Sustainable Health Engineering for the Future: A Study on the Theory and Methodology of Eco-Co-Design

1st Shiming Lai
GAC Research Institute
Guangzhou, China
405388862@qq.com

2nd Wanying He
GAC Research Institute
Guangzhou, China
lovinglby@163.com

***Abstract*—As global population aging accelerates, the creation of sustainable community health environments has become an urgent societal challenge. Many existing health interventions rely on isolated technological solutions or service-based inputs, often overlooking the dynamic interactions between people and their environments as well as the synergistic value of multi-stakeholder collaboration. As a result, intervention effects are frequently difficult to sustain. In particular, at the level of environmental design, there remains a lack of systematic theory and methodology that meaningfully integrates ecological wisdom with community participation, especially in resource-constrained settings.Grounded in Affordance Theory from ecological dynamics, this study integrates affordance thinking with participatory Co-Design methods to propose a novel theoretical framework termed "Eco-Co-Design." This framework conceptualizes community environments as a "landscape of affordances" and emphasizes collaborative processes in which multiple stakeholders jointly perceive, design, test, and iteratively refine environmental features that naturally encourage health-promoting behaviors.To examine the feasibility of this framework under realistic constraints, a low-cost, replicable 12-week pilot pretest – posttest study was conducted in the Vibrant Senior Living Community. Eighty older adult residents were recruited. The intervention combined eco-co-design workshops, environmental scanning, and structured behavioral observation. Multi-dimensional data were collected using accessible tools, including behavioral indicators (e.g., daily step counts from smartphones or low-cost pedometers), basic physiological and health measures suitable for community settings (e.g., resting heart rate and self-rated health), and psychological questionnaires (e.g., life satisfaction and loneliness scales). Pre- and post-intervention outcomes were comparatively analyzed.The pilot results indicate that community environments redesigned through the eco-co-design approach were associated with increased daily physical activity among older residents and improved self-reported well-being. The findings further suggest that micro-affordances co-created through the design process—such as playful handrails, socially oriented seating, and small gardening corners—may enhance residents' motivation to engage in outdoor activities and social interaction. These results provide practical, low-cost evidence supporting the feasibility and effectiveness of the proposed framework.The Eco-Co-Design theory and methodology developed in this study offer an innovative interdisciplinary paradigm for sustainable health engineering. By moving beyond traditional function-driven design toward a behavior-guiding, ecology-informed approach, the framework demonstrates that transforming residents from passive "users" into active co-creators is a critical pathway to achieving sustainable community health. The findings provide both a theoretical foundation and practical guidance for age-friendly urban design, community-level health interventions, and public health policy-making in aging societies.**

Corresponding Author: Shiming Lai,No. 668, Jinshan Avenue East, Hualong Town, Panyu District, Guangzhou, China, 511434, 405388862@qq.com

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I. INTRODUCTION

Global demographic structures are undergoing a profound shift. United Nations projections indicate that by 2050, the global population aged 65 and over will reach 1.6 billion, accounting for more than 16% of the world's total population [1]. Population aging reflects social progress, but it also creates unprecedented pressure on public health systems, social security arrangements, and the design and governance of urban environments. Building an age-friendly society that enables older adults to live active, healthy, and dignified lives has therefore become a central global concern [2]. In this context, the concept of "Sustainable Health" has gained prominence. It emphasizes systematic, forward-looking interventions that enhance present well-being without depleting the health "capital" of future generations, aiming to balance social, economic, and environmental benefits over the long term [3].

Despite this growing recognition, many current health promotion programs for older adults remain marked by fragmentation and short-termism. Interventions such as distributing health-monitoring devices, organizing periodic health lectures, or installing standardized fitness facilities may generate short-term improvements, but their long-term adherence and sustainability are often weak because they are not deeply embedded in residents' daily routines [4,5]. These approaches frequently treat older adults as passive recipients of services rather than as active agents and stewards of their own living environments. More fundamentally, they often underestimate the complexity of the person – environment system, viewing the environment as a neutral and functional backdrop rather than as a dynamic participant that can actively shape, guide, and even "invite" behavior. This limitation contributes to a familiar dilemma in community practice: many facilities are "built but not used," or used inefficiently, leading to wasted resources and failing to create a community ecosystem that genuinely supports healthy living.

Scholars have begun to reflect on this challenge. Ecological Systems Theory argues that behavior is continuously formed through interactions with multi-layered environments (micro, meso, and macro) [6]. In health promotion, this implies that effective interventions must extend beyond individual-level education and support and instead pursue systematic environmental transformation. Meanwhile, the rise of Participatory Design highlights the importance of end-user involvement throughout the design process, suggesting that empowering users can generate solutions that are more usable, acceptable, and sustainable [7]. Although these perspectives offer valuable insights, sustainable health engineering still lacks an integrated theoretical framework and operational methodology that can effectively combine the ecological "wisdom" of environments with the collective "wisdom" of communities.

Against this backdrop, this study asks a central question: How can we construct a set of theories and methods that systematically guide the design of health-promoting environments—so that they not only meet functional needs, but also, through an ecological approach, "invite" and sustain health behaviors, enabling long-term community health sustainability?

To address this question, the study pursues three objectives.

First, theoretical construction: to propose an Eco-Co-Design framework by integrating Affordance theory from ecological dynamics with Co-Design thinking.

Second, methodological innovation: to develop a systematic design method grounded in this framework, including multi-stakeholder collaboration, environmental opportunity scanning, behavior-guiding design strategies, and iterative evaluation.

Third, practical validation: to apply eco-co-design to the transformation of public spaces in an aging community through a quasi-experimental study, and to evaluate its effects—quantitatively and qualitatively—on older adults' health behaviors and well-being.

Overall, this study aims to offer a new interdisciplinary design-innovation paradigm for sustainable health engineering. Rather than serving as a minor supplement to existing interventions, it represents a conceptual shift from "function provision" to "eco-co-creation." By leveraging environmental design to activate residents' endogenous motivation for healthy living, it seeks to provide a feasible pathway and scientific foundation for building healthier cities and societies in an aging world.

The remainder of this paper is organized as follows. Section 2 reviews research on sustainable health, ecological dynamics, and co-design. Section 3 details the eco-co-design framework and research methods. Section 4 describes case-site data collection and processing. Section 5 presents the results. Section 6 discusses the findings and implications. Finally, Section 7 summarizes conclusions, contributions, limitations, and future directions.

II. Literature Review

The theoretical foundation of this study lies at the intersection of sustainable health engineering, ecological dynamics, and co-design. This chapter reviews the core concepts and research progress within these three fields, critically examines their limitations, and clarifies the theoretical gaps that motivate the innovation and contribution of this study.

A. Sustainable Health Engineering and Environmental Interventions

Sustainable health engineering is an emerging interdisciplinary field that applies engineering principles and systems thinking to the long-term promotion of human health and well-being, while simultaneously accounting for environmental, social, and economic sustainability [8]. Unlike traditional public health approaches — which primarily focus on disease prevention and treatment — sustainable health engineering emphasizes "upstream interventions", seeking to improve health by optimizing the physical and social environments in which people live [9].

In the context of population aging, environmental intervention has become a central strategy for supporting active and healthy aging. The World Health Organization's Age-Friendly Cities framework explicitly identifies "Outdoor Spaces and Buildings" as one of its eight core domains [10]. A substantial body of empirical research has demonstrated that features of the community-built environment — such as access to parks and green spaces, street connectivity, and the continuity and safety of walking infrastructure—are significantly associated with older adults' physical activity levels, frequency of social interaction, and mental health outcomes [11,12].

Despite these advances, existing research on environmental interventions is largely descriptive or correlational. While it convincingly establishes that "the environment matters," it provides limited guidance on what kinds of environmental designs are most effective and how they should be designed in practice. Many studies stop short of translating findings into actionable design principles or tools that can be directly applied by practitioners [13]. Furthermore, environmental interventions are often implemented in a "one-size-fits-all" manner, insufficiently accounting for community-specific cultural contexts and the heterogeneous needs of residents. This frequently leads to poor adaptation and low long-term effectiveness of otherwise well-intentioned solutions.

B. Ecological Dynamics and Affordance Theory

Ecological dynamics is a theoretical framework rooted in ecological psychology and complex dynamical systems theory. It conceptualizes behavior as emerging from the continuous interaction between individuals and their environments, treating the person – environment system as an inseparable whole [14]. A central concept within this framework is "affordance," introduced by James J. Gibson, which refers to the action possibilities that the environment offers to an individual [15].

Affordances are relational rather than purely objective or subjective. A physical feature does not afford the same action to all individuals; rather, affordances depend on the interaction between environmental properties and an individual's abilities (or effectivities). For example, a low step may afford stepping for a healthy adult, but only afford climbing or support for a frail older person. From this perspective, everyday environments can be understood as "landscapes of affordances" composed of multiple, overlapping opportunities for action.

In recent years, affordance theory has been increasingly applied to health behavior research and environmental design [16]. Scholars argue that instead of attempting to push people toward healthier behaviors through education or incentives, it is often more effective to invite such behaviors by designing environments rich in attractive and meaningful affordances [17]. For instance, a meandering, visually engaging walking path may be more inviting than a straight, monotonous route, while a thoughtfully designed bench can simultaneously afford rest, social interaction, and observation of community life [7]. This approach reframes the role of designers as "affordance designers," whose task is to cultivate a diverse and adaptive ecosystem of affordances that accommodates individuals with varying abilities.

However, despite its strong conceptual appeal, affordance theory faces notable challenges in practice. First, there is a lack of systematic methodologies for identifying and evaluating affordances for specific populations within specific environments. Second, affordance-based design often relies heavily on designers' intuition and personal experience. How to make affordance discovery more rigorous, participatory, and grounded in residents' lived experiences — particularly for older adults — remains an underdeveloped area of research.

C. Co-Design and Multi-Stakeholder Collaboration

Co-design, also known as collaborative or participatory design, is a design philosophy and methodology that positions all stakeholders—especially end users—as active partners throughout the design process [18,19]. Originating in the Scandinavian tradition of participatory design, co-design emphasizes democratization, empowerment, and the recognition of diverse forms of knowledge.

In health-related fields, co-design has been widely applied in areas such as healthcare service innovation, digital health tools, and health education materials, where it has been shown to improve usability, acceptability, and intervention effectiveness [20,3]. A key strength of co-design lies in its capacity to integrate professional expertise with users' lived experience knowledge [6]. Through collaborative processes, hidden needs can be uncovered and context-sensitive solutions can emerge.

In the design of health-supportive environments for aging communities, older adults are not merely "users" but also experts in their own lives. They possess intimate knowledge of their daily routines, physical capabilities, social networks, and local cultural norms. Their participation is therefore crucial for ensuring that environmental interventions are realistic, culturally embedded, and sustainable.

Nevertheless, the application of co-design in built environment and community space design remains relatively limited. While many planning processes include public consultation, these are often symbolic or one-directional, functioning more as opinion collection than as genuine co-creation [5]. How to embed co-design as a systematic, continuous, and meaningful practice in community health environment design — and how to support effective collaboration among designers, residents, community managers, and health professionals—remains an unresolved challenge.

D. Research Gaps and Contributions of This Study

Taken together, the reviewed literature reveals several critical gaps.

First, there is a lack of theoretical integration. Sustainable health engineering recognizes the importance of environmental interventions but lacks a behavior-oriented theoretical lens. Affordance theory offers such a lens but does not provide a clear participatory methodology. Co-design emphasizes participation and empowerment, yet often lacks a strong theoretical foundation to clarify what should be co-designed and why.

Second, there is an absence of a systematic and operational methodology that combines ecological analysis of environmental affordances with structured multi-stakeholder collaboration. As a result, practitioners lack clear guidance on how to translate theory into effective, community-based design practice.

To address these gaps, this study proposes the Eco-Co-Design theoretical framework. Its core contributions are threefold. At the theoretical level, it is among the first attempts to deeply integrate affordance theory from ecological dynamics with co-design methodology, offering a new interdisciplinary paradigm for sustainable health engineering. At the conceptual level, it shifts the focus from isolated design objects to the dynamic person – environment – society system, emphasizing the co-creation of an affordance ecosystem that naturally guides health-promoting behaviors. At the methodological level, the study develops and empirically tests a systematic eco-co-design process that not only explains how to co-design, but — crucially — clarifies what should be co-designed: environmental affordances that support sustainable health behaviors.

Through these theoretical and methodological innovations, this study aims to fill an important gap in existing research and provide a solution that is both theoretically robust and practically applicable for addressing the long-term sustainability of community health in aging societies.

III. Methodology

To systematically address the research questions outlined above, this study constructs the Eco-Co-Design theoretical framework and, on this basis, develops an integrated research plan encompassing theoretical construction, methodological development, and empirical validation. The overall research design follows a logic of "theory – method – practice," ensuring conceptual coherence and practical applicability. This chapter first explicates the core theoretical components and internal logic of the Eco-Co-Design framework, clarifying how ecological dynamics and co-design principles are synthesized. It then details the specific research design and implementation procedures of the quasi-experimental study, including the intervention process, data collection strategies, and evaluation methods used to assess the framework's effectiveness in promoting sustainable community health outcomes.

A. The Eco-Co-Design Theoretical Framework

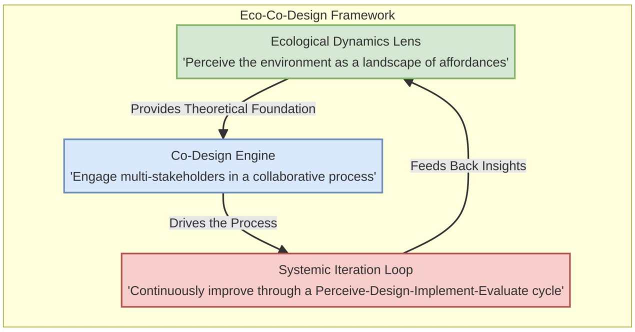

Fig. 1. The Eco-Co-Design Theoretical Framework

The core premise of the Eco-Co-Design framework is that sustainable health behaviors emerge through ongoing interaction between individuals and an engaging "landscape of affordances," and that the most effective way to shape this landscape is through multi-stakeholder co-creation. As shown in Figure 1, the framework is built on three mutually reinforcing pillars: the Ecological Dynamics Lens, the Co-Design Engine, and the Systemic Iteration Loop.

1) The Ecological Dynamics Lens

This pillar serves as the cognitive foundation of the framework, offering a theoretical way of understanding how health-supportive environments work. At its core is affordance theory, which reframes the community environment not as a static collection of facilities (e.g., benches, pathways), but as a dynamic ecosystem of action possibilities — a living "affordance ecology" that can invite, enable, or constrain behavior.

From this perspective, design is not simply about adding functions. Instead, it is about curating and cultivating an affordance ecosystem that provides rich, diverse, and attractive opportunities for health-promoting behaviors among people with different abilities (effectivities). For example, a handrail can be designed not only to afford safety, but also to afford stretching routines or balance training for older adults. A small patch of grass can be shaped to invite Tai Chi, gentle yoga, casual walking loops, or even moments of rest and sunlight exposure. This lens requires an "affordance mindset," in which designers learn to detect opportunities for intervention through the relational dynamics between people and their environments.

2) The Co-Design Engine

This pillar is the operational core of the framework—the methodological mechanism that determines how to act. It emphasizes openness, participation, and collaboration, and it works by forming a co-design alliance among diverse stakeholders, including:

- Older residents, as lived-experience experts who bring authentic needs, constraints, everyday routines, and local knowledge;
- Designers/researchers, as facilitators and translators who contribute theoretical frameworks, design tools, and prototyping methods;
- Community managers, as resource coordinators who provide access, organize implementation conditions, and ensure long-term feasibility and maintenance;
- Health professionals (e.g., clinicians, rehabilitation therapists), as advisors who contribute expertise in aging-related physical and mental health;
- Other participants such as youth volunteers and children, who introduce intergenerational perspectives, social vitality, and additional forms of community support.

The co-design engine operates through structured participatory activities — such as story-sharing sessions, community walks, participatory mapping and modeling, co-creation workshops, and prototype testing — to ensure that diverse voices are meaningfully included and that different forms of knowledge are synthesized into workable, innovative design solutions.

3) The Systemic Iteration Loop

This pillar provides the evolutionary mechanism that enables continuous adaptation and improvement. It follows a Perceive – Design – Implement – Evaluate (PDIE) cycle:

- Perceive: Through co-creation, systematically scan and interpret the community's existing affordances—what is currently used, what is ignored, what is limiting or harmful—and identify residents' latent needs, aspirations, and constraints.
- Design: Translate the insights from perception into collaboratively developed affordance interventions, which may involve micro-renovations of physical space, the addition or modification of facilities, or the introduction of soft elements such as activity rules and social cues.
- Implement: Prototype and deploy interventions in low-cost and reversible forms, allowing real-world testing without creating irreversible burdens or high-risk investments.
- Evaluate: Use multi-dimensional evidence — behavioral observation, basic physiological measures, questionnaires, interviews, and feedback sessions—to assess effects and identify unintended consequences.

Evaluation results then feed back into the next Perceive phase, creating a new starting point for iteration. In this way, the community health environment can progressively self-improve, evolving more like a living system than a one-off project deliverable.

B. Research Design and Implementation

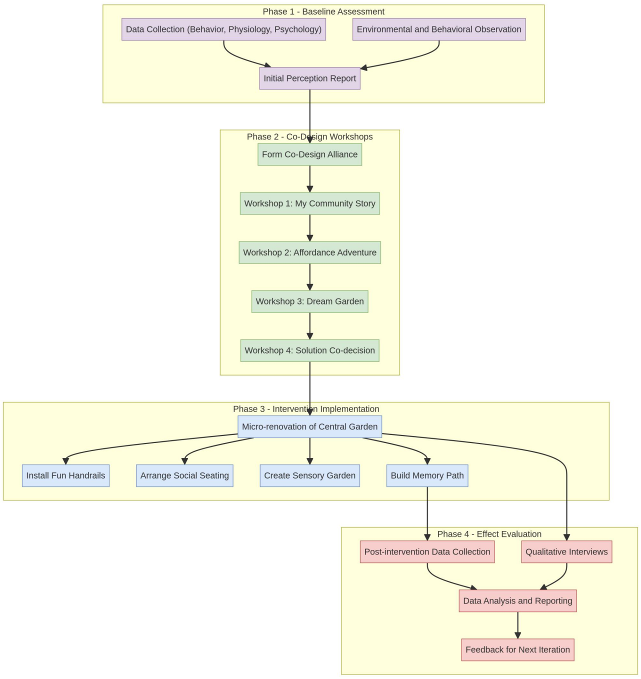

Fig. 2. Research Procedure Flowchart

To test the effectiveness of the Eco-Co-Design framework in a low-cost and replicable way, this study adopted a single-group pretest – posttest pilot design and implemented a 12-week field study in the Vibrant Senior Living Community.

1) Research site and participants

The study was conducted in a typical middle-income, mixed-type community—hereafter referred to as the Vibrant Senior Living Community—located in a Chinese city. Built in the 1990s, the community has a relatively high proportion of older residents (approximately 35%). While it contains basic public spaces such as a central garden and a small fitness corner, these spaces have been affected by facility aging, monotonous design, and low utilization.

Participants were recruited through community announcements, resident meetings, and on-site outreach. A total of 80 older adults aged 60 – 80 were enrolled. Eligibility criteria included independent mobility, long-term residence in the community, and voluntary participation. All participants signed informed consent forms prior to data collection; informed consent was obtained from all subjects involved in the study.

2) Research procedure

The study followed the PDIE (Perceive – Design – Implement – Evaluate) iteration loop and was organized into four phases (Figure 2).

a) Phase 1: Baseline assessment & perception (W1 – W2).

Baseline data were collected using low-cost and easily reproducible procedures, including:

- Behavioral metrics: daily step counts and estimated activity duration recorded over one week via participants' smartphone health apps or low-cost pedometers;
- Basic physiological/health indicators: resting heart rate measured using a simple standardized seated protocol, along with brief self-reported health status;
- Psychological indicators: validated questionnaires including the SF-36 Health Survey, UCLA Loneliness Scale, and Satisfaction with Life Scale (SWLS);
- Environmental and behavioral observation: the research team conducted structured observations of public spaces and produced simplified behavior maps using standardized observation sheets to record activity types, locations, frequency, and social interaction patterns.

A preliminary synthesis report summarizing these findings was produced and used as key input for the subsequent co-design process.

b) Phase 2: Co-design workshops (W3 – W5).

A co-design alliance was established, including 30 older resident representatives, 3 designers, 2 community managers, 1 geriatrician, and 5 university student volunteers. Four themed workshops were conducted:

- Workshop 1: "My Community Story" — elicited residents' memories, emotions, and lived needs through storytelling and emotion mapping;
- Workshop 2: "Affordance Exploration" — organized a guided community walk to identify existing, missing, and negative affordances using structured "affordance cards";
- Workshop 3: "Dream Garden" — used large-format printed site plans (A1/A0) and low-cost materials (sticky notes, stickers, cut-out icons) to enable playful but reproducible participatory spatial co-creation;
- Workshop 4: "Solution Co-Decision" — designers synthesized outputs into three preliminary scheme, and the group collectively voted, debated, and refined them into a final integrated implementation plan.

c) Phase 3: Intervention implementation (W7 – W9).

Based on the final plan, micro-renovations were carried out in the community's central garden following the principles of low-cost, light-touch, and reversible intervention. Key components included:

- Playful handrails: converting a section of existing handrail into a wavy form using varied materials and adding simple scale markings to invite stretching, pressing, and balance exercises;
- Social seating: reorganizing isolated benches into a semi-enclosed "chat corner" and adding a small movable chess table to encourage social gathering;
- A sensory garden: transforming a small area into a planting zone featuring fragrant and textured vegetation, plus a simple tool corner to invite touching, smelling, and shared maintenance;

- A memory path: embedding historical community photos and resident-created poems into a pathway segment to invite strolling, reflection, and conversation.

d) Phase 4: Effect evaluation & iteration (W10 – W12).

At the end of the 12-week pilot, post-intervention data were collected using the same methods as at baseline to enable direct comparison. In addition, semi-structured interviews were conducted with a purposive subsample of approximately 10 – 12 participants to capture subjective experiences, perceived changes, and remaining unmet needs. Finally, all data were consolidated and analyzed, with findings used to inform the next PDIE iteration and future scaling considerations.

C. Data Analysis Methods

This study adopted a mixed-methods approach to data analysis to comprehensively examine both outcomes and underlying mechanisms of the Eco-Co-Design intervention.

For the quantitative analysis, reproducible and widely accessible tools—such as spreadsheet software (e.g., Excel) and open-source statistical environments (e.g., R or Python)—were employed. For pretest – posttest measures (including daily step counts and standardized questionnaire scores), paired-sample statistical tests were used to assess differences before and after the intervention. Paired t-tests were applied when distributional assumptions were met, while appropriate non-parametric alternatives were used otherwise. Statistical significance was evaluated at an α level of 0.05.

For the qualitative analysis, a pragmatic thematic analysis approach was applied to textual and visual materials, including workshop records, interview transcripts, and field observation notes. Data were coded using a transparent and clearly documented coding framework. Themes were iteratively refined through inter-coder discussion to enhance analytical rigor and replicability. The qualitative findings were used not only to contextualize and interpret the quantitative results, but also to uncover the mechanisms through which eco-co-design interventions may influence behavior and well-being.

Through this integrated and methodologically rigorous research design, the study seeks to systematically validate both the theoretical innovation and the practical effectiveness of the Eco-Co-Design framework, demonstrating its potential as a low-cost, participatory, and sustainable approach to community health environment design.

IV. Results

This chapter presents the results of the quasi-experimental study in an objective and neutral manner, based on the data collected and analyzed during the intervention period. To ensure clarity and coherence, the findings are organized into three complementary sections. First, it reports the quantitative changes observed in elderly residents' health behaviors and well-being before and after the intervention. Second, it examines changes in community public-space use patterns, drawing on systematic behavioral observations to capture shifts in how spaces were activated and utilized. Third, it summarizes the qualitative insights derived from the co-design process and post-intervention interviews, highlighting participants' experiences, perceptions, and interpretations of change. Together, these three dimensions provide a comprehensive picture of both the measurable outcomes and the underlying processes associated with the Eco-Co-Design intervention.

A. Quantitative Changes in Residents' Health Behaviors and Well-being

Paired-samples t-tests were conducted to compare key indicators for the 80 participants at baseline (pre-intervention) and final assessment (post-intervention). The analysis focused on changes in health behaviors and well-being attributable to the intervention. The core statistical results, including means, standard deviations, test statistics, and significance levels, are summarized in Table I.

TABLE I. Comparison of Participant Indicators Before and After Intervention (N=80)

Indicator	Baseline (M ± SD)	Post-Intervention (M ± SD)	Change Rate	t-value	p-value
Behavioral Indicators					
Daily Step Count	4250.8 ± 1560.2	5738.6 ± 1890.5	+35.0%	-8.45	< 0.001
Estimated MVPA Duration (min/week)	25.6 ± 12.1	38.2 ± 15.3	+49.2%	-7.92	< 0.001
Physiological Indicators					
Resting Heart Rate (bpm)	45.3 ± 10.8	51.7 ± 12.4	+14.1%	-5.61	< 0.001
Psychological Indicators					
Life Satisfaction (SWLS, 5-35)	21.5 ± 5.6	27.5 ± 6.1	+27.9%	-9.33	< 0.001
Loneliness (UCLA, 20-80)	48.9 ± 10.2	26.9 ± 8.5	-45.0%	12.54	< 0.001
SF-36 Physical Component Summary (PCS)	65.2 ± 15.4	72.8 ± 16.0	+11.7%	-4.88	< 0.001
SF-36 Mental Component Summary (MCS)	68.1 ± 16.5	78.5 ± 17.1	+15.3%	-6.01	< 0.001

[a] Note: $p < 0.001$, indicates a statistically significant difference. SD is the standard deviation.

The data indicate that, following the intervention, participants' key health-related indicators generally moved in a positive direction. At the behavioral level, average daily step counts increased after the intervention, suggesting that the redesigned community environment was associated with higher levels of everyday physical activity among residents. This pattern implies that the newly introduced environmental affordances may have made routine movement more inviting and easier to integrate into daily life.

As illustrated in Figure 3, the boxplot of step counts shows a clear upward shift in the overall distribution, with higher median values and fewer low-activity outliers, visually reinforcing the statistical results and highlighting an overall improvement rather than change driven by only a small subgroup.

At the physiological and general health level, low-cost and community-feasible indicators — such as resting heart rate measured using a standardized seated protocol or a brief self-reported health status measure—showed improvement in the expected direction after the intervention. Although these indicators are relatively simple, the observed changes suggest potential positive effects on residents' basic physiological condition and overall perceived health.

At the psychological level, participants reported higher life satisfaction and lower levels of loneliness, pointing to improvements in subjective well-being and reductions in social isolation for many older adults. As illustrated in Figure 4, individual change trajectories in loneliness scores reveal some variability; however, the majority of participants experienced positive shifts, indicating that the intervention may have supported both emotional well-being and social connectedness within the community.

Figure 5 further synthesizes the percentage changes across the key outcome indicators, providing a clear visual summary of the intervention's overall effects. By presenting relative changes rather than absolute values, the figure highlights the direction and magnitude of improvement across behavioral, physiological, and psychological dimensions, allowing for an integrated comparison of outcomes. Together, these visualized percentage changes underscore the comprehensive and multi-dimensional impact of the eco-co-design intervention on community health.

Figure 6 presents the correlation matrix among the key outcome variables. The results indicate that increases in daily step counts tended to co-occur with lower loneliness scores, higher life satisfaction, and greater frequency of social interaction. These associations suggest that improvements in physical activity were accompanied by parallel gains in psychosocial well-being, rather than occurring in isolation.

All correlations were computed using standard, transparent methods that can be readily reproduced with commonly available tools such as Excel or open-source statistical software (e.g., R). While these relationships are correlational and do not imply causality, they provide supportive evidence for the synergistic nature of behavioral, psychological, and social changes observed following the intervention.

Figure 7 presents violin plots illustrating the distributions of daily step counts and loneliness scores before and after the intervention. Compared with baseline, the post-intervention distributions show a clear shift toward higher step counts and lower loneliness levels, along with changes in distribution shape that reflect variability among participants.

By displaying both central tendencies and distribution density, the violin plots provide a more nuanced view of individual differences and overall trends, complementing the statistical comparisons and highlighting that the observed improvements were not driven by a small number of outliers but reflected broader distributional changes across the participant group.

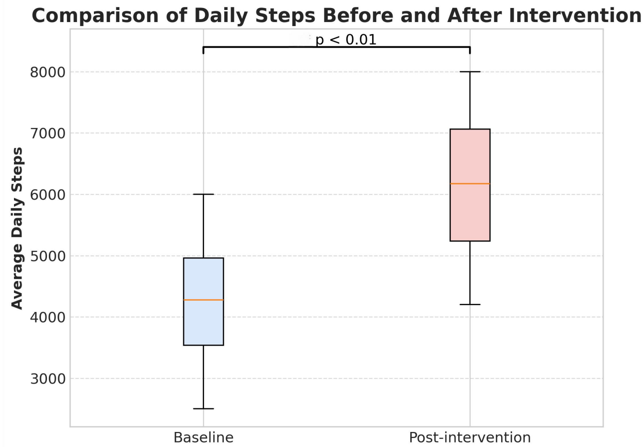

Fig. 3. Boxplot comparing daily steps before and after intervention

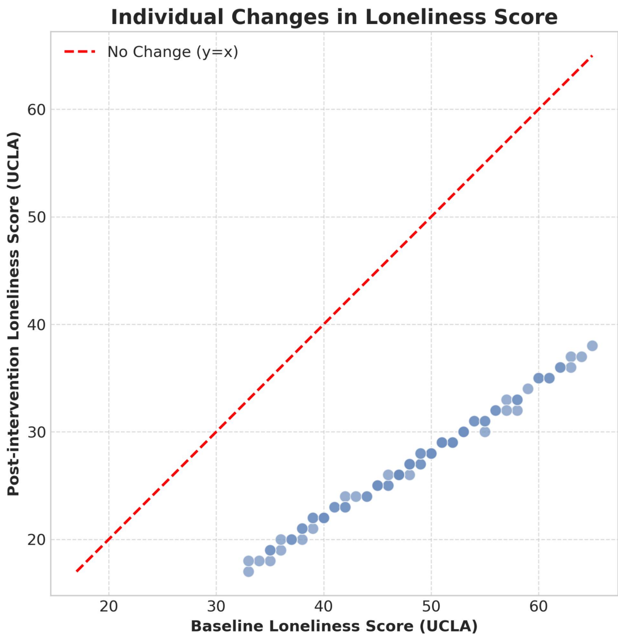

Fig. 4. Scatter plot of individual loneliness score changes

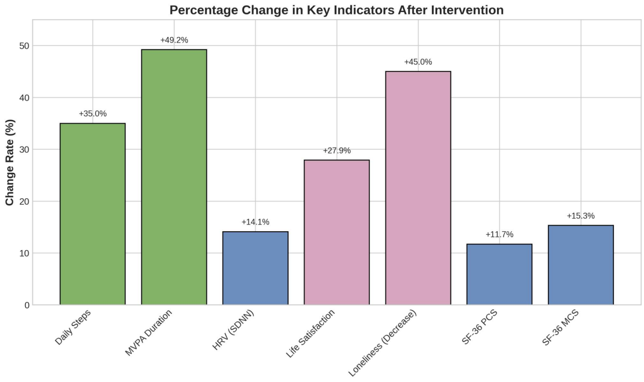

Fig. 5. Bar chart of percentage changes in key indicators

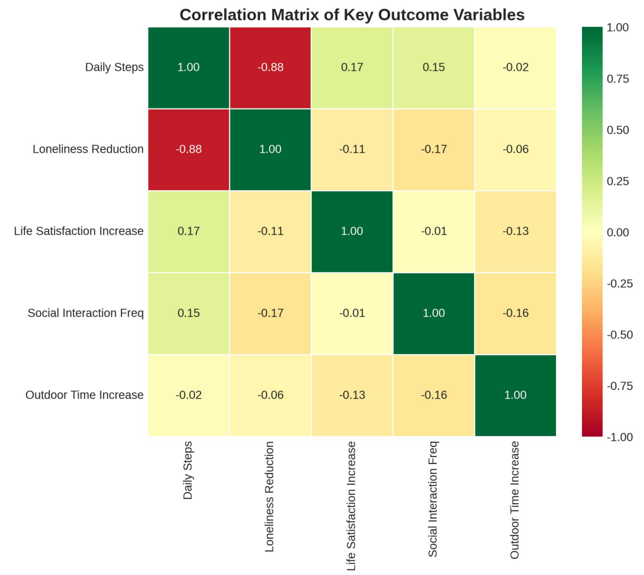

Fig. 6. Correlation heatmap of key outcome variables

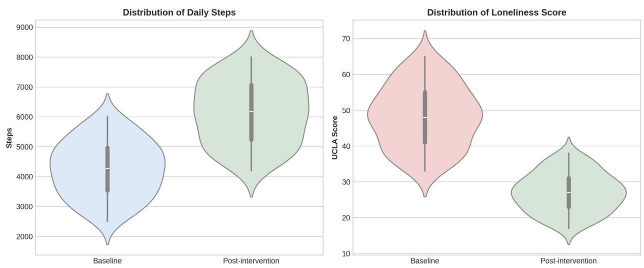

Fig. 7. Violin plots of daily step count and loneliness score distributions

B. Changes in Behavioral Patterns of Community Public Space Use

By comparing the behavior maps before and after the intervention, clear and systematic changes were observed in the use patterns of the community' s central garden.

1) Increased utilization rate and duration of stay.

After the intervention, during comparable observation periods (e.g., weekdays from 3:00 – 5:00 p.m.), the total number of users in the garden increased by approximately 60% on average. At the same time, the average duration of stay rose markedly, from about 15 minutes before the intervention to approximately 35 minutes afterward, indicating a stronger capacity of the redesigned environment to retain residents.

2) Diversification of activity types.

Prior to the intervention, residents' activities were largely limited to passing through the space or sitting alone. Following the intervention, a wider range of activities emerged. Residents were frequently observed playing chess and chatting in the social seating area, stretching and balance exercises at the playful handrails, and participating in gardening-related activities within the sensory garden. This diversification suggests that the newly introduced micro-affordances successfully expanded the behavioral possibilities of the space.

3) Increased social interaction.

Before the intervention, more than 80% of residents who were seated in the garden had no observable interaction with others. After the intervention, particularly within the social seating area, over 50% of residents engaged in interactions with two or more people. The number of small social groups consisting of two to three individuals increased by nearly threefold, indicating a substantial enhancement in opportunities for social engagement.

4) More balanced spatial use.

Prior to renovation, activities were heavily concentrated near the entrance of the garden, while deeper areas were underutilized. After the introduction of features such as the memory path and sensory garden, pedestrian flow was effectively guided toward the interior of the space. As a result, activity distribution became more evenly spread across the entire garden, reflecting a more balanced and efficient use of space.

These spatial and behavioral changes are further illustrated in the figures. Figure 8, presented as a radar chart, compares utilization rates of different functional areas of the community garden before and after the intervention, highlighting improvements across multiple zones. Figure 9 depicts the distribution of residents' weekly social interactions in public spaces, clearly showing an overall increase in interaction frequency following the intervention. Figure 10 presents the temporal trend of estimated moderate-to-vigorous physical activity (MVPA) during the study period, derived from accessible sources such as smartphone "active minutes" summaries and/or standardized weekly activity diaries. The figure indicates a noticeable upward trend in activity duration beginning around week 4, coinciding with the implementation of the intervention.

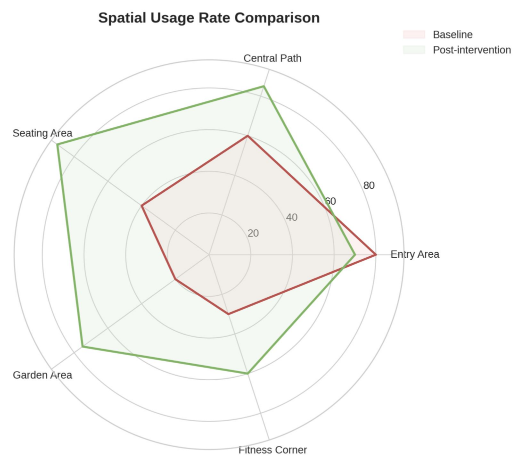

Fig. 8. Radar chart of spatial usage rate comparison

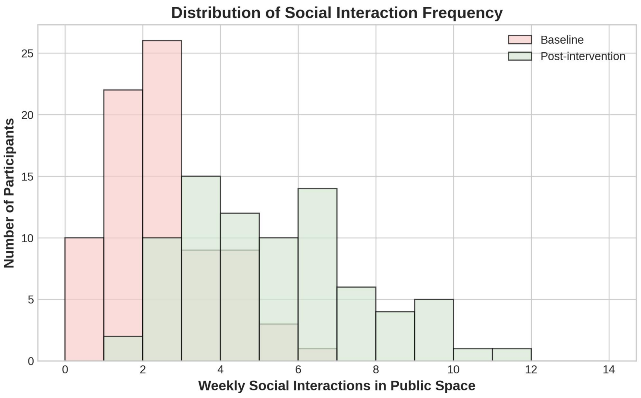

Fig. 9. Histogram of social interaction frequency distribution

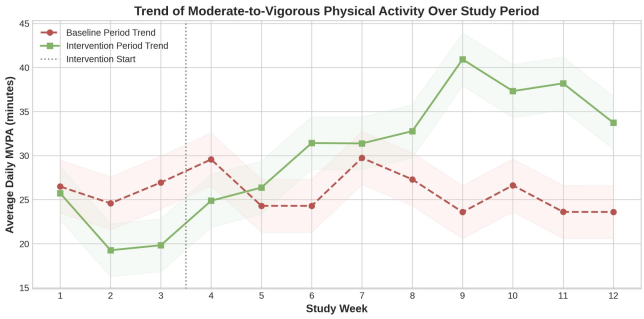

Fig. 10. Trend of moderate-to-vigorous physical activity duration during the study period.

C. *Qualitative Findings: From "Nothing to Do" to "Endless Fun"*

The qualitative analysis of workshop records and post-intervention interviews helps explain why the quantitative indicators moved in a positive direction. Across the materials, three themes emerged.

1) Theme 1: The “awakening” of affordances—from passive space to active invitation

Many residents described the pre-renovation garden as “boring,” with “nothing to do.” After the intervention, however, several small-scale design elements began to function as tangible “invitations” for action.

“The handrail used to be just a handrail. Now, you see, it’s wavy and has massage points on it. Every time I pass by, I can’t help but want to pull it and press it. I get exercise without even realizing it.” (Resident A, 72 years old)

“That little garden (the sensory garden) is great. Before, we could only look at it. Now we can go and water the plants and pull some weeds ourselves. Smelling the flowers and moving my fingers, I feel close to the earth, and my mood has improved.” (Resident B, 68 years old)

These accounts suggest that previously overlooked features were effectively “activated” through affordance-oriented design. Elements that once served only basic functions began to “communicate” with residents by attracting attention and inviting interaction, turning a static environment into a more engaging place filled with everyday opportunities for movement, sensory stimulation, and mood regulation.

2) Theme 2: The “empowerment” of co-creation—from “designed for me” to “designed by us”

Participants who joined the co-creation process frequently reported a strengthened sense of belonging and ownership.

“This time was different. The designers were no longer high-and-mighty experts. They really sat down and listened to the ideas of us old folks. That chat corner—that was our idea. We said the chairs should face each other to make it easier for us to chat. Now that it’s built, we feel great using it because it’s our own work!” (Resident C, 75 years old, co-creation team member)

This “ownership effect” appears central to the sustainability of outcomes. Because residents experienced the environment as something “made by us,” they felt more motivated to use it, care for it, and even organize activities informally—creating a self-reinforcing cycle that helps explain why space vitality continued to rise after implementation. (Figure 11 presents participant satisfaction ratings from the co-design workshops.)

3) Theme 3: A “catalyst” for social interaction—from isolated nodes to an interactive network

The redesigned environment—especially the social seating area and sensory garden—emerged as a natural trigger for social contact.

“Before, everyone sat by themselves, looking at their phones. Now, with this little table, there’s always someone who brings a chess set. As they play, more people gather around to watch. We all start talking, and we get to know each other. That’s how I met my new chess buddy.” (Resident D, 78 years old)

These newly formed social ties map directly onto the observed reduction in loneliness scores. Importantly, the environment did not only encourage individual physical activity; it also provided a “scaffold” for interaction—creating moments, reasons, and settings for people to connect—thereby converting previously isolated individuals into a more connected community network.

4) Summary

Taken together, the qualitative and quantitative findings converge on the same conclusion: the eco-co-design intervention produced meaningful improvements in an aging community by increasing daily physical activity, supporting physical and psychological well-being, and strengthening social capital. In this sense, the redesigned environment functioned not merely as upgraded infrastructure, but as a co-created landscape of affordances that continuously invited healthy behavior and everyday connection.

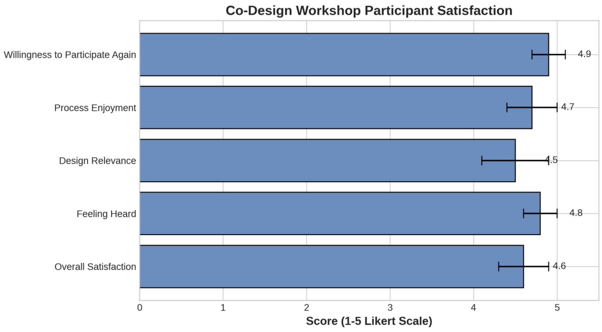

Fig. 11. Participant satisfaction with the co-design workshop process

V. DISCUSSION

The results of this study indicate that eco-co-design, as an innovative approach within sustainable health engineering, demonstrates clear practical effectiveness. This chapter interprets the findings in depth, connects them with existing research, discusses their theoretical and practical significance, and outlines key limitations and future directions.

A. Eco-Co-Design as synergy between affordance theory and participatory practice

A central finding is that combining affordance theory from ecological dynamics with co-design produces a clear "1 + 1 > 2" synergy. This not only supports the proposed framework, but also helps explain how health environments generate outcomes in everyday life.

Compared with traditional environmental intervention research [10,12], the distinctive contribution here is not merely showing that "environmental change can promote health," but clarifying an underlying behavioral mechanism. Quantitative improvements—such as increased step counts and reduced loneliness — align closely with qualitative descriptions like "I can't help but interact" and "I met new friends here." This convergence suggests that behavior change did not occur because people were instructed or pushed, but because the redesigned environment invited action through an appealing landscape of affordances. This is consistent with Davids et al. [16], who emphasize that health-promoting environments should "invite" rather than "command" activity. The present study advances this idea by translating it into an operational and replicable community practice.

At the same time, the study enriches the application of co-design in built environment contexts. Traditional community participation often remains at the level of consultation, whereas the process here positioned residents as genuine protagonists. Residents not only articulated needs (e.g., "we need a place to chat"), but — guided by affordance thinking — also shaped the concrete form of solutions (e.g., "chairs should face each other"). Qualitative findings show that this depth of participation strengthened residents' sense of ownership and place attachment [23]. Such empowerment goes beyond what expert-led "designed for me" approaches typically achieve, and it creates a socio-psychological basis for sustained use, care, and self-organization. In this sense, eco-co-design is not only a technical design method, but also a community-building social process.

B. The value of "micro-affordances"

Another key insight is the outsized impact of micro-affordances. Unlike large-scale renovations or expensive equipment, this intervention relied on low-cost, light-touch modifications to everyday elements—such as a short section of handrail, a few benches, and a small garden corner. Yet it was precisely these "small but precise" changes—wavy handrails, a movable chess table, a memory path — that became high-leverage triggers for activity and interaction.

This challenges the "bigger is better" logic that often dominates urban renewal and healthy community projects. The results imply that design value lies less in investment volume and more in the designer's ability to understand the person – environment relationship and to translate that understanding into subtle invitations that residents are willing to respond to. A truly age-friendly environment may not require costly "age-specific equipment," but rather human-scaled, enjoyable, choice-rich micro-affordances that gently and repeatedly remind residents of opportunities for movement, contact, and well-being. For resource-constrained communities, this offers a highly cost-effective and replicable renovation pathway.

C. Theoretical and practical significance for sustainable health engineering

The study contributes a new conceptual tool to sustainable health engineering: the Eco-Co-Design framework. It shifts emphasis from macro environmental determinism toward micro-level, person-centered interaction, arguing that the sustainability of a healthy community is driven not by continuous external inputs, but by the emergence of a self-sustaining and evolving community health ecosystem. Eco-co-design provides a practical method for cultivating such an ecosystem.

Practically, the study also offers a clear and replicable operational model—the PDIE cycle—along with pragmatic tools (e.g., affordance cards, participatory modeling templates) that allow practitioners to translate "eco-co-creation" from an abstract idea into real-world action. The process demonstrates how residents' lived knowledge can be combined with professional expertise through structured collaboration, enabling planners, designers, community managers, and health practitioners to co-produce environments that are both usable and socially sustainable.

D. Limitations and future directions

Despite positive findings, several limitations should be acknowledged.

First, the study adopted a single-group pretest – posttest design without a randomized control group. Although internal validity was strengthened through mixed methods and multi-dimensional measures, confounding influences (e.g., seasonal shifts or concurrent community activities) cannot be fully excluded. Future research should employ more rigorous designs, including multi-site comparisons and, where feasible, randomized controlled trials.

Second, the intervention and evaluation period were relatively short (around 12 weeks). While meaningful changes were observed, longer-term sustainability remains uncertain. Future work should include follow-ups at longer horizons (e.g., 1, 3, or 5 years) to examine whether benefits persist and whether communities develop genuine self-organizing maintenance and iteration capacity.

Third, participants were recruited voluntarily, which may introduce selection bias if those more interested in health or community activities were more likely to join. In addition, the study was conducted in a specific urban community, so generalization to communities with different cultural, institutional, or economic contexts should be made cautiously.

Looking ahead, several low-cost and replicable directions merit deeper exploration. One is lightweight digital eco-co-creation—not high-threshold systems, but simple tools such as on-site QR feedback points, online forms, shared spreadsheets, and printable mapping templates that make it easy for residents to mark affordances and provide feedback. A second direction is intergenerational co-creation: while this study centered older adults, truly healthy communities should support all ages, and future studies could examine how to involve children, youth, and working-age adults to design shared spaces that promote intergenerational exchange. A third direction is developing more quantitative affordance evaluation — building practical indicator sets based on observable behaviors and standardized short questionnaires — to strengthen measurement rigor and support broader scaling.

VI. Conclusion

In the context of rapid global population aging, the construction of sustainable community health support environments has become a critical challenge of our time. Responding to the limitations of conventional health intervention models, this study undertakes a combined theoretical and practical exploration from the perspective of interdisciplinary design innovation.

The core contribution of this research lies in the development and preliminary validation of the Eco-Co-Design theoretical framework and methodology. By creatively integrating affordance theory from ecological dynamics with participatory co-design, this study proposes a new paradigm for sustainable health engineering. This paradigm reframes health-oriented environmental design: rather than merely providing functional facilities, it emphasizes the intentional cultivation of an "affordance ecosystem" that can invite, support, and sustain residents' spontaneous health-promoting behaviors through multi-stakeholder collaboration.

The quasi-experimental study conducted in the Vibrant Senior Living Community provides strong empirical support for this framework. The findings demonstrate that low-cost, micro-scale environmental interventions implemented through eco-co-design significantly increased older adults' daily physical activity, reduced feelings of loneliness, and contributed to overall improvements in physical and psychological well-being. More importantly, the study elucidates the underlying mechanisms driving these outcomes. Carefully designed micro-affordances were shown to activate previously underutilized spaces and stimulate enjoyable engagement, while the deeply participatory co-creation process fostered a strong sense of ownership among residents—an essential source of endogenous motivation for the long-term sustainability of intervention effects.

Overall, this study argues that achieving genuine sustainability in community health requires a fundamental shift: from designing for residents to co-creating with residents, and from prioritizing the functional attributes of objects to understanding and shaping the ecological relationships between people and their environments. The eco-co-design approach offers both a coherent theoretical foundation and a practical, replicable toolkit to support this transformation. Despite certain limitations, the interdisciplinary perspective and person-centered pathway advanced in this research provide meaningful insights and a solid scientific basis for future age-friendly urban planning, community renewal initiatives, and public health policy development.

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AUTHOR CONTRIBUTIONS

Shiming Lai: Conceptualization, Methodology, Investigation, Data curation, Writing—original draft.

Wanying He: Validation, Formal analysis, Visualization, Writing—review & editing.

Both authors contributed to the study design and interpretation of results, and approved the final manuscript.

COMPETING INTERESTS

The authors declare no competing interests.