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Construction and Optimization Strategies for Rural Residential Spatial Models Based on the Concept of Resource Metabolism: A Case Study of Rural Areas in the Shandong Plain

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Abstract: Rural communities can be conceptualized as spatial organisms interconnected by optimized resource utilization systems. Investigating the efficient utilization of rural resources and spatial construction methods grounded in resource metabolism is a pivotal step toward achieving the ecological transformation of rural spaces. This paper examined rural settlements in the Shandong Plain as a case study, exploring the relationships among three scales: village, neighborhoods, and courtyards. This analysis was based on elucidating the interaction mechanisms between "space and resource" and the integration of key resources and spatial elements. From the perspective of resource circulation and metabolism, this study aimed to elucidate the equilibrium of each resource element within three resource metabolism subsystems: the agricultural production system (core element), the ecological technology system (technological link), and the human life system (spatial carrier) in Shandong Plain's villages, considering general climatic conditions. To achieve this, this research utilized the resource production volume, the utilization and transformation volume of resource metabolism technology facilities per unit area, and the average per capita resource consumption as fundamental measurement units. The concept of a rationing relationship is introduced to clarify resource allocation. Combining the aforementioned research on spatial resource metabolism in ecological villages in Shandong Province with the material flow analysis method, this study constructed a bottom–up spatial model of resource metabolism at three scales, courtyards, neighborhoods, and villages, under various resource metabolism scenarios. This study is anticipated to significantly contribute to the theoretical understanding of rural habitat environments, offering novel methods and perspectives for constructing ecological rural settlements.

Keywords: resource metabolism; Shandong Plain-Type Rural Area; spatial modelling; Optimal Design Strategy; material flow analysis

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1. Introduction

Exploring efficient and sustainable patterns of resource use and spatial construction methods is a significant avenue for alleviating urban–rural conflicts and achieving the transformation and development of rural areas. The current approach to resource utilization in China's rural areas is characterized by imprecision, hindering the rational allocation and efficient use of resources. Consequently, this increases in both per capita and overall resource consumption in rural areas poses significant challenges to their resource carrying capacity and energy transformation. Furthermore, the integration of rural production, living styles, and spatial elements is deficient, resulting in uniform spatial patterns of rural settlements and a trend toward "urbanization". As a major agricultural province in northern China, Shandong boasts diverse rural habitats and natural resources. Its sustainable remediation strategy and development model for rural settlements in the plains, the most prevalent rural settlement type in the province, has long served as a valuable reference and exemplar for similar initiatives across China. Therefore, it is crucial to consider the potential positive impact on enhancing the quality of the rural habitat environment in China, particularly in the northern region. However, a key challenge remains in achieving the ecological transformation of rural settlement spaces, based on understanding the intrinsic flow laws of rural resource elements and the characteristics of suitable resource utilization technologies. Nevertheless, there is a dearth of systematic theoretical research and practical investigation into achieving the ecological transformation and rational construction of rural settlements, based on the intrinsic flow laws of rural resource elements and the technical characteristics of suitable resource utilization.

Rural settlements are the most important spatial carriers for the lives of rural residents, and they are also the common object of research in a number of disciplines. In the early stages of research in related fields, fewer studies crossed disciplinary boundaries to pay in-depth attention to the construction of rural human settlements. In recent years, based on the cross-disciplinary perspective, taking the efficient utilization of resources as the goal and the quantitative analysis of resource flow as the main method, we have devoted ourselves to exploring the theory of “resource metabolism”, which integrates the efficient utilization of resources and human settlements, opening up a brand-new perspective of systematically examining the coupled and coordinated relationship between the human settlement environment and the natural environment. It has become an important theory for solving the problem of sustainable development in rural settlements. It has opened up a new perspective for systematically scrutinizing the coupled and coordinated relationship between human settlements and the natural environment, and it has become an important theory and frontier perspective for solving the sustainable development of rural settlements. In terms of theoretical research on the connection between human habitat space and resource metabolism, the American ecologist Abel Wolman put forward the concept of “Urban Metabolism”, which combines the concept of resource metabolism and related methods with the study of urban human habitat space [1]. Since then, relevant scholars and institutions have extended the concept of resource metabolism to the urban economy and industrial system, studying the metabolic flow process of various elements such as capital, raw material, water, waste, and other factors at different scales within the boundaries of urban and rural systems, as well as their impact assessment on the environment [2–5]. Agudelo-Vera pointed out that the cyclic efficiency and balanced management of resource metabolism are key factors in optimizing the sustainable development of urban and rural human settlements [6] and that recycling and the efficient use of resources reduces the dependence and impact of human settlements on external resources [7]. Based on the concept of resource metabolism, Kennedy has established indicators for the sustainable development of built spaces, which can be used to account for greenhouse gas emissions, construct dynamic analytical models, and set up sustainable design tools to dynamically evaluate the sustainable development of human settlements [8]. Researchers at the University of Groningen proposed the FEW-Nexus design tool and methodology based on the concept of resource metabolism from the perspective of the interaction between food, energy, and water resources, which affects the function of the human environment system. They furthermore carried out experimental design explorations on objects at different scales, such as neighborhoods, blocks, and districts, in some areas of the Netherlands and Japan [9]. The Dutch design office “upuse Studio”, together with a team of researchers (REAP), proposed the “Cyclifiler” design strategy, which takes into account the characteristics of the transformation, distribution, and consumption processes of various types of resources, in an attempt to construct a spatial operation model that was compatible with the metabolism of resources and that advanced layer by layer from the bottom to the top [10,11]. Based on the theory of urban metabolism, Zhao Qianjun explored the driving relationship, optimization path, and evaluation mechanism of the metabolic process and efficiency on the functional layout and spatial form of urban settlements from a cross-disciplinary perspective [12].

From the systematic view of resource metabolism, the space of rural settlements can be regarded as a metabolic organism, which is in essence an ecosystem of various resource and energy flows. Incorporating metabolic thinking implies the synergistic integration of resource management and sustainable design of rural space, which in essence explores the way of efficient utilization of various resources in the countryside under the support of an appropriate spatial system. Metabolic research is therefore more direct and closer to the essence. Metabolism research, which focuses on the flow process and efficiency of resource elements, is more direct and close to the essence perspective method, which can reveal the dynamic change mechanism of rural settlements from a deeper level. The eco-village constructions developed in Europe and the United States since the 1970s can be regarded as the initial practice of combining the rural habitat with resource metabolism, and their distinctive feature is that a large number of cash crops have been planted in the countryside to act as greening, which is organically integrated with passive solar energy, a good walking environment, and natural drainage to form a complete ecosystem [13]. With the popularization and application of eco-agriculture in China's rural areas in the 1980s, Chinese scholars in the field of agricultural economics paid early attention to the energy flow and material cycle of rural ecosystems, laying a theoretical foundation for the application of resource metabolism analysis to the study of rural spatial problems [14]. For example, Wombach pointed out that eco-villages should make full use of natural resources within their spatial boundaries, accelerating material circulation and energy transformation, so as to realize simultaneous improvement in eco-agriculture and the living environment of human beings [15]. Some scholars have summarized the four models, construction principles, and technical components of eco-village construction in China [16], or the construction of an eco-village resource metabolism technology system containing energy, nutrient, and water cycles based on the principles of ecology, with agricultural production as the core [17]. The theory of resource metabolism has been applied to the study of rural human settlement space, but so far, there is a lack of systematic quantitative research methodology and effective application at the level of rural settlements with small scales.

Based on the above considerations, this study used resource cycle metabolism as an entry point. By integrating theoretical studies on resource metabolism with practical cases of urban and rural settlements, it explores the metabolic flow processes of resource elements such as water, energy, food, and waste in rural settlements in the plain area of Shandong Province. Additionally, it examines the interaction and integration characteristics of spatial form elements at three scales, courtyards, neighborhoods, and villages within rural settlement systems, from the bottom up. By combining appropriate resource utilization technologies and their basic resource metabolism data, this study set a resource metabolism target scenario of "complete organic waste elimination". This study then constructed a multi-scale resource metabolism flow model and spatial morphology model, proposing a spatial optimization strategy for rural settlements accordingly. The results and conclusions of this study strengthen the role of resource optimization in adjusting and guiding the spatial structure of rural settlements in China. They hold theoretical significance and practical value in promoting the integrated development of urban and rural areas, while broadening the concepts of rural construction design.

2. Overview of the Concept of Resource Metabolism in Rural Areas

Resource metabolism, originating from the biological term "metabolism", encompasses both "material metabolism" and "energy metabolism" [18]. The concept of resource metabolism in rural areas is predicated on the premise that a village functions as the boundary of the system. This includes the flow, accumulation, transformation, and other input and output processes related to the primary resources within the production and living systems of the area. Rural settlements can be conceptualized as human habitat spatial units with a fully integrated resource metabolism mechanism. In the early development of the field, resource metabolism was predominantly studied within urban contexts. American ecologist Abel Wolman initially introduced the concept of "urban metabolism", which integrates the flow processes of resource metabolism with the spatial elements of human settlements [1]. Currently, the theory of resource metabolism encompasses all scales, ranging from macro urban agglomerations to micro urban and rural settlements. Through interdisciplinary exploration, research on resource metabolism has developed a range of relatively mature analytical methods. Notably, the quantitative analysis method represented by material flow analysis (MFA), which quantifies mass fluxes of resource storage and flow conditions, has been employed to analyze the intrinsic characteristics and operational mechanisms of various resource flows within spatial systems and to elucidate the interactions between resource flows and the environment at specific locations. This approach elucidates the interactive relationship between resource flows and the environment at specific locations, facilitating the rational allocation and optimization of spatial resources. Such insights are significant for developing spatial construction strategies and methods for rural settlements aimed at the efficient utilization of resources.

The comprehensive recycling of resources has long embodied traditional ecological wisdom and remains a core concept in rural China. This principle aligns with the concepts and methods of urban resource metabolism applied in rural areas. Since the era of agrarian society in China, rural villagers have engaged in resource recycling and intensive land use within the framework of a self-sufficient small farm economic model. They have leveraged limited technology and space to develop various sustainable practices, including courtyard economy, household biogas production, and four-in-one facility agriculture. Numerous examples of eco-village construction have emerged, with Beijing’s Illumining Village serving as a prominent representative. These villages have collectively amassed a wealth of invaluable experience [19]. From the perspective of resource elements and spatial composition, the configuration of rural settlements is more conducive to constructing an ideal resource metabolism and spatial modelling in rural areas. Firstly, the metabolic processes in rural areas are characterized by a comprehensive range of resource elements, a relatively straightforward spatial hierarchy, and a small scale. The agricultural space, forming the core link in the ago-ecological system, is capable of fulfilling multiple functions, including food production and the consumption and transformation of biomass resources. Furthermore, the metabolic processes in rural areas are based on three fundamental elements of resource metabolism: production, life, and ecology. Additionally, a complete cyclic path is in place, making it relatively straightforward to establish a resource production and utilization mode of “local resource recycling”. Conversely, the spatial elements within the settlement are highly integrated, with production, living, and ecological spaces permeating and integrating with each other, and their boundaries are less defined. The spaces dedicated to agricultural production, water resource treatment, and human life are multifaceted and complex, making them more conducive to the integrated metabolic function of various resource elements in a complementary and symbiotic manner (Figure 1) [20].

Fruit and vegetable planting in front of village houses as a public productive landscape.

A lotus root planting pool with rainwater collection and purification functions is used as the village public space.

Figure 1. Integration of production and living space in rural residential areas.

3. Characteristics of the Interaction between Resource Metabolism in Rural Settlements and Spatial Elements

The layout of rural settlements is characterized by small and dispersed sites, complicating the direct application of traditional centralized spatial construction and infrastructure layout models to rural spaces. Findings from related research, exemplified by urban metabolism and agricultural resource management, have established a hierarchical recycling model of multiple resource mixing and a bottom–up distributed spatial operation method in terms of both technology and space [21]. These findings can effectively inform the study of resource metabolism characteristics in rural areas, the integration of spatial elements, and the rational allocation of spatial resources, in a manner closely aligned with the characteristics of agricultural resource utilization.

3.1. Spatial Layout Based on Resource Complementarity

The relative positioning of spatial elements in rural settlements necessitates comprehensive consideration of the economic and physical properties of resource elements. Enhanced spatial proximity of relevant functional facilities can ensure resource utilization efficiency and foster collaborative sharing [22]. Given the relatively loose and flat spatial characteristics of villages and the abundance of biomass resources, the distributed integration of resource treatment technology facilities with the spatial distribution of various living and production functions can reduce resource transmission and distribution losses. For example, biogas production facilities can be situated near courtyards and greenhouse planting facilities that require biogas. Small greenhouses and water resource collection systems can be integrated with courtyards, while solar water-heating devices can be installed on the sloping roofs of village buildings to provide domestic hot water or house heating. These arrangements enable the production, use, and recycling of resources in close proximity to the village, leveraging spatial proximity.

3.2. Bottom–Up Cascading Metabolic Flow of Resources

Resource metabolism in rural settlements operates at three spatial levels, the courtyard, the neighborhood, and the village, each of which can be structured to incorporate social, energy, food, and organic waste elements [23]. Interventions starting at the courtyard level are suitable for integrating resource utilization technologies, facilities, and spatial form elements. A bottom–up progressive approach allows resources that are not fully metabolized at lower levels to be transferred upward for recycling. This iterative process effectively reduces resource depletion, improves utilization efficiency, and ultimately controls and reduces the waste exported outside of a settlement system (Figure 2).

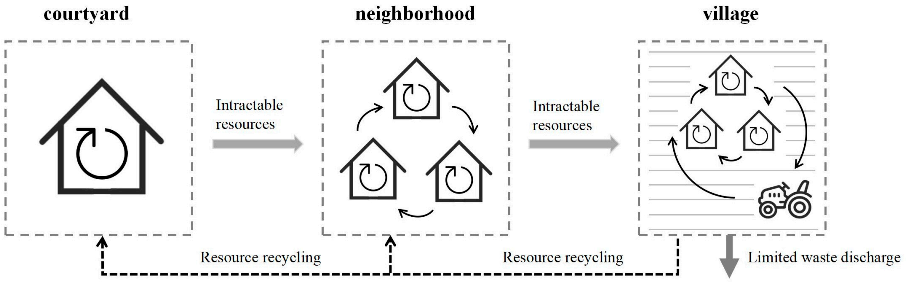


Figure 2. Bottom–up rural space optimization method.

3.3. Integration of Resource Metabolism Technology and Spatial Element Distribution

The distributed integration of appropriate resource utilization technologies and facilities with the spatial elements of rural settlements can facilitate resource recycling and preserve the rural landscape. This approach effectively reduces the input of manpower and material resources, and it better adapts to the decentralized and flat spatial layout of villages [24]. Some scholars have proposed strategies for optimizing the functional spatial layout of courtyards based on the “four-in-one” courtyard ecosystem operation model, which integrates biogas production and use [25]. A practical example is the Schoonschip design in Amsterdam, the Netherlands, which integrates a wide range of resource recycling technology facilities with small-scale grouped living spaces (Figure 3) [26]. Another example, the reconstruction project of Jintai Village in Sichuan, designed by Kenneth Lam of the University of Hong Kong, integrates various resource recycling technologies and facilities, such as livestock farming, rainwater collection, biogas production and use, and plant-based water purification systems, at the village unit and neighborhood levels. This project created a rural community space with efficient resource metabolism [27] (Figure 4).

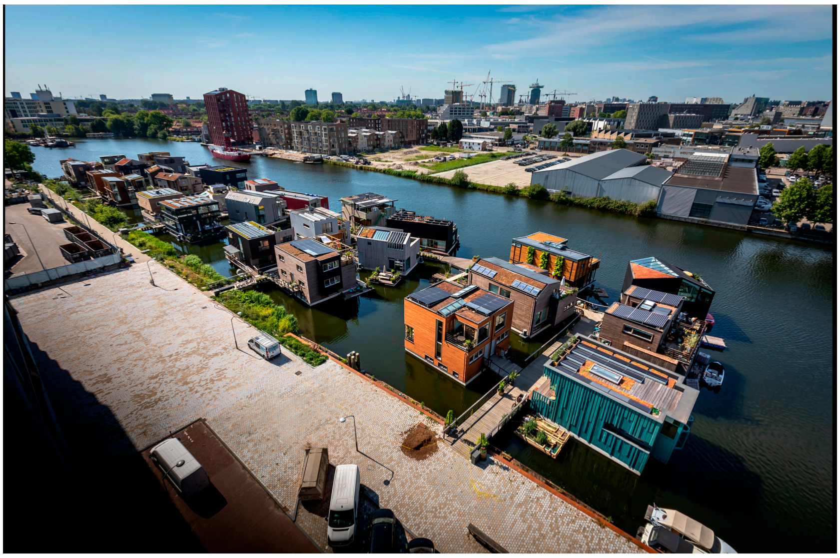


Figure 3. Schoonschip ecological community in the Netherlands (available online at: https://schoonschipamsterdam.org/en/) accessed on 1 May 2024.

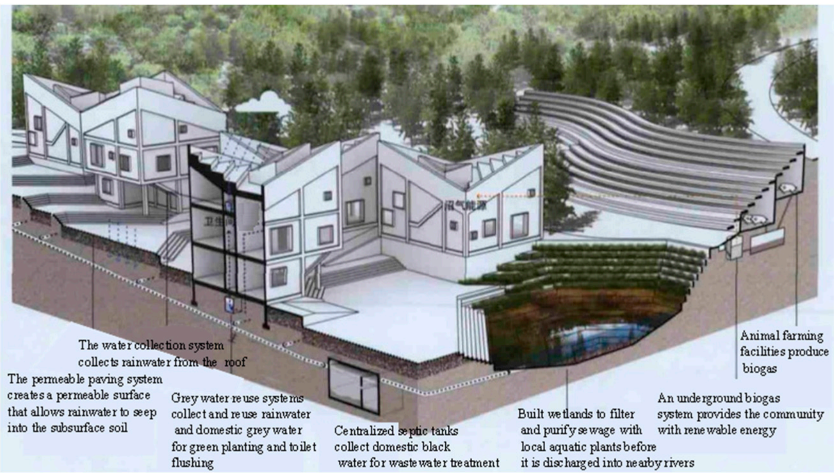


Figure 4. Resource metabolism system of spatial integration between Jintai Village and its neighbors in Sichuan Province (available online at: https://www.archdaily.cn/) accessed on 30 May 2024.

4. Research on the Methodology of Resource Metabolism Modelling

On the basis of elucidating the flow law of resource metabolism in rural settlements and its interaction with spatial patterns, resource metabolism in rural areas can be modelled based on the interdependence of resource elements and their quantitative flow dynamics, combined with the target state of resource metabolism in rural areas. The construction method of resource metabolism models has evolved from qualitative models based on the optimization of resource metabolism pathways to quantitative models grounded in the quantitative flow of resource metabolism accounting and spatial occupation.

Research on model construction based on quantitative resource flow metabolism accounting involves the quantitative analysis of the equilibrium-rationing relationship between the demand and supply of various types of resources at different process stages within a system, combined with the visualization of resource metabolism flow charts, to achieve quantitative model construction. Liu Changan constructed the resource metabolism model of an "agricultural community", based on rural production and nutrient metabolism, optimizing and improving the resource cycle system of the associated production and living space at the scale of an urban community [28]. Some scholars have employed the system dynamics method to establish a resource metabolism model for eco-villages under the zero-waste paradigm by measuring the quantitative correspondence between resource consumption and spatial occupation, based on the "3R" principles of resource reduction, reuse, and recycling (Figure 5) [29].

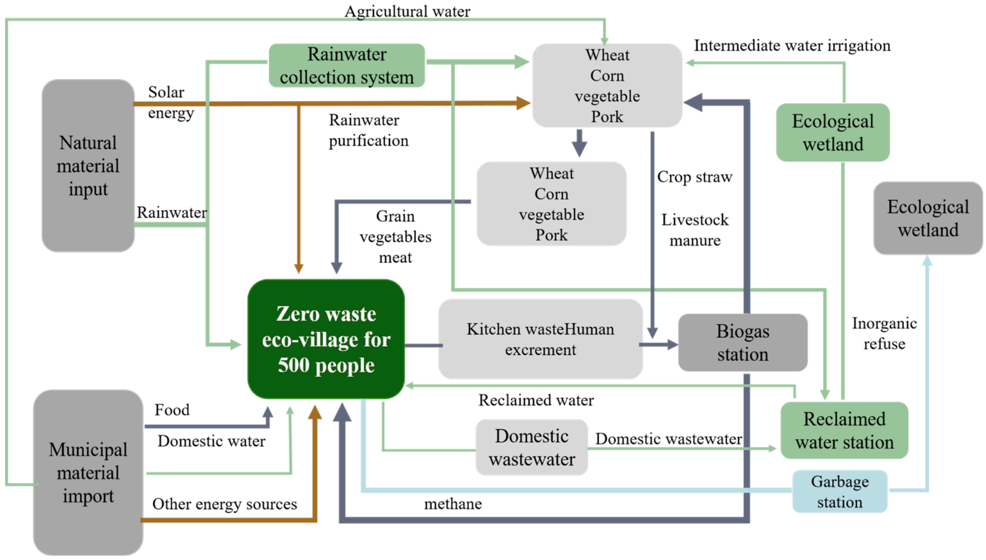


Figure 5. Resource metabolism modelling for "zero-waste" eco-villages.

Research on the construction of spatial occupancy models based on the quantitative metabolic flow of resources involves measuring and establishing a quantitative model of a functional spatial land use scale to achieve balanced resource metabolism rationing, grounded in the analysis of the resource demand, transformation, and output of relevant spatial elements. For example, Edward Yiu of the Chinese University of Hong Kong, through quantitative calculations of the cyclic metabolism of energy, water, food, and organic waste, demonstrated that 40 hectares of land were required to satisfy the food demand of 10,000 people in a zero-waste community. He established a novel planning model aimed at creating a zero-food and zero-organic waste community (ZFW community) [30]. In the Synergy between Regional Planning and Exergy (SREX) Project, Wageningen University in the Netherlands introduced the concept of "Urban Tissue", which is based on the utilization of energy and water resources. The "Urban Tissue" concept uses a 1-hectare land area (100 m × 100 m) as a proposed spatial unit. Its goal is to achieve a closed cycle of resources, using per capita resource consumption and waste emissions as basic data. This concept determines various types of functional space and land area indicators to construct a metabolic spatial model of the urban functional unit [31] (Figure 6). At the scale of rural settlements, the Netherlands' "Regen Village" project, based on the concept of resource metabolism, integrated community size with the per capita consumption of major resources. This project established a small ecological community resource metabolism model covering an area of 15,500 m^2 to meet the basic living needs of 60 residents, by combining appropriate functional space layouts and technical facilities for resource use. Japanese scholars, such as Takeuchi, regard rural space as an area capable of self-sufficiency. By combining the characteristics of rural resources with the flow of urban and rural factors and considering the distance from urban areas, they constructed three types of ecological rural spatial models: suburban villages, peri-urban villages, and natural villages, each with a self-cycling resource metabolism mechanism [32] (Figure 7).

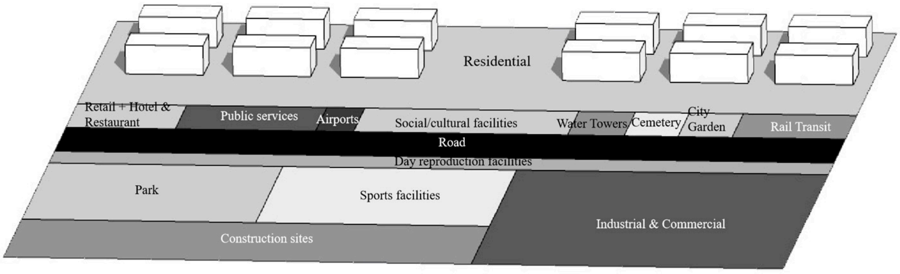


Figure 6. Conversion of quantitative metabolic values for resource metabolism balancing categories in the "Urban Functional Unit" into land area indicators.

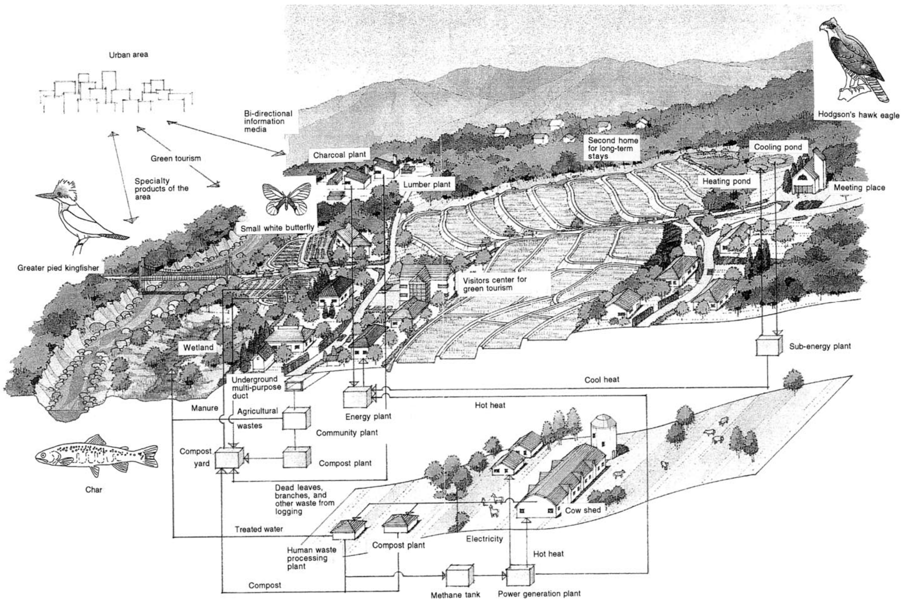


Figure 7. A spatial model of a Japanese eco-village based on the concept of in situ recycling of resources (source from: reference [16]).

5. Modelling of Resource Metabolism in Rural Settlements in the Shandong Plain Area

5.1. Characteristics of the Habitat Environment and Current Status of Resource Utilization in the Shandong Plain Region

The plain terrain of Shandong Province comprises approximately 55% of the province's total land area [33]. Additionally, the number of villages, the size of the agricultural population, and the economic volume in these plain areas are proportionally higher [34]. These settlements, representing the quintessential rural habitat of Shandong, are characterized by relatively complete infrastructure and public service facilities. They are anticipated to survive and develop over the long term and thus are a central focus of both current and future rural development efforts in Shandong. Although the villages in Shandong's plain areas have a relatively plain character, they benefit from convenient transportation and location. This proximity fosters closer interactions with urban areas in terms of economy, population, space, and resources. Consequently, these villages are more susceptible to urban influences, exacerbating the conflict between human settlement development and resource utilization [35]. Combined with a large number of case field studies in plain villages, a large amount of basic information looking into ways of utilizing the four types of resources associated with the living and production systems, namely water, organic waste, energy, and agriculture, has been collected (Figure 8), which mainly contained the following characteristics.

Lotus root cultivation in ecologically stabilized ponds (Zhuyuanzi Village).

Abandoned biogas digester used as rainwater harvesting tank (Hongmen Village).

Vertical farming-based water resource utilization (Shakkan Village, Mu Feng Lan Gui Agricultural Cooperative).

Photovoltaic energy for Village House Roofs (Huangtuzhuang, Gaogai Village).

Centralized biogas station (Shangbo village).

Organic waste consumption by yard poultry farming (Huangtuzhuang).

Rural landscape with planting and raising (Hongmen Village).

Open field used as an open-air vegetable garden (Xidan Village).

Planting space in conjunction with the village (Huangtuzhuang).

Fruit and vegetable planting as an alternative to conventional greening (Wanglou Village).

Figure 8. Types of resource metabolism in research cases.

With regard to water resource utilization, the penetration of piped water facilities in rural Shandong Province has achieved 97% coverage [36], Nonetheless, numerous farmers continue to rely on personal or communal wells due to the costs associated with piped water. Furthermore, sewage collection and treatment are predominantly managed by small-scale centralized facilities. In some villages, ecological sewage treatment is integrated with landscaping and agricultural practices; however, overall water use remains relatively unsophisticated, with insufficient recycling and tiered utilization. Regarding organic waste treatment, plain villages are abundant in biomass resources. Most villages have implemented on-site resource utilization strategies, converting agricultural organic waste into straw biogas or biomass fuels, thereby enhancing the connection between production and living systems. However, the sorting and recycling rates of domestic organic waste remain inadequate. Concerning energy use (heat and electricity), with the exception of a few peri-urban villages employing centralized heating systems, most villages depend primarily on ambient heat or electricity for winter heating. Additionally, some villages utilize centralized biogas stations or small household digesters for biogas production for cooking purposes. Distributed solar photovoltaic and solar thermal systems, integrating with the roofs of village houses and unused land, are increasingly prevalent. Regarding agricultural production, traditional large-field cultivation, greenhouse planting, and large-scale farming are predominant methods in plain villages. Continuous greenhouses have emerged as prominent features in the rural landscape on the periphery of some villages. These practices utilize both courtyard areas and previously underutilized vacant land for small-scale "production and residence integration" farming methods, thereby contributing to a distinctive productive landscape.

5.2. Resource Metabolism Spatial Modelling Path

To investigate the mechanism of resource metabolism in rural settlements, it was imperative to examine both resource and spatial elements comprehensively. Resource metabolism in rural areas begins with fundamental material elements that sustain the normal function of the rural environment. It involves analyzing the mechanisms of nutrient, water, and energy cycles within the community, with particular emphasis on the nutrient cycle, which focuses primarily on food production and the cyclic metabolism of organic waste [37]. The resource elements addressed in this study, excluding inorganic waste (e.g., solid waste and old building material) that are challenging to recycle effectively within the spatial and technological constraints of villages, encompass four primary categories: water, energy (both electrical and thermal), food (agricultural production), and organic waste (nutrients). Regarding spatial elements, the typical rural spatial framework comprises four main categories: built-up elements (roads, courtyards, public buildings), natural environmental components (vegetation, water bodies), agricultural production elements (arable land, greenhouses), and infrastructural components (electric power transmission and distribution facilities, water and sewage systems). These elements are interwoven and integrated at various scales. The courtyard comprises the residence and its ancillary functional rooms, hardscaped areas, planted vegetable gardens, small greenhouses or livestock spaces, integrated solar photovoltaic and solar thermal facilities on roofs, walls, or underground, rainwater catchment areas, and organic waste collection ponds (septic tanks). The neighborhood extends beyond basic courtyard elements to include the road in front of residences, public spaces, and areas where resource metabolism can be integrated, such as agricultural greenhouses, open vegetable gardens, small ecological wetlands, breeding spaces, and underground biogas facilities. The village encompasses additional functional elements outside the courtyard, including rural public service buildings, large public open spaces, medium- to large-scale biogas and sewage treatment stations, agricultural land, extensive greenhouses, and various natural water bodies. Adhering to the principle of achieving balanced resource metabolism across varying spatial scales, this study approached the task from three hierarchical levels—the courtyard, neighborhood, and village. Following the framework of "resource metabolism data and spatial indicator calculation—resource metabolism scenario setting—balanced rationing model analysis—resource metabolism and spatial model construction", this study developed a comprehensive resource metabolism model and spatial morphology model incorporating agricultural production factors, ecological and technological facilities, and human living systems (Figure 9).

(1) Data Accounting

Data accounting encompasses both resource and spatial data related to resource metabolism in rural areas. Concerning resource metabolism data, basic information on the rural per capita or household consumption within the agricultural system, ecological facility system, and human living system was obtained from sources such as the China Statistical Yearbook, the Shandong Statistical Yearbook, and the China Household Energy Consumption Research Report. These data, covering the metabolic flow of four primary resource elements—water, food, energy, and organic waste—formed the foundational basis for constructing the resource metabolism model. By integrating spatial occupancy data for open land and greenhouses used in the production of major crops and livestock under the typical environmental and climatic conditions of the Shandong Plain, along with spatial data for land or buildings equipped with appropriate resource processing technologies, the basic spatial data indices for resource metabolism in rural areas were established.

(2) Situation Setting

Compared to the resource metabolism in urban areas, which primarily involves a unidirectional input of resources, plain-type rural settlements generally function as resource output systems due to their agricultural production roles. In these settlements, the volume of agricultural output typically exceeds the consumption levels within the villages (considering only the essential food requirements of residents and livestock). Therefore, addressing the villages' self-sustaining development needs and habitat remediation goals—focusing on the utilization of organic waste resources—and considering the village development model and spatial resource needs required the establishment of different resource metabolism scenarios. This included evaluating various types of resource metabolic flows, balanced ration data, quantitative resource flow, the degree of functional integration at different scales, resource self-sufficiency rates, and spatial element diversity.

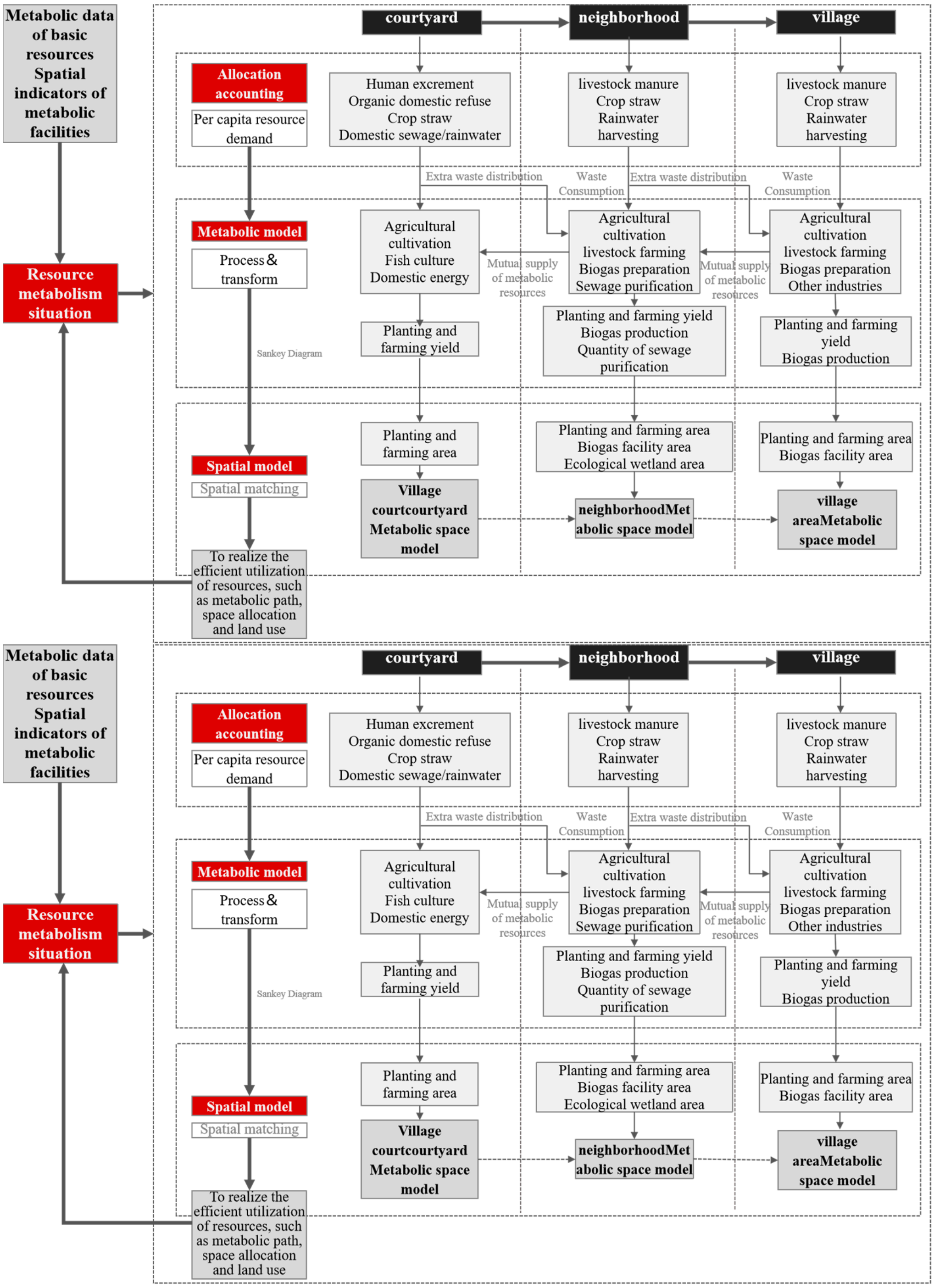


Figure 9. Resource metabolism in rural areas and spatial model construction ideas.

(3) Modelling

Quantitative Metabolic Analysis. By integrating the interaction characteristics of appropriate resource metabolism technologies and rural spatial elements, and utilizing resource metabolism quotas derived from human resource consumption data, this study performed a bottom–up analysis of resource metabolism objectives at three spatial scales—the courtyard, neighborhood, and village. This analysis considered the capacity of ecological technology systems (resource metabolism facilities) applicable to these scales. This study assessed the metabolic flow of major resources and their balanced quota relationships within and between different scales, employing Sankey diagrams for visualization. This balanced quota analysis helped determine resource flow statuses and established a model of resource metabolism in rural areas.

Spatial Modelling. Constructing a spatial model for rural resource metabolism required integrating the abstract resource metabolism model with the tangible spatial morphology of the village. This involved translating quantitative resource flow data at various scales into categorized spatial morphology indices which included relevant technological facilities. For example, this included the area occupied by photovoltaic installations on village roofs, road space used for domestic wastewater transmission, and courtyard or neighborhood open spaces allocated for small greenhouses. By converting quantitative resource indicators into spatial form indicators, this study could develop a spatial model that achieved balanced resource metabolism within the village boundaries (Figure 10).

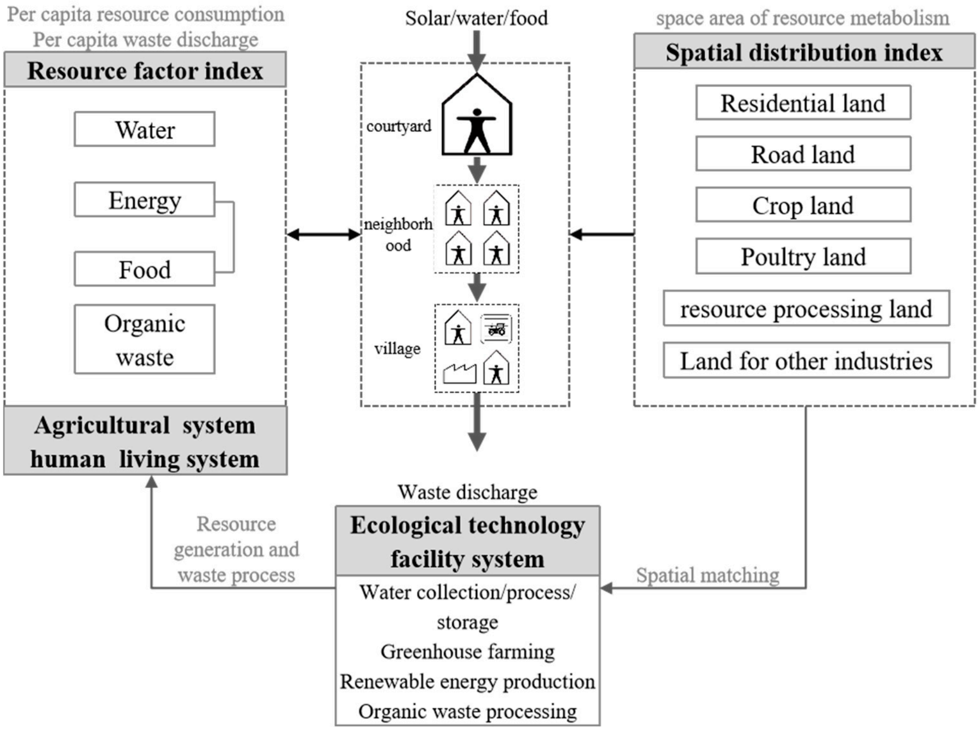


Figure 10. "Resource-space" rationing of rural human space.

5.3. Setting of Relevant Technical and Spatial Indicators for Resource Metabolism Systems in Rural Areas

The resource metabolism in the rural areas was quantitatively assessed with a focus on the needs of individuals, addressing their fundamental production, living, and ecological requirements. The analysis categorized resource metabolism into three subsystems: the human living system, the agricultural production system, and the ecological and technological system. This assessment was informed by data from statistical yearbooks of China and Shandong Province, along with the relevant literature [38,39]. Basic consumption data for the four primary resources—water, energy (both thermal and electrical), food (planting and breeding), and organic waste—were compiled separately. Additionally, data on the production and conversion of resources through agricultural and ecological technologies (such as biogas production, solar photovoltaic systems, and ecological sewage treatment) were integrated to achieve balanced resource rationing. This approach provided the foundation for constructing robust resource metabolism models.

5.3.1. Basic Data on the Resource Elements of the Three Living Systems

Given that this study aimed to achieve metabolic spatial modelling through quantitative resource metabolism analysis, the focus of data screening was not on pursuing exact precision but on establishing the reasonable availability of data. According to the 2021 Shandong Statistical Yearbook, the average number of permanent residents in Shandong's rural areas was 3.1 per household. Consequently, resource consumption for courtyard households was calculated based on this average, and resource quantities such as those related to livestock breeding were adjusted in accordance with the general population of villages and the spatial scale of courtyard areas (Tables 1–3).

Table 1. Resource element ratios for human living systems.

Resource Type			**Use**	**Annual Resource Consumption per Capita**	**Average Annual Resource Consumption per Household (Calculated for 3.1 Persons)**	**Marginal Notes**
Resource input	Energy	Electric	Living electricity	714 kwh/yr	2213 kwh/yr	Included water for drinking, washing, cooking, etc.
		Heat	Cooking	106 m^3/yr (biogas)	317 m^3/yr (biogas)	
			Heating	61 kg/yr	184 kg/yr	
			Total amount of energy	135.06 kg/person/yr	405 kg/person/yr	
	Water		Domestic water use	24.6 m^3/yr	76 m^3/yr	Included water for drinking, washing, cooking, etc.
			Natural precipitation		114 m^3/household/yr	The average precipitation in Shandong was 710 mm/year, and the area of precipitation collection per household was calculated according to the average household's hard interface area of 160 square meters
	Food needs		Cereal consumption	168.4 kg/yr	522 kg/yr	Contained grains, potatoes, beans
			Meat consumption	27.4 kg/yr	85 kg/yr	Reference to the China Statistical Yearbook (2020) and China Food and Nutrition Development Program (2014–2020)
			Fish consumption	11.2 kg/yr	34.72 kg/yr	
			Vegetable consumption	140 kg/yr	434 kg/yr	
Resource output	Organic waste		Human excreta	164.25 kg/yr	509 kg/yr	
			Domestic sewage	21.4 m^3/yr	66 m^3/yr	
			Organic waste	182.5 kg/yr	566 kg/yr	

Table 2. Resource factor rations for agricultural production systems.

Resource Type				Average Annual Resource Production	Average Household Resources	Volume of Resources for the Cluster	Volume of Resources in the Village Area	Notes
Resource input	Nutrients	Greenhouse		Biogas: 3.5 kg/m^2/yr Residue: 3 kg/m^2/yr	–	–	–	1. Priority was given to the use of rainwater harvesting for watering agricultural plantations, and any shortfalls were mainly imported from outside the system using municipal pipeline networks or river and lake water bodies 2. The use of greenhouse intensive cultivation on the roofs of village houses and public sites of neighboring groups could produce 12.69 kg/m^2/year (8452 kg/mu/yr) of vegetables per square meter of the rooftop greenhouse 3. Feeding cycles: 365 days for cattle and sheep, 180 days for pigs, 50 days for broilers 4. Needed to be measured in relation to specific acreage
		Open-air vegetable plots						
		Cropland		Biogas: 5000 kg/mu/yr Biogas: 3750 kg/mu/year				
	Food	Pigs		Digestate: 1460 kg/pc				
		Poultry		36.5 kg/pc				
Resource output	Food and vegetables	Greenhouse vegetables		8452 kg/mu	–	–	–	
		Open-air garden		3330 kg/mu				
		Cropland grains		416 kg/mu				
	Meats	Hog		70 kg/head	–	11 heads	–	
		Meat and poultry		3.5 kg/pc		13 pc		
		Cow		250 kg/pc		–	17 pc	
		Goats		20 kg/pc			186 pc	
	Caviar	Pond aquaculture		11.2 kg/yr	34.7 kg/household/yr	–	–	
	Organic waste	Pig manure		1930 kg	–	21,230 kg	-	
		Poultry manure		36.5 kg		475 kg		
		Cattle manure		9855 kg		–	167,535 kg	
		Sheep manure		865 kg			160,890 kg	
		Quantity of straw	Greenhouse vegetables	740 kg/mu (1.54 kg/m^2)			–	
			Open-air garden	633 kg/mu (0.95 kg/m^2)				
			Grains	376 kg/mi				

Table 3. Eco-technology system resource element rations.

Resource Type	Use		Resource Handling Capacity	Appropriate Scale			Notes
				Courtyard	Neighborhood	Village	
Electricity	Solar photovoltaic installations		262.8 kwh/m^2/yr	●	●	●	1. Based on an average of 6 h of effective light per day 2. Rooftop greenhouses integrated with village buildings could transport some of the heat to the building interior 3. Processing 1 m^3 (tons) of domestic wastewater required an approximate footprint of 1.7–2 m^2 4. Treatment of 10,000 m^3 of sewage per day, with a treatment facility covering an area of approximately 17,900 square meters 5. According to the calculation of a 6 m^3 small-scale biogas digester, the annual gas production was about 288.72 m^3, and then the annual biogas production of the 1 m^3 biogas digester was 48.12 m^3 6. The biogas production of animal manure was 0.06 m^3/kg, the biogas production of domestic organic waste was 0.1 m^3/kg, and the biogas production of straw was 0.28 m^3/kg 7. A total of 1 m^3 biogas could produce 3.42 kg of digestate and 2.28 kg of digestate 8. Average annual consumption of organic waste per unit area of cultivation space
Heat energy	Solar thermal facilities		304 kwh/m^2/yr	●	●		
	Rooftop greenhouse		255 kwh/m^2/yr	●			
Sewage treatment	Small-scale artificial ecological wetland sewage treatment		2 m^2/m^3	○	●		
	Artificial sewage treatment plant		17,900 m^2 = 10,000 m^3 wastewater treatment capacity			●	
Organic waste treatment	Landfill gas	Household biogas facilities	48.12 m^3/yr		●		
		Medium and large biogas plants	418.75 m^3/m^3/yr			●	
	Plantation	Small-scale greenhouse cultivation	Organic waste 1.53 kg/m^2/ yrWastewater 2.92 m^3/m^2/yr	●	●		
		Open-air garden planting		●	●		

Clarification: ● indicates the optimal scale for a resource metabolism technology facility, ○ indicates a more appropriate scale.

5.3.2. Spatial Hierarchy of Rural Settlements and Indicator Setting

The balance quota accounting of the resource metabolism system, which involved tracking the flow of various resource elements at different scales within the village, had to be integrated with rural community planning and relevant technical specifications. This integration included setting spatial indicators for the three scales, the courtyard, neighborhood, and village, and defining their resource metabolism spatial layouts. This process provided a spatial operational basis for the subsequent transition from quantitative resource metabolism indicators to spatial morphology indicators of resource metabolism.

(1) Courtyard

Spatial indicator setting. According to the Technical Guidelines for the Construction of New Rural Communities in Shandong Province (for trial implementation), the land control indices for village settlements (Table 4) indicated that the average residential land area in the plain regions was 200 m^2 per household. Combining this with the 2021 statistical data showing an average per capita residential floor area of 43.41 m^2 for rural residents in Shandong Province, the average household floor area was approximately 135 m^2. This figure was used as the minimum spatial index for the village building model [40]. Regarding basic spatial form control, current regulations stipulate that rural settlements should feature 2–3-story low-rise townhouses and multi-story residential units not exceeding six stories. Considering the traditional rural landscape, which primarily consists of low-rise buildings, the proposed model for courtyard spaces utilizes low-rise townhouses as the fundamental residential units. The architectural design combines flat and sloping roofs, with flat roofs for the south-facing main houses and sloping roofs for the main rooms facing south. Auxiliary rooms on the east and west have flat roofs. This design reflects the traditional architectural style of Shandong Province's plains while accommodating ecological and technological facilities, such as solar photovoltaic panels and small greenhouses. The integration of these elements with courtyard walls creates an open space suitable for family activities, outdoor vegetable gardens, family farming, and resource metabolism facilities like rainwater collection.

Table 4. Spatial indicators for courtyards (basic spatial units).

Type of Village	Households per Capita Homestead	Average Household Floor Area	Story	Plot Ratio
Plain-type villages	$\leq$200 m^2	135 square meters	2–3 floors	$\geq$0.3

Note: This indicator was calculated on the basis of the land control indicators for the construction of village settlements in the Technical Guidelines for the Construction of New Rural Communities in Shandong Province (for trial implementation), combined with the data from the Statistical Bulletin on National Economic and Social Development of Shandong Province in 2022.

Space Usage Settings. Based on the aforementioned spatial control indices and the morphological characteristics of low-rise courtyards and physical buildings in the Shandong Plain, the spatial allocation and area index range for resource metabolism in rural courtyards were established. To meet basic access requirements, a small rooftop greenhouse, approximately 24 m^2 in area, was installed on the roofs of the east and west rooms on the first floor. An open vegetable garden, not exceeding 30 m^2, and a pond (fish pond), not exceeding 8 m^2, were positioned in the adjacent open space. Additionally, solar photovoltaic or solar thermal panels were installed on the south side of the sloping roof of the main house, sized according to the energy needs for living and production. These spatial and quantitative indices for various resource metabolism facilities are outlined, with specific ranges to be refined through subsequent metabolism accounting under different resource metabolism scenarios. The greenhouse planting and open vegetable gardens were designed to be adaptable and replaceable (Figures 11 and 12).

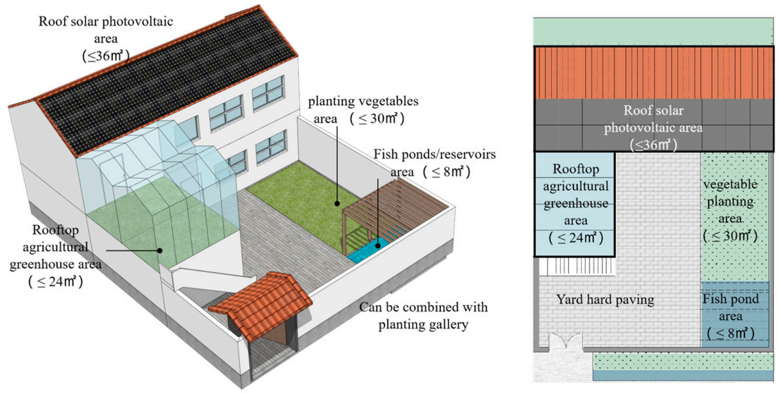
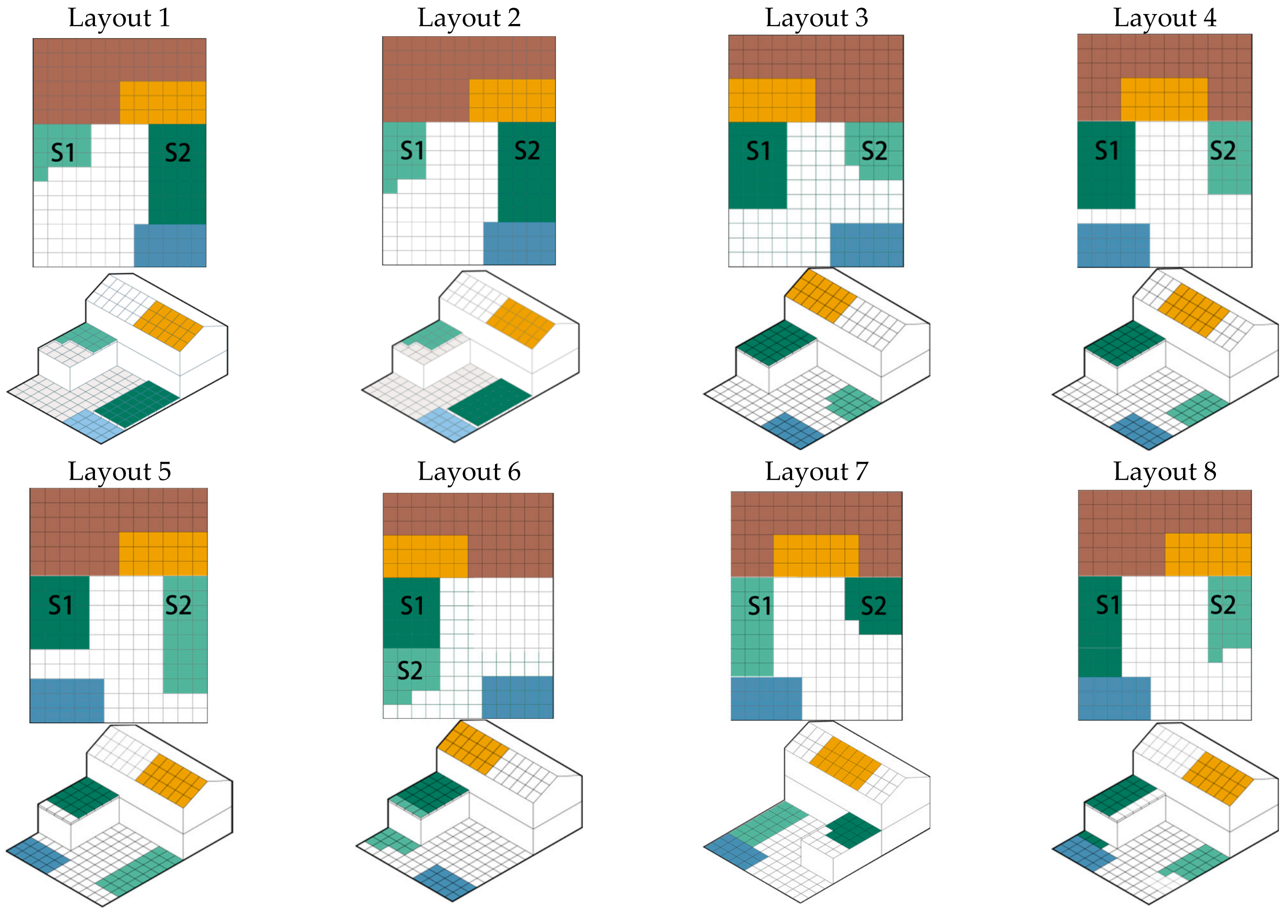


Figure 11. Basic model of the courtyard and setting of the spatial use model.



Description: 200 m² (16 m × 12.5 m) of residential area, 135 m² of building area of village house, S1 is greenhouse planting combined with the roof of the village house, S2 is the ground vegetable garden in the courtyard, yellow is solar photovoltaic and solar thermal panels combined with the south-facing sloped roof, and blue is the water-collecting fish pond in the courtyard.

Figure 12. Schematic layout of the courtyard to realize the balance of resource metabolism.

(2) Neighborhood

Spatial Indicator Setting. Neighborhoods in rural settlements are medium-scale spatial aggregates comprising multiple courtyards, public spaces, and community facilities. These clusters serve as crucial links between individual courtyards and the broader spatial-scale resource metabolism. The number of courtyards within a neighborhood must be evaluated from both technical and social perspectives. Technically, the use of "household biogas" systems for balancing resource production and consumption provides a key basis for determining the appropriate scale of neighborhoods. By integrating technology and spatial considerations, and minimizing the distance for biomass resource transfer, the total amount of organic waste input and biogas output could be calculated to estimate the number of courtyards within a cluster. Practical examples and feedback from research supported this approach: for instance, 32 households in Jiangfang Xincun, Yongyang townships shared a biogas digester and an 8 m^3 storage tank; seven households in Longpi Village shared a 10 m^3 digester; and eight households in the EVA-Lanxmeer settlement in the Netherlands had a biogas production unit for every eight households [41]. Additionally, considering the social dynamics of "acquaintance societies", where neighborly interaction and a sense of community are significant, research indicates that residential clusters of 8–12 households foster a positive social atmosphere [42,43]. Thus, balancing both technical and social factors, the recommended number of courtyards in a neighborhood was set at 10 (Figure 13).

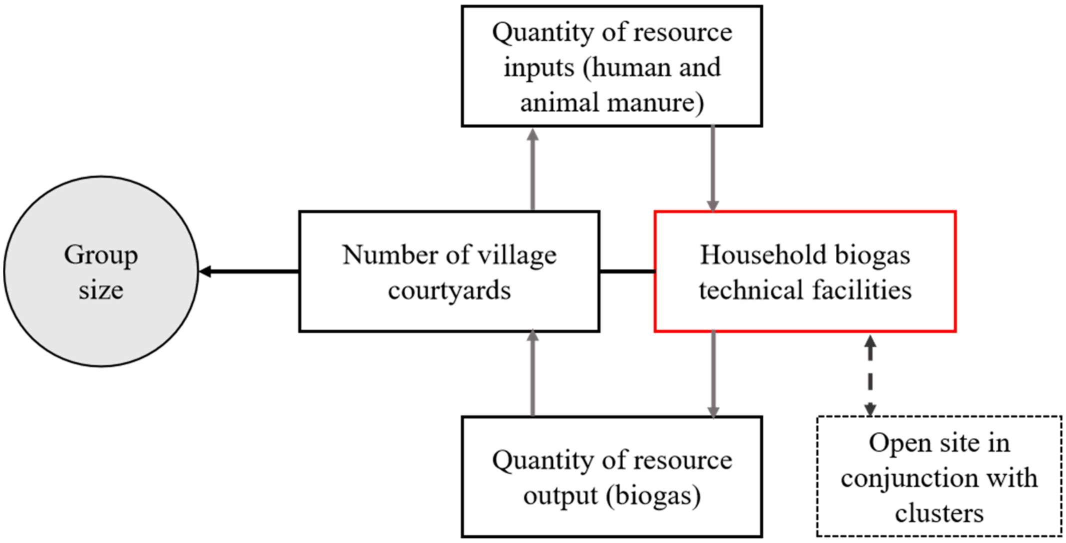


Figure 13. Flow chart outlining the determination of neighborhood sizes.

Space Use Mode Setting. Taking as an example the proposed enclosed neighborhood composed of 10 courtyards, the spatial components included two main categories: courtyards and neighborhood open spaces. Besides the road interface, which was dedicated to precipitation collection, the remaining areas between the courtyard walls and the road, as well as the open spaces (primarily unused vacant or residential land), could be utilized for various purposes. These included vegetable gardens, greenhouses, livestock breeding (such as pigs and poultry), and small-scale artificial wetlands integrated with hydroponics and vegetable cultivation (encompassing water transfer and distribution ditches, anaerobic ponds, regulating ponds, ecological oxidation ponds, and other components). The spatial indices for resource metabolism, excluding the road (which covered approximately 10–15% of the total area) and the roadside productive greenery (around 235 m^2), should be precisely determined based on the specific metabolic targets for each resource through rationing calculations (Figure 14). Additionally, for the 10 courtyards and public open spaces, different combinations of organic waste metabolism technologies should be integrated. Depending on the current situation, these spaces can be fully occupied and utilized for various scales and types of unused open areas, leading to different layout patterns such as enclosing groups, rows, and columns, to accommodate or develop diverse village morphologies (Figure 15).

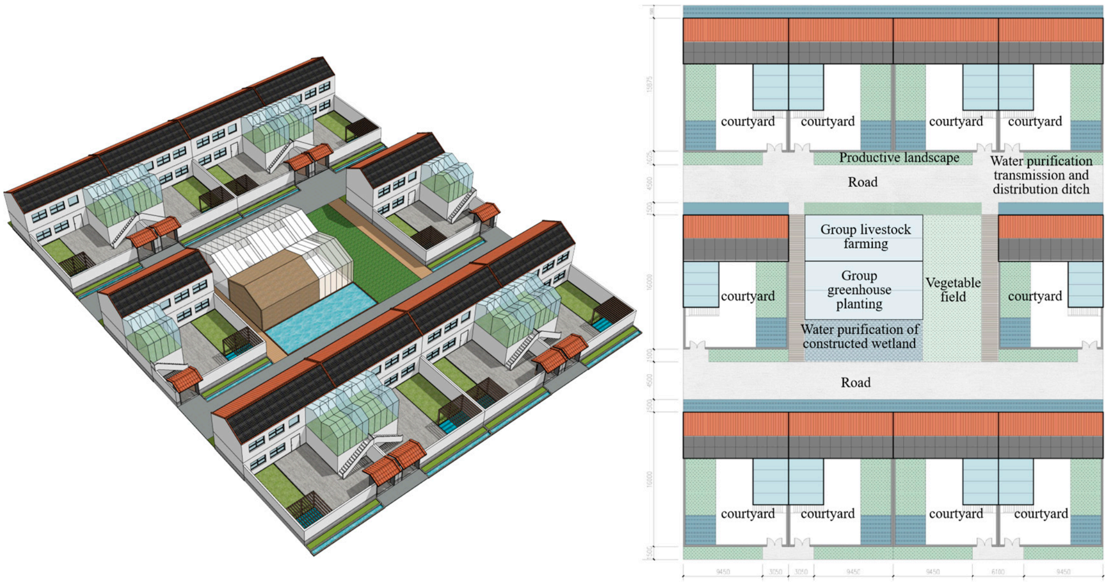


Figure 14. Basic layout setting for a neighborhood space.

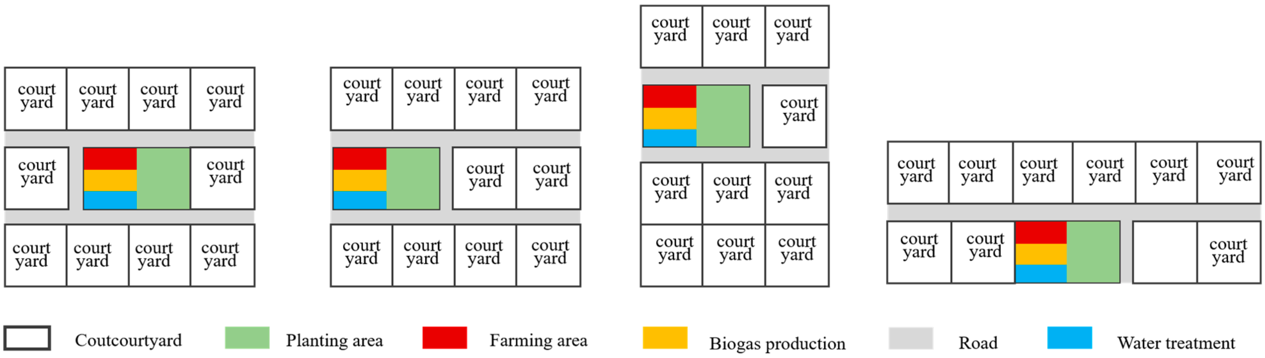


Figure 15. Schematic illustration of the metabolic spatial layout approach for neighborhoods.

(3) Whole Village

Area Allocation of Spatial Elements. To facilitate the measurement of overall resource metabolism within a village, it was essential to determine the village size and land use indicators. The village scale was based on population or household numbers. Using data from Shandong Province, where the average village population was 530 and the average household size was 3.1 in 2020, it was estimated that each village had approximately 170 courtyards. With a basic residential land area of 200 m^2 per household, the total residential land area amounted to about 34,000 m^2. Given the per capita arable land in Shandong Province was approximately 1.21 mu (3.75 mu per household), the total agricultural land within the village was estimated to be around 638 mu (424,575 m^2). Dividing the village into groups of 10 households each resulted in 17 neighborhood spaces. Public buildings and green spaces should accommodate centralized resource metabolism functions, while other spaces should be allocated based on quantitative resource metabolism accounting results.

5.4. Resource Metabolism Modelling and Spatial Modelling in Rural Settlements—Based on the "Organic Waste Self-Consumption" Situation

The study of the resource metabolism in the rural settlements within the Shandong Plain was based on the fundamental data of resource metabolism and considered the current production, living conditions, and resource utilization in these areas. This study established a resource metabolism scenario focused on "organic waste self-consumption", integrating this with the concepts of resource metabolism and the "Production-Living-Ecology" framework. This scenario allowed for the analysis of resource metabolism flows and the calculation of balanced quantities within the village. By incorporating these concepts, this study analyzed resource metabolism flows and balanced rationing. Subsequently, this study constructed a resource metabolism model and a spatial pattern model from the ground up to optimize and enhance the resource metabolism system in rural settlements, improving its integration with spatial elements.

The framework of "organic waste self-consumption" in resource metabolism was established, ensuring that while meeting the fundamental food needs of the village population and livestock, organic waste such as sewage, feces, and straw generated from human, livestock, and agricultural activities was systematically utilized. This approach addresses the primary issues concerning the ecological improvement in rural environments today. This approach tackles critical issues in rural ecological enhancement, encompassing sewage management and local organic waste resource utilization. It is crucial to note that the aim of resource metabolism equilibrium is to maximize the metabolic cycle and self-sufficiency of resource elements within a system. However, this does not imply a completely closed-loop metabolic system without external inputs. Firstly, the rural resource metabolic system requires the continuous external input of solar energy and water resources, including municipal water sources and natural precipitation, as solar energy is essential for all metabolic activities. Secondly, energy self-sufficiency does not imply 100% self-production and consumption but aims for a quantitative balance between energy production and utilization within the system. Lastly, the fertilizers and elements needed for crop production cannot be entirely self-sufficient and must be supplemented externally.

5.4.1. Accounting for the Resource Metabolism Base Allocation

Basic Resource Requirements: Using the smallest spatial unit—a courtyard with an average of 3.1 persons per household—as the base parameter for resource consumption, Table 5 illustrates the annual consumption of major food and water resources and the production of organic waste at the courtyard (3.1 persons), neighborhood (31 persons), and village (530 persons) scales. The resource metabolism capacities and spatial elements at these three scales, along with appropriate resource metabolism technologies, varied. Consequently, the organic waste produced was not directly proportional across scales. For example, in courtyards, organic waste primarily consisted of human feces, domestic organic waste, domestic sewage, and planting organic waste. Small greenhouses, open-air vegetable gardens, and fish farming ponds could consume some of this waste. At the neighborhood scale, additional fecal organic waste from pig and poultry farming was managed, utilizing household biogas tanks and small-scale artificial ecological wetlands to process animal organic waste, domestic sewage, and rainwater. At the village scale, organic waste increased due to the large-scale breeding of cows and sheep, necessitating medium- and large-sized biogas stations for centralized digestion and treatment.

Table 5. Biomass resource base to be consumed (annual average).

Scale Levels	**Human and Animal Waste**			**Domestic Organic Waste**	**Water**		**Crop Straw**	**Notes**
	Human	**Pig + Poultry**	**Cow + Sheep**		**Domestic Sewage**	**Rainwater**		
Courtyard	509 kg	–	–	566 kg	66 m^3	114 m^3	Calculated on the basis of crops that consumed organic waste	Courtyard:neighborhood:village = 3.1:31:530
Neighborhood	5090 kg	21,705 kg	–	5660 kg	660 m^3	345 m^3		
Village	86,530 kg	–	134,228 kg	96,220 kg	–	–		

5.4.2. Resource Metabolism Modelling

Effective organic waste metabolism and consumption require appropriate transformation and utilization of various biomass resources, following the spatial hierarchy of "courtyard-neighborhood-village" from the bottom up. According to the spatial hierarchy of "courtyard-neighborhood-village" and the principle of "integrating production and life, metabolizing and consuming locally", it was essential to measure the resources required for metabolizing and transforming organic waste at the courtyard scale, along with the spatial indices of various productive spaces and appropriate resource metabolism technologies.

(1) Courtyard

Courtyard space primarily functions for water storage and managing the output of human excreta and organic waste, which is then transported and distributed to neighborhoods. A total of 114 m^3 of collected rainwater directly supplemented fish pond water, followed by the irrigation for fruits and vegetables in courtyards, with any shortfall made up by municipal pipeline water. Based on a 10-day water exchange frequency for fish farming, an ideal pond area of 6.3 m^2 (with a depth of 0.5 m) could meet the annual demand of 34.7 kg of fish per household. Considering gradient utilization and odor issues, 509 kg of human excreta and 566 kg of domestic organic waste were transferred to neighborhood-scale household biogas facilities for oxidative fermentation, generating 87.14 m^3 of biogas for village cooking energy (fecal biogas: 0.06 m^3/kg × 509 kg = 30.54 m^3; domestic organic waste biogas: 0.1 m^3/kg × 566 kg = 56.6 m^3). This process also produced 198.7 kg of methane and 298 kg of digestate, prioritized for fish farming and crop cultivation. Integrating the courtyard space, fish farming required 35 kg/year of methane liquid. The courtyard could support 24 m^2 of rooftop greenhouse and 30 m^2 of an open-air vegetable garden, needing 3.5 kg/m^2/year of methane liquid and 3 kg/m^2/year of methane residue. Methane liquid was fully utilized for fish farming and garden planting, with some residues used for planting. The remaining 276 kg of residues were exported to the neighboring group space. A 24 m^2 rooftop greenhouse could produce 305 kg of vegetables annually (12.7 kg/m^2 × 24 m^2). The remaining digestate was used in the neighborhood space. The 30 m^2 open-air vegetable garden produced 150 kg annually (5 kg/m^2 × 30 m^2), resulting in a total of 455 kg of vegetables and 65.46 kg of straw per year (1.54 kg/m^2 × 24 m^2 + 0.95 kg/m^2 × 30 m^2 = 65.46 kg). These vegetables met the annual demand of 434 kg per household, achieving a vegetable self-sufficiency rate of 105%. Straw was delivered to the group level to feed livestock (Table 6, Figure 16).

Table 6. Resource metabolism status and metabolic modelling at the courtyard level (3.1 persons/household).

Metabolic State	Resource Type	Indicator (yr)	Clarification
Resource input	Rainwater harvesting	114 m^3	Municipal domestic water supply was not included in the calculation process
	Biogas	264.6 m^3	Biogas was the total amount of biogas from both the neighborhood and village scales, and digestate was the total amount of resources to satisfy the cultivation of fruits and vegetables in gardens
	Biogas slurry	198.7 kg	
	Biogas residue	7.22 kg	
Internal metabolism (biology)	Vegetable growing	455 kg	Yard gardening for self-sufficiency
	Aquaculture	34.7 kg	
Resource output	Human waste	509 kg	Distribution to neighborhood spaces for metabolic treatment use
	Domestic sewage	66 m^3	
	Domestic organic waste	566 kg	
	stalk	65.46 kg	

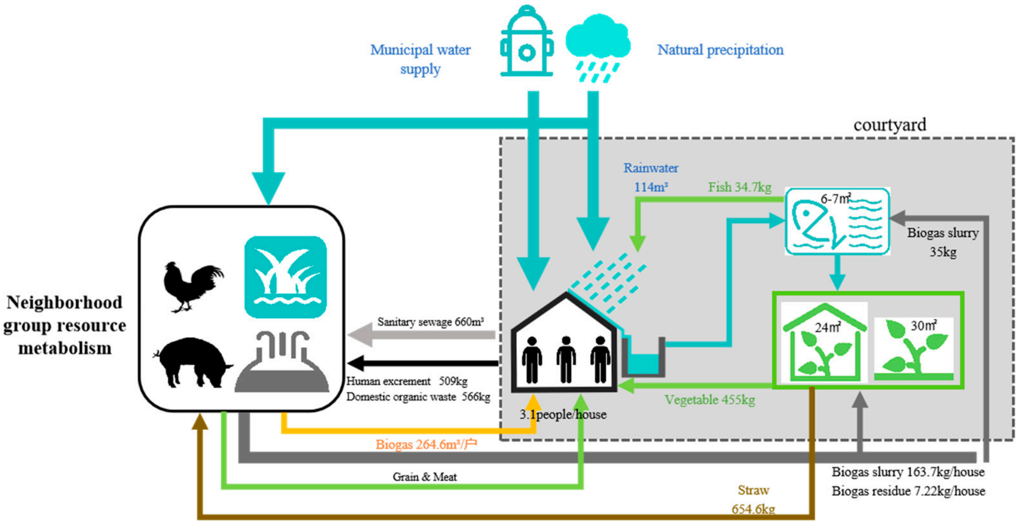


Figure 16. Resource metabolism modelling of courtyards.

(2) Neighborhood

The neighborhood primarily managed livestock manure and domestic sewage in the communal space. With courtyards already meeting vegetable demands, group plantings focused on cereals. To meet the annual meat demand of 10 villagers, 11 pigs and 13 meat birds were raised in the group's communal area, producing sufficient meat and generating 21,705 kg of manure. Approximately 500 m^2 of green space was used for cereal cultivation, yielding 282 kg of cereals annually (28.2 kg per household) and 312 kg of straw. The total straw production from 10 households' vegetable gardens was 967 kg (655 kg from gardens + 312 kg from the cluster), used for livestock breeding. The cluster's household biogas facilities processed 26,795 kg of manure (21,705 kg from livestock + 5090 kg from villagers) and 5660 kg of domestic waste, producing 2173 m^3 of biogas. The biogas residue from 21,705 kg of livestock manure, combined with 2760 kg of residue from 10 village gardens, totaled 7214 kg of biogas residue. The 500 m^2 cereal planting area within the cluster consumed 2969 kg of biogas and 586 kg of digestate. The remaining 6628 kg of digestate was transferred to the village area for centralized agricultural use (Table 7, Figure 17). The resource metabolism flow within the courtyard system boundary is illustrated through a Sankey diagram, reflecting the integration of resource metabolism processes with the spatial morphology of the village, facilitating subsequent spatial metabolism modelling.

Table 7. Resource metabolism status and metabolism models at the neighborhood level (10 households/groups, 31 persons).

Metabolic State	Resource Type	Indicator (yr)	Clarification
Resource input	Rainwater harvesting	412 m^3	Municipal water supply was not included in the calculation process
	Human waste	5090 kg	From the courtyard
	Domestic sewage	660 m^3	
	Domestic organic waste	5660 kg	
	Fruit and vegetable stalks	655 kg	
	Livestock breeding feed	15,568 kg	The amount of external straw feed still needed to be supplied

Table 7. *Cont.*

Metabolic State	Resource Type	Indicator (yr)	Clarification
Internal metabolism (biology)	Grain stalk	312 kg	Group cereal farming
	Animal manure	21,705 kg	–
	Digestate	2969 kg	
	Digestate	586 kg	
Resource export	Cereal cultivation	282 kg	Distribution to courtyards
	Poultry and meat	706 kg	
	Landfill gas	2173 m^3	
	Digestate	1987 kg	
	Digestate	72.2 kg	
		6628 kg	Distribution to villages

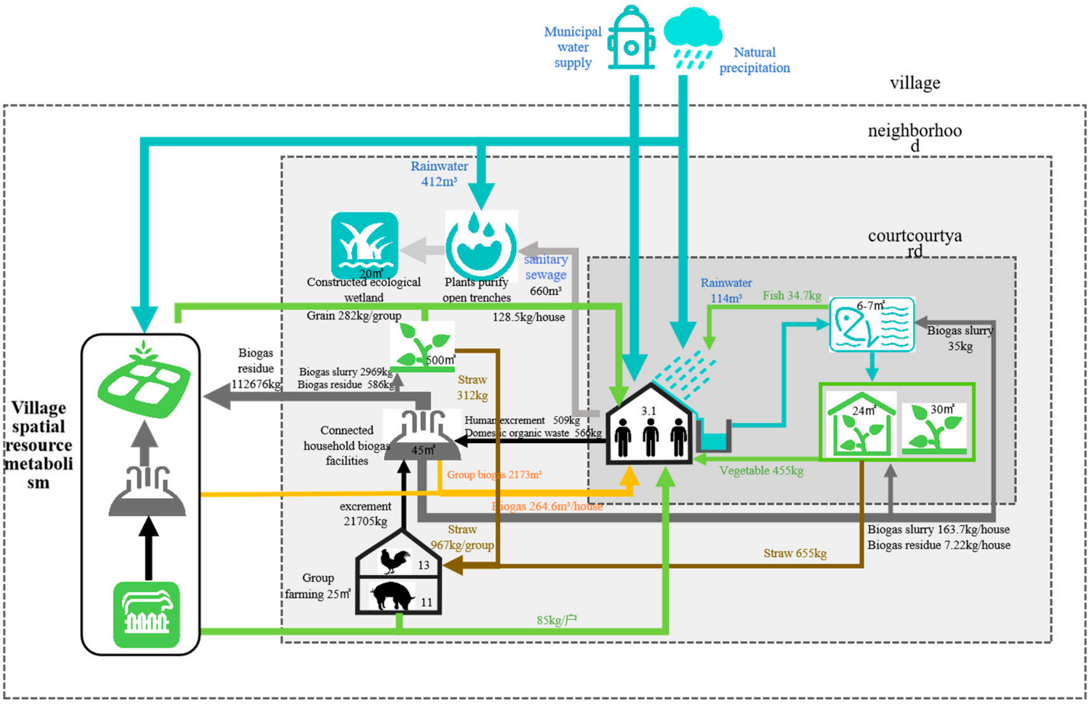


Figure 17. Resource metabolism modelling for neighborhoods.

(3) Whole Village

The metabolic accounting of village resources involved setting up a centralized breeding plant to raise 17 cows and 186 sheep, generating 134,228 kg of manure. A centralized breeding plant for 17 cows and 186 sheep generated 134,228 kg of manure. A centralized biogas station in the breeding space produced 8054 m^3 of biogas, 27,545 kg of biogas residue, and 18,363 kg of biogas slurry. The biogas was distributed to 170 households, each receiving 47.4 m^3, along with 217.3 m^3/household from group biogas plants, totaling 264.7 m^3/household. Each household received 264.7 m^3 of biogas, covering 83.5% of the annual cooking biogas consumption of 317 m^3 per household. The biogas slurry was primarily used for grain cultivation on the village's peripheral arable land. Combining 18,363 kg of biogas residue and 27,545 kg of biogas slurry from the central biogas station with 122,638 kg of biogas residue from 17 clusters provided 140,221 kg of biogas slurry. This mixture could fertilize 41 hectares of grain fields, producing 17,056 kg of grains and 15,416 kg of straw annually. The combined grain output from village farmland and group planting, totaling

21,850 kg, fell short of the annual food demand of 89,252 kg for 530 villagers. Additionally, the straw production was insufficient to meet the feed requirements for cattle and sheep farming (Table 8, Figure 18).

Table 8. Resource metabolism status and metabolic modelling at the village spatial level (530 people).

Metabolic State	Resource Type	Indicator (yr)	Clarification
Resource input	Digestate	112,676 kg	Volume of residual digestate from neighborhoods
	Livestock breeding feed (cattle and sheep)	312,354 kg	The amount of external straw feed still needed to be supplied
Internal metabolism (biology)	Grain stalk	15,416 kg	Cattle and sheep breeding feed
	Animal manure	134,228 kg	Biogas preparation at biogas plants
	Digestate	18,363 kg	Nutrient requirements for supplying cereals for arable cultivation
	Digestate	27,545 kg	
Resource export	Cereal cultivation	17,056 kg	Distribution to courtyards
	Livestock meat (cattle and sheep)	706 kg	
	Landfill gas	8054 m^3	

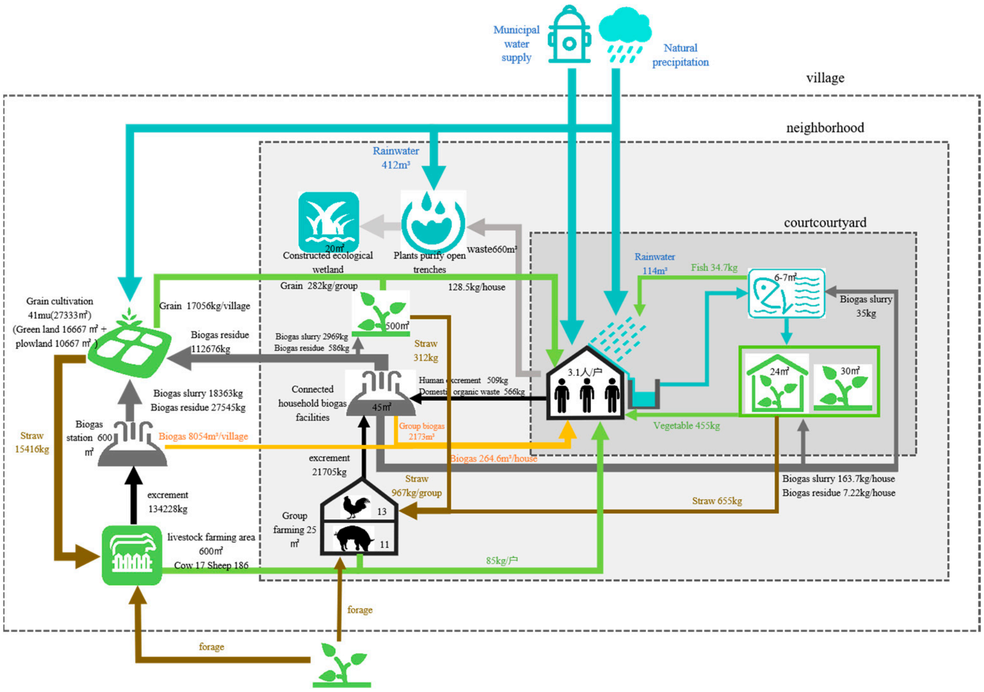


Figure 18. Resource metabolism modelling in the village.

Space allocation for resource metabolism facilities. The breeding area for 17 cows and 186 sheep covered approximately 600 m^2. Adjacent to it, the centralized biogas station, with an annual production capacity of 8054 m^3 of biogas, also occupied 600 m^2. For agricultural cultivation, there were 41 mu of land designated for grains, including 17,000 m^2 of public green space within the village. An additional 16 mu of cultivated land was provided, bringing the total cultivated area of the village to 622 mu.

Analyzing the metabolic flow of various resources at different scales and calculating the self-sufficiency index (SSI) based on the ratio of recycled resources to minimized demand revealed that, under ideal conditions, with 100% self-consumption of organic wastes, the self-sufficiency rate for vegetable cultivation at the yard scale of village residences was 105%, and for grain cultivation at the neighborhood and village scales, 24.5%. The self-sufficiency rate for straw from fruit, vegetable, and grain cultivation to meet livestock feed demand was 7.3%, and the self-sufficiency rate for cooking energy (biogas) was 83.5% (Table 9, Figure 19). The village had a remaining land area of 622 mu.

Table 9. Statistics on the self-sufficiency of major resources under the situation of organic waste self-consumption.

Resource Type	Quantity Demanded	Supply	Self-Sufficiency Index (SSI)	Metabolic Scale
Landfill gas	317 m^3/household	264.7 m^3/household	83.5%	Neighborhood + village
Fruits	434 kg/household	455 kg/household	105%	Courtyard
Grains	525 kg/household	128.5 kg/household	24.5%	Neighborhood + village
Stalk	465,288 kg/village	33,855 kg/village	7.3%	Courtyard + neighborhood + village

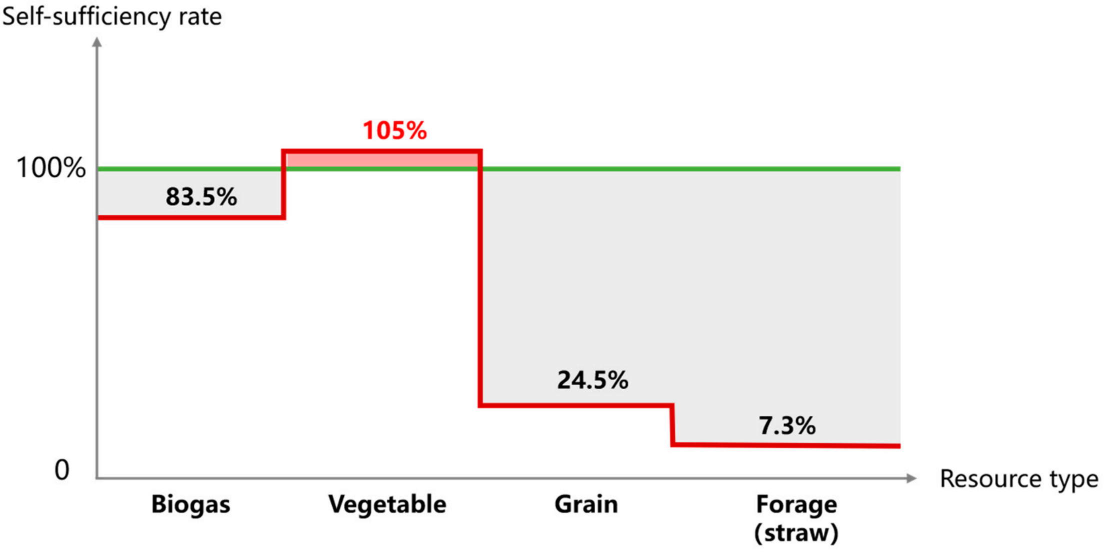


Figure 19. Self-sufficiency rates.

5.4.3. Resource Metabolism Spatial Modelling

The quantitative flow metabolism model and corresponding spatial occupation indices of the main resources for human life and farming production at the three scales—the courtyard, neighborhood, and village—are related from the bottom up. Main resource metabolism elements were allocated reasonably and effectively at each scale, in conjunction with the allocation of basic spatial indices and setting of morphological elements. This approach better adapted to and reflected the spatial layout model of rural settlements under the objective of "organic waste self-consumption". The spatial layout model of rural settlements can better adapt to and reflect the goal of "self-consumption of organic waste".

(1) Spatial Modelling of Courtyards

At the courtyard scale, based on the quantitative measurement of the resource metabolism model, the location and area of various resource metabolism and productive spaces were reasonably allocated (Figure 16). On a 200 m^2 residential base, excluding the village house area of about 90–100 m^2 and courtyard traffic, the remaining 40–50% open space could be used for agricultural cultivation. The roof and ground of a one-story village house provided about 54 m^2 for planting, with 24 m^2 of the roof suitable for a small greenhouse. Vegetable cultivation could assist in heat transfer to neighboring rooms, raising room temperatures in winter. Depending on vegetable yield targets, the courtyard' open vegetable garden could be allocated different areas and locations for resource metabolism and productive spaces (Figures 20 and 21). Depending on vegetable yield targets, the courtyard open vegetable garden could be converted into a small vegetable greenhouse. Pools of 6–7 m^2 near the courtyard wall could collect precipitation, breed fish, and form an aquaponics system with the planting gallery. Excess water, along with domestic sewage (gray water), could be discharged into the plant purification ditch along the external road, ultimately transferring to the group's small-scale artificial ecological purification wetland system.

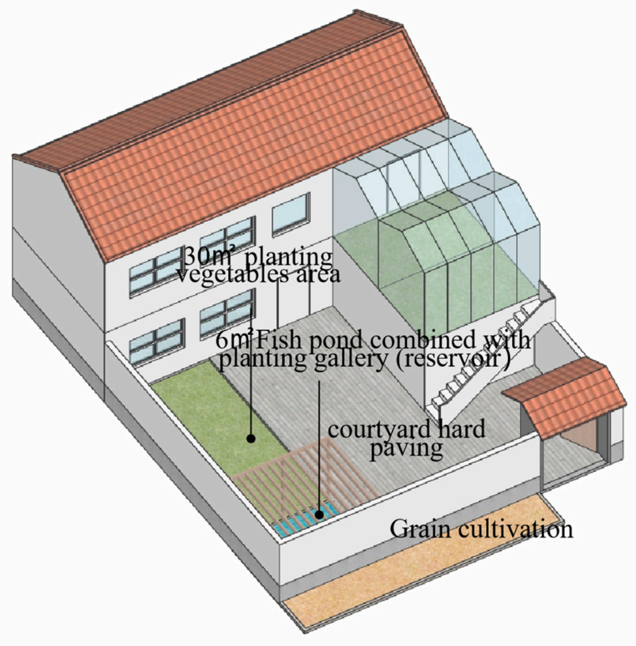


Figure 20. Spatial model of the courtyard.

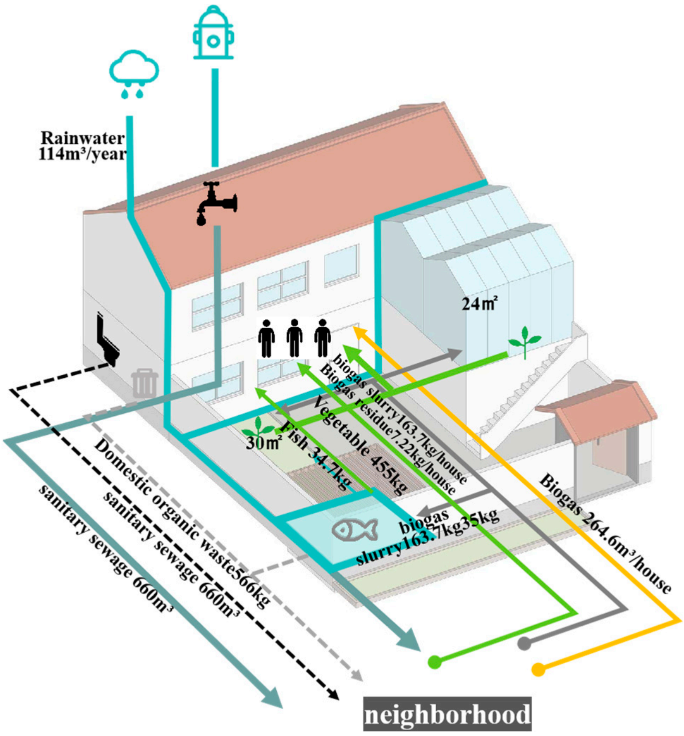


Figure 21. Metabolic spatial model of the courtyard.

(2) Spatial Modelling of Neighborhoods

The neighborhood comprised 10 courtyards responsible for the input, consumption, and distribution of most organic waste resources. Limited open space sites, often unused or abandoned areas, were utilized to integrate various resource-producing and -utilizing technologies and facilities, such as agricultural cultivation spaces, artificial ecological water purification wetlands, and small-scale household biogas digesters. The metabolic space model of the neighborhood was constructed based on the complete recycling and consumption of all types of living and production organic waste by 10 households. The location and area of various facilities, including biogas digesters, were reasonably configured and measured.

Based on the total amount of organic waste at the group scale, it was estimated that a continuous household biogas digester (underground) with an annual biogas production capacity of 2173 m^3 required 45 m^2 of floor space. It is advisable to establish livestock breeding and small-scale greenhouse spaces above it. In the group, 11 pigs and 13 meat birds were raised in a vertical layout. The breeding space was determined to be 25 m^2 based on the number of livestock. The remaining 20 m^2 served as a neighborhood-shared greenhouse. The complementary heat effect of the resource metabolism facilities ensures the underground biogas digester maintains a normal vapor production temperature in winter, while the waste heat from the anaerobic fermentation process insulates the livestock breeding space above. From estimating the artificial ecological wetland area, 10 households in the village produced a total of 660 m^3 of domestic sewage per year. Approximately 580 m^2 of roads and other hard surfaces in the group could collect 412 m^3 of rainwater, totaling 1072 m^3 of gray water. Based on a calculation of 3 m^3/day, the small-scale artificial ecological wetland occupied about 20 m^2 (including 10 m^2 of regulating ponds and 10 m^2 of stabilized ponds combined with lotus root planting, with a water bed depth of 0.7 m). The remaining block vegetable land in front of the house was 140 m^2, and there was 366 m^2 of centralized planting land in the public site, totaling about 500 m^2 mainly used for planting grains. Additionally, a fruit and vegetable planting corridor of about 290 m^2 could be established above the road (Figures 22 and 23). The 10 courtyards in the neighborhood could be flexibly deployed and combined with the open space, integrating suitable resources and metabolic technology facilities to form various group layouts such as enclosed and row types (Figure 24).

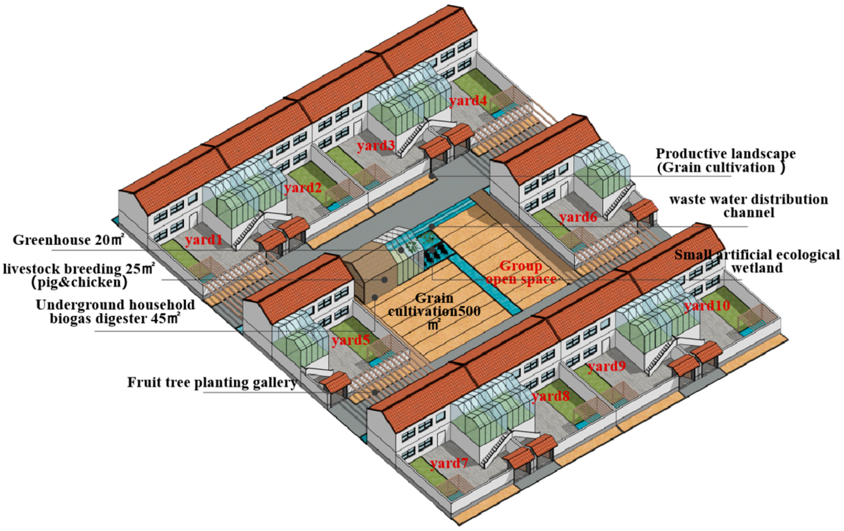


Figure 22. Layout of spatial facilities.

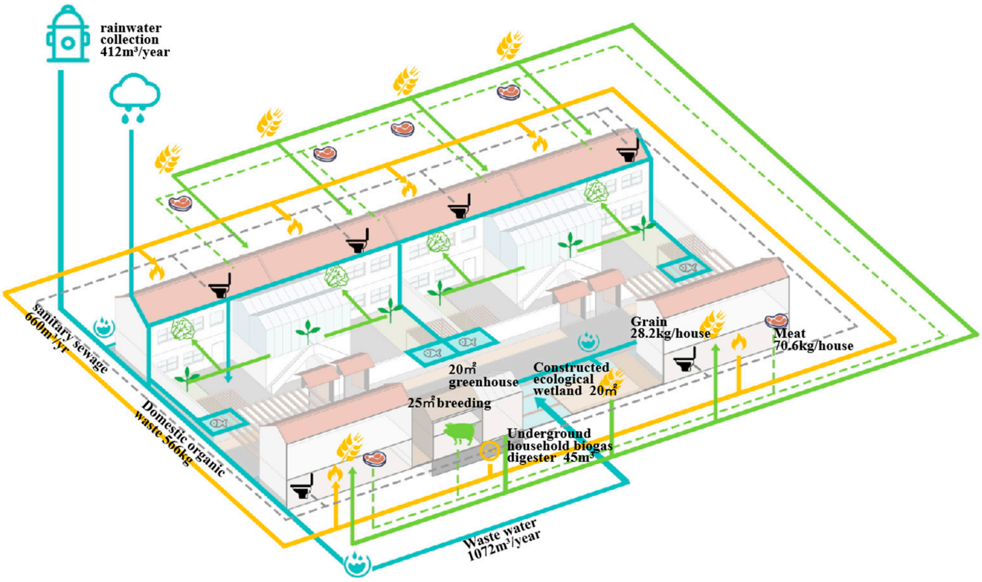


Figure 23. Schematic resource metabolism for the neighborhood spatial model.

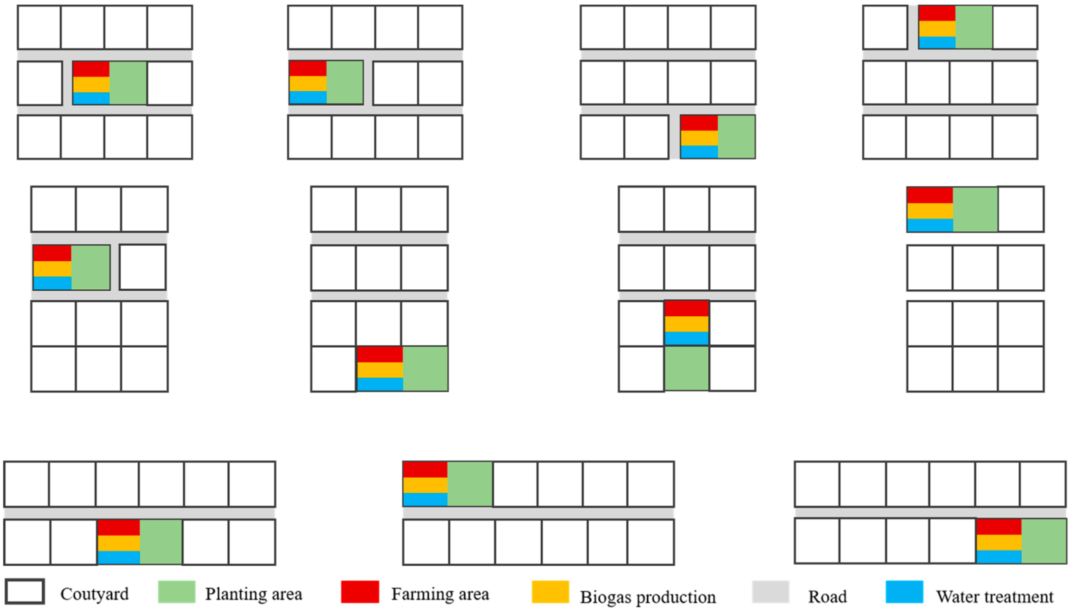


Figure 24. Neighborhood layout.

(3) Village Spatial Modelling

The village, housing 530 residents, covered an area of 766 mu (509,575 m^2). The living area was centralized into 17 neighborhoods, divided by a cross-shaped main road. These clusters were connected through streets and lanes. Land for public buildings (such as the village committee, commerce, health stations, and other public facilities) and green areas were concentrated in the village center. Public green spaces in the village were transformed into productive areas for grain cultivation to meet agricultural production needs and facilitate the consumption of organic waste. The primary resource metabolism facilities were centrally located downwind of the prevailing winds to ensure the efficient metabolism of organic waste and water resources. These facilities were separated from residential areas by green belts to minimize their impact on the living environment (Figure 25).

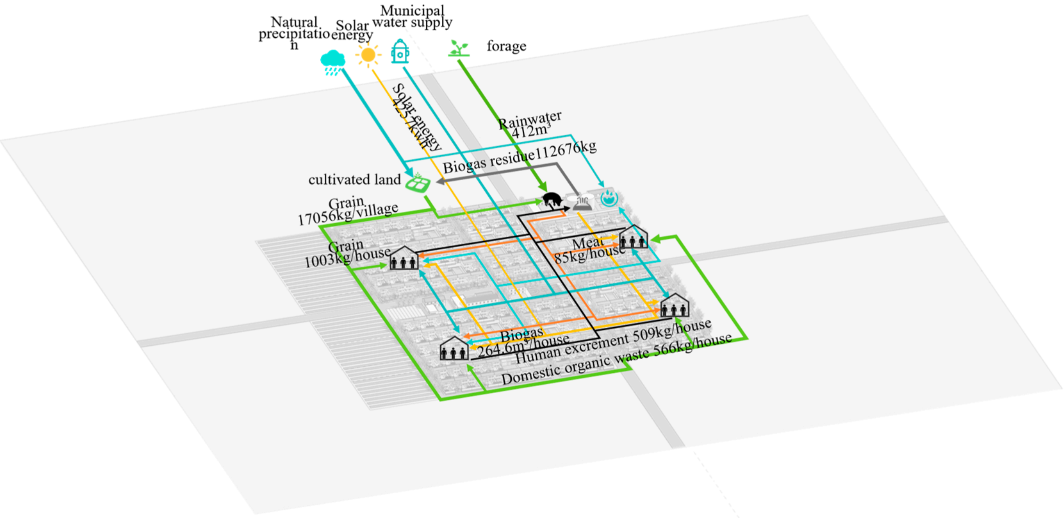


Figure 25. Spatial model of the spatial metabolism in the village area.

6. Conclusions

The resource metabolism modelling process under organic waste self-consumption, utilizing appropriate technologies and integrating spatial elements at different scales, achieved full cyclical metabolism of human and animal organic waste in rural areas. This approach saved significant arable land on the periphery of the village's built-up area. However, it is challenging to achieve self-sufficiency in food resources, necessitating the import of additional nutrients to meet food production needs. The neighborhood scale is crucial in transitioning resource flow and facilitating local transformation. By utilizing public land for livestock breeding, the cultivation of fruits, vegetables, or grains, and water purification and reuse, it is possible to efficiently transform various organic waste resources from village yards. This significantly reduces and decentralizes the burden of constructing and operating resource metabolism facilities at the village scale. This approach also minimizes the distance and process losses associated with resource transmission and distribution. At the courtyard and neighborhood scales, various unused spatial resources are effectively utilized to establish facilities for organic waste resource utilization, achieving the efficient integration of production, living, and ecological spatial elements. While the complete recycling of organic waste from the village population (530 people) and their livestock, meeting nutrient needs for basic food cultivation (especially grains) and cooking energy, remained challenging, modelling the complete consumption of organic waste helped for understanding the dynamic coupling between organic waste consumption and the available space for agricultural support. Modelling organic waste adequacy helps elucidate the dynamic coupling between organic waste consumption and the spatial requirements for agricultural support.

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