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Systemic operative framework to support the integration of urban agriculture and socio-ecological resilience in informal settlements: A dynamic urban metabolism approach to food security

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ABSTRACT

Urban informal settlements face acute challenges in food, water, and energy security, compounded by fragile governance and fragmented infrastructure. This study demonstrates that urban agriculture (UA), when embedded within a systemic urban metabolism (UM) framework, serves as a leverage point to drive circular resource flows and improve food security in these contexts. We develop and validate a four-stage diagnostic-to-simulation framework comprising multidimensional indicator derivation, a five-layer systemic scaffold, Interactive Loop Diagrams (ILDs), and a Forrester-style system dynamics model calibrated for Ciudad de Gosen, Lima, Peru, an informal settlement of approximately 6300 inhabitants. Simulation results show that rooftop and unbuilt-land cultivation can satisfy household vegetable and fruit demand, biodigestion can supply 17–52 % of household energy needs, and greywater reuse sustains irrigation for most cultivated areas, stabilizing at approximately 77 %. Critically, governance reforms and land tenure security emerge as the primary accelerators of adoption dynamics, producing cumulative improvements in diet diversity, waste reduction, and household food expenditures, underscoring that UA performance is conditioned more by governance and participation feedbacks than by technical capacity alone. The framework provides a transferable diagnostic pipeline linking indicators, feedback logic, and dynamic simulation to support circular food security assessment in data-scarce informal settlements worldwide.

1. Introduction

1.1. Informal settlement challenges and primary drivers

Rural-urban migration is a significant global driver of the growth of informal settlements, influenced by economic, social, demographic, environmental, and political factors (Maurel and Tuccio, 2016). Economic dynamics such as employment opportunities, unequal land distribution, and limited access to resources drive populations toward cities in search of better livelihoods (Davis and Henderson, 2003). Social determinants, including family structure, conflict, and access to services, also shape migration patterns (Farah et al., 2018). Demographic variables such as age, gender, education, and population growth further influence urban expansion (Singh et al., 2015). Environmental and climatic stressors, including natural disasters, water and soil quality, temperature, and rainfall variability, serve as additional push factors (Moore and Wesselbaum, 2023). Finally, political instability, weak governance, and inadequate planning policies affect migration flows (Nyberg–Sørensen et al., 2002).

Rapid urbanization, without effective planning, accelerates the growth of informal settlements, often overwhelming urban systems. Globally, over one billion people reside in informal settlements (UN-Habitat, 2020). These areas emerge informally and lack recognition, secure tenure, and access to basic services (Musango et al., 2020; Acevedo et al., 2017). Because of the scarcity of affordable land, communities frequently settle in environmentally hazardous areas, such as floodplains or unstable slopes (Kabiru et al., 2023). Informal settlements thus operate at the margins of legal frameworks, reflecting systemic failures in urban planning and governance (Choueiri et al., 2025; Roy, 2005).

Their main challenges include deficient infrastructure, environmental and social vulnerability, and limited access to water, sanitation, and energy (Reichhuber et al., 2023; Henderson et al., 2017). Climate change intensifies these risks, heightening poverty, malnutrition, and

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food insecurity (Nguyen et al., 2023).

1.2. Food security and informal settlements

Food security is a multidimensional challenge closely linked to urbanization, poverty, and environmental change. The Food and Agriculture Organization (FAO, 2006) defines it in terms of four dimensions: availability, accessibility, utilization, and stability. In informal settlements, these are weakened by unreliable food supply chains, precarious employment, poor infrastructure, and exposure to climate-related risks (Abualtaher and Bar, 2020). Excluded from formal distribution networks, residents depend on informal markets and self-sufficient production, which can remain unstable and disproportionately vulnerable to economic shocks (Fox-Kämper et al., 2023).

Insecure land tenure discourages long-term food production, deepening dependence on external food sources (Nchanji et al., 2023). Additionally, contaminated water supplies, inadequate sanitation, and unregulated waste disposal pose serious risks to food safety, leading to malnutrition and foodborne diseases (Vågsholm et al., 2020; Fernandez-Mena et al., 2016). Limited affordability constrains diets, leading to a high dependence on processed, nutrient-poor foods and an increased incidence of non-communicable diseases, such as obesity and diabetes (FAO, 2023).

As cities expand, circular agro-food systems offer a sustainable strategy to improve food security while reducing resource consumption and waste generation (Caputo et al., 2021). These systems integrate nutrient recycling, waste reduction, and decentralized food production to create more resilient and efficient urban food networks (Bahers et al., 2020). Urban agriculture (UA) is central to this approach, as it shortens supply chains, reduces reliance on external markets, and localizes food sources (Orsini et al., 2014). However, UA practices tend to be underutilized and their value underleveraged, as the systemic co-benefits across scales are often not recognized by decision makers and different stakeholders. Here, the application of urban metabolism (UM) frameworks has demonstrated that integrating UA within informal settlements can optimize resource flows, remediate environmental degradation, reduce urban heat island effects, repurpose organic waste, and improve self-sufficiency, thereby addressing multiple sustainability challenges (Guibrunet and Sánchez Jiménez, 2023).

UA has been increasingly recognized as a viable strategy for improving food security, livelihoods, and environmental resilience in informal settlements (Fox-Kämper et al., 2023). Practices such as sack gardening, rooftop farming, hydroponics, and community-based initiatives offer adaptable solutions to limited space and resources while providing nutritional, economic, and ecological benefits (A. Acevedo--De-los-Ríos et al., 2025; Yuan et al., 2022; Gallaher et al., 2013). For example, in Nairobi's Kibera settlement, sack gardening increased household vegetable consumption by 35 % and reduced food insecurity (Zivkovic et al., 2022). Similarly, in Lima, hydroponic farming has enhanced food security while conserving water in drought-prone areas (Orsini et al., 2010).

Beyond direct food provision, UA acts as a systemic leverage point in circular UM by supporting nutrient recovery, waste minimization, and decentralized resource management. It contributes positively to environmental sustainability, reducing pollution, mitigating heat islands, and expanding urban green infrastructure (Kirstgen and Moller, 2025; Thwaites et al., 2025). Yet, significant barriers persist, including insecure land tenure, fragmented policy frameworks, and limited institutional support (Magigi, 2013). Additionally, UA provides ecosystem services often overlooked in assessment frameworks, including biodiversity support, improved air and water quality, and microclimate regulation (Ciardullo et al., 2023; Mankiewicz et al., 2022). Overcoming these barriers requires embedding UA into broader urban resilience strategies, ensuring regulatory support, and securing access to vital resources (FAO et al., 2024).

1.3. Systems thinking and urban metabolism in informal settlements

Systems thinking provides an epistemological foundation for understanding urban complexity, enabling the study of dynamic interrelations and emergent properties within socio-ecological systems (Cristiano et al., 2020; Lezak and Thibodeau, 2016). It draws from cybernetics (Wiener, 1948), general systems theory (von Bertalanffy, 1968), and system dynamics (Forrester, 1969), all of which emphasize feedback loops, nonlinearity, and adaptive behavior. These approaches are complemented by information theory (Shannon and Weaver, 1949; Shannon, 1948), which formalized communication flows, and structuralist (Piaget and Inhelder, 1948) and constructivist epistemologies (Maturana and Varela, 1987; von Foerster and Varela, 1984), which stress relational and contextual knowledge.

Together, these perspectives offer a transdisciplinary lens for analyzing UM as a dynamic, multi-scalar process within socio-political, infrastructural, and ecological contexts, rather than just as a resource flow model. This view is relevant in informal settlements, where conventional models overlook decentralized organization, non-formal governance, and adaptive feedback mechanisms that shape socio-ecological performance (Krueger et al., 2022; Forrester, 1969). Scholars argue the need to reconceptualize UM in such contexts, recognizing informal settlements as active metabolic agents rather than marginal anomalies (Choueiri et al., 2025; Kaviti Musango et al., 2020; P. M. Allen, 2012).

System dynamics (SD) modeling supports this approach by simulating feedbacks, time delays, and non-linearities across urban systems. It has been used to analyze socio-ecological transformations and planning interventions. Sanders and Sanders (2004) extended Forrester's original Urban Dynamics model with a spatially disaggregated structure that captured intra-urban feedbacks, while Winz (2005) applied SD to urban water systems, linking economic, regulatory, and behavioral dynamics. More recent models integrate production, ecology, and living conditions (Wu and Huang, 2023) or improve policy under uncertainty (Yeomans and Kozlova, 2023). Fabolude et al. (2025) reviewed SD in the big-data era, noting challenges such as data scarcity, structural bias, and limited real-time calibration.

Despite its strengths, SD faces three main constraints: limited access to disaggregated data, particularly in informal contexts where data collection is sporadic or unavailable (Winz, 2005; Wu and Huang, 2023); assumptions that overlook behavioral or institutional heterogeneity, which can undermine the credibility of long-term scenario projections (Yeomans and Kozlova, 2023; Sanders and Sanders, 2004); and scarce empirical validation of models or post-evaluation, limiting their operational relevance for urban policy and investment planning (Fabolude et al., 2025). These challenges are particularly relevant when applying SD in data-scarce, rapidly changing urban environments such as informal settlements.

Traditionally, UM refers to the flows of materials, energy, and information within a city (Golubiewski, 2012; Pincetl et al., 2012; Kennedy et al., 2011; Stonier, 1990; Wolman, 1965). Yet its conceptual scope needs to expand to include institutional fragmentation, informal adaptation, and inequality (May 2022; Gunderson, 2012; Gandy, 2004). Following Stonier (1990), who argues that any system can be modeled in terms of matter (M), energy (E), and information (I), UM can be understood as the integrated circulation of these components. The interactions among M, E, and I produce emergent properties, such as resilience, vulnerability, or inequality. In this expanded view, UM operationalizes systems thinking by framing cities as open, adaptive systems that continuously exchange resources across formal and informal boundaries (Cristiano et al., 2020; John et al., 2019).

Informal settlements function as adaptive socio-ecological subsystems within broader urban metabolic systems. They act as active metabolic nodes where food, water, energy, waste, and labor circulate across boundaries (Acevedo-De-los-Ríos et al., 2024; Diep et al., 2019). These systems emerge from structural inequalities, such as tenure

insecurity, infrastructure deficits, and institutional exclusion, yet also display innovation and adaptive capacity (Bryan et al., 2024; Cruz and Forman, 2022; Simone, 2019). Their metabolisms differ from formal areas through decentralized cycles, informal governance, and context-specific norms (Choueiri et al., 2025), producing variability, path dependence, and emergent behaviors characteristic of complex adaptive systems (Folke et al., 2010; Grimm et al., 2008). This aligns with resilience theory and urban political ecology, which emphasize the co-evolution of material flows and governance (Borie et al., 2019; Allen P.M, 2012).

Urban systems, in informal contexts, are hierarchically structured across spatial, temporal, and functional scales (Yang and Zhang, 2025). Micro-scale practices are often linked to macro-scale sustainability outcomes (Lwasa et al., 2022; Andersson et al., 2021), but temporal mismatches between rapid community adaptation and slow formal planning lead to institutional fragmentation (UN-Habitat, 2020; Sovacool et al., 2020). Addressing this disjunction requires multilevel co-production strategies that connect short-term resilience with

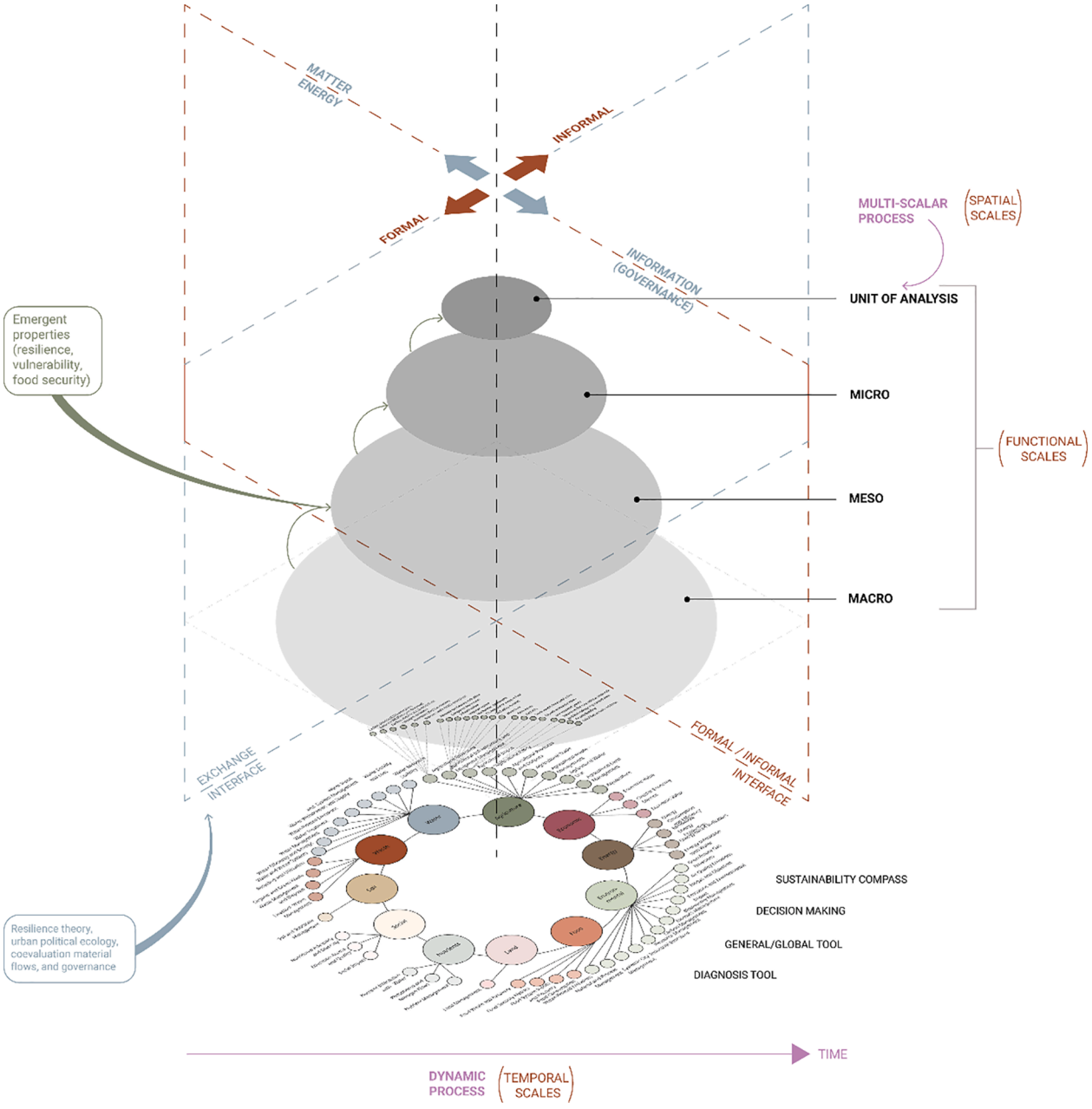


Fig. 1. Systemic Interconnections of Formal and Informal Urban Systems within the City and Regional Metabolism. The diagram highlights that food security and resource circularity in informal settlements emerge from multi-scalar feedback between formal governance structures and informal adaptive practices, rather than from either domain alone.

Note: This conceptual diagram illustrates the nested, dynamic integration of formal and informal systems within urban metabolic processes across spatial (unit of analysis, micro, *meso*, macro), functional, and temporal scales. The layered conical structure represents multiple levels of governance resource exchange, and socio-ecological interaction, intersected by material–energy flows, information–governance channels, and formal–informal exchanges. At the base, a sustainability compass organizes indicators related to resource access, equity, resilience, and infrastructure performance. Bidirectional arrows represent top-down policies and bottom-up adaptations, leading to emergent outcomes such as food security and resilience. The framework links diagnostic indicators, decision-support tools, and multilevel feedback processes, showing how informal infrastructures, including waste reuse, urban agriculture, and nutrient cycling, interact with formal governance within complex adaptive urban systems.

long-term planning. Practices such as urban agriculture, on-site water capture and bioremediation, decentralized composting, and community-based services can act as critical infrastructure for sustainability transitions, challenging the formal-informal divide (Bricas et al., 2019; Choguill, 2008).

Systemic modeling must capture this duality: informal settlements are both components of broader urban flows and self-regulating microsystems shaped by local constraints (Al and Verebes, 2025; Fransen et al., 2024; Zhang et al., 2015). Fig. 1 illustrates interactions between formal and informal subsystems, particularly across the domains of food, water, energy, and waste.

Urban scales are conceptualized as hierarchical yet interconnected domains that organize material, ecological, and social processes across space and time. The macro scale corresponds to the metropolitan or regional level, comprising ecosystem processes, food–water–energy exchanges, and governance networks that shape city–region metaboli sm (Yang and Zhang, 2025; Sharifi, 2019). The *meso* scale corresponds to the district or neighborhood level, capturing land-use dynamics, infrastructure distribution, and socio-spatial inequalities within the urban fabric (Dooghe et al., 2023; Irwin et al., 2009). The micro scale focuses on community and settlement structures, where local resource loops, informal governance, and adaptive behaviors emerge (Fransen et al., 2024; Olğun et al., 2022). Finally, the unit of analysis scale represents the operational unit in which daily metabolic practices, such as on-site water capture and purification, greywater reuse, composting, and household food production, materialize systemic interactions (Khadim et al., 2022). At this scale, infrastructure, particularly green infrastructure, acts as a key metabolic interface that connects personal behaviors with urban ecological performance. Together, these scales define the multilevel organization of urban metabolism, linking localized actions with city-wide sustainability outcomes.

Ultimately, integrated, multi-scalar governance is essential. Feedback-informed planning and co-design with communities can amplify the benefits of targeted interventions. For instance, nutrient recovery through urban agriculture can generate cascading improvements in water reuse, food availability, and social cohesion (Guzman-Molina et al., 2025; Arcas-Pilz et al., 2023). Additionally, emerging technologies are establishing the water-energy-food nexus within UA by using food-growing plants for on-site water purification, particularly in drought-prone regions (Pretorius and Dyson, 2024). This system-based rationale supports the framework developed in this study, which translates complex interactions into diagnostic tools for improving urban resilience, sustainability, and food security, especially in informal settings where standard planning methods often fall short.

The systemic approach developed in this study also connects to broader perspectives in network science and complexity on socio-ecological resilience. Research on the robustness and resilience of complex networks (Artime et al., 2024) demonstrates that topological and functional redundancy in interconnected systems underlies adaptive capacity under stress, a principle directly applicable to the multi-loop feedback architecture proposed here. Complementary insights from social physics (Jusup et al., 2022) reveal how collective behavior, resource sharing, and social norms emerge from local interactions in densely connected communities, providing a theoretical foundation for the participation and knowledge-transfer dynamics modeled in this study. An early synthesis by Helbing et al. (2015) on the contributions of complexity science to societal challenges further illustrates how information flows and feedback mechanisms can guide intervention design for vulnerable urban populations.

1.4. Research gaps, objectives, hypothesis, and structure of the study

Despite a growing body of research on urban metabolism, food security, and informal settlements, key gaps remain. While prior studies have integrated urban metabolism, system dynamics, food–energy–water nexus approaches, and urban agriculture in various configurations, existing frameworks often lack systemic coherence and fail to incorporate explicitly operational, feedback-sensitive structures that reflect the dynamic interrelations within informal urban environments. Moreover, urban agriculture is frequently treated as a localized intervention, not embedded in a broader metabolic framework that accounts for Interactive resource flows, governance, and socio-environmental feedbacks. This limits its potential as a strategic tool for food security and circularity. In addition, most existing models emphasize sectoral efficiency or resource optimization, but lack diagnostic capacity tailored to informal settlements, omitting adaptive factors such as tenure insecurity, informal service provision, and decentralized resource management.

This study addresses these gaps by proposing a systemic operative framework grounded in systems thinking and UM, to enhance food security in informal settlements through the strategic integration of UA. Rather than claiming novelty in the integration of UM, SD, and UA per se, the contribution lies in the operative structuring and diagnostic workflow that translates literature-derived indicators into a system dynamics–ready architecture suitable for informal contexts. The research pursues four key objectives: (1) develop a systemic operative framework positioning UA as a metabolic intervention for food security in informal contexts; (2) operationalize the framework through dimensions, variables, indicators, and a five-layer systemic scaffold that capture resource flows and feedbacks; (3) construct Interactive-loop diagrams (ILDs) to identify dynamic feedbacks and leverage points within the metabolism of informal settlements; and (4) validate the framework through a system dynamics model calibrated for Ciudad de Gosen settlement in Lima, Peru.

To guide the research, the following questions are examined:

- RQ1: How can UA be integrated within a UM framework to promote food security and circular resource flows in informal settlements?
- RQ2: Which variables and indicators, informed by systems thinking, are required to characterize food–water–energy–waste interdependencies in these contexts?
- RQ3: How can ILDs help identify leverage points, feedback mechanisms, and systemic barriers to circularity, especially in relation to food security?
- RQ4: How can a system dynamics model test the coherence and leverage potential of the proposed framework in informal urban systems?

Based on these questions, the study formulates the following hypothesis: Integrating UA within a feedback-sensitive urban metabolism framework enhances food security in informal settlements by activating systemic leverage points that optimize resource circularity and resilience.

2. State of the art

2.1. Definitions of frameworks

In research fields related to social-ecological systems, governance, economics, and sustainability sciences, frameworks provide conceptual and methodological structures that organize empirical investigations and ensure clarity and transparency in theoretical development (X. Shi and Ling, 2025; William, 2024; Pulver et al., 2018; Binder et al., 2013). In computational disciplines, they serve as structural foundations composed of components and libraries that control function flows (Traoré, 2017). However, semantic inconsistencies, ontological ambiguities, and translation gaps often challenge interdisciplinary use (Bevan, 2022). Such discrepancies reduce coherence and interoperability, especially when frameworks are transferred across disciplines with differing assumptions. Many frameworks also rely on rigid classifications, limiting their adaptability required to represent dynamic and emergent systems (Evans, 2004). Although no universal definition

exists, frameworks generally function as conceptual structures that organize key variables and their relationships, offering a shared language for interdisciplinary integration (Cox et al., 2016; McGinnis and Ostrom, 2014).

From a systems theory perspective, frameworks act as boundary constructs that support integrative thinking across complex domains with multi-and cross-scale interactions (Cash et al., 2006; A. W. Moore et al., 2018). They may serve diagnostic, descriptive, or prescriptive purposes, helping researchers explore Interactive mechanisms, identify leverage points, or simulate policy outcomes (Maxwell, 2013; Scholz and Tietje, 2002). In this sense, frameworks function as both theoretical and practical tools, connecting diverse epistemologies to support interdisciplinary synthesis and collaboration (Ligtermoet et al., 2025; Morse, 2014).

Frameworks typically arise from two primary epistemological approaches: empirical synthesis and theoretical conceptualization (Lawrence, 2015). Empirical frameworks derive from real-world observations, capturing context-specific dynamics, while theoretical ones originate from abstract paradigms to generalize systemic relationships (Partelow, 2023; Nilsen, 2020). These approaches often interact iteratively, with empirical evidence refining theory and vice versa, especially in complex domains like sustainability, governance, or urban metabolism. In both cases, frameworks act as boundary objects that bridge theory and practice and facilitate the knowledge integration across research and application (McGinnis and Ostrom, 2014).

Despite their value, the role of frameworks remains ambiguous. Ban and Cox (2017) question what defines a successful framework, while Partelow (2018) notes that many lack clarity in their application and operationalization. This black-box nature produces frameworks that vary in structure and applicability, ranging from those that provide measurable indicators to others that outline conceptual relationships without specific methodological guidance (Nagel and Partelow, 2022). Moreover, overreliance on internal structure can lead to over-abstraction, oversimplification, and exclusion of contextual nuances (Etman et al., 2020). Addressing these issues requires clear conceptual boundaries and robust operational strategies (Superti et al., 2021; Sala et al., 2015).

Building on recent advances in diagnostic and multi-scalar systems approaches (A. Acevedo-De-los-Ríos et al., 2025; C. Allen et al., 2023; Kanger and Sovacool, 2022; Pahl-Wostl et al., 2021), this study proposes an operative framework that extends beyond descriptive typologies or parametric indicator sets. Operative frameworks are explicitly designed to bridge theory and action by integrating systemic modeling, diagnostic analysis, and contextual decision support. In this view, an operative framework is not only conceptual but actionable, providing a transdisciplinary tool for guiding intervention design and systemic evaluation, especially in complex and adaptive contexts such as informal settlements.

This approach responds to the need for flexible, feedback-sensitive, and context-aware frameworks capable of capturing emergent interactions and inter-scalar dependencies rather than prescribing fixed inputs or outputs. It aligns with recent calls for dynamic, modular, and adaptive scaffolds that evolve with knowledge systems and governance conditions.

2.2. Consistency matrix, and operationalization of the variables

A framework's consistency matrix refers to the process of aligning conceptual elements with empirical data, ensuring coherence between theoretical constructs and practical applications. This involves defining dimensions, variables, and indicators that can be operationalized within contexts (Partelow, 2023). Operationalization translates abstract concepts into measurable variables, categorized as independent, dependent, or intervening, and supported by dimensions and indicators that guide data collection and analysis (Gan et al., 2017). This explicit process strengthens transparency, replicability, and robustness in empirical research (Zimek and Baumgartner, 2024; Sala et al., 2015).

Framework development can follow top-down or bottom-up approaches. The top-down method refines broad paradigms into specific theories and models (Smeets et al., 1999), whereas the bottom-up approach synthesizes empirical observations into overarching theoretical structures (Maxwell, 2013). In practice, these methods interact iteratively, where empirical results refine theory and theory informs new data collection, requiring continuous validation and adaptive management (Collins and Stockton, 2018).

The structure of a framework typically progresses from broad paradigms to measurable indicators (Reed et al., 2021). These levels include: a) Paradigm: the theoretical foundation guiding development, b) Theory: principles explaining the component interaction, c) Framework: the conceptual model structuring relationships, d) Model: an empirical representation of reality; and e) Indicators: measurable variables that operationalize theoretical concepts.

Frameworks often comprise multiple dimensions, each representing a thematic area of analysis (Naeem et al., 2023). In social-ecological systems, standard dimensions include governance, environmental sustainability, economic viability, technological innovation, and social well-being (Hessami et al., 2015; Sala et al., 2015). Within each dimension, variables define the structure, can be qualitative or quantitative, depending on the research focus (Barroga and Matanguihan, 2022). For example, in sustainability studies, variables may include resource availability, consumption patterns, and resilience indicators (Scordato and Gulbrandsen, 2024; Merino-Saum et al., 2020). Indicators represent the most granular level of analysis, linking theory to observation; they must be specific, measurable, and contextually relevant. For instance, under the economic dimension, indicators may include GDP growth, employment rates, or income distribution (Zimek and Baumgartner, 2024). The explicit alignment of indicators with theoretical dimensions ensures systematic and rigorous evaluation.

2.3. Existing frameworks related to urban metabolism and food security, urban agriculture, and informal settlements

Urban metabolism is presented first because it served as the overarching analytical lens guiding the structure of the previous literature review (Acevedo-De-los-Ríos and Perrotti, 2024). It provides a foundation for assessing material and energy flows, central to environmental sustainability, and for integrating interconnected domains such as food security, urban agriculture, and informal settlement dynamics.

The study of UM, food security (FS), UA, and informal settlements (IS) has led to the development of various conceptual and operational frameworks. These frameworks structure the environmental, economic, social, technological, and governance dimensions of urban settings, drawing from systems theory, ecological economics, urban planning, and sustainability sciences to analyze resource flows, governance structures, and socio-economic interactions (Guibrunet and Sánchez Jiménez, 2023; Kaviti Musango et al., 2020; Kennedy et al., 2014, 2011). Together, this body of literature provides a comprehensive basis for identifying both conceptual convergences and persistent gaps across UM-, FEW-, UA-, and informality-oriented frameworks.

Urban metabolism frameworks conceptualize cities as living systems, examining how material and energy flows affect sustainability. Wolman's concept of "The Metabolism of Cities," introduced the city-organism analogy, emphasizing input, transformation, and output of resources (Wolman, 1965). Subsequent work by Kennedy and Hoornweg (2012) integrated socio-economic variables into metabolic models, leading to a more holistic understanding of urban sustainability.

Food security frameworks evolved around the four classical dimensions, including availability, access, utilization, and stability, and incorporate nutritional, economic, and environmental factors to evaluate food system resilience in urban settings (Giuseppe, 2015; Newell et al., 2019). These frameworks often intersect with UM approaches, particularly when addressing resource efficiency and waste reduction

strategies in food systems (Zeinstra et al., 2020; Jacobi et al., 2018).

Urban agriculture frameworks have focused on integrating food production within urban environments, linking land-use planning with socio-economic development and environmental goals. They emphasize resource recycling, economic growth, and socio-ecological resilience (Hammelman et al., 2022; Bahers and Giacchè, 2019).

Frameworks for informal settlements address governance, land tenure security, infrastructure, and community adaptation. Studies highlight how governance failures and resource inequities heighten environmental and social vulnerability (Anwar et al., 2023; Kooy, 2014).

Recent studies have proposed integrative frameworks that bridge these domains, emphasizing their interconnectedness (Acevedo-De-los-Ríos and Perrotti, 2024; Kuhn et al., 2017; Shillington, 2013). **Supplementary Material 1, Table S1** summarizes key frameworks identified in the previous literature review, comparing their scope, variables, indicators, and methods. This comparative synthesis enables a structured identification of where existing frameworks converge (e.g., on material and energy flows) and where they remain fragmented (e.g., in governance treatment, feedback operationalization, and informality-specific diagnostics).

However, most existing integrative frameworks prioritize thematic coupling (e.g., UM–FEW nexus or UA–circularity linkages) rather than providing an explicit indicator-to-model translation logic or a diagnostic pipeline designed for informal urban contexts. Food insecurity in informal settlements remains a major challenge, intensified by rapid urbanization, weak governance, resource constraints, and environmental stress. Residents face precarious living conditions, limited access to nutritious food, and climate-related risks, which amplify inequalities and undermine urban resilience. Despite progress in sustainability research and food security, the literature reveals a consistent gap in operative frameworks capable of systematically linking indicators, feedback logic, governance dynamics, and simulation-based validation under conditions of informality.

This study proposes a systemic operative framework for urban metabolism assessment that explicitly integrates urban agriculture as a core intervention to address food security in informal settlements. Unlike previous models, the contribution lies not in introducing new metabolic relationships, but in the systematic consolidation of insights from the reviewed frameworks into a five-layer operative scaffold and a diagnostic-to-simulation pipeline that enables translation from indicators to feedback structures and stock–flow models. By integrating UA into broader UM systems, the framework advances resource optimization, circular economy strategies, and context-sensitive governance pathways designed for informal urban settings.

3. Methodology

The methodology follows a four-stage process (Fig. 2,) to develop and validate a systemic operative framework for urban metabolism assessment, integrating UA in informal settlements to enhance food security. This process operationalizes a diagnostic-to-simulation sequence that links literature-derived indicators, systemic layers, Interactive Loop Diagrams, and a Forrester-style system dynamics model. It builds on a systematic literature review (Acevedo-De-los-Ríos and Perrotti, 2024), and incorporates principles from systems theory (von Bertalanffy, 1968), urban metabolism (Pincetl et al., 2012; Kennedy et al., 2011), sustainability assessment frameworks (Sala et al., 2015; Ness et al., 2007), and systemic modeling for resilience (Zimek and Baumgartner, 2024; Hessami et al., 2015).

3.1. Stage 1: derivation of the multidimensional indicator framework

This stage identified and structured the variables and indicators that support metabolic performance and the food security potential of informal settlements. Building on the previous review of 273 scientific and grey literature sources conducted by Acevedo-De-los-Ríos & Perrotti (2024), 82 variables were extracted and grouped into 12 dimensions: Agriculture, Demographics, Economy, Energy, Environment, Food, Land, Nutrients, Social, Soil, Waste, and Water (See **Supplementary Material 1 Table S2**).

A consistency matrix was developed, aligning each variable with urban metabolism and food system domains (Arias et al., 2000; Binder et al., 2013). Using a bottom-up synthesis, the process integrated deductive insights from system frameworks with inductive categorization from case-based evidence (Partelow, 2018; Maxwell, 2013). Each dimension includes multiple variables. For example, Agriculture (inputs, production, residues, and land use) and Nutrients (phosphorus cycles, nitrogen flows, and fertilizer management). Variables were classified using diagnostic and descriptive criteria (Díaz et al., 2015; Ness et al., 2007), enabling the framework to support both assessment and planning.

3.2. Stage 2: systemic reorganization and operative framework structuring

In Stage 2, the linear indicator framework was transformed into a systemic model that explicitly incorporated feedbacks, interdependencies, and leverage points typical of complex adaptive systems (Zimek and Baumgartner, 2024; Sala et al., 2015; Meadows and Wright, 2008; von Bertalanffy, 1968). The 82 variables were reorganized into five systemic layers: stock and flow structures (resource availability and input–output dynamics), processes and interactions (internal transformations), subsystem feedback (bidirectional

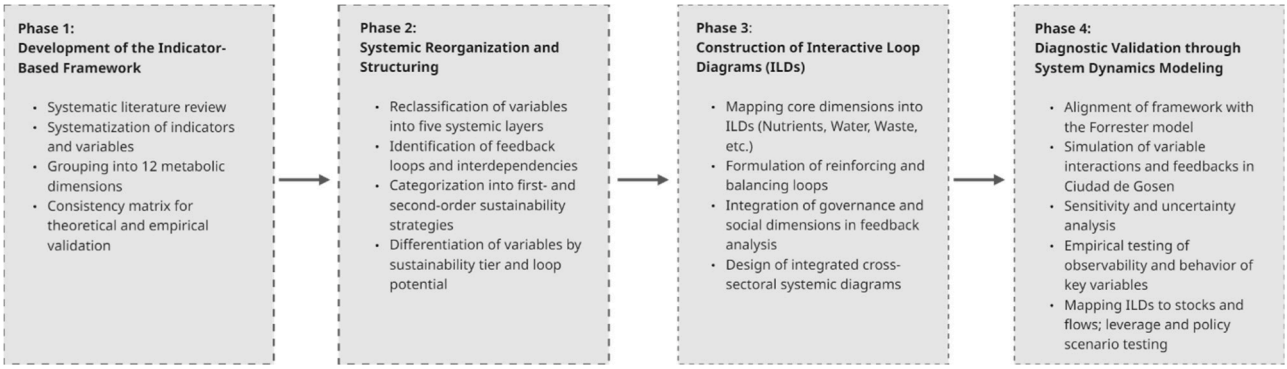


Fig. 2. Methodological Flowchart for a Systemic Operative Framework Integrating Urban Agriculture in Informal Settlements.
The flowchart illustrates how the proposed framework progresses from indicator derivation to executable simulation via a structured sequence that ensures methodological coherence at each transition.

relationships), governance and control (institutional arrangements), and outcomes and impacts (system-wide results).

Each variable was linked to first-order sustainability (efficiency improvements within existing systems) or to second-order sustainability (transformational shifts toward resilience) (Zimek and Baumgartner, 2024). This layered structure allows multidimensional visualization of how variables interact across metabolic and governance domains (see **Supplementary Material 2 Table S4** for the full classification).

3.3. Stage 3: development of systemic interactive-loop diagrams (ILDs)

To represent the dynamic behavior of informal settlement metabolisms, five systemic Interactive-loop diagrams (ILDs) were developed following system dynamics methods (Sterman, 2000; Forrester, 1969). These diagrams are causal in nature and explicitly represent directional cause–effect relationships, as well as reinforcing and balancing feedback structures, consistent with standard Causal Loop Diagrams (CLDs). The ILDs visualize the reinforcing and balancing feedback across the Food, Water, Energy, and Waste dimensions identified in Stage 1.

The terminology evolved from Causal Loop Diagrams (CLDs) to Interactive Loop Diagrams (ILDs) to emphasize the functional and operational use of the diagrams, rather than to introduce a different diagrammatic construct. Methodologically, ILDs remain equivalent to CLDs in terms of causal logic, feedback polarity, and system structure. Unlike conventional CLDs, which are typically static conceptual tools, ILDs in this framework are explicitly designed to support interaction, iterative refinement, and diagnostic exploration, including scenario testing and stakeholder-informed discussion. The qualifier "interactive" therefore refers to how the diagrams are used within the framework, not to a departure from causal loop methodology.

They were designed to identify feedback-rich structures, identify leverage points for systemic improvement, and support the integration of circularity through closed material and energy loops. ILDs function as an intermediate interface between conceptual causal reasoning and the executable Forrester-style stock–flow model developed in Stage 4; execution and simulation occur only after this translation step, ensuring full alignment with established system dynamics practice. The previous stages informed each ILD and served as a conceptual tool for scenario testing and participatory engagement.

3.4. Stage 4: diagnostic validation through system dynamics modeling in an informal settlement in Lima, Peru

The final stage validates the framework using a Forrester-based System Dynamics model developed in Vensim, for the Ciudad de Gosen informal settlement in Lima, Peru (Acevedo-De-los-Ríos and Perrotti, 2024). Ciudad de Gosen was selected as a model case because it represents a consolidating informal settlement with well-documented socio-ecological dynamics and the availability of high-resolution empirical data derived from previous urban metabolism and system dynamics studies. Ciudad de Gosen is located in the district of Villa María del Triunfo, in the southern periphery of metropolitan Lima (see Fig. 5). The settlement comprises approximately 107 urban blocks and 792 residential plots, with an estimated population of about 6300 inhabitants. It is characterized by partial access to water, sanitation, and energy services, ongoing land tenure regularization processes, limited availability of green and productive spaces, and a high reliance on informal and community-based resource management practices. These features make Ciudad de Gosen a representative of a consolidated informal settlement where food security, circular resource flows, and governance dynamics interact strongly.

This model simulates multi-scalar urban dynamics, emphasizing food security, resource circularity, and social-ecological resilience. The underlying Food–Energy–Water–Waste (FEW–W) nexus structure and feedback logic are treated as generic and transferable, reflecting widely established causal relationships in urban metabolism and system dynamics literature. Context specificity arises primarily from the model's parameterization and boundary conditions, including yields, water availability, waste composition, adoption rates, governance variables, and behavioral decision rules, which must be recalibrated for each application context.

Validation assessed whether the framework's Interactive feedback logic could be operationalized within a calibrated model. Two objectives guided the process: to evaluate whether key variables and feedback could be empirically modeled using available data and settlement-level indicators, and to confirm the compatibility between the CDLs and the Forester model's behavior and structure. The selection of Ciudad de Gosen enables this validation because prior studies provide an established baseline of household-level surveys, socio-metabolic indicators, and governance data, allowing transparent calibration and consistency checks across model stages. A subset of variables was selected based on empirical observability, relevance to metabolic performance, and systemic leverage within food-water-waste governance. The simulated sectors included nutrient recovery, urban agriculture, composting, greywater reuse, energy efficiency, and land tenure governance.

The executable Vensim model file (FWEW_Nexus_SD_Model_Gosen.mdl), the full equation spreadsheet (SDModel_equations.xlsx), and a reproducibility guide (README_Model_Reproducibility.txt) are included as Supplementary Material S1 and archived in a public repository (https://doi.org/10.5281/zenodo.18727731), enabling direct inspection, modification, and re-execution of all simulations.

Table 1 provides a compact overview of the model's key state variables (stocks), principal flows, units, baseline values, and scenario levers.

The model was implemented in Vensim using Euler numerical integration with a time step (dt) of 0.25 months and a 10-year (120-month) simulation horizon. The core functional forms governing the four principal subsystems are presented below. Food production and demand coverage: Settlement food demand is computed as $SFD = SFDPC \times SP$, where $SFDPC = 0.020$ Ton/(person·month) and $SP = 6268$ persons. The food self-sufficiency proxy (Purchase of Food, PF) is defined as $PF = \max(SFD - UG \times UGFPm, 0) / SFD$, where UG is urban garden area (m^2) and $UGFPm = 0.005$ Ton/(m^2·month) is the mean yield. Food Security is computed as a weighted composite of three FAO-aligned dimensions: Availability ($A = 1 - PF$), Accessibility ($AC = \min(1, LocalFoodValue / FoodExpenditurePerCapita)$), and Nutrition ($N = DietDiversityProxy$), with equal weights. The framework explicitly models Availability and Accessibility; Nutrition is approximated through the access to healthy community food indicator (AHFC), which aggregates community kitchen area, community garden area, and household UA participation relative to per-capita norms. The Stability dimension is not directly modeled as a time-series variable but is captured implicitly through the Drought Resilience stock ($DR = f(GII, WCI, SC)$). Greywater generation, treatment, and irrigation allocation: Total irrigation water demand is $WDUG = UG \times WDUGm + GA \times WDGAm$, where $WDUGm = 0.09$ m^3/(m^2·month) and $WDGAm = 2.0$ m^3/(m^2·month). Available recycled water is $WCC = WSDG \times WRR$, where WSDG is greywater supply and $WRR = 0.75$ [0.50–0.85] is the treatment efficiency. Irrigation coverage is expressed as the ratio WCC/WDUG (capped at 1.0). Biodigester energy conversion: Energy from biodigesters is parameterized as a function of organic waste allocated to energy recovery. When 100 % of organic waste is directed to biogas, the model yields approximately 9 MW/month; when 25 % is allocated and the remainder to compost, approximately 3 MW/month. These bounds correspond to the 17–52 % household energy coverage reported in the scenario analysis, derived from the ratio of biodigester energy output to total settlement energy demand. Adoption dynamics: Urban garden area expands as $UG(t) = UG(t - dt) + NIUG \times dt$, where the Net Increase of Urban Garden (NIUG) is a scenario-controlled flow with baseline $NIRUG = 20$ m^2/month and range [10–40] m^2/month. Governance endogeneity is operationalized through Land Tenure Security ($LTS = \text{mean}(ABSW, ABSE, ABSS)$), which feeds back into Housing Consolidation, Infrastructure Investment,

Table 1
Compact overview of key model state variables, flows, units, baseline values, and scenario levers.

Variable Name	Type	Unit	Baseline Value	Scenario Range	Source
Settlement Consolidation (SC)	Stock	Dimensionless	0.80	0.80–1.00	Fieldwork
Urban Garden (UG)	Stock	m^2	16,307	16,307–TUGPS	Fieldwork
Women in Formal Employment (WFE)	Stock	Persons	73	73–WARE-driven	INEI (2012)
Green Areas (GA)	Stock	m^2	19,872	19,872–TGAPS	Fieldwork
Soil Fertility (SF)	Stock	Dimensionless	0.50	0.30–0.70	Literature
Settlement Food Demand (SFD)	Flow/Aux	Ton/month	125.4 (=0.02×6268)	Fixed	INEI (2012)
Water Demand – Urban Garden (WDUG)	Flow/Aux	m^3/month	UG×0.09	Scenario-dependent	Literature
Land Tenure Security (LTS)	Aux (endogenous)	Dimensionless	0.82	0.70–0.95	Fieldwork
Food Self-Sufficiency (1−PF)	Aux	Dimensionless	~0.0 (baseline)	0.0–1.0	Computed
Greywater Recycling Rate (WRR)	Parameter	Dimensionless	0.75	0.50–0.85	Literature
Net Increase Urban Garden (NIRUG)	Scenario lever	m^2/month	20	10–40	Scenario
Net Increase Green Areas (NIRGA)	Scenario lever	m^2/month	7.79	3.0–15.0	Scenario

Note: This table summarizes the 12 main stocks, key flows, units, baseline values from fieldwork/literature, and the scenario levers used in this study. Stock = state variable (accumulation over time); Flow = rate of change; Aux = auxiliary variable (instantaneous algebraic variable used for intermediate calculations); Parameter = exogenous constant; Scenario lever = externally controlled input for simulation experiments.

and Energy Demand functions. Accordingly, governance-related adoption feedback is endogenous in the model; however, the adoption rates (NIRUG, NIRGA) are treated as exogenous scenario parameters that represent policy-determined investment trajectories rather than emergent behavioral dynamics.

In the absence of complete time-series data for Ciudad de Gosen, the adopted validation protocol includes a multi-level approach consistent with standard SD validation practice (Sterman, 2000): (i) Structural validation: All equations were checked for dimensional consistency; units are specified for each variable in **Supplementary Material 1** and in Table 1. Extreme-condition tests were conducted by setting population to near-zero and adoption rates to maximum values, confirming expected boundary behaviors without numerical instability. (ii) Behavioral validation: Simulated settlement consolidation trajectories, household income dynamics, and food expenditure trends were compared against the settlement-level empirical baseline established in Acevedo-De-los-Ríos et al. (2024; 2025) and against stylized facts from the urban metabolism literature for similar consolidating informal settlements. Qualitative pattern matching confirmed the expected reinforcing behavior between land tenure security, infrastructure access, and circular practice adoption. (iii) Sensitivity and uncertainty analysis: A Monte Carlo simulation with Latin Hypercube Sampling across 24 parameters confirmed the robustness of key results (Section 4.4.2). Headline outcomes (17–52 % energy coverage from biodigesters; ~77 % greywater irrigation coverage) fall within the 10th–90th percentile of the Monte Carlo distribution, confirming they are not artifacts of point-estimate parameterization. (iv) Plausibility checks: Model-predicted UA production capacities (117–2450 household food baskets per month under conservative and integral scenarios) were cross-validated against published empirical benchmarks from comparable contexts (Gunapala et al., 2025; Toboso-Chavero et al., 2021), yielding consistent order-of-magnitude estimates. The validation approach acknowledges that this is a structural and behavioral validation, not a predictive calibration against an independent time series, which is standard practice for exploratory SD models applied to data-scarce contexts (Fabolude et al., 2025).

4. Results

The results presented in this section do not introduce new urban metabolic relationships per se; rather, they demonstrate the internal coherence, operability, and diagnostic capacity of the proposed systemic operative framework. Results are organized to follow the four methodological stages, progressing from intermediate analytical outputs to integrated system behavior.

Sections 4.1 and 4.2 report the derivation and systemic reorganization of the multidimensional indicator framework, showing how literature-derived variables are translated into a five-layer operative structure. Section 4.3 presents the development of Interactive Loop Diagrams, documenting the feedback structures linking food, water, energy, waste, and social dimensions. Section 4.4 synthesizes these elements through dynamic validation, reporting system behavior under alternative scenarios for an informal settlement in Lima, including sensitivity and uncertainty analysis.

4.1. Derivation of the multidimensional indicator framework

The first stage of the systemic operative framework focused on identifying and organizing variables and indicators relevant to urban metabolism, food security, and urban agriculture in informal settlements. Building on the systematic literature review by Acevedo-De-los-Ríos & Perrotti (2024), which analyzed 273 peer-reviewed and grey literature sources, the study extracted empirical evidence on the dynamics of sustainability in resource-constrained urban contexts.

From this review, 82 key variables were identified and grouped into 12 core dimensions: Agriculture, Demographics, Economy, Energy, Environment, Food, Land, Nutrients, Social, Soil, Waste, and Water (**see Supplementary Material 1 Table S2** for the breakdown of the 12 dimensions and their associated variables). These dimensions represent the metabolic and socio-ecological complexity of informal settlements. These dimensions capture the main drivers of food systems' performance and urban resilience in vulnerable urban areas. Variables were systematically coded, validated for relevance and recurrence, and cross-checked across multiple disciplines (Díaz et al., 2015; Maxwell, 2013; Ness et al., 2007).

To ensure theoretical coherence and methodological alignment, a consistency matrix (see Table 2) was developed to map the 82 variables identified in Stage 1 across core analytical categories from sustainability science and UM. The matrix cross-tabulated thematic dimensions (e.g., energy, food, soil) with analytical models such as Life-Cycle Assessment (LCA), Circular Economy (CE), and UM to quantify the degree of overlap among indicators. This reveals areas of theoretical convergence and empirical emphasis across frameworks, drawing UM studies (Kennedy et al., 2011), the Food-Energy-Water nexus, circular economy principles, and SDG-based evaluation methods (Kennedy et al., 2014; Binder et al., 2013).

A bottom-up synthesis combined deductive structuring from established frameworks with inductive coding from empirical studies of informal settlements, emphasizing local adaptive strategies and multi-scale resource flows. This process ensures analytical transparency and reinforces both the theoretical robustness and practical applicability of the proposed framework for subsequent modeling and assessment phases.

Table 3 presents a selection of representative indicators for each variable. A complete inventory is included in **Supplementary Material 2 Table S6.**

Table 2
Cross-classification matrix of 82 variables by thematic dimensions and analytical frameworks.

}		FLW	CBSD	CE	ENA	EFA	EWF	EWMFA	EWF	INT	FEW+ MuSIASEM	FEW + SD	FA	FAN	FEW	IA + FA	IO—NBS	LCIA + LCA	LCA	LCIA	LR	MFA	MFA + LCA	MFA + SFA	MFA + SD	MuSIASEM	NEIA	PB	SLCA	SEFA	SFA	UMAn	}	
DIMENSIONS	**Agriculture**	**0**	**0**	**2**	**0**	**0**	**0**	**11**	**4**	**3**	**3**	**0**	**2**	**6**	**8**	**0**	**0**	**0**	**4**	**0**	**7**	**60**	**12**	**10**	**9**	**0**	**2**	**0**	**0**	**0**	**11**	**0**	**INDICATOR COUNT**
	Demographic	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	1	0	
	Economic	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	1	2	0	0	1	0	0	0	0	0	0	
	Energy	**0**	**0**	**4**	**3**	**0**	**1**	**0**	**10**	**0**	**7**	**1**	**0**	**1**	**21**	**0**	**0**	**0**	**5**	**0**	**0**	**8**	**3**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	
	Environmental	0	2	15	0	1	1	6	4	0	0	0	0	15	7	0	0	4	12	1	9	48	5	2	4	0	3	0	0	0	10	0	
	Food	**1**	**0**	**0**	**0**	**0**	**0**	**7**	**7**	**0**	**2**	**2**	**1**	**2**	**3**	**0**	**2**	**0**	**0**	**0**	**8**	**43**	**1**	**7**	**7**	**1**	**0**	**0**	**0**	**0**	**12**	**7**	
	Land	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	3	1	1	0	0	0	0	0	0	0	0	0	
	Nutrients	**1**	**0**	**0**	**4**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**5**	**0**	**3**	**83**	**4**	**15**	**2**	**0**	**3**	**3**	**0**	**0**	**42**	**0**	
	Social	0	4	4	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	0	2	1	1	0	0	4	0	0	0	0	0	0	
	Soil	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	2	0	0	0	0	0	0	0	0	0	
	Waste	**0**	**1**	**7**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**2**	**0**	**3**	**0**	**0**	**0**	**0**	**1**	**0**	**4**	**44**	**7**	**4**	**2**	**0**	**0**	**0**	**0**	**1**	**20**	**2**	
	Water	**0**	**1**	**1**	**2**	**0**	**0**	**0**	**15**	**0**	**5**	**2**	**0**	**0**	**17**	**0**	**0**	**1**	**4**	**0**	**2**	**35**	**9**	**2**	**0**	**0**	**0**	**0**	**1**	**0**	**10**	**0**	
	Total	**3**	**9**	**40**	**9**	**1**	**2**	**25**	**44**	**7**	**17**	**7**	**3**	**28**	**58**	**1**	**2**	**5**	**36**	**1**	**44**	**325**	**47**	**40**	**24**	**7**	**8**	**3**	**1**	**1**	**107**	**9**	

Note: The acronyms in the table refer to key analytical approaches identified during the literature review. These include:
FLW (Food Loss and Waste), CBSD (Community-Based System Dynamics), CE (Circular Economy), ENA (Ecological Network Analysis), EFA (Energy Flow Analysis), EWF (Energy-Water-Food Nexus), EWMFA (Economy-Wide Material Flow Accounts), INT (Expert Interviews), FEW + MuSIASEM (Food-Energy-Water Nexus and Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism), FEW + SD (Food-Energy-Water Nexus and System Dynamics), FA (Flow Accounting), FAN (Flows in Agro-Food Networks), FEW (Food-Energy-Water Nexus), IA+FA (Impact Assessment and Flow Accounting), IO—NBS (Input and Output of Nature-Based Solutions), LCIA + LCA (Life Cycle Impact Assessment and Life Cycle Assessment), LCA (Life Cycle Assessment), LCIA (Life Cycle Impact Assessment), LR (Literature Review), MFA (Material Flow Analysis), MFA+LCA (Material Flow Analysis and Life Cycle Assessment), MFA+SFA (Material Flow Analysis and Substance Flow Analysis), MFA+SD (Material Flow Analysis and System Dynamics), MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism), NEIA (Nutrient-Derived Environmental Impact Assessment), PB (Phosphorus Mass Balance), SLCA (Social Life Cycle Assessment), SEFA (Substance and Energy Flow Analysis), SFA (Substance Flow Analysis), and UMAn (Urban Metabolism Analyst).

Table 3
Summary of dimensions, variables, and indicators in the systemic operative framework for urban metabolism and food security in informal settlements.

Dimension	# Variables	# Indicators	Example Variables
Agriculture	9	184	Inputs, Production, Waste, Trade
Environment	13	195	Air Emissions, Biodiversity, Biogas
Water	10	111	Water Quality and Loss, Emissions, Management
Nutrients	14	176	P/N Flows, Efficiency, Loss, Trade
Energy	6	46	Electricity, Use, Efficiency, Emergy
Food	7	65	Supply, Processing, Waste
Economic	4	16	Performance, Circular Economy, Value Added
Land	3	32	Land Use, Urban Gardens, Green Space
Social	6	17	Services, Equity, Employment
Soil	1	5	Substrate Management
Waste	6	87	General Waste, Recycling, Organic Waste
Demographics	1	4	Population

4.2. *Systemic reorganization of the indicator framework*

In the second stage, the linear, literature-based framework was restructured into a systemic model that emphasizes interdependencies, feedbacks, and leverage points within informal urban systems. This reorganization follows principles of systems thinking (Meadows and Wright, 2008; von Bertalanffy, 1968), systemic sustainability science (Sala et al., 2015), and emerging classifications of first- and second-order sustainability (Zimek and Baumgartner, 2024).

Each of the 82 variables identified in Stage 1 was reclassified into five systemic layers representing distinct urban functions: (1) stock and flow structures (e.g., water withdrawals, fertilizer availability, energy demand); (2) processes and interactions (e.g., composting, urban farming, food processing); (3) subsystem feedbacks (e.g., organic waste ↔ compost ↔ soil fertility ↔ crop yield); (4) governance and control (e.g., land tenure, CE incentives, water pricing); and (5) outcomes and impacts (e.g., food security, environmental health, equity, resilience).

Fig. 3 summarizes the distribution of variables across these layers for all 12 dimensions. Table 4 presents the corresponding counts, comparing the number of indicators per layer with the 1048 indicators identified in Stage 1. While most dimensions showed strong alignment, some exhibited moderate variation. For example, Agriculture (+15) and Food (+63) were slightly overrepresented because cross-cutting indicators span multiple systemic roles, whereas Environment (−26) and Land (−23) were underrepresented, suggesting the need for finer disaggregation. These variations confirm the framework's flexibility and adaptability rather than inconsistencies, supporting its iterative refinement for contextual applications.

A complete mapping of each variable, its assigned systemic layer, and its sustainability tier (first- or second-order) is provided in **Supplementary Material 2, Table S5**.

Each variable was also evaluated for its contribution to sustainability outcomes. First-order sustainability reflects incremental efficiency improvements within existing systems (e.g., energy efficiency, water reuse). In contrast, second-order sustainability captures transformative structural transformations or adaptive capacity that improve systemic resilience (e.g., circular food policies, decentralized nutrient loops). This typology, adapted from Zimek & Baumgartner (2024), allows the framework to support both incremental and structural transitions, particularly relevant for informal settlements where formal governance is limited, but adaptive capacity is high.

By overlaying indicators across the two analytical axes (systemic role and sustainability tier), the framework captures both the structural position and the transformative potential of each dimension. Indicators in the Nutrients and Waste dimensions often span from stock-level inputs to feedback-rich subsystems, identifying them as key metabolic leverage

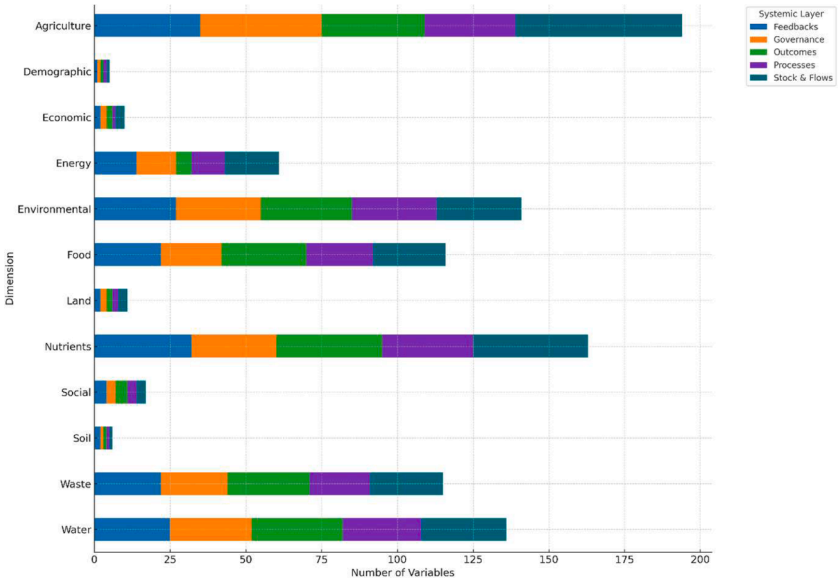


Fig. 3. Systemic layer classification of variables across dimensions.
Agriculture and Food dimensions exhibit the highest cross-layer density, confirming their role as metabolic leverage points linking resource stocks, process feedbacks, and governance outcomes.
Note: This figure visualizes the classification of the 82 variables across five systemic layers: Stock & Flows, Processes, Feedbacks, Governance, and Outcomes. The vertical axis represents the 12 dimensions (e.g., Agriculture, Water, Waste), while the horizontal axis shows the distribution by systemic layer.

Table 4
Summary of systemic layer classification of the 82 variables by dimension.

Dimension	Feedbacks	Governance	Outcomes	Processes	Stock & Flows	# Indicators from Linear Framework	Sum of Layered Assignments	Difference from Linear
Agriculture	37	48	36	35	43	184	199	15
Demographic	5	1	0	0	1	4	7	3
Economic	6	5	1	2	2	16	16	0
Energy	18	17	9	9	21	46	74	28
Environmental	24	37	38	39	31	195	169	−26
Food	21	25	31	25	26	65	128	63
Land	0	2	2	1	4	32	9	−23
Nutrients	37	29	44	38	40	176	188	12
Social	5	4	4	4	3	17	20	3
Soil	2	0	0	2	1	5	5	0
Waste	23	25	23	20	25	87	116	29
Water	23	22	24	23	25	111	117	6

points linking food security and circularity. Although second-order indicators are fewer in number, they represent the framework's most transformative leverage points. In the Waste dimension, examples include energy generation from biodigesters and community-managed compost systems that convert organic waste into productive loops. In Agriculture, vertical and hydroponic farming initiatives and co-managed urban gardens introduce structural changes toward localized food production and self-sufficiency. These examples illustrate the framework's ability to identify transformative processes even when their quantitative representation remains limited.

Given its layered, cross-scalar structure, the framework functions as an operational diagnostic tool rather than a static taxonomy. It enables users to visualize interconnections, locate leverage points, and design targeted interventions, offering a semantically accessible, adaptable platform for multi-stakeholder decision-making in diverse governance contexts.

4.3. Systemic interactive-loop diagrams and feedback structures

To complement the structural classification of variables into systemic layers, a set of systemic Interactive-loop diagrams (ILDs) was developed to model the dynamic behavior of informal settlement metabolisms. Constructed following system dynamics principles (Sterman, 2000; Forrester, 1969), these diagrams are grounded in the variables and indicators identified in Stage 1 and operationalized in the Vensim simulation model.

The ILDs focus on four metabolic subsystems—food, water, energy, and waste—which showed the highest indicator density and cross-dimensional interactions within the framework. These domains reinforce food security and resource resilience, providing a dynamic representation of interactive feedback within informal urban metabolism. The ILDs visualize feedback loops, leverage points, and circularity pathways, enabling the design of integrated interventions.

These results illustrate that the proposed five-layer scaffold and diagnostic-to-simulation pipeline enable the operationalization of established UM and FEW interactions in an informal settlement context, rather than redefining the underlying metabolic mechanisms.

4.3.1. ILD 1–2: nutrient recycling, urban agriculture, and energy loop (Fig. 4a)

The first two loops integrate food–water–energy–waste dynamics, illustrating how urban agriculture, composting, greywater reuse, and biodigester systems reinforce each other. Compost from household and market waste improves soil fertility, increasing crop yields and food

access, which encourages further waste recovery. Treated greywater and compost support irrigation and food production, reducing dependence on centralized systems. Energy from biodigesters powers community kitchens and vertical farming, creating a feedback system that enhances both circularity and drought resilience.

Key indicators: organic waste generation, compost production, soil fertility, crop yield, greywater reuse, biodigester energy output, and food access.

Loop logic: more waste reuse → improved compost and irrigation → higher yields → greater food availability → expanded waste input → enhanced energy and income → improved resource circularity.

4.3.2. ILD 3: governance–access–infrastructure loop (Fig. 4b)

This loop captures how secure land tenure, infrastructure provision, and governance support reinforce circular practices such as composting, recycling, and greywater reuse. Improved infrastructure supports settlement consolidation and safer, healthier living conditions. Housing consolidation and equipment depend on each family's available income and their capacity to invest in improvements. Circular processes, such as urban agriculture production and energy generation from compost, can reduce everyday expenses. Intervention from the state, in the form of subsidies and employment programs, can also increase capacities, which in turn improve the well-being of the community.

Key Indicators: Land tenure, infrastructure provision, access to inputs, and household investments.

Loop Logic: More formal land tenure and governance → increased access to basic services → greater participation in circular practices → improved housing and health → feedback into investment and policy prioritization.

4.3.3. ILD 4: social–resilience–knowledge loop (Fig. 4c)

This loop links community engagement, knowledge transfer, and urban agriculture as drivers of resilience. Community kitchens, childcare centers, and elderly care facilities serve as hubs for food redistribution, education, and the generation of local knowledge. As participation increases, so does resilience to food and climate shocks, further strengthening social institutions and reinforcing adaptive learning. More specifically, in this model, we consider the influence and knowledge of elderly people regarding agricultural practices. They pass their lived experience and expertise to other members of the community, which translates into active participation in urban agriculture practices and subsequently, labor.

Key Indicators: Community organization, knowledge transfer, urban agriculture participation, resilience indicators.

Loop Logic: More community engagement and services → improved knowledge and participation in UA → increased food access and resilience → stronger institutions → feedback into engagement, knowledge, and services.

4.3.4. Systemic insights

Together, the ILDs reveal how cross-domain feedback, spanning governance, infrastructure, and social organization, generates the most

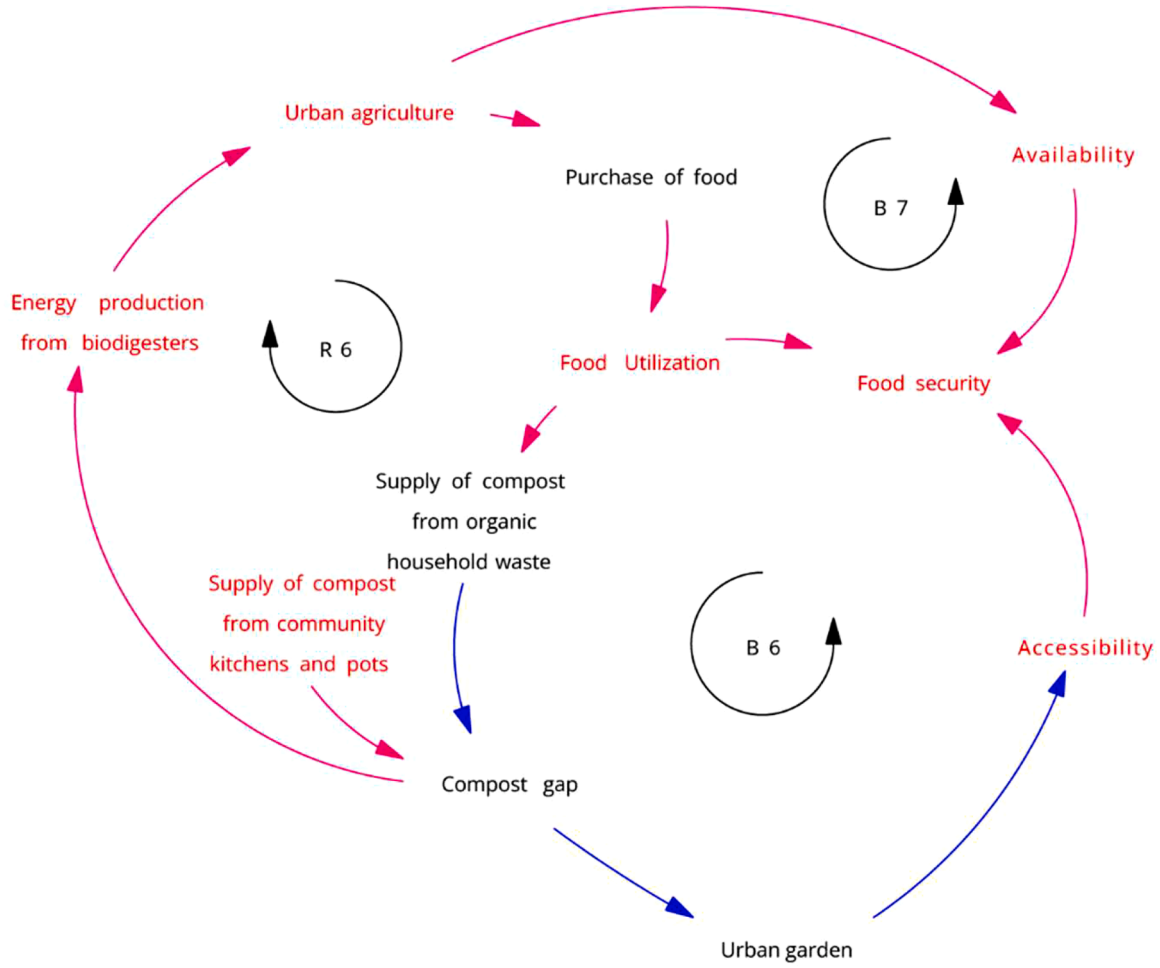


Fig. 4a. Nutrient recycling, urban agriculture, and energy loop.
The reinforcing loop structure shows that even modest improvements in composting and greywater reuse generate cascading gains in soil fertility, crop yield, and energy availability.

effective leverage points for intervention. Rather than treating these domains in isolation, integrated and multiscale policy frameworks are required to advance food security, resilience, and circularity in vulnerable urban systems.

4.4. Integrated system behavior and feedback summary with diagnostic validation in Lima, Peru

The compatibility between the ILDs and the Forrester model confirms the internal coherence of the proposed framework. Key indicators from each loop were translated into simulation equations, enabling the model to reproduce dynamic behaviors such as nutrient cycling, water reuse, and resilience enhancement within informal urban systems

Building on the four ILDs described in Section 4.3, Fig. 4d integrates these subsystems into a unified representation of urban metabolic behavior. The diagram captures multiscale interactions linking food security, urban agriculture, nutrient recycling, the water-energy-food-waste nexus, governance, infrastructure access, social resilience, and knowledge exchange. This synthesis expands the structural model proposed by Acevedo-De-los-Ríos et al. (2025) by incorporating additional variables and feedback identified through the present framework. The system dynamics model equations, variables, and parameters are documented in **Supplementary Material 1** through a Vensim listing report to support transparency and reproducibility. Accordingly, the Lima case demonstrates the operability of a generic FEW–W nexus structure in an informal context, whereas numerical outcomes reflect context-specific parameterization rather than universal values.

Fig. 4d consolidates the reinforcing and balancing feedback loops across the system, presenting a unified model of circularity and resource dynamics in resource-constrained urban settlements. This synthesis enables a systemic interpretation of feedback relationships, intervention points, and emergent behavior.

The integrated system model also enables diagnostic validation of potential interventions. Using the Forrester simulation framework, various feedback configurations and resource management strategies were tested under conditions relevant to the Lima case study. This allowed testing the sensitivity of feedback loops and identifying optimal pathways to improve food security, resilience, and sustainability in informal settlements. The mapping between ILDs and simulation structures is summarized in **Supplementary Material 1 Table S3**, which details the correspondence between each loop and its modeled stock–flow components.

4.4.1. Dynamic validation scenarios based on the ILDs

The system dynamics model was validated using context-specific data from a representative informal settlement in Lima, Peru, and was used to simulate the co-evolution of food security, resource flows, and community resilience across different policy and infrastructure scenarios. Feedback structures from the Interactive loop diagrams (ILDs) were converted into dynamic simulation modules using Vensim, capturing nonlinear relationships, time delays, and reinforcing/balancing behaviors across the system. To account for socio-economic changes, the "Time Quality" and "Women in formal employment" scenarios from Acevedo-De-los-Ríos et al. (2025) were considered in the assessment. The parameters that are modified in both scenarios are shown in Table 5. A set of exploratory indicators, namely, Vertical Farming Ratio (VFR), Agricultural Production Labor Intensity (APLI), and Waste for Compost (WFC), is used to determine the optimal scenario in terms of UA and Energy production at the settlement level.

See **Supplementary Material 1 Figure S1** for the complete Forrester diagram.

4.4.1.1. Scenario 1: food–waste–compost subsystem. Simulation results indicate that enhancing composting practices by improving organic waste recovery yields gains in soil fertility and urban food production. Soil fertility increases over time due to the steady contribution of compost. However, by year seven, the system reaches a saturation point at which compost absorption by the soil plateaus, and crop yield gains

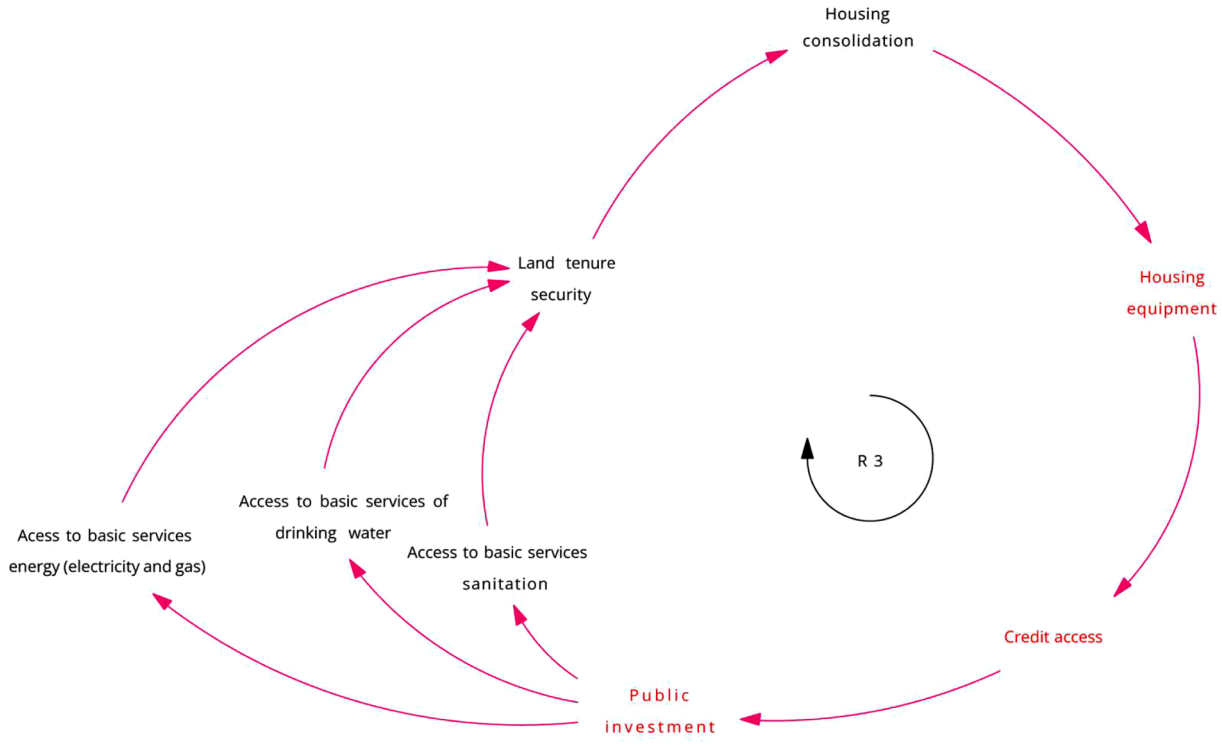


Fig. 4b. Governance-Access-Infrastructure Loop.
Land tenure security emerges as the central accelerator, demonstrating that without governance legitimacy, circular infrastructure investments fail to generate sustained adoption.

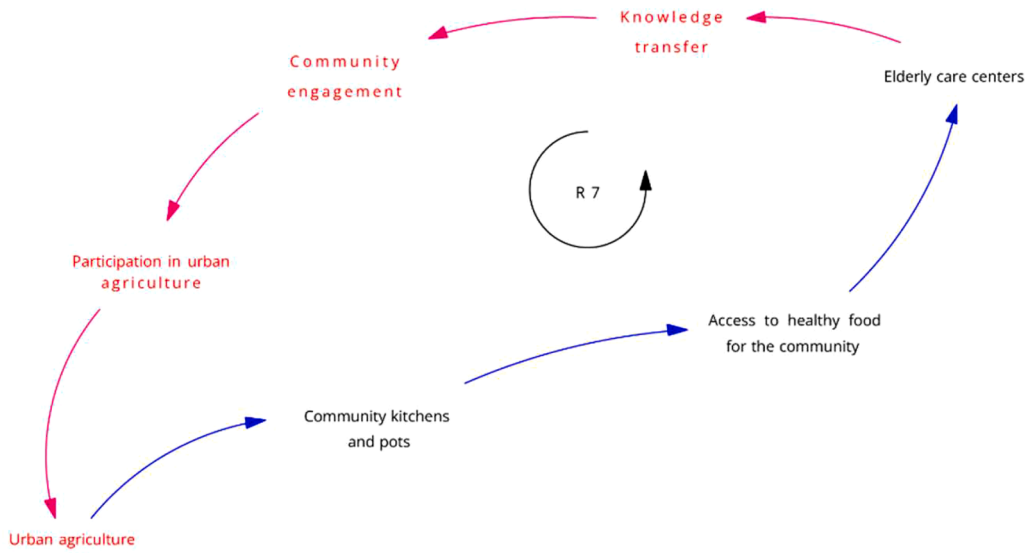


Fig. 4c. Social–resilience–knowledge loop.
Intergenerational knowledge transfer from elderly community members is identified as a low-cost, high-leverage mechanism for sustaining participation in urban agriculture over time.

stabilize. This reflects a system-level constraint related to compost application rates and soil capacity, suggesting the need for complementary soil management strategies (e.g., biochar amendment or crop rotation) to sustain productivity gains. In the BAU case, the FS is constrained by the availability of local food production at 133 tons, as shown in Fig. 7. In the integral scenario, food security is achieved just before the end of the 10th year.

Fig. 6.

4.4.1.2. Scenario 2: water–energy nexus subsystem. The integration of greywater reuse and biodigester systems demonstrates strong potential to improve metabolic efficiency. In the modeled scenario, in the initial years, treated greywater meets up to 2.4 times the irrigation demand, significantly reducing dependence on centralized water infrastructure. Moreover, near the 7th year, as Green Infrastructure for Urban Agriculture increases, this gap closes, reducing the total capacity of the reused water supply to meet demand. In this case, measures such as fog catchers are present, but their contribution is minimal. Concurrently, biodigesters that convert food and organic waste into biogas produce varying amounts of biogas depending on the scenario. In this case, if organic domestic waste is prioritized for energy recovery, the amount of energy produced is 9 MW per month. On the other hand, if greater emphasis is placed on using compost for UA, the total energy output would be 3 MW per month. The simulations reveal a clear link between food production, water reuse, and energy generation, emphasizing that optimal performance depends on the coordinated deployment and maintenance of infrastructure. Notably, delays in greywater treatment impact irrigation cycles, highlighting the importance of technological reliability and user training.

Table 6 provides a simplified overview of the mass and energy balances for the two primary circular subsystems modeled. These checks are intended to verify internal consistency and distinguish between areas of enforced conservation (water recycling) versus approximations (nutrient cycling). In this iteration, water and energy circularity are operationalized through explicit efficiency parameters (WRR, scenario bounds); however, nutrient cycling is limited to a proxy representation via a dimensionless soil fertility increment (compost effectiveness, CE = 0.02 per kg of compost applied). While this approach provides a baseline for compost effectiveness, it does not account for full nitrogen or phosphorus substance-flows. Consequently, more granular accounting is required in future versions to fully capture the nutritional and resource-equity implications of the system.

4.4.1.3. Scenario 3: governance and infrastructure access subsystem. Scenarios involving land tenure formalization and increased public infrastructure investment show positive cascading effects across the system. Secure land rights catalyze an 8 % increase in access to infrastructure (including water, sanitation, and energy) within the first two years of the simulation. This, in turn, supports greater household participation in circular practices, such as composting, urban agriculture, and greywater reuse. The feedback loops between formalization, infrastructure investment, and community engagement result in a virtuous cycle of improved well-being and environmental performance. Furthermore, when combined with municipal subsidies for circular infrastructure, the adoption rate accelerates, reinforcing settlement consolidation and long-term planning capacity.

Fig. 8.

4.4.1.4. Scenario 4: social–resilience–knowledge subsystem. Community-based infrastructure, such as communal kitchens, gardens, childcare centers, and elderly care facilities, functions as a stabilizing backbone of social resilience. The simulation shows that under investment scenarios where these spaces are maintained and used as hubs for food redistribution and knowledge exchange, community resilience to external shocks increases steadily. Participation in urban agriculture and local food networks increased by 80 people compared to the BAU scenario. The involvement of elderly community members in the transfer of agricultural knowledge is a key driver, promoting intergenerational learning and labor stability. However, the most dominant factor in these subsystems is the presence of male and female labor in UA activities. Given that many women are switching their time from dedicating to UA to possessing formal jobs, the amount of time available diminishes over time in both upper and lower bound scenarios, displaying the importance of women's role in the community and the tradeoff between domestic and community labor, and the improvement of conditions within the household.

Fig. 9.

4.4.1.5. Summary of dynamic behavior. These results highlight the importance of reinforcing feedback loops in amplifying circular strategies across informal urban systems. Each subsystem responds differently to interventions, with nonlinear thresholds, saturation points, and

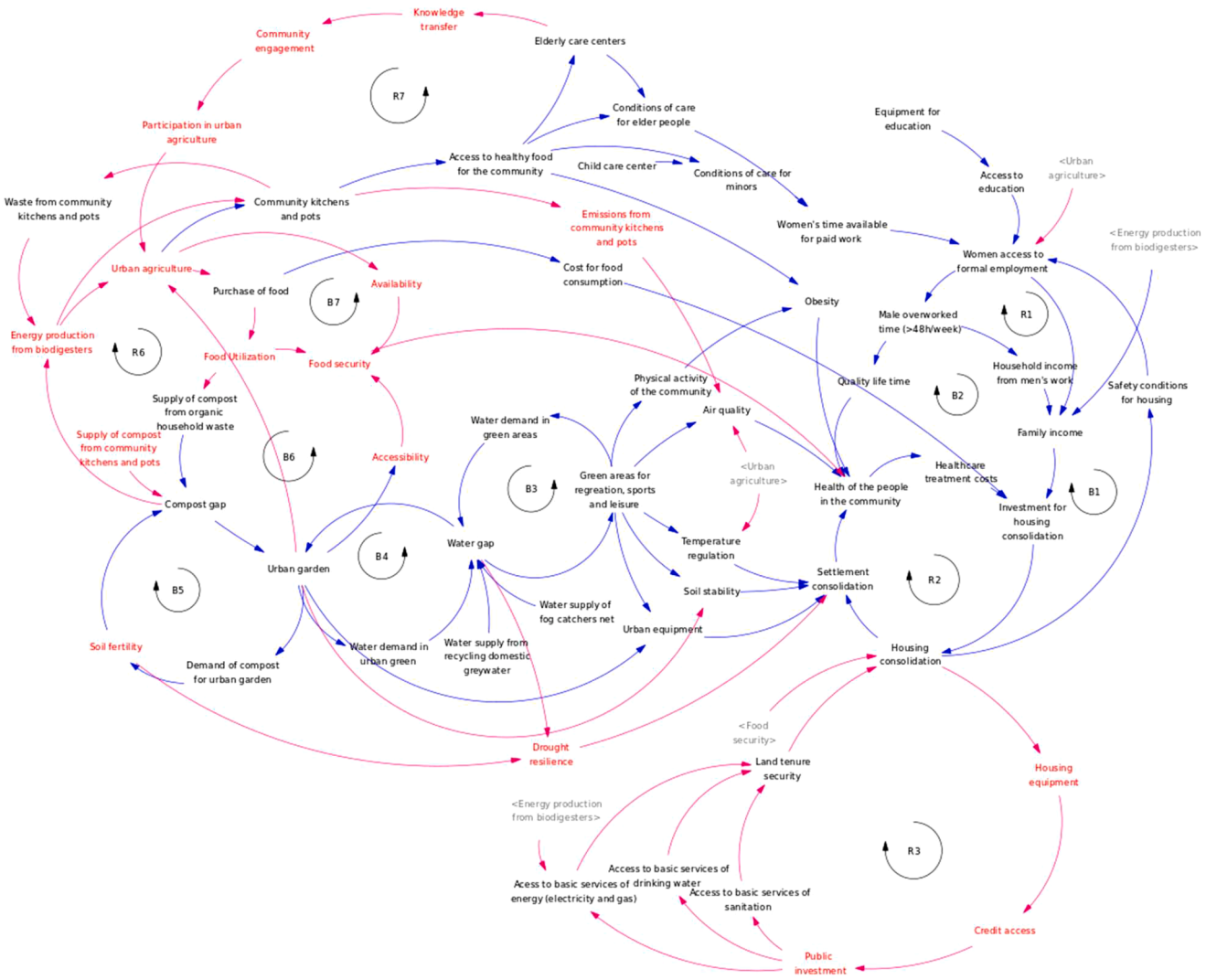


Fig. 4d. Integrated Urban Metabolic Systemic changes compared with Acevedo-De-los-Ríos et al. (2025).
The integrated diagram reveals that the food-waste-compost loop and the governance-tenure-adoption loop are the two dominant reinforcing structures governing system-wide performance.
Note: Pink arrows represent new Interactive relationships, and red variables denote new indicators added during model refinement.

delays affecting outcomes. For example, the compost–food loop stabilizes after several years, while social resilience increases more gradually but continuously. The integration of infrastructure and social strategies, such as combining greywater systems with community gardens, produces synergistic effects that enhance overall system performance. These insights underscore the importance of cross-sectoral planning and the strategic sequencing of interventions to prevent bottlenecks or diminished returns.

Binding constraints by scenario: In the BAU scenario, cultivated area is the primary binding constraint (additional potential capped at TUGPS = 1588 m^2), limiting food self-sufficiency near 0 % without policy-driven expansion. In the integral scenario, soil compost absorption capacity saturates first (year 7), followed by greywater supply equalling irrigation demand (also near year 7). Labor availability (estimated at 160–216 h/week under conservative participation assumptions) does not bind in any scenario tested. Biodigester energy output is constrained by the organic waste allocation fraction (25–100 % to energy vs. compost), constituting a policy trade-off rather than a physical limit.

4.4.2. *Sensitivity and uncertainty analysis*

To assess the robustness of the model, a combined uncertainty and global sensitivity analysis was conducted. Uncertainty analysis was performed using a Monte Carlo (MC) simulation framework based on Latin Hypercube Sampling (LHS), enabling efficient, stratified exploration of the multidimensional input parameter space. We selected 24 model parameters (See **Supplementary Material Table S5**) and assigned plausible ranges based on literature values, expert judgment, or scenario assumptions, which were then propagated through the model to generate a distribution of output values for 9 main variables. The resulting Monte Carlo output distributions for these nine variables are presented in **Supplementary Material Figure S2**. The output variables analyzed were: Food Security, Settlement Consolidation, Health of People in the Community, Drought Resilience, Local Food Production, Labor for Urban Agriculture, Women in formal Employment, Water demand for Urban Agriculture, and Energy from Biodigesters.

In the case of Food Security, values tend to cluster near the upper bound, with a point mass at 1 for the 120-month run. It confirms strong saturation of the results due to the allocation of weights to its three components: Availability, Nutrition, and Accessibility. Since we considered no variations in the diet of the dwellers and no changes in the urban form of the IS, Availability is the only variable that influences the result over time. Moreover, it represents a percentage of total food consumption, thereby reducing the variable's influence on food security. Settlement consolidation and Health of People of the community have

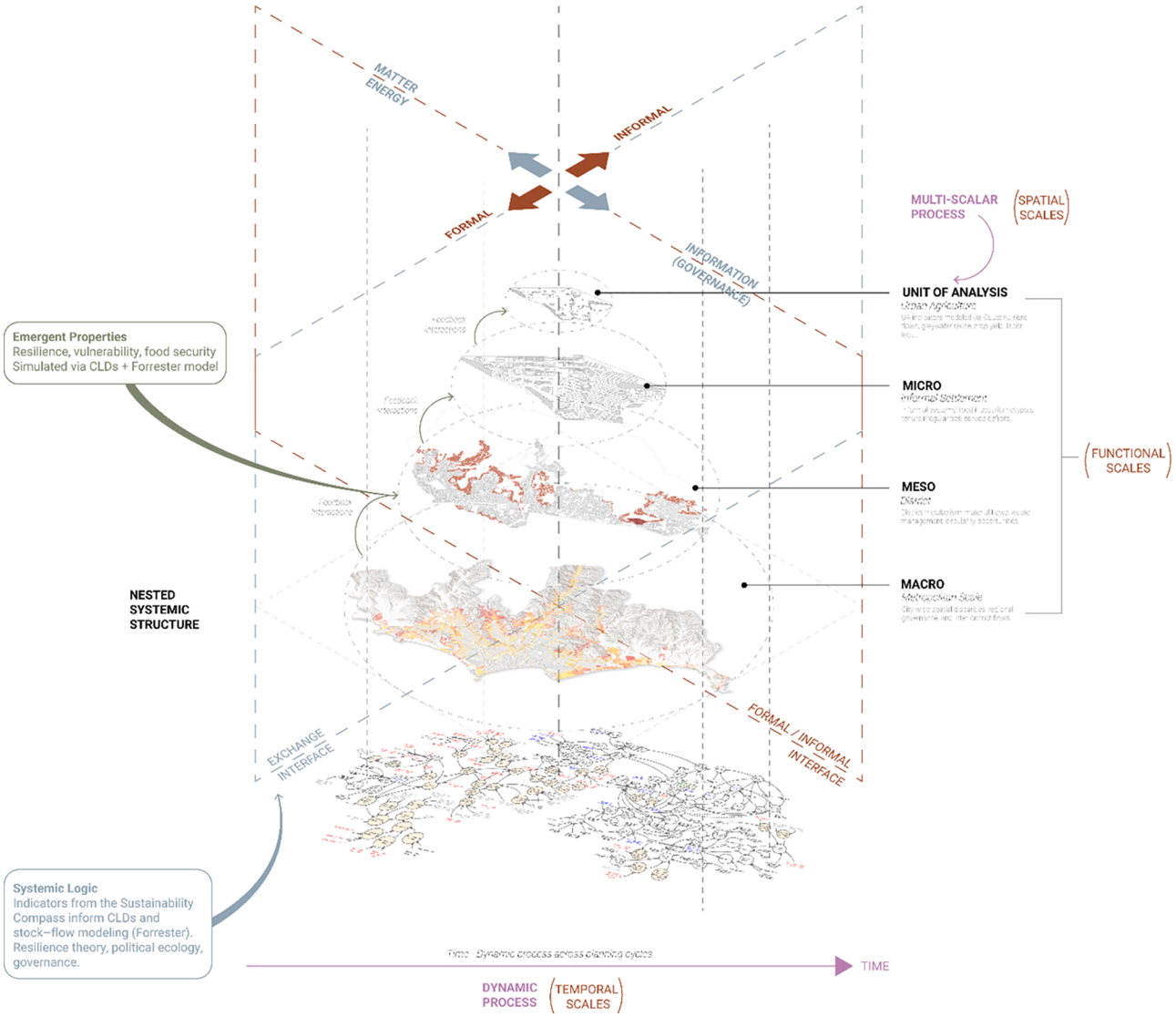


Fig. 5. Contextual Application of the Systemic Operative Framework for Urban Agriculture Integration in Lima, Peru. The spatial layering from metropolitan to unit-of-analysis scale demonstrates how the systemic framework translates from abstract metabolic principles to actionable settlement-level interventions in Ciudad de Gosen.

Note: This diagram operationalizes the conceptual framework presented in Fig. 1 by using spatial data from a case study in Lima, Peru. The four nested layers represent functional scales—Macro (Metropolitan), Meso (District), Micro (Informal Settlement), and Unit of analysis (Urban Agriculture), mapped across formal and informal systems, dynamic interactions, and resource exchanges. The diagram integrates specific variables from the Sustainability Compass (e.g., land tenure, greywater reuse, organic waste flows) and translates them into system dynamics via Interactive Loop Diagrams (ILDs) and Forrester modeling. Each layer reflects a vertical integration of information, governance, and material flows across spatial, functional, and temporal dimensions, supporting circularity-oriented interventions and resilience-building strategies. Maps adapted from A. Acevedo-De-los-Ríos et al. (2025; 2024).

also low uncertainties and are close to the upper bound, because the starting point of these variables were already high: the consolidation of the is 0.80, which means that most of the settlement is almost at its end stages of consolidation, and the variation depends on changes on the socio-economic factors of the families. Drought Resilience, Local Food Production, and Labor for Urban Agriculture have higher uncertainty, mainly because they are connected to multiple loops, which increases complexity. In the three cases, the biophysical and social dimensions are bundled and influence more than the previous three indicators do. Water dynamics, which account for the inclusion of new ways to reuse or collect water, influence Drought Resilience and Local Food Production. Social dynamics, such as the inclusion of women in the workforce, participation by other family members, such as the elderly, and specific policy plans to enhance UA, lead to greater variation in the model's outputs.

In conclusion, although applying MC simulation to the Forrester urban dynamic model presents challenges due to its reliance on "behavior modes" rather than precise prediction, the uncertainty analysis reveals strong heterogeneity in output variability: composite normalized indicators exhibit low variance due to saturation effects, whereas biophysical and resource-based outputs show greater uncertainty. While this analysis characterizes variability within the selected parameter space, it does not resolve whether the current model specification is over- or under-parameterized. Moreover, spatial layout, intra-neighborhood heterogeneity, and regional interaction effects are treated as exogenous boundary conditions rather than endogenous processes, and their potential influence on system behavior remains an open source of uncertainty. These limitations indicate the need for spatially explicit and multi-scale extensions in future validation efforts.

Connecting MC results to headline outcomes: the stated range of 17–52 % household energy coverage reflects both the scenario-driven waste allocation trade-off and Monte Carlo parameter uncertainty;

Table 5
Description of the two scenarios explored in this model, with upper and lower bound limits, variables, and units.

	Variables	Units	Business as Usual	Integrated Scenario	Scenario description
Male Overwork Average Time	MOAT	Hours/ Persons*month	144	0	Men no longer need to work overtime because women can generate higher incomes
Male percentage overworking in the settlement population	MPOS	1	0.51	0	Since men no longer need to work overtime, the percentage of men overworking is zero
Average women's income per capita	AWIPC	US $/(Persons*month)	217.36	471.7	Income conditions for women are the same as those for men
Females work average time	FWAT	Hours/ (Persons*month	96	192	Women can work full-time and not just part-time
Male overwork average time	MOAT	Hours/ (Persons*month)	144	0	Men no longer need to work overtime because women can generate higher incomes
Male percentage overworking in the settlement population	MPOS	1	0.51	0	Since men no longer need to work overtime, the percentage of men overworking is zero
Women's access rate to formal employment	WARE	1/Month	0.01	0.02	The hiring rate of women in formal jobs has doubled
Wastewater recycling rate	WRR	1	0	0.75	Households start recycling wastewater for agricultural uses
Net increase in fog catcher implementation	NIFC	1	0	0.25	The community adopts fog catchers as a new water source for consumption, installing one every 4 months.
Net increase of rooftop gardens	NIRG	m2	0	1460	Households with the structural capacity to build rooftop farms build them at a rate of 15 households per month
Biogas yield	BY	m3/Ton	0	150	The community adopts biogas harvesting for electricity production
Subsidized Jobs for UA	SJUA	Persons	0	100	The government supports women in UA activities
Participation of Elderly People	PEP	Persons	0	22	Elderly people who migrated from agricultural regions are directly involved in urban agriculture
Knowledge transfer	KT	1	0	0.1	10 % of elders share their knowledge on agricultural activities with other members of the community
Explorative scenario parameters			Lower bound	Upper bound	
Vertical farming ratio	VFR	1	0.25	0.75	Which UA spatial configuration, per crop type, is most optimal for the community?
Agricultural production labor intensity	APLI	Hours/Ton	250	1000	Explore the range of labor intensity based on the literature and its effects on agricultural outputs.
Waste for compost	WFC	1	0.25	0.75	What is the ideal configuration for waste management at the end of use?

Note: All scenario descriptions and parameter ranges are based on data and assumptions detailed in (Acevedo De-los-Ríos et al., 2025; Acevedo De-los-Ríos et al., 2024).

within the MC ensemble, this range covers approximately the 10th–90th percentile of the biodigester energy output distribution, though actual performance remains subject to unmodeled operational shocks. While the ~77 % greywater irrigation coverage is robust across the sampled parameter space, with the 80th percentile of MC simulations exceeding 70 % irrigation coverage. Dominant uncertainty drivers for biophysical outputs are highly sensitive yield parameters (MHY, VFY) and Waste for Compost fraction (WFC); for social outputs, additional predictive uncertainty stems from Women's access to formal employment (WARE) and time dedicated to UA (TNEW) dominate, as reflected in the relative spread of distributions in **SM Figure S2**, indicating that social outcomes are significantly dependent on external labor market conditions.

5. Discussion

5.1. Systemic integration of food security and circular urban metabolism

This study contributes to the growing body of knowledge on urban metabolism by demonstrating how food security strategies in informal settlements can be enhanced through systemic interventions grounded in circular economy principles. Rather than proposing a novel integration of urban metabolism, system dynamics, and urban agriculture, the contribution lies in the operative structuring of these approaches into a feedback-sensitive, diagnostic framework tailored to informality. The integration of food–water–energy–waste (FWEW) flows within a dynamic systems model enabled a comprehensive analysis of how urban agriculture, composting, greywater reuse, and biodigestion can jointly reinforce metabolic resilience and local livelihoods when embedded within a governance- and adoption-sensitive feedback structures.

The combined feedback structures derived from the ILDs, implemented in the dynamic model, validate the hypothesis that reinforcing loops, when properly supported by enabling infrastructure and governance, can drive sustained improvements in urban resource efficiency. Urban agriculture is shown not as a singular solution, but as a leverage point within a larger system of interconnected metabolic flows, aligning with the findings of Qiu et al. (2024), Caputo et al. (2021; 2022), and systems theory approaches to urban complexity (Y. Shi et al., 2021; Gallotti et al., 2021; Lezak and Thibodeau, 2016).

Two minimal operational metrics for equity and nutrition are operationalized in the model. First, Cost for Food Consumption (CFC = SP × CFCP × PF) captures household food expenditure as a function of population, per-capita food cost, and the food purchase ratio (PF), providing a proxy for food affordability that decreases as local UA production substitutes market purchases. Second, Access to Healthy Food for the Community (AHFC = (CK + CP + UG) / (SP × DAHGC)) represents the ratio of available food-provision infrastructure to per-capita normative demand, serving as a proxy for diet diversity and community food access. Both metrics are documented in SM1 and are consistent with FAO (2006) food security monitoring conventions. Equity claims in this study pertain to the modeled dimensions of affordability and community food access; intra-household distributional equity and micronutrient adequacy fall outside the model's scope.

An important extension of these findings concerns UA's contribution to household food security in Ciudad de Gosen. Based on local consumption patterns reported by INEI for Metropolitan Lima (INEI, 2012), the average household demand for cultivable food categories (tubers, vegetables, fruits) is approximately 44.8 kg per month for a four-person family.

When these demand levels are compared with the cultivation capacity represented in the model scenarios, both unbuilt land and rooftop areas represent significant productive potential. Conservative soil-based production and rooftop container cultivation simulated in the model indicate that decentralized production can supply a substantial share of cultivable food demand under gradual adoption pathways. These

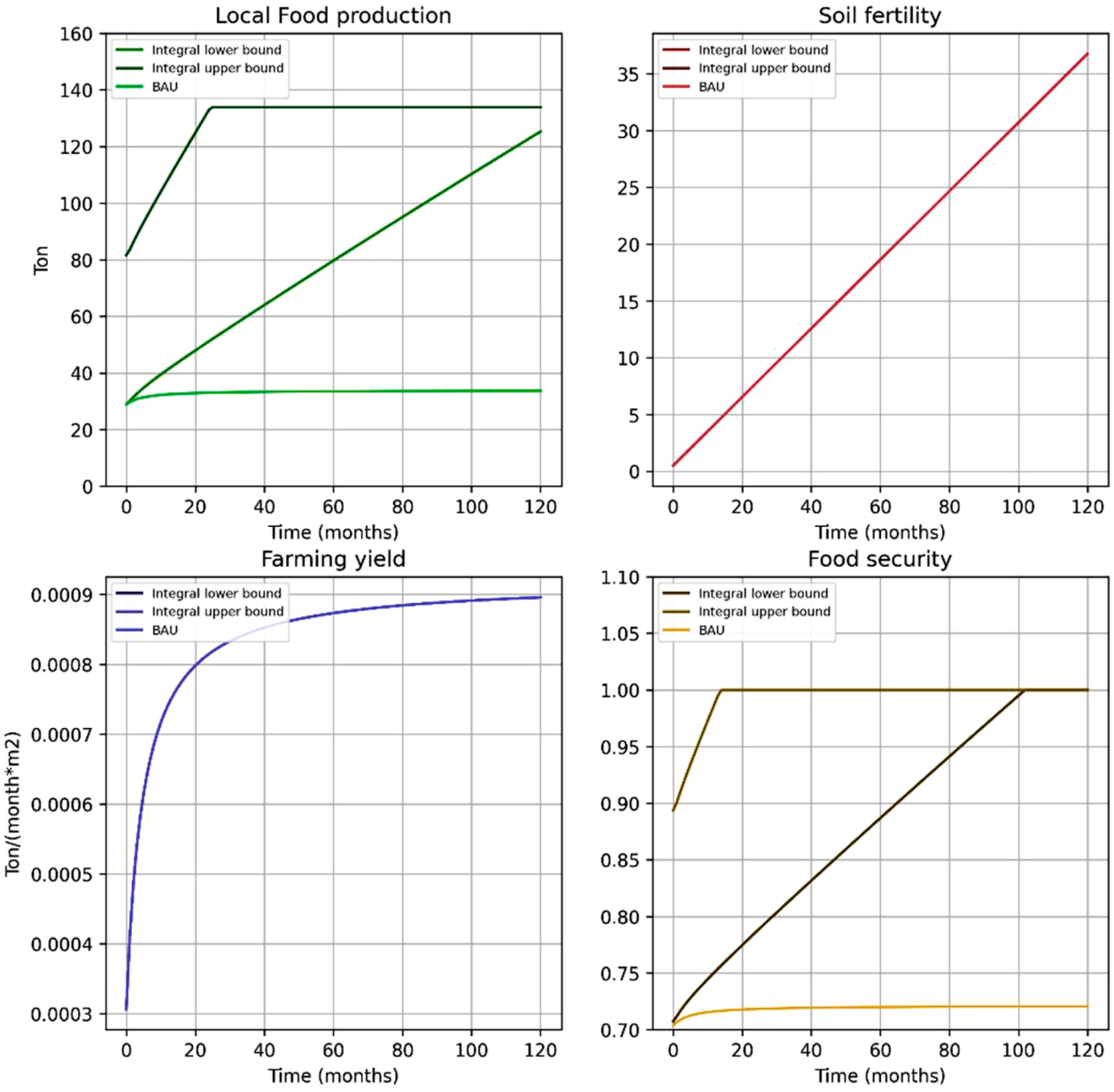


Fig. 6. Contribution of compost to fertility vs. Food Yield and production Over Time – Scenario 1: Baseline vs. Integral scenario (Enhanced Composting). Soil fertility saturation by year 7 highlights the need for complementary agronomic strategies (e.g., crop rotation, biochar) to sustain productivity gains beyond the composting absorption threshold.

Table 6
Simplified mass and energy input-output verifications for the two primary circular subsystems modeled.

Subsystem	Input	Transformation	Output	Efficiency/Loss Factor	Conservation Status
Water (greywater)	Greywater supply (WSDG, m^3/month)	Treatment (WRR = 0.75)	Irrigation supply (WCC, m^3/month)	25 % losses assumed	Explicitly modeled
Energy (biodigester)	Organic waste input (kg/month)	Biogas conversion	Energy output (MW/month)	Conversion efficiency ~30–40 % (literature)	Parameterized via scenario bounds
Nutrients (N, P)	Organic waste/compost (kg/month)	Composting process (CE = 0.02/kg)	Soil fertility increment (Dimensionless)	Mass balance not fully closed; CE is a dimensionless effectiveness factor approximating nutrient uptake	Approximated; not mass-balanced

outputs would theoretically cover between 117 and 2450 household food baskets per month, surpassing the local cultivable demand even under conservative assumptions.

A gradual adoption scenario, starting with 14 households and expanding at 10 % per month toward the 146 structurally consolidated homes (58 % of the total), demonstrates that even modest 20 m^2 rooftop modules can help reduce food insecurity within the first year. By month 12, simulated rooftop systems serve an increasing share of households, indicating measurable gains in dietary resilience. Moreover, combining community-level plots for tubers and fruits with rooftop leafy-green

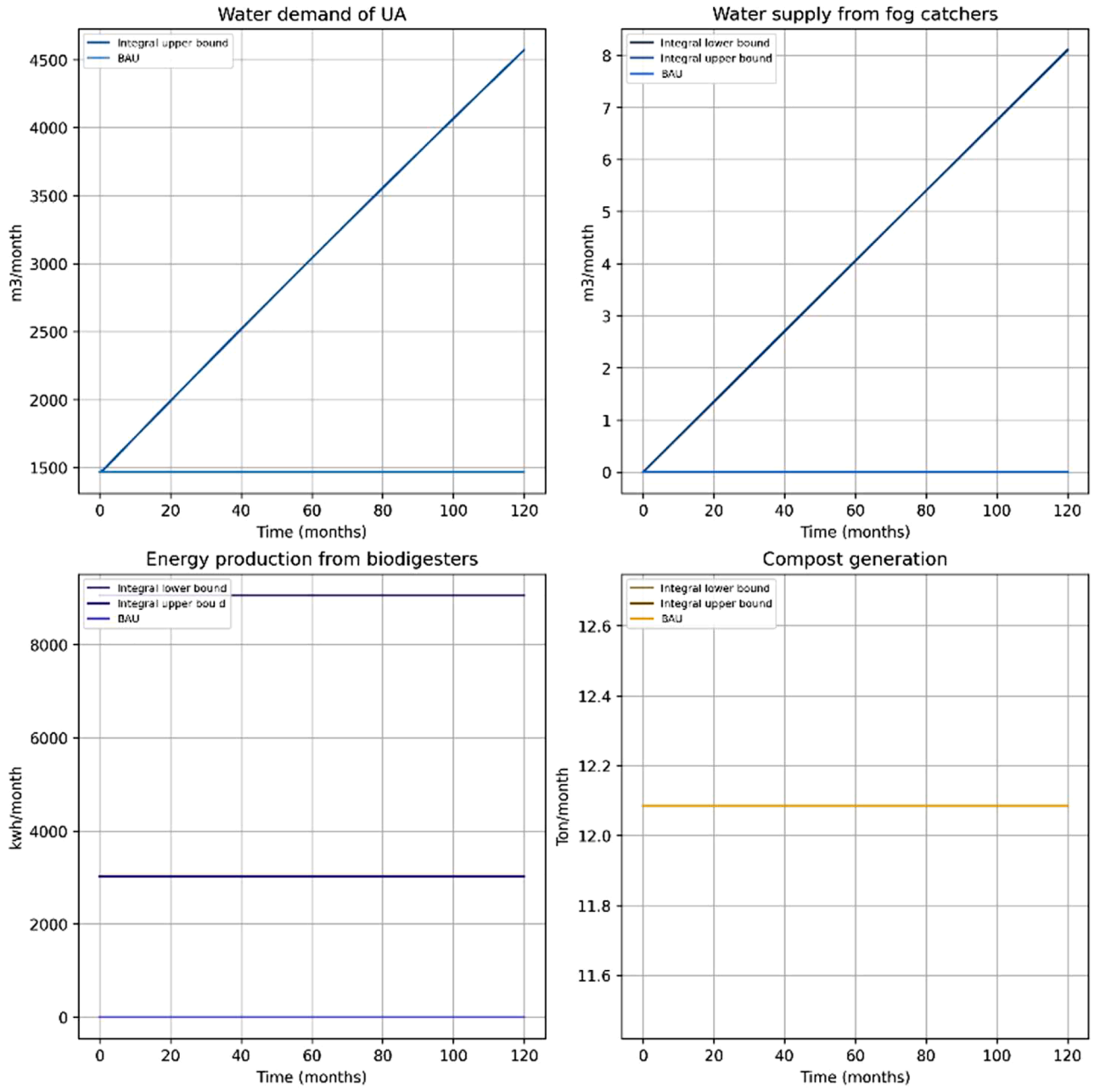


Fig. 7. Greywater Reuse and Biodigester Output – Scenario 2: Circular Water-Energy Integration.
The convergence of irrigation supply and demand near year 7 signals a critical transition point at which additional water-capture strategies (e.g., fog catchers, expanded greywater systems) become necessary to maintain irrigation coverage.

production supports both caloric supply and micronutrient diversity, addressing known deficits in vegetable intake in urban Peruvian diets (FAO, 2022; Dorr et al., 2021; Wielemaker et al., 2019; Willett et al., 2019).

Thus, beyond household-level impacts, UA offers a systemic opportunity to reinforce social food infrastructure in informal settlements, ensuring that vulnerable groups relying on community kitchens have access not only to adequate caloric intake but also to diversified, micronutrient-rich diets.

Together, the simulation results indicate that strategic distribution and adoption of UA in Ciudad de Gosen can significantly strengthen dietary diversity, reduce the risk of food insecurity, and enhance circular resource use. These results converge with prior empirical validations, which estimated that moderate rooftop and public land conversion could cover 17–27 % of food flows in similar contexts (Gunapala et al., 2025; Toboso-Chavero et al., 2021). These dynamics emerge from reinforcing feedbacks linking production capacity, governance support, resource recovery, and household participation.

5.2. *Trade-offs, thresholds, and synergies across subsystems*

Scenario analysis reveals nonlinear dynamics and interdependencies among urban subsystems. Simulation behavior indicates that composting initially improves soil fertility and food yields; however, marginal productivity gains diminish beyond a saturation threshold as nutrient availability approaches equilibrium. This pattern reflects declining system responsiveness once soil organic matter reaches higher levels and is consistent with long-term compost application studies (Morra et al., 2021).

The effectiveness of greywater reuse is conditioned by treatment

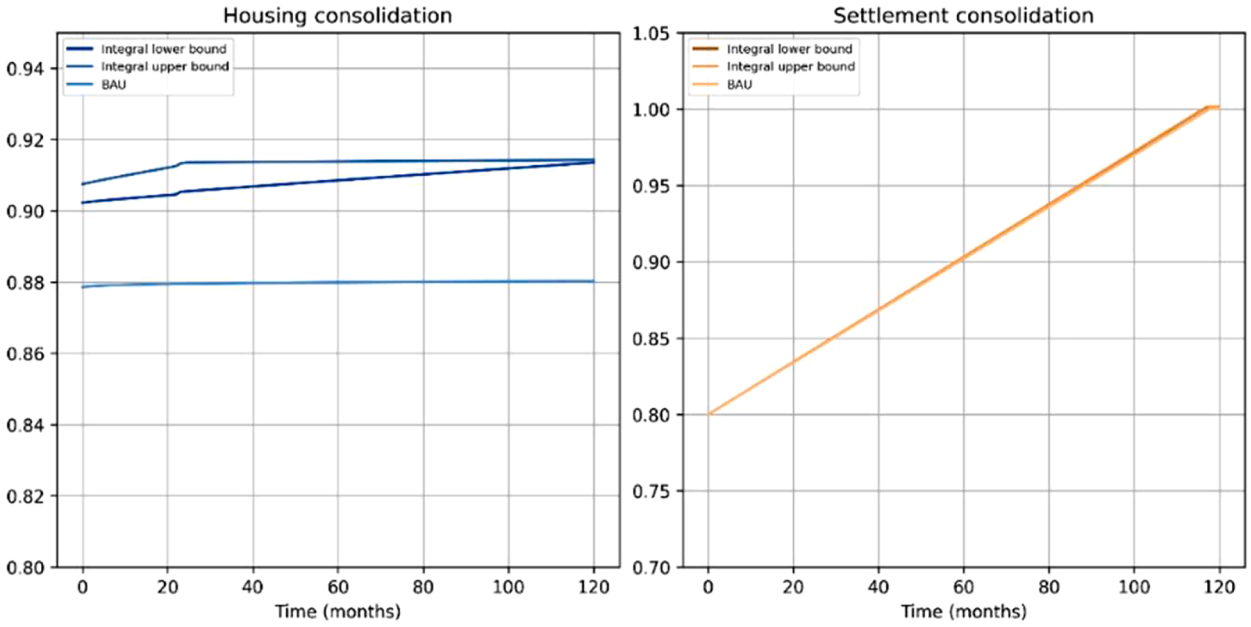


Fig. 8. Scenario 3 – Formalization of Land and Infrastructure Investment Effects on Circular Practice Uptake.The 8 % cascading increase in infrastructure access within the first two simulation years demonstrates that land tenure formalization is the highest-leverage single governance intervention available in consolidating informal settlements.

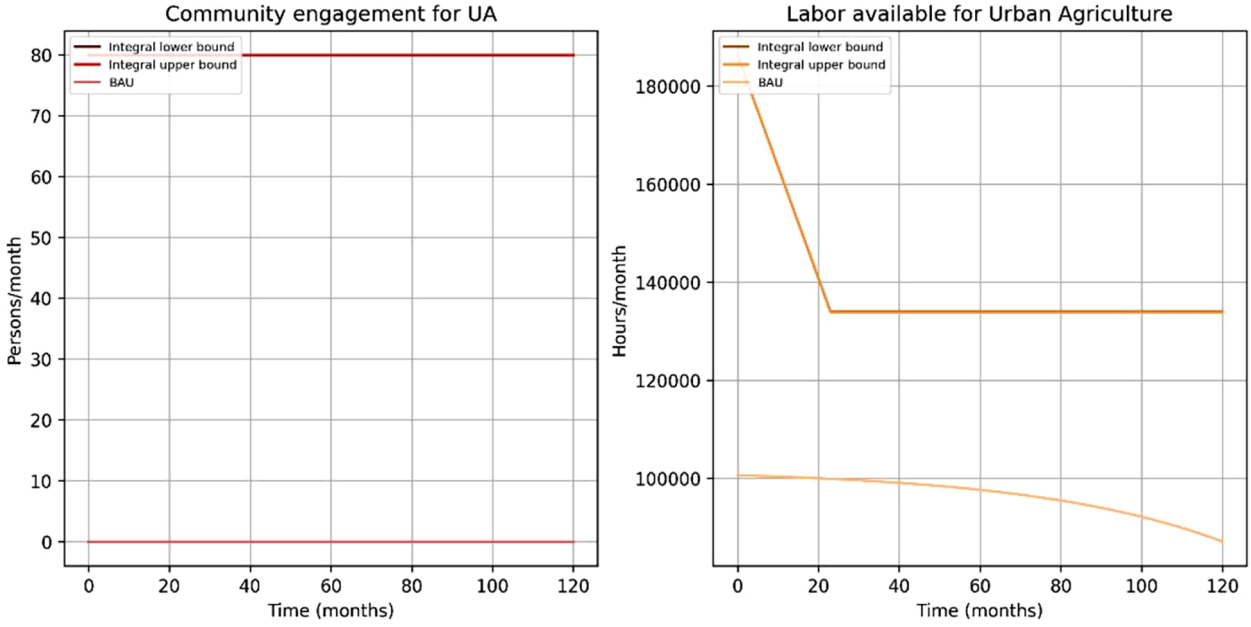


Fig. 9. Scenario 4 – Social Participation (Community engagement).
The declining trajectory of female labor hours available for UA, as women access formal employment, emphasizes the need for childcare and flexible UA participation schemes to sustain adoption without imposing additional burdens on women.

capacity, water quality thresholds, and infrastructure-related time delays, which introduce lags between investment and irrigation reliability. These delays influence both crop productivity and public health risk mitigation (Van de Walle et al., 2023; Shaikh and Ahammed, 2020), demonstrating how the timing of infrastructure affects feedback strength and system performance.

Several reinforcing synergies emerge across subsystems. Simulation results show that biodigestion reduces organic waste accumulation while increasing energy availability, strengthening reinforcing loops linking waste recovery, energy access, and food preparation capacity. Reduced waste accumulation also contributes to improved environmental health conditions associated with unmanaged dumping.

On the water side, greywater reuse increases irrigation reliability while reducing dependence on tanker-supplied water. When combined with complementary water capture strategies within the resource subsystem, this produces a stabilizing effect on the viability of cultivated areas and household water expenditures. Greywater reuse also reduces labor burdens associated with water collection, reinforcing social–resource feedback linkages.

These trade-offs and synergies illustrate how subsystem interactions

generate both enabling effects and threshold constraints. Reinforcing loops enhance system performance when resource recovery infrastructures are present, while balancing loops emerge as saturation limits, infrastructure delays, or quality constraints reduce marginal gains.

Overall, model behavior demonstrates that metabolic improvements in informal settlements do not arise from isolated interventions but from the interaction of reinforcing and balancing feedback structures. The model identifies leverage points where coordinated investments in waste recovery, water reuse, and decentralized energy systems produce synergistic resilience gains, while also revealing thresholds beyond which additional inputs yield diminishing returns.

5.3. The role of governance, informality, and participation

Governance serves as a fundamental support system for circularity. Secure land tenure, as showcased in Scenario 3, is crucial for encouraging household-level investment in infrastructure and fostering long-term planning. The novelty of the framework lies in embedding these governance variables as endogenous feedback structures within the system dynamics model, rather than treating them as external assumptions or boundary conditions, as is common in much of the existing literature. The simulation confirms that improvements in legal recognition and public investment correlate with increased adoption of composting, water reuse, and clean energy technologies. While the direction of these governance–investment–adoption feedbacks is structurally generic across informal settlement contexts, their magnitude, timing, and thresholds are highly context-dependent and require local parameterization rather than modification of the underlying feedback structure.

However, the results also reveal the structural limits imposed by informality. Without clear rights or institutional support, circular practices are prone to remaining fragmented and short-lived. The modeled reinforcing loop between governance legitimacy, infrastructure access, and circular engagement suggests that policy interventions likely need to address not only technical gaps but also socio-political barriers. These findings align with the literature on informality and urban equity (Parikh et al., 2020; Satterthwaite and Mitlin, 2013) and reinforce the need for participatory and inclusive planning processes. Accordingly, the governance-related insights derived from the Lima case should be interpreted as diagnostically transferable with respect to causal structure, whereas quantitative outcomes remain contingent on locally specified institutional, economic, and socio-political conditions.

To clarify the treatment of governance within the model structure, governance is operationalized at two levels with inherent simplifying assumptions. First, at the endogenous level, Land Tenure Security (LTS) is computed as the mean of three access-to-services variables (water, energy, and sanitation), which, in turn, influence Housing Consolidation, Infrastructure Investment, and household energy demand functions, thereby creating postulated feedback loops between governance legitimacy and metabolic performance. Second, adoption rates for urban garden expansion (NIRUG) and green area growth (NIRGA) are treated as exogenous scenario parameters, representing policy-determined investment trajectories rather than emergent behavioral outcomes. This distinction is important: the reinforcing feedback among LTS, infrastructure, and circular-practice engagement is endogenous to the model; the pace of UA expansion depends on exogenous governance commitments. Future model extensions should endogenize adoption rates using behavioral decision rules that link participation probability relative to perceived tenure security and institutional support.

5.3.1. Participation dynamics, labor mobilization, and governance leverage

Time-use data incorporated into the model reveal structurally gendered labor constraints that also reflect a latent capacity for adopting urban agriculture (UA). Only 42 % of residents participate in paid work, while unpaid domestic labor accounts for 43 % of total human activity; women perform 68 % of household tasks and invest substantially more time than men. These conditions indicate that participation in UA can provide immediate food security benefits while creating pathways toward economic participation when supported by childcare and training.

Simulation scenarios model a conservative adoption pathway in which 14 consolidated households initiate UA activities, and participation grows by 10 % per month toward the settlement's structurally consolidated dwellings. Under this trajectory, participation peaks at approximately 40 households during the first year. If one adult woman per participating household contributes four hours per week, the system supplies roughly 160 labor-hours per week by month twelve. Including limited co-participation by employed men and older adults increases available labor to approximately 216 h per week under modest uptake assumptions.

These results indicate that labor availability is not a limiting factor for early UA expansion; rather, participation depends on enabling governance conditions and institutional support. The model shows that tenure security, organizational support, and collective arrangements function as reinforcing feedback, stabilizing adoption and sustaining system performance over time.

To match labor supply with system requirements, the model differentiates between production modalities. Horizontal soil-based systems distribute labor across seasonal cycles, while container or hydroponic systems concentrate tasks into shorter, routine activities suitable for rotating participation schedules. At the settlement scale, combining rooftop cultivation with ground-level plots supports both caloric supply and micronutrient production while maintaining manageable labor demands. Once household consumption needs are met, surplus production can circulate through local exchange networks, reinforcing nutrient and monetary loops and strengthening local food access.

5.3.2. Social resilience and knowledge transfer as systemic enablers

Simulation outputs indicate that community institutions function as critical nodes that enhance adaptive capacity when integrated with UA initiatives and knowledge-sharing mechanisms. Facilities such as community kitchens, childcare centers, and neighborhood organizations strengthen coordination, facilitate participation, and support the continuity of resource loops.

The model suggests that knowledge transfer, particularly agroecological practices and food preparation traditions, acts as a reinforcing mechanism that accelerates adoption and improves system performance over time. Intergenerational knowledge and skills contribute to improved crop management, dietary diversification, and maintenance of productive spaces, strengthening resilience within the settlement.

When institutional support and knowledge exchange operate together, the system exhibits increased stability, improved dietary diversity, and stronger adaptive responses to resource constraints. These dynamics demonstrate how social-ecological memory and collective learning enhance the durability of circular practices and reinforce resilience in informal urban settings.

5.4. Methodological contributions: from ILDs to dynamic validation

A central contribution of this study is the integration of qualitative Interactive Loop Diagrams (ILDs) with quantitative system dynamics modeling. The ILDs captured the interdependencies among food flows, water scarcity, waste accumulation, and energy access observed in Ciudad de Gosen, and their translation into stock–flow structures enabled formal testing of these relationships under dynamic conditions.

Beyond structural mapping, this translation allowed validation of system behavior against contextual constraints. Once feedback loops were formalized, dynamic patterns such as time delays, threshold effects, and unintended consequences became visible phenomena that static frameworks cannot capture. For example, delays in greywater treatment influence irrigation reliability, while changes in waste recovery propagate through energy and nutrient loops.

Comparing simulated behavior with settlement conditions enhanced both internal coherence and contextual validity. This integration demonstrates that system dynamics models grounded in place-based evidence can support scenario testing and resilience planning by identifying leverage points and potential system overloads (Sterman, 2000; Richardson, 2011).

Methodologically, the ILDs function as heuristic and operational interfaces between qualitative system understanding and executable simulation. Their use emphasizes relational dependencies and feedback structures rather than deterministic prediction, aligning the framework with systems-thinking approaches that support participatory validation and interdisciplinary application.

5.5. Policy implications and strategic leverage points

Simulation results indicate that improvements in food production, energy recovery, and water reuse are mutually reinforcing when supported by enabling governance structures. The integrated assessment underscores that policy interventions in informal settlements must be framed not as isolated technical fixes but as Interactive strategies within the broader food–energy–water–waste (FEWW) nexus. For food systems, policy attention should shift from subsistence support toward the institutionalization of urban agriculture and community-based food provision within municipal planning instruments. Embedding agricultural education in schools, supporting productive community gardens, and integrating produce from local rooftop or ground-level farms into state-led nutrition programs can provide durable pathways to reduce food insecurity while simultaneously addressing malnutrition.

On the energy side, policies that incentivize decentralized renewable generation, such as biogas from organic waste or solar micro-grids, can significantly lower household expenditures and reduce reliance on polluting fuels. Linking these initiatives with community kitchens ensures that the energy transition also strengthens social safety nets. The water subsystem similarly requires institutional innovation: formal recognition of greywater reuse and fog-harvesting technologies in public health and urban planning codes would legitimize practices that are already occurring informally, while ensuring that safety standards are upheld. Moreover, aligning tariff structures with inclusive access is crucial, given the disproportionate costs currently borne by households reliant on tanker water.

In the waste sector, municipal ordinances that treat organic fractions not as residuals but as resources could incentivize composting and the adoption of biodigesters at the settlement scale. Such measures would reduce the pressure on landfills, cut greenhouse gas emissions, and provide a locally controlled input stream for food production. Cross-sectoral governance frameworks are indispensable: by linking food provision, energy supply, water management, and waste recovery into a coherent strategy, municipalities can move from fragmented service delivery toward integrated circular infrastructures. These initiatives not only enhance metabolic resilience but also create opportunities for labor inclusion, gender-responsive participation, and alignment with international commitments such as the Sustainable Development Goals.

Finally, future developments should explicitly address the epistemic and behavioral boundaries of system dynamics when applied to informal contexts.

5.6. Limitations and future research

Despite its systemic scope, the present model has several limitations that require further iterative development to continue to more comprehensively address both epistemic uncertainty and systemic nonlinearity. Behavioral dimensions such as household decision-making, institutional trust, and community cooperation were simplified, even though they strongly influence the feasibility of policy interventions in informal settlements. Economic dynamics were also modeled under static assumptions; yet, price volatility in food, energy, and water markets can sharply alter household vulnerability and the stability of metabolic loops. Furthermore, the model treated social networks and governance as aggregated variables, introducing potential aggregation bias, and failing to capture actor heterogeneity or the uneven distribution of power within settlements. Rather than striving for predictive precision, subsequent iterations should prioritize transparent representation of uncertainty, bias, and nonlinearity, reinforcing the framework's role as an adaptive learning tool. Integrating Interactive Loop Diagrams into participatory co-design processes can support iterative assumption validation, bridge disciplinary perspectives, and expand the operational relevance of dynamic models for urban policy and planning.

Additional limitations include the following. First, food security operationalization in the model covers the Availability and Accessibility dimensions of the FAO four-pillar framework (availability, accessibility, utilization, stability); the Utilization dimension (diet quality, micronutrient composition) is approximated through the AHFC indicator, while Stability is captured indirectly through Drought Resilience (DR). Claims about full improvement in food security should therefore be understood as pertaining primarily to these modeled dimensions. Second, the model does not explicitly simulate climate extreme scenarios (e.g., multi-year El Niño droughts, flood events). The Drought Resilience variable captures baseline water scarcity and governance-conditioned adaptive capacity, but not tail-risk disruptions. While DR serves as a baseline proxy for adaptive capacity, it underestimates the systemic vulnerability associated with acute climate shocks. Stress-testing under extreme climate scenarios is identified as a high-priority direction for future research. Third, regarding transferability: while the causal feedback architecture is generic and transferable, quantitative application to a new settlement requires re-estimation of at minimum three parameter blocks: (a) biophysical parameters (yields, water demand, soil fertility), which depend on climate zone and crop selection; (b) socio-demographic parameters (population, income, labor availability, gender ratios), which must be derived from local surveys; and (c) governance parameters (access to basic services, tenure security), which reflect local institutional conditions. Settlement typologies most analogous to Ciudad de Gosen include consolidating peri-urban settlements in semi-arid climates with partial service access (coverage 0.70–0.90), populations of 2000–15,000 inhabitants, and ongoing tenure regularization. Application to settlements with very different characteristics (e.g., flood-prone coastal slums, high-density inner-city tenements) would require structural model adaptations beyond reparameterization.

Future research should therefore deepen both the technical and socio-political dimensions of the framework. On the technical side, integrating granular geospatial modeling would allow for more precise identification of rooftop potential, interstitial or unused spaces, water-harvesting catchments, and waste generation hotspots. Climate-sensitive testing, particularly under extreme-event scenarios such as El Niño or prolonged droughts, could refine the resilience dimension of the model. On the social side, participatory modeling that incorporates residents, community leaders, and municipal authorities would enhance legitimacy, improve parameter calibration, and foster a sense of co-ownership of solutions. Comparative studies across cities in diverse ecological zones and governance regimes are required to determine whether identified leverage points remain robust or are merely artifacts of the current model's geographical and institutional boundaries, thereby providing insight into their transferability.

6. Conclusions

This study set out to understand how urban metabolism might be mobilized to address food insecurity in informal settlements, using Ciudad de Gosen as a case study. By integrating a multidimensional indicator framework, systemic structuring, Interactive Loop Diagrams (ILDs), and a Forrester-style system dynamics model, the research provides a diagnostic-to-simulation workflow capable of translating socio-metabolic assessments into dynamic decision-support tools.

Simulation results show that embedding urban agriculture within settlement metabolic flows could substantially improve food security and resource circularity. Rooftop and unbuilt-land cultivation can meet household demand for vegetables and fruit, biodigestion can supply approximately 17–52 % of household energy needs, and greywater reuse can sustain irrigation for most cultivated areas, stabilizing at approximately 77 % over time. Scenario analysis demonstrates that governance conditions, particularly land tenure security and institutional support, strongly influence adoption dynamics, generating cumulative improvements in diet diversity, waste reduction, and household expenditures. These results indicate that system performance is shaped more by governance and participation feedback than by technical capacity alone.

The model reveals reinforcing interactions across the food–energy–water–waste nexus, where nutrient recovery, organic waste diversion, and decentralized energy production strengthen circular metabolic loops. At the same time, delays, saturation effects, and threshold dynamics highlight limits to productivity gains and underscore the importance of adaptive governance and staged implementation.

Methodologically, the study contributes an operative framework that links indicators, feedback structures, and stock–flow modeling, enabling scenario exploration, leverage-point identification, and policy learning in data-scarce environments. While the causal architecture is transferable, quantitative outcomes remain context-dependent and therefore carry inherent epistemic uncertainty requiring rigorous local re-parameterization

Overall, the findings position informal settlements as socio-ecological systems with latent capacity for circular resource management and resilience. Integrating urban agriculture within urban metabolism planning provides a systems-based pathway to enhance food security while advancing sustainability and equity in rapidly urbanizing regions.

CRediT authorship contribution statement

Alejandra Acevedo-De-los-Ríos: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Anna Dyson:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Damien Claeys:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Ursula Cardenas-Mamani:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2026.111632.

Data availability

The data associated with this article are available in the article, in the supplementary material, and in an open-access repository cited in the manuscript.

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