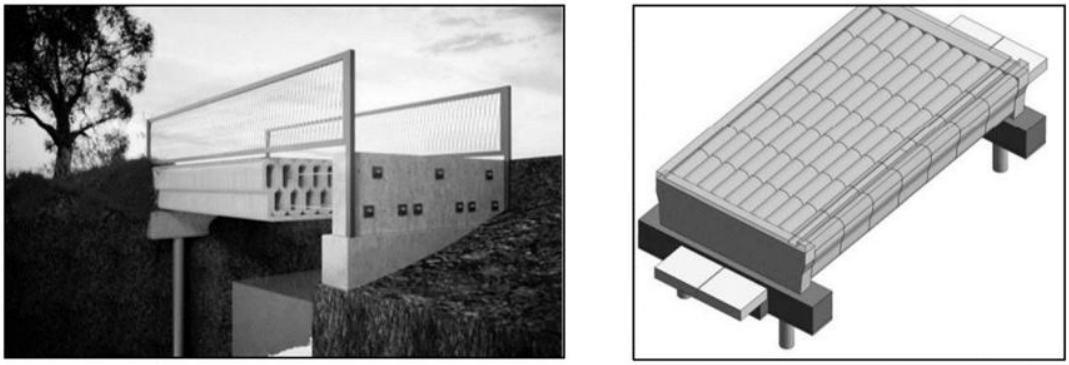


**Figure 11** (Right) bridge tensioning elements and (left) the model of the bridge structure composed of seven parts (Salet et al., 2018)

Weber Print Mortar was used as the printing material. The bridge consists of hollow-section elements (Figure 12) through which the tendons are passed and tensioned. Each unit is 3.44 m wide and 0.92 m high; the total printing time of all components was 48 hours (Salet et al., 2018). This project is recognised as the world's first 3D-printed bridge built with pre-tensioned elements using Fused Deposition Modeling (FDM) technology (Salet et al., 2018).



**Figure 12** (Left) element printing with a gantry crane; (right) printing with reinforcement added in a hollow-section structure (Salet et al., 2018)

### 3.2.3. Tsinghua University 3D-Printed Bridge / Shanghai, China / 2019

Built as a pedestrian bridge in Shanghai, China, in 2019, the Tsinghua University 3D-Printed Bridge (Figure 13) held the record at the time of its completion for the longest span composed entirely of 3D-printed segments. In this full-scale 3D concrete printing project, several critical factors had to be considered beyond determining the ratios of cement, sand, fibre, and water. Because the structure was produced with a 3D robotic printing arm, the extrudability of the concrete mixture was particularly important. While water-reducing admixtures increased the fluidity of the mixture, the use of thinning agents was also necessary to maintain the correct viscosity.



**Figure 13.** Tsinghua pedestrian bridge (Xu et al., 2020)

The bridge consists of 44 three-dimensionally printed concrete segments. The railings comprise 68 printed components, and the deck is made up of 64 patterned panels (Xu et al., 2020). With a total length of 23.6 m and a span of 14.4 m (Figure 14), the structural design of the bridge was inspired by the historic Anji Bridge.

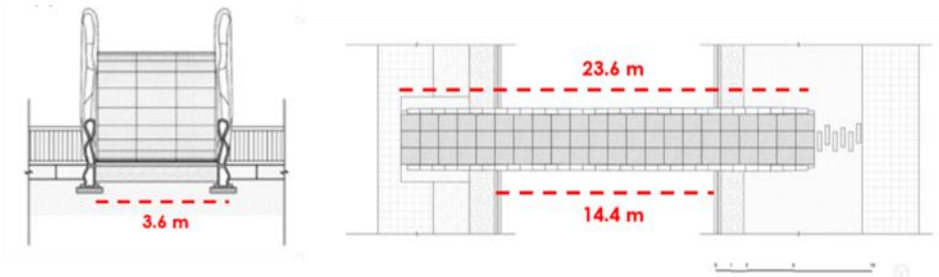



**Figure 14.** Tsinghua Baoshan pedestrian bridge cross-section and plan dimensions (Xu et al., 2020)

Two robotic printing arms were used in the production process; the 44 segments forming the main body were produced in 200 hours, and the patterned deck and railing components in 250 hours, so that the entire structure was completed in a total of 450 hours. Polyethylene-fibre-reinforced composite concrete was used as the material (Xu et al., 2020). Each element, measuring 90 × 90 cm, was placed in sequence on five temporary steel support arches (Figure 16) (Xu et al., 2020). Neither reinforcement nor formwork was used in production (Figure 15). Examination of the printed elements shows that their cross-sections consist of a special hollow geometry, which both increases structural strength and allows the bridge to be built without the need for reinforcement. According to the producers, this method reduced the total manufacturing time by approximately one-third compared with conventional bridge construction and also provided cost savings (Xu et al., 2020).



**Figure 15.** (Left) hollow-section structure of the bridge unit elements; (right) printing of the bridge railings with a robotic arm (Xu et al., 2020)



**Figure 16.** Tsinghua pedestrian bridge, image from the application: steel support girders and concrete parts (Xu et al., 2020).

### 3.2.4. Ghent University – Vertico Pedestrian Bridge / Ghent, Belgium / 2020

Topology optimisation is a method used to optimise the placement of materials within a given design space according to design constraints (Vantyghem et al., 2020).In this bridge study, ultra-high-performance concrete and post-tensioning tendons were used to create an efficient design. The bridge consists of 18 symmetrical parts, 9 on the right and 9 on the left (Figure 17); each part has a maximum total weight of 30 kg and a height not exceeding 40 cm (Vantyghem et al., 2020). After the parts are printed and a 14-day hardening period is observed, a tensioning process is applied with a special mould (Figure 18).



**Figure 17.** (Left) Image of the girder-bridge structure (Vantyghem et al., 2020) (right-up)bridge tendon and reinforcement placement; (right-down)the segmented structure of the bridge (Vantyghem et al., 2020)



**Figure 18** (Left) printed parts, (centre) insertion of reinforcement, (right) injection application (Vantyghem et al., 2020)

The girder spans 4 m (Vantyghem et al., 2020). The researchers state that, after accounting for live loads and the self-weight of the girder, the total material saving achieved with this method was 20%. The study demonstrates that, in addition to formwork-free production of complex geometry, robotic production through 3D printing is feasible (Vantyghem et al., 2020).

### 3.2.5. Striatus, Unreinforced 3D-Printed Bridge / Venice, Italy / 2021

Built in 2021 using 3D concrete printing technology, the Striatus Bridge (Figure 19) is an unreinforced arch-form pedestrian bridge designed to be demountable and reusable. Developed as a full-scale field application, the project was realised through the collaboration of Zaha Hadid Architects and ETH Zurich. All components were engineered to work in compression only, making it possible to build the bridge without any need for reinforcement or tensile elements (Dell'Endice et al., 2023). This design strategy enabled maximum efficiency with minimum material and allowed the structure to be dismantled and relocated, or individual blocks to be repaired, when required (Dell'Endice et al., 2023).



**Figure 19.** View of the Striatus Bridge (Dell'Endice et al., 2023)

The bridge has a 16 m span and consists of a total of 53 printed blocks; all blocks were produced within a printing time of 84 hours. According to the project report, the total weight of the blocks is approximately 24.5 tonnes (Bhooshan et al., 2022). The orthographic representations of the bridge are shown in Figure 20. A spider crane and a five-person team were used for on-site assembly; including a two-week logistical delay (Figure 21), the installation and construction process was completed in 35 days. All joints were applied using the dry-connection method (Bhooshan et al., 2022).

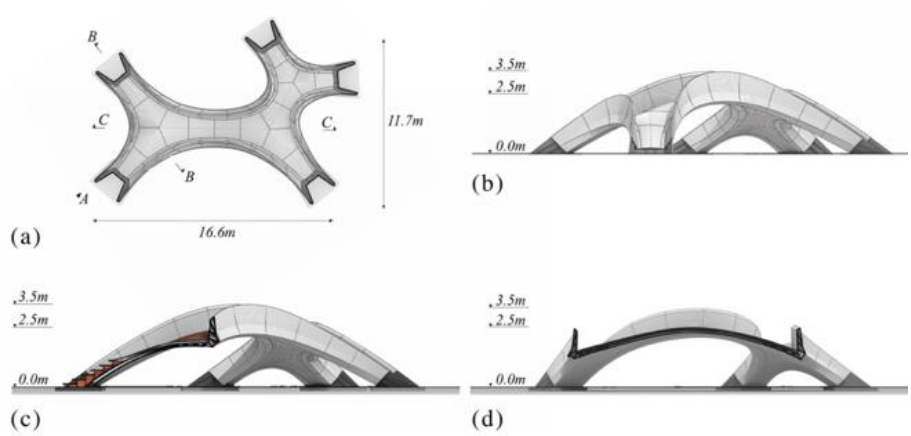



**Figure 20.** Striatus Bridge, plan, section, and elevation (Bhooshan et al., 2022)

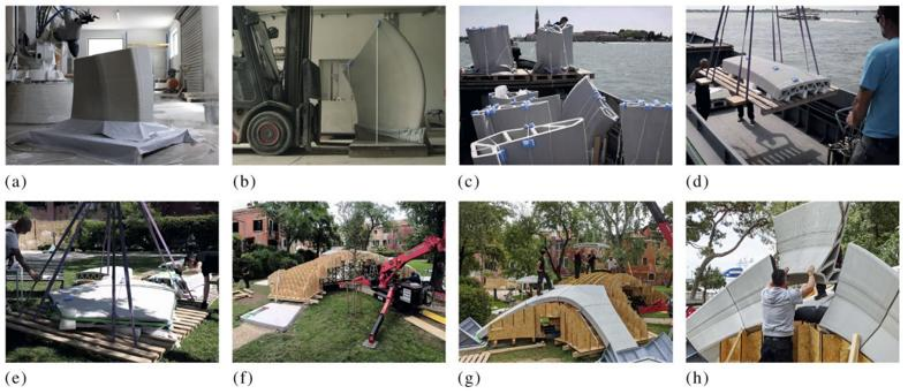



**Figure 21.** Image of bridge production from part manufacturing in the factory to on-site application (Bhooshan et al., 2022)

### 3.2.6. Nijmegen Bicycle and Pedestrian Bridge / The Netherlands / 2021

Built in Nijmegen, the Netherlands, in 2021, this bridge (Figure 22) holds the title of the longest-span bridge produced with 3D concrete printing technology. The project was carried out in collaboration with TU Eindhoven, and its design was made by Michael van der Kley. The structure consists of five superstructure girders and eight columns (Figure 23), with four pairs of columns anchored to pile foundations (Ahmed et al., 2022).



**Figure 22.** Completed bridge image (Adapted from Eindhoven University of Technology, 2021)



**Figure 23.** Images during application: the body anchored with abutments at the start, pre-tensioned elements in the middle, and the bridge view at the end (Ahmed et al., 2022)

After production was completed, both the columns and the bridge segments were rotated 180 degrees before assembly. Filler material was used during the printing process to achieve the outward-curved geometry of the columns; after the first printing attempt failed (Figure 24), the column geometry was revised (Ahmed et al., 2022).



**Figure 24.** Printing of the column elements: (left) the first column design, (right) the updated version (Ahmed et al., 2022)

After printing, the girder elements were covered with plastic sheets to ensure proper curing. The thin components of each girder, visible as cross-sections in the second photograph of Figure 25, were bonded to one another with a synthetic epoxy-based resin. To connect the six girder segments, anchor blocks made of cast-in-place concrete were placed at the front and rear of each part (Ahmed et al., 2022).

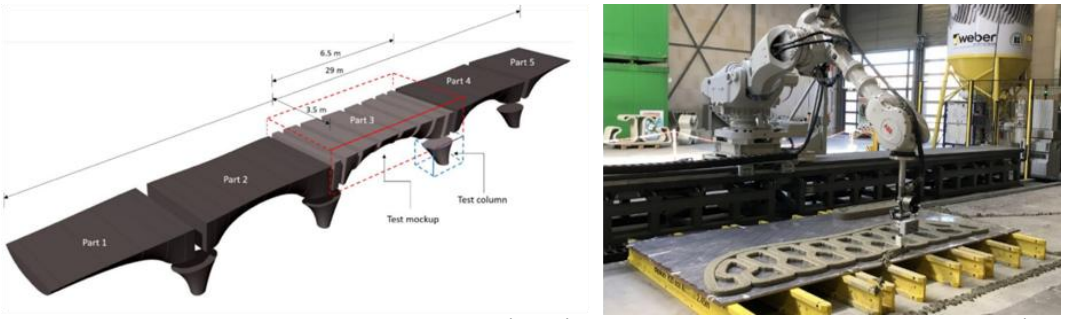



**Figure 25.** Bridge part distribution and dimensions; (right) the robotic arm printing the girder parts (Ahmed et al., 2022)

This experimental project, carried out in a university partnership, investigated the feasibility of the robotic production method for long-span, large-scale applications. The researchers verified the structural safety and practical applicability of the method; however, they also noted that, in its current form, it is not yet ideal in terms of material efficiency and cost (Ahmed et al., 2022).

### 3.2.7. Xiang Phoenix 3D Box Bridge / Shanghai, China / 2021

Built in 2021 as a pedestrian landscape bridge (Figure 26) in the Xi'ang district of Shanghai, this two-hinged arch bridge was constructed using a masonry technique. With a width of 2 m, the bridge has a total length of 9.5 m and spans 6 m (Yang et al., 2024). The parts were 3D-printed off-site using a robotic arm and the polypropylene-modified concrete layer-printing method (Yang et al., 2024). It consists of a total of 53 blocks in four categories (Figure 27-right), with dimensions ranging from 59 to 69.5 cm and from 35.3 to 55.7 cm, and a thickness of 11.5 cm (Yang et al., 2024). For aesthetic effect, 40 'wave-shaped wing' railing parts (Figure 27-left) were also concrete-printed and produced off-site (Yang et al., 2024).



**Figure 26.** (Left) conceptual design image, (right) the produced bridge structure, taken from the article (Yang et al., 2024)

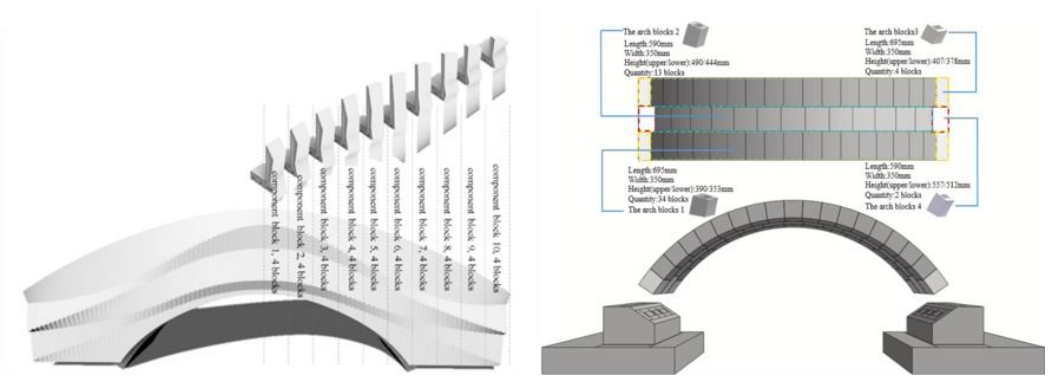


**Figure 27.** (Left) distribution of the 10 different parts for the 3D-printed railing; (right) distribution of the boxes forming the ring-shaped arch, taken from the article (Yang et al., 2024)

The concrete parts (Figure 28) were first exposed to moisture for 24 hours for initial curing, then standard-cured for 28 days (Yang et al., 2024). On-site installation took approximately 3 days (Yang et al., 2024). No information is available on the total printing time of the elements by the robotic arm.



**Figure 28.** (Top) concrete box parts of the arch ring, (bottom) concrete-printed railing element, (side) the robotic arm used in concrete printing (Yang et al., 2024).

As a proof-of-concept engineering demonstration project, this bridge tested the applicability of large-scale 3D concrete printing with a robotic arm in a real, complex, load-bearing structure, while demonstrating the producibility of a long-span bridge that does not require conventional formwork or scaffolding. With an installation time as short as 3 days, it also demonstrates engineering validity and material efficiency in the field (Yang et al., 2024).

### 3.2.8. Phoenix Bridge – Lyon, France / 2023

The Phoenix Bridge (Figure 29), also referred to as Striatus 2.0, was produced in France as a pedestrian and bicycle bridge as an improved and developed version of the bridge built in 2021. Lessons learned from the previously built bridge were taken into account in the new design. The new design has a shallower arch form and a greater number of blocks, and the height of the railing blocks was reduced. The main reason for this is that the size of the blocks in the 2021 design caused difficulties in portability and manoeuvring during assembly.



**Figure 29.** Image of the Phoenix Bridge (Dell'Endice et al., 2024)

The design consists of a total of 75 printed concrete parts (Figure 30), produced in 67 hours (Dell'Endice et al., 2024). The clear span of the arch is 16 m and the total length of the bridge is 18 m (Dell'Endice et al., 2024).



**Figure 30.** (Left) one of the concrete elements printed through layer printing; (right) bridge assembly and the scaffolding structure (Dell'Endice et al., 2024)

Assembly was completed with the aid of temporary scaffolding, and neoprene pads were used to reduce stresses between the blocks (Dell'Endice et al., 2024). A concrete printing mortar called Tector Print was used for this project; unlike the Striatus bridge, no fibre admixtures were used (Dell'Endice et al., 2024).

### 3.2.9. Robotic Knitcrete: 3D Shotcrete-Printed Pedestrian Bridge / 2023

The project is a pedestrian bridge prototype (Figure 31) realised at the Digital Building Fabrication Laboratory (DBFL) of TU Braunschweig in Germany. The main objective of this study was stated to be the development of an additive, design-based production process as an alternative to conventional formwork and conventional production methods, by combining 3D-knitted formwork technology (Figure 32) and robotic shotcrete 3D-printing technology. Unlike the other examples, the bridge structure was produced as a single-piece shell structure. With dimensions of 4.5 m in length and 1.6 m in width, the bridge prototype spans 4 m (Rennen et al., 2023).

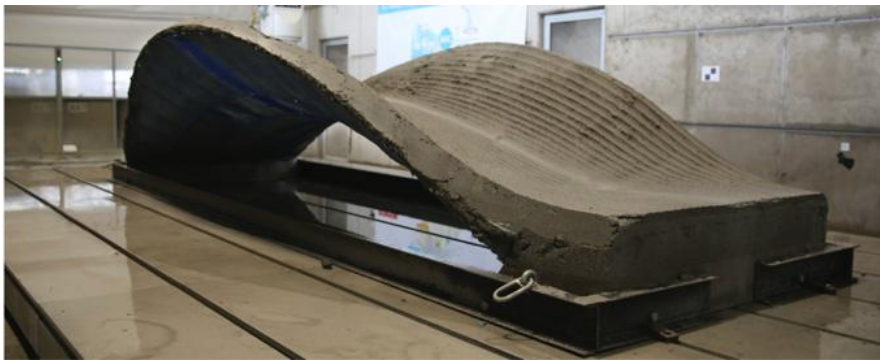


**Figure 31.** Finished state of the bridge produced with the shotcrete 3D-spraying method (Rennen et al., 2023)



**Figure 32.** (Left) the knitcrete formwork structure of the bridge; (right) the concrete-spraying process (Rennen et al., 2023)

In its construction, a Portland-cement-based cement grout without fine aggregate and a (micro-polypropylene) polymer-reinforced, cement-based, fine-grained concrete (Nafufill KM 250) were used (Rennen et al., 2023). The production of the knitted formwork took 4 hours (Rennen et al., 2023). The

robotic fibre winding required approximately 110 minutes, and 24 hours of curing time was required for the epoxy. It was applied with 15 spraying passes. A six-axis robotic arm was used (Rennen et al., 2023).

### 3.2.10. Flat Concrete Bridge Reinforced with External Cables / 2024

This study is a pedestrian bridge prototype carried out through the collaboration of Tongji University (Shanghai, China) and RMIT University (Melbourne, Australia). Multi-material topology optimisation was applied. Composed of 9 printed concrete elements working in compression and 2 parallel steel cables working in tension, the bridge structure (Figure 33) has an internally unreinforced, demountable, and re-assemblable form (Li et al., 2024).



**Figure 33.** Conceptual image of the bridge (Li et al., 2024)

The parts have a hollow cross-section. With a width of 60 cm and a span of 4 m, the bridge structure was printed using a six-axis industrial robotic arm (Li et al., 2024). The parts (Figure 34) were produced off-site and joined on-site using the dry-assembly method. A high-strength (50 MPa), fine-aggregate concrete suitable for 3D printing was used as the concrete type (Li et al., 2024).



**Figure 34.** (Top) bridge parts and (bottom) the assembled bridge structure (Li et al., 2024)

### 3.3 Comparative Summary of Production Methods, Cross Sections, and Materials

Having examined each bridge individually, this section presents a comparative summary of the production methods, cross-section strategies, and material properties across all ten cases, based on Tables 2, 3, and 4. Table 2 summarises the printing method, equipment, and production time for each bridge.

Among the structures listed in Table 2, in which the method, equipment, and durations used are specified, the Vertico and Nijmegen bridges were left to reach a certain hardness while the printed parts were removed from the printer, because sand was used as filler during printing. The fastest production among them was achieved in the Gemert bridge in the Netherlands. When the Striatus and Phoenix bridges are compared, it is seen that the printing time decreased in the Phoenix bridge.

**Table 2.** Summary of the 3D printing methods, equipment used, and production time of the bridges (Pons-Valladares et al., 2023; Salet et al., 2018; Vantyghem et al., 2020; Xu et al., 2020; Bhooshan et al., 2022; Yang et al., 2024; Ahmed et al., 2022; Dell'Endice et al., 2024; Rennen et al., 2023; Li et al., 2024)

| Bridge | Method used | Equipment used | Printing time |
|---|---|---|---|
| IAAC Bridge | D-Shape | D-Shape | 45 days |
| Gemert Bridge | 3D printing | Gantry crane | 48 hours |
| Vertico Bridge | 3D printing | Robotic arm | n/a – 14-day strength period |
| Baoshan Bridge | 3D printing | Robotic arm | 250 + 200 hours (≈19 days) |
| Striatus Bridge | 3D printing | Robotic arm | 84 hours + 35 days |
| Nijmegen Bridge | 3D printing | Robotic arm | n/a – 48 h de-moulding time |
| Xiang Phoenix Bridge | 3D printing | Robotic arm | n/a, 3 days installation |
| Phoenix Bridge | 3D printing | Robotic arm | 67 hours |
| Knitcrete & Shotcrete Bridge | Shotcrete spraying | Robotic arm | n/a |
| External-cable reinforced bridge | 3D printing | Robotic arm | n/a |

Sand is used in parametrically formed structures in order to preserve the form during printing. When the printing time is considered, three-dimensional printing technology is seen to be fast compared with conventional production. Among the printed bridges, the three-dimensional printing method was mostly used among additive production methods, and the robotic arm was largely chosen as equipment.

As summarized in Table 3, the examined bridge structures exhibit significant variations in terms of unit element cross-sections, reinforcement strategies, printing infill conditions, and the total number of constituent blocks. While hollow and box-like cross-sections are predominantly preferred to optimize material efficiency and structural weight, several complex geometries rely on specialized internal layouts or external support strategies during the printing process. Furthermore, the variation in unit element counts; ranging from monolithic shell applications to multi-segment masonry and post-tensioned assemblies, highlights how different structural systems address the scalability and constructability challenges of 3D concrete printing at the pedestrian- and bicycle-bridge scale.

**Table 3.** Summary of the cross-section forms, reinforcement conditions, and number of unit elements of the bridges (Pons-Valladares et al., 2023; Salet et al., 2018; Vantyghem et al., 2020; Xu et al., 2020; Bhooshan et al., 2022; Yang et al., 2024; Ahmed et al., 2022; Dell'Endice et al., 2024; Rennen et al., 2023; Li et al., 2024).

| Bridge name | Unit element section | Reinforced / unreinforced | Printing: filled / unfilled | Unit count (body) |
|---|---|---|---|---|
| IAAC Bridge | Solid section | Unreinforced | Printed into filler | 8 |
| Gemert Bridge | Hollow section | Reinforced – pre/post-tension | Unfilled | 7 |
| Vertico Bridge | Hollow section | Reinforced – tendon | Sand-filled | 18 |
| Baoshan Bridge | Hollow section | Unreinforced | Unfilled | 44 |
| Striatus Bridge | Hollow section | Unreinforced | Unfilled | 53 |

| | | | | |
|---|---|---|---|---|
| Nijmegen Bridge | Hollow section | Reinforced – pre/post-tension | Sand-filled | 44 (36+8) |
| Xiang Phoenix Bridge | Box section | Unreinforced | Unfilled | 53 |
| Phoenix Bridge | Hollow section | Unreinforced | Unfilled | 75 |
| Knitcrete & Shotcrete Bridge | Sprayed solid | Knitcrete mesh | Unfilled | 1 (single piece) |
| External-cable reinforced bridge | Hollow section | Reinforced / external | Unfilled | 9 |

Table 4 lists the type of concrete used and its compressive strength. In the listed bridge structures, it is seen that strength increases on a year basis, and that admixed and ultra-high-performance concrete are used (Miri et al. 2025). Concrete is inherently strong in compression and weak in tension. In 3D-printed concrete elements, tensile stress is the weakest limit of the material, and when this limit is exceeded, the probability of micro-cracks, inter-layer separations, and consequently macro-cracks and fractures increases (Yang et al., 2024). For this reason, during the design stage, geometry, strengths, and support conditions (such as reinforcement and tendons) are configured so as not to approach the laboratory-measured tensile strength (Li et al., 2024; Salet et al., 2018). Before field application, checks are carried out to prevent unexpected tensile stresses (Dell'Endice et al., 2024). Confirming this information, the examination of the bridges shows that the hollow-section, unreinforced elements have a particular cross-section geometry, and that pre- and post-tensioning elements were used in some examples.

**Table 4.** Summary of the concrete type and strength data used in the bridge productions (Pons-Valladares et al., 2023; Salet et al., 2018; Vantyghem et al., 2020; Xu et al., 2020; Dell'Endice et al., 2023; Bhooshan et al., 2022; Yang et al., 2024; Ahmed et al., 2022; Rennen et al., 2023; Li et al., 2024).

| Bridge | Concrete type used | 28-day compressive strength | Tensile strength |
|---|---|---|---|
| IAAC Bridge | Steel-reinforced mortar | < 25 MPa | n/a |
| Gemert Bridge | Weber Print Mortar | 22 MPa | 1.3 MPa |
| Vertico Bridge | UHPC (ultra-high-performance concrete) | 80 MPa | 1 MPa |
| Baoshan Bridge | Polyethylene-fibre concrete | 70–75 MPa | 1.5–2 MPa |
| Striatus Bridge | Fibre-reinforced concrete mix | 75–80 MPa | 3.5 MPa |
| Nijmegen Bridge | Weber Print Mortar (Weber 3D 145-2) | 30 MPa | 1–2 MPa |
| Xiang Phoenix Bridge | Polypropylene-modified concrete | 60 MPa | 4–5 MPa |
| Phoenix Bridge | Tector Print Mortar | 50 MPa | 1.52 MPa |
| Knitcrete & Shotcrete Bridge | Micro-PP-reinforced fine concrete (Nafufill KM 250) | n/a | n/a |
| External-cable reinforced bridge | Fine-aggregate concrete for 3D printing | 50 MPa | n/a |

Among the ten bridges examined, only the Vertico–external-cable-reinforced pair and the Striatus–Phoenix pair exhibit sufficient formal and methodological continuity—namely, a shared or closely related design team, comparable structural typology, and an explicitly documented design evolution—to allow a meaningful paired comparison. The remaining six bridges, while informative individually, do not share such a direct developmental relationship with one another; their critical strengths and limitations are instead summarised collectively in Table 5.

**Table 5.** Critical summary of key advantages and limitations of the ten examined 3D-printed concrete bridges(Pons-Valladares et al., 2023; Salet et al., 2018; Vantyghem et al., 2020; Xu et al., 2020; Dell'Endice et al., 2023; Bhooshan et al., 2022; Yang et al., 2024; Ahmed et al., 2022; Rennen et al., 2023; Li et al., 2024).

| Bridge | Key Advantages | Key Limitations |
|---|---|---|
| IAAC Bridge | First proof-of-concept application of 3D printing in civil engineering; complex parametric ornamentation achieved without formwork | Long production time (45 days); required temporary steel girders for assembly; small unit size (2×2×2 m) limited scale |
| Gemert Bridge | First pre-tensioned bridge produced via FDM; fast printing time (48 hours) | Reliance on post-printing tensioning process adds construction complexity; hollow units required precise tendon alignment |
| Vertico Bridge | Demonstrated feasibility of topology-optimised, post-tensioned robotic printing; 20% material saving | Small scale (4 m span) limits direct applicability to full-size infrastructure; 14-day hardening period before tensioning |
| Baoshan Bridge | Longest span at the time; formwork- and reinforcement-free hollow geometry; ~1/3 reduction in manufacturing time versus conventional methods | Long total process time (~450 hours including deck/railing); required five temporary steel support arches |
| Striatus Bridge | Fully unreinforced, compression-only design; demountable and repairable | Long installation time (35 days incl. logistics); steep arch reduced accessibility (required steps) |
| Nijmegen Bridge | Longest-span 3D-printed bridge to date (29 m); validated large-scale robotic feasibility | Column geometry failed on first attempt and required redesign; not yet cost- or material-efficient in its current form |
| Xiang Phoenix Bridge | Fast on-site installation (3 days); validated long-span masonry-type arch without scaffolding | No data available on total printing time, limiting comparability; material efficiency not yet optimal |
| Phoenix Bridge | Improved version of Striatus; reduced installation time (3 days vs. 35); smaller, more manoeuvrable blocks | Flatter arch reduced clear height beneath the bridge, limiting passage |
| Knitcrete & Shotcrete Bridge | Novel single-piece shell structure combining knitted formwork and shotcrete printing; formwork-free complex geometry | Limited to small-scale prototype (4 m span); no data on cost or scalability |
| External-cable reinforced bridge | Reduced material strength requirement (50 MPa) via external tensioning; demountable and reassemblable, improving sustainability | Small scale (4 m span); reliance on external steel cables partially offsets the "unreinforced" printing advantage |

### 3.4. Comparative Evaluation of Methodologically Related Bridges

Among the examined examples, the Vertico post-tensioned girder bridge produced in 2020 and the external-cable reinforced bridge produced in 2024 carry formal and methodological similarities, and therefore offer the potential for a comparative evaluation of the development of robotic production. Both bridge structures (Figure 35) were produced as research prototypes.



**Figure 35.** (Left) the 2020 Vertico post-tensioned girder (Vantyghem et al., 2020) and (right) the 2024 external-cable reinforced bridge (Li et al., 2024).

Tensioning elements were used in both bridges. The main difference in the bridge built in 2024 is that the external-cable reinforced bridge was configured to be dismantled and rebuilt, with the cables able to be integrated into the system during installation. This provides an advantage in terms of carbon emissions and sustainability. In the Vertico bridge, channels for the girder segments and tendons were opened; on the other hand, in the external-cable reinforced bridge, even though it is a similar segmental bridge, the need for cavities is reduced because the cables are passed externally. In terms of strength, since the external cables carry the tensile load, less reliance on the high tensile capacity of the material is required; the material strengths of 80 MPa and 50 MPa respectively confirm this.

Similarly, the Striatus bridge built in 2021 and the Phoenix bridge built in 2023—described as its improved 2.0 version—carry formal and methodological similarities (Figure 36), and therefore offer data potential regarding the development of the method used. The arch geometry of the Striatus bridge is steeper, while in the Phoenix bridge this arch form became wider and flatter. This change in geometry reduced the clear height beneath the arch from approximately 2 m to levels of 1.5–1.3 m (Dell'Endice et al., 2024). With this change, the new design eliminated the need for steps and produced a more accessible design, although it limited passage beneath it. This situation shows that 3D concrete printing technology reshapes design decisions not only in terms of production ease but also in terms of urban context and usage typologies.



**Figure 36.** (Left) Striatus (Dell'Endice et al., 2023) and (right) the Phoenix bridge (Dell'Endice et al., 2024).

In the Phoenix bridge, the block sizes were reduced and their number increased. This was stated to provide convenience in transport and assembly. The installation time, which was 35 days including transport, was reduced to 3 days in the Phoenix bridge (Dell'Endice et al., 2024).

## 4. Conclusion and Suggestions

Based on this study, the following conclusions can be drawn:

- In bridge production, additive design through three-dimensional production methods achieved a maximum span of 16.6 m and a minimum production time of 48 hours. This demonstrates the advantage of additive production for fast and structurally efficient design.

- Among the examined examples, the hollow section was frequently preferred as the cross-section form. With an efficient form, the material is also used efficiently, which results in economy in the structure.
- Over the years, external-cable bridge prototypes have been developed in order to support disassembly and re-installation and to contribute to construction economy.
- Among the production methods, 3D concrete printing technology was mostly preferred, and the robotic arm was preferred as equipment. This confirms, in the context of bridges produced with this method, the observation reported in robotic-production studies that the robotic arm is the most preferred equipment.
- In all productions, admixed or high-strength concrete was preferred as the concrete material.
- In parts with hollow sections that lack an internal infill geometry, sand filling was used during printing to prevent collapse. This emphasises the importance of efficient geometry for applicability.
- Three-dimensional printing technology, which is widely used in the production of complex-shaped and small-scale objects, has, with the development of the technology and hence the capacity of the machines over the years, made the production of larger parts possible. Unit element sizes began at 2 m in the IAAC Madrid bridge. However, for ease of manoeuvring and application during on-site assembly (as in the Striatus and Phoenix examples), smaller and more numerous parts are also seen to be preferred.
- During the application of the bridges, temporary support girders and formwork are seen to have been used on-site.
- When the structural designs of the ten bridges are examined, it is seen that five bridges were designed in arch form and unreinforced, four bridges in flat form together with post-tensioning elements, and one structure was built in shell form.
- As stated in the Xiang Phoenix bridge study, there are no regulations or standards regarding 3D-printed bridges, which are structures that require load-bearing and safety preconditions. It is emphasised that, as a result of these trials becoming widespread between 2017 and 2025, such standards may be needed in the future.

The examples examined in this study reveal the advances achieved between 2017 and 2025 in the material, production time, and assembly strategies of robotic and three-dimensional concrete-printed bridges. Applications such as geometric optimisation, reduction of part sizes, external-cable tensioning solutions, and the use of local or recycled materials strongly demonstrate the potential of these technologies in terms of both sustainability and construction economy. However, for these developments to evolve from temporary prototypes into permanent structures, it appears inevitable that the data obtained from experimental processes be shared in a way that contributes to standardisation, that regulations regarding production and material performance be established, and that long-term performance analyses be carried out at the urban scale.

In this respect, the present review complements the existing literature rather than duplicating it. While process-oriented reviews such as Zhang and Sanjayan (2025) systematise 3D concrete printing for bridges according to printing-process categories and material-handling technologies, the case-based and paired-evolution approach adopted here foregrounds architectural design decisions, on-site assembly strategies, and integration with architectural education. Read together, the two perspectives—engineering-process classification on the one hand and project-based architectural evaluation on the other—offer a more complete picture of where 3D-printed bridge construction stands and where it may develop. In this context, it is anticipated that 3D concrete printing and robotic production techniques will become not only an innovative field of research but also an effective part of safe and sustainable architectural practice.

More specifically, this review contributes to the literature in three concrete ways. First, by compiling and cross-referencing all documented 3D-printed concrete bridges realised between 2017 and 2025 into a single, consistent comparative framework (Tables 1–5), it provides a ready reference point for

future case-based studies, which was previously scattered across individual project reports and disciplinary-specific publications. Second, through the paired comparison of formally and methodologically related bridges (Vertico–external-cable bridge; Striatus–Phoenix), it makes explicit a developmental trajectory—showing, for instance, the measurable reduction in installation time and material strength requirements achieved between successive design iterations—that is not addressed by process-category-based reviews. Third, by explicitly linking the identified technological trends (e.g., hollow-section optimisation, external tensioning, modular disassembly) to architectural design and educational practice, this review offers a foundation for integrating 3D concrete printing into architecture curricula and design studios, an aspect largely absent from the predominantly engineering-oriented literature on the subject.

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