

## Research Insight

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# Data-Driven Evaluation of Sustainable Agricultural Practices in Zhejiang Small Farms

Yu Zhan ✉

Zhejiang Green Giant Biotechnology Co., Ltd., Jinhua, 321071, Zhejiang, China

✉ Corresponding author: [3601303@qq.com](mailto:3601303@qq.com)Computational Molecular Biology, 2026, Vol.16, No.5 doi: [10.5376/cmb.2026.16.0023](https://doi.org/10.5376/cmb.2026.16.0023)

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**Abstract** Small-scale farms play an important role in promoting sustainable agricultural development, rural revitalization, and ecological conservation in Zhejiang Province. However, the assessment of sustainability performance in these farms is often limited by fragmented production data and insufficient quantitative evaluation approaches. This study proposes a data-driven framework for evaluating sustainable agricultural practices in Zhejiang small-scale farms by integrating multi-source agricultural data, sustainability indicators, and analytical models. The framework incorporates ecological, economic, and social dimensions, including resource-use efficiency, soil health, production performance, environmental benefits, and farm management efficiency. Advanced approaches such as machine learning, spatial analysis, and multi-objective optimization are discussed to identify key drivers affecting sustainable outcomes and support precision decision-making. A case study of a typical small-scale farm in Zhejiang Province is presented to evaluate the effectiveness of sustainable practices, including precision irrigation, optimized fertilization, and digital management strategies. The results provide insights into how data technologies can enhance resource efficiency, reduce environmental impacts, and improve the resilience of small-scale farming systems. This study highlights the potential of integrating digital agriculture and sustainability assessment frameworks to accelerate the green transformation of small-scale farms.

**Keywords** Small-scale farms; Sustainable agriculture; Data-driven evaluation; Precision agriculture; Zhejiang Province

## 1 Introduction

Small-scale farming remains a foundational part of agricultural production in China, and Zhejiang Province is a particularly important case because its agriculture combines very small average farm size, rapid structural transformation, and strong policy pressure for green and high-quality development (Ren et al., 2023). In China more broadly, smallholders still dominate agricultural production, yet these systems often face persistent constraints in nutrient use efficiency, farm income, and pollution control. Zhejiang illustrates both the urgency and the opportunity of this transition: province-level evaluation shows that agricultural sustainability improved steadily from 2013 to 2019, but that progress was uneven across cities and pilot zones, indicating substantial regional heterogeneity in resource conditions, technology levels, and ecological, economic, and social outcomes. This matters because resource use efficiency has a significant effect on sustainable agricultural development in Zhejiang, linking farm management directly to broader carbon, land, water, and livelihood goals. At the same time, Zhejiang's rural transformation has been shaped by labor outflow and land transfer: although the province's average cultivated land area was only 0.10 ha, its farmland transfer rate was among the highest in China, and by the end of 2013 about 48% of rural household farmland had been transferred. This has encouraged moderate-scale and service-based farming models, but it has not eliminated the continuing importance of small farms in local production systems. More broadly, recent evidence shows that demographic ageing threatens the sustainability of Chinese smallholder agriculture by reducing farm size, increasing land abandonment, lowering output and labor productivity, and raising fertilizer losses, while newer farming models with younger and better educated operators can partly reverse those trends. Other field evidence similarly shows that alternative farming models can produce higher yields with lower fertilizer use, greater fertilizer use efficiency, and markedly lower pollutant emissions, although they also rely on greater investment in facilities, machinery, and specialized labor. These findings suggest that sustainable development in Zhejiang cannot be understood through scale alone: the key issue is how small farms adopt resource-efficient, knowledge-intensive, and locally adapted practices within a changing institutional and environmental context.

Against this background, data-driven evaluation has become increasingly important for sustainable agriculture because conventional analytical methods often capture only part of the complexity created by multi-dimensional indicators, spatial heterogeneity, and real-time management demands. Recent studies have therefore expanded from static indicator scoring toward predictive and integrated frameworks that combine ecological, economic, and social variables with machine learning, remote sensing, and sensor-based monitoring. At the regional level, machine-learning models such as random forest, regression models, and classification trees have been used to predict composite sustainability indices with high explanatory performance and to identify the most influential drivers behind sustainability variation across districts and policy contexts (Deshmukh et al., 2025). In parallel, the smart-farming literature shows that machine learning can analyze historical and real-time environmental data to support crop selection, disease detection, irrigation management, and more efficient fertilizer and energy use, thereby improving productivity while reducing environmental pressure (Mohyuddin et al., 2024). Soil assessment has been a particularly active area of development, with studies showing that integrating soil chemistry, climate, geolocation, satellite data, remote sensors, and IoT systems can strengthen real-time evaluation of soil quality, moisture, fertility, and irrigation needs for more sustainable land and input management (Chaudhary et al., 2026). Geostatistical and AI-based approaches also outperform slower conventional tools for spatial interpolation and robust analysis of heterogeneous soil conditions, which is especially relevant for fragmented farming landscapes. Yet the literature also identifies important limitations: data quality, infrastructure costs, digital literacy, fragmented model development, local adaptation, and the trade-off between predictive accuracy and interpretability remain major barriers to broad deployment, especially for smallholders rather than capital-intensive large farms. Even broader conceptual work argues that data-driven agriculture is still at an early stage in terms of demonstrating how digital tools reliably advance sustainability, and that future systems must integrate multiple data streams while remaining trustworthy, practical, and usable in farmer decision-making. For smallholder contexts, this implies that data-driven evaluation should not be limited to technical prediction; it should also reveal actionable sustainability pathways that fit local constraints, farmer behavior, and extension systems.

In this context, the present study aims to develop a data-driven evaluation of sustainable agricultural practices in Zhejiang small farms by linking farm-level practice assessment to the province's broader goals of green, efficient, and high-quality agricultural development. The study is motivated by two gaps in the existing literature. First, while Zhejiang has been evaluated at provincial and prefectural scales through composite sustainability frameworks, less attention has been given to fine-grained assessment of how small farms themselves differ in sustainable practices and performance. Second, while machine learning and other data-driven methods have advanced rapidly in sustainable agriculture, many studies either emphasize technical performance alone or focus on non-Chinese contexts, leaving a need for locally grounded frameworks that connect predictive analytics to practical sustainability evaluation in smallholder systems. Accordingly, this paper proposes an overall framework that integrates multidimensional indicators of ecological performance, resource use, economic viability, and social sustainability, drawing on the same broad logic used in recent sustainability index systems while adapting it to Zhejiang's small-farm realities. The framework further incorporates data-driven tools to identify patterns, classify sustainability performance, and detect the key variables associated with more sustainable practice bundles, consistent with recent work showing that real-time and multi-source data can support policy monitoring, soil and input management, and predictive decision support. At the same time, the analytical design recognizes that sustainable transformation depends not only on data availability but also on adoption conditions, farmer acceptance, and collaboration among researchers, government, enterprises, and farmers. The ultimate objective is therefore not simply to rank farms, but to provide an evidence base for targeted intervention: identifying which sustainable practices are most effective, which constraints most strongly limit uptake, and which policy or service arrangements can support wider diffusion among Zhejiang's small farms. In this sense, the study's overall framework positions data-driven evaluation as both a measurement tool and a governance tool for sustainable agricultural development in Zhejiang small farms.

## **2 Production Systems and Current Status of Sustainable Agricultural Practices in Small-Scale Farms in Zhejiang Province**

### **2.1 Development characteristics and production models of small-scale farms in Zhejiang Province**

Zhejiang's small-scale farms are shaped by a highly fragmented land endowment, strong non-farm employment

pull, and rapid but uneven agricultural restructuring. The province's average cultivated land area per household has been reported at only 0.10 ha, while its farmland transfer rate is among the highest in China, reflecting an agricultural system in which smallholder operation remains dominant but is increasingly reorganized through land circulation and service-based coordination (Huang et al., 2017). At the same time, the transfer of rural labor into non-agricultural sectors has altered household production strategies, pushing many farms toward part-time farming, specialization, or outsourcing of key operations.

Under these conditions, Zhejiang has developed a mixed production pattern in which traditional family farming coexists with moderate-scale and service-centered forms of organization. Evidence from Zhejiang-based studies indicates two main models: scale operations based on concentrated farmland and scale operations based on agricultural services, with the latter expected to continue expanding because it reduces the need for full land consolidation. In practice, this transition also involves shifts from rice-centered systems toward higher-value vegetables and more mechanized production where farm size permits, since larger operational scales make mechanization increasingly necessary and improve the feasibility of income-oriented crop restructuring (Berg et al., 2007).

## 2.2 Major sustainable agricultural practices in small-scale farms

The main sustainable agricultural practices relevant to Zhejiang small farms are centered on input efficiency, ecological soil management, and reduced chemical dependence. Across Chinese smallholder systems, recommended practices consistently include nitrogen reduction, formula fertilization, and optimization of crop management, with nitrogen reduction showing the largest overall sustainability gain in one recent assessment (Guo et al., 2024). Broader ecological farming research in China also identifies soil testing and formula fertilization, straw return, crop rotation, green manure, organic fertilizer use, and reduced chemical fertilizer application as core practices because they conserve cultivated land quality while lowering resource waste and environmental pressure (Figure 1).

Pest management is another major dimension of sustainable practice, especially in high-value crops common in Zhejiang such as tea, fruit, and vegetables. Current sustainability frameworks emphasize integrated pest management, improved nutrient management, agroforestry-related measures, no-tillage or conservation practices, and organic manure use as principal pathways for reducing ecological risk while maintaining production (Arhin et al., 2024). Recent reviews further show that IPM is most effective when biological, cultural, mechanical, and carefully targeted chemical measures are combined, and when it is integrated with broader agroecological or precision-based management rather than used as a stand-alone technique.

## 2.3 Current challenges and constraints in sustainable development

The sustainable development of Zhejiang's small farms is constrained by the interaction of fragmented land, labor loss, and weak conditions for technology diffusion. Meta-analytic evidence from China shows that land fragmentation has a significantly negative effect on the adoption of pro-environmental agricultural technologies, while land transfer and government subsidies have positive effects on adoption behavior. This constraint is especially relevant in Zhejiang because mountainous terrain, strict farmland-use controls, and fragmented facility layouts continue to limit the expansion of modern agricultural infrastructure, even as demand for facility-based and high-efficiency agriculture grows (Wang et al., 2025).

Adoption barriers are not only structural but also economic, cognitive, and institutional. Smallholders often face higher costs, additional labor requirements, and limited acceptance of recommended sustainable practices, which slows implementation even when technical solutions are available (Guo et al., 2024). Similar evidence across ecological and IPM studies shows that sustainable practices are knowledge-intensive, that farmers frequently have only partial understanding of what "sustainable farming" entails, and that extension, peer learning, and multi-stakeholder support platforms are therefore essential for wider uptake. Overall, Zhejiang small farms are characterized by persistent smallholder foundations, growing service-based scale operations, and gradual adoption of input-saving, ecological, and pest-management practices. Their sustainable transition depends on overcoming fragmentation, labor and knowledge constraints, and mismatches between emerging production models and the institutional support available to farmers.

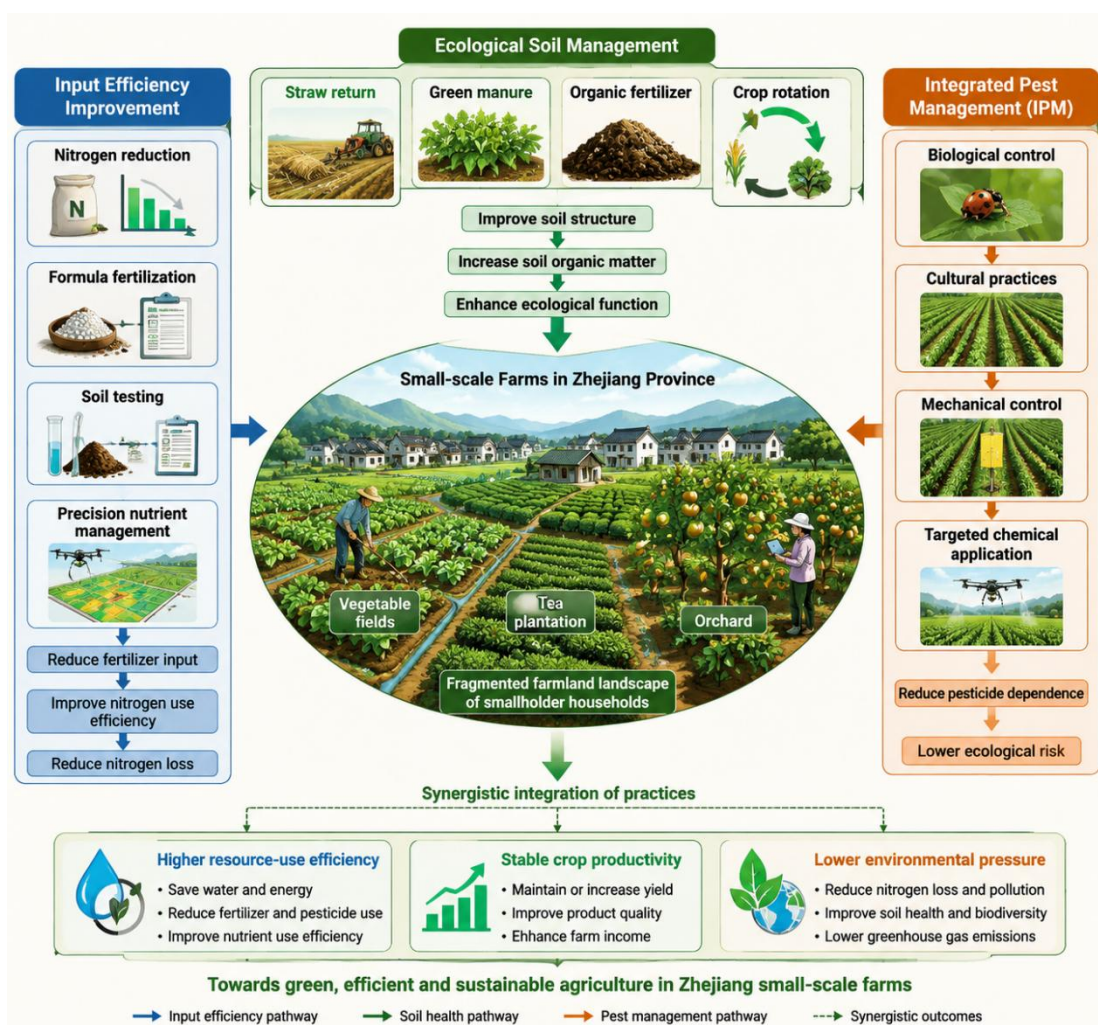


Figure 1 Conceptual framework of sustainable agricultural practices in Zhejiang small-scale farms, integrating input efficiency improvement, ecological soil management, and integrated pest management pathways

### 3 Construction and Theoretical Framework of a Data-Driven Evaluation System

#### 3.1 Design of sustainability evaluation indicators for agricultural systems

The evaluation indicator system for Zhejiang small farms should be constructed as a multidimensional framework because agricultural sustainability is consistently defined through environmental, economic, and social dimensions rather than by single-output performance alone (Bathaei and Štreimikienė, 2023). At the farm scale, however, these broad dimensions need to be translated into operational indicators that reflect local cropping conditions, land resources, and management constraints, since regionally adapted frameworks are more interpretable and more useful for policy and farm diagnosis than generic national-level indices. For Zhejiang small farms, this implies selecting indicators that can simultaneously capture input efficiency, soil and water conservation, farm profitability, and livelihood stability, while preserving comparability across heterogeneous household production units.

In theoretical terms, the present study adopts a composite evaluation logic that combines the classical three-pillar model with a more practice-oriented set of agricultural targets, namely food production, economic profitability, resource conservation, and environmental friendliness. This design also recognizes that indicator systems are not purely technical constructions but normative tools whose weighting and aggregation affect final sustainability rankings, making transparency in indicator selection and scoring essential for credible evaluation (Sinisterra-Solis et al., 2024). Accordingly, the indicator set for Zhejiang is structured hierarchically into criterion and sub-criterion levels, so that later empirical analysis can distinguish overall sustainability from specific weaknesses such as irrigation pressure, soil degradation, or unstable economic returns.

### 3.2 Agricultural data acquisition and database construction

A data-driven evaluation system for small farms depends on acquiring farm-level information that is timely, spatially specific, and consistent across production cycles, because conventional agricultural data are often incomplete, outdated, or poorly matched to plot-level decision needs (Bayih et al., 2022). Existing research shows that smallholder data can be collected through four complementary channels-conventional surveys, remote sensing, proximal sensing, and in-field sensing-allowing environmental, technical, and socio-economic variables to be integrated within one monitoring architecture. For Zhejiang, where farm plots are fragmented and management intensity varies sharply across villages, this mixed-source acquisition strategy is more appropriate than dependence on a single observation mode.

The database should therefore be designed as a layered architecture linking perception, transmission, storage, and application functions, so that heterogeneous sensor, survey, and platform data can move from collection to decision support in a standardized workflow. Because agricultural data are inherently spatial, temporal, and semantic, the storage layer should support interoperable structures that preserve location, timestamp, and management meaning rather than storing observations as isolated records (De La Parte et al., 2023). In implementation, low-cost and scalable storage solutions such as cloud-linked NoSQL repositories are well suited to high-redundancy sensing data and can reduce deployment barriers for small farms while retaining the capacity for later analytics and visualization.

### 3.3 Data analysis methods and evaluation models

The analytical component of the evaluation system should combine expert-informed multicriteria methods with data-driven statistical and machine learning tools, because sustainable agriculture assessment involves both normative judgment and empirical pattern recognition (Kumar and Pant, 2022). In this context, AHP remains useful for structuring indicator hierarchies and assigning interpretable weights to soil, climate, resource, and management factors, especially when local knowledge must be incorporated into model design. For Zhejiang small farms, such a framework allows expert judgment, farmer realities, and sustainability objectives to be embedded in the same scoring system before large-scale computation begins.

After indicator weighting, the evaluation model should proceed through normalization, aggregation, and sensitivity testing so that composite sustainability scores remain interpretable and methodologically robust across different farm types. Machine learning can then be introduced as a complementary layer for classification, prediction, and scenario discovery, especially where nonlinear interactions among soil, climate, topography, and management variables reduce the reliability of purely manual assessment (Agrawal et al., 2024). To improve robustness, the final model for this study can further incorporate uncertainty validation and adaptive weighting strategies, since recent work shows that dynamic entropy weighting and Monte Carlo validation strengthen reliability and scalability in multidimensional agricultural decision systems. Taken together, these three components support a data-driven evaluation system for Zhejiang small farms that is locally grounded, technically scalable, and methodologically transparent. The framework answers the core needs of Section 3 by linking indicator design, data infrastructure, and evaluation modeling into one coherent sustainability assessment architecture.

## 4 Data Characteristics of Sustainable Practices in Small-Scale Farms in Zhejiang Province

### 4.1 Data analysis of agricultural resource use efficiency

In Zhejiang, the data pattern for sustainable small-farm practice is defined less by simple input reduction than by a broader improvement in resource-use efficiency across land, water, labor, material inputs, and agricultural technology. Provincial evidence shows that Zhejiang's agricultural sustainability improved steadily from 2013 to 2019, although clear spatial disparities persisted across prefecture-level cities and pilot zones, indicating that efficiency gains were real but unevenly distributed. This interpretation is consistent with recent national FEW-nexus evidence showing that Zhejiang is in an upward phase of on-farm resource-use efficiency, having reduced fertilizer, machinery, and fuel inputs while maintaining relatively stable output (Huang et al., 2025).

At the farm-operation level, the strongest efficiency signal concerns fertilizer management. Large on-farm experiment evidence from China shows that optimizing nitrogen application can raise yields by 10%-19% while cutting N rates by 15%-19%, thereby increasing nitrogen use efficiency by 32%-46% and reducing N surplus by 40%, even without changing the basic smallholder operational structure. At the same time, the relationship between scale and fertilizer efficiency is not linear across all contexts: one national study reports that a 1% increase in farm size is associated with a 0.2% increase in fertilizer use efficiency (Zhu et al., 2022), whereas evidence from Jiangsu finds the smallest farm-size group achieved the highest fertilizer use efficiency score, suggesting that Zhejiang small farms should be evaluated by management quality and service access rather than scale alone.

#### 4.2 Data responses of different production management practices

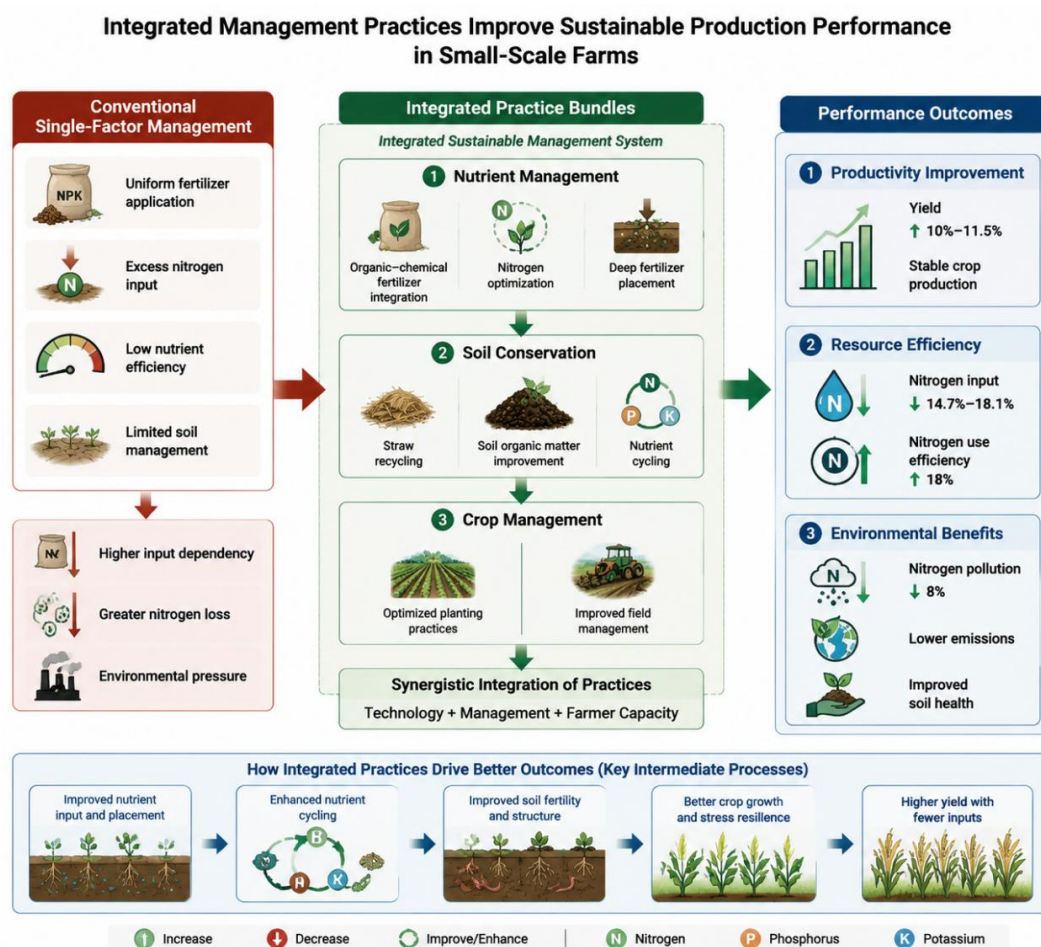
The response of production data to different management practices shows that sustainable gains are most visible when farmers adopt integrated rather than single-factor adjustments. A large national intervention involving Chinese smallholders found that enhanced management practices increased average maize, rice, and wheat yields by 10.8%-11.5% while reducing nitrogen application by 14.7%-18.1%. More recent census-based evidence similarly indicates that the spread of combined practices such as organic-chemical fertilizer integration, straw recycling, and deep fertilizer placement contributed to a 10% rise in crop yields, an 18% increase in nitrogen use efficiency, and an 8% reduction in nitrogen pollution between 2007 and 2017 (Duan et al., 2024).

For Zhejiang small farms, these results imply that practice bundles with organizational or technical support are more responsive than isolated input cuts. Pilot evidence from the Tai Lake watershed shows that alternative farming models outperformed conventional smallholder farming by producing 7% more yield with 8% less fertilizer, which reduced pollutant emissions per hectare by 28% (Yu et al., 2021). Complementary evidence from millions of surveyed Chinese smallholders shows that the top 10% of producers achieved 15.3%-35.4% higher yields while using 16.0%-21.0% less nitrogen fertilizer than their peers, demonstrating that the response to better management is already observable within smallholder systems rather than only on large commercial farms (Figure 2).

#### 4.3 Evaluation of environmental benefits and ecological functions

The environmental data indicate that sustainable practices in small farms can generate measurable ecological co-benefits, but these benefits depend on whether management is coordinated across production and environmental objectives. National optimization evidence shows that coordinated crop switching can simultaneously reduce blue water use, green water use, greenhouse gas emissions, fertilizer use, and pesticide use while also increasing farmer income, which is directly relevant for Zhejiang's need to balance high land-use intensity with ecological constraints (Xie et al., 2023). This aligns with broader ecosystem-service research showing that trade-offs between agricultural provisioning and regulating services are common, but can be reduced through better management choices such as diversified crop systems and context-specific ecological planning.

From the perspective of specific ecological functions, the most policy-relevant benefits concern carbon sequestration, soil quality, and pollution mitigation. Diversified crop rotations have been shown to reduce net greenhouse gas emissions, increase soil carbon sequestration, and improve soil health scores by 45%, while also raising farmer income, indicating that ecological improvement need not come at the expense of production performance. At a broader carbon-accounting scale, China's cropland systems are generally net carbon sinks, with the three major staple crops contributing an annual net carbon sink of about 165.76 TgC, while residue-based biochar systems can further strengthen carbon sequestration and mitigate soil and water acidification and biodiversity-related damage. In sum, the data characteristics of sustainable practice in Zhejiang small farms are best described as a transition toward higher efficiency, integrated management, and multi-functional ecological performance. Within this pattern, differences across places and farm types remain substantial, so Zhejiang's future evaluation framework should prioritize region-specific and management-specific indicators rather than assuming that one practice model fits all contexts.



Note: Quantitative indicators are based on recent large-scale evidence from Chinese smallholder systems (Duan et al., 2024).

Figure 2 Mechanistic framework illustrating how integrated agricultural management practices improve productivity, nutrient-use efficiency, and environmental sustainability in small-scale farming systems

## 5 Application of Data-Driven Evaluation Models in Sustainability Assessment of Small-Scale Farms

### 5.1 Machine learning-based prediction of agricultural production performance

Machine learning has become a practical tool for evaluating agricultural production performance because it can integrate soil, weather, and management variables into prediction frameworks that support farm-level decisions (Morales and Villalobos, 2023). For Zhejiang's small farms, this is especially useful because digital agriculture systems increasingly rely on sensor and operational data to generate faster and more accurate management insights, although the value of these models depends on whether they are connected to real decision processes rather than used as isolated technical exercises. In this context, machine learning should be treated not only as a forecasting instrument but also as a screening tool for identifying which combinations of agronomic conditions and management choices are most likely to improve sustainable performance.

At the same time, the evidence suggests that prediction quality depends strongly on model design, data volume, and validation strategy. Comparative research shows that random forest often performs better than neural networks or regularized linear models for crop-yield prediction tasks, including both farm-level forecasting studies and global assessments of conservation agriculture outcomes. However, machine-learning models are generally more reliable for reconstructing past or in-system patterns than for forecasting future yields under changing conditions, and random data partitioning can overstate real predictive ability (Morales and Villalobos, 2023). A promising way forward for Zhejiang is the hybrid use of process-based crop models with machine learning, because such emulators have reproduced more than 90% of the spatial variance in simulated yield and soil organic carbon while requiring fewer inputs, making regional sustainability assessment more scalable.

## 5.2 Spatial data-based optimization analysis of agricultural resources

Spatially explicit evaluation models are essential for Zhejiang because small farms operate under strong heterogeneity in land quality, water access, and local ecological constraints. Recent research shows that optimization based on coarse administrative units can miss critical environmental differences, whereas high-resolution remote sensing combined with spatial programming produces more precise and feasible crop allocation results (Yu et al., 2026). For sustainable assessment, this means that resource-use efficiency should be mapped at fine spatial scales so that cultivated land, irrigation demand, and expected returns can be evaluated according to actual landscape conditions rather than average county-level assumptions.

The benefits of this approach are substantial. In the Hetao case, optimization at 300 m resolution generated up to 205% higher economic benefit increments and 283% greater water savings than county-scale models, showing that spatial granularity directly affects the quality of resource allocation decisions. Geospatial machine-learning research on rice production in China similarly finds that yield outcomes are shaped by spatial interactions among climate, soil, environmental, and geographical factors, and that identifying these heterogeneous determinants improves regional management and resource optimization (Wang et al., 2024). For Zhejiang small farms, spatial data-based evaluation therefore supports more targeted zoning of irrigation, nutrient inputs, and crop structure, and is likely to outperform uniform policy recommendations.

## 5.3 Multi-objective optimization for sustainable production decision-making

Multi-objective optimization is particularly relevant for sustainable small-farm assessment because production decisions must reconcile economic returns with environmental pressure and, in many cases, social constraints. Farm-system research shows that optimization models can generate Pareto-optimal sets of alternatives rather than a single fixed recommendation, allowing decision makers to compare trade-offs among profit, labor demand, soil nitrogen loss, and other sustainability indicators. This is important for Zhejiang, where small farms differ widely in labor availability, capital endowment, and land fragmentation, so the best sustainable strategy is unlikely to be identical across households.

Evidence from recent applied studies shows that these models can deliver measurable sustainability gains when used to redesign resource combinations. A water-energy-food nexus model solved with a multi-objective genetic algorithm reduced water use by 2.56%, energy use by 12.71%, and environmental impacts by 6.82% while improving farmers' social conditions under the optimized cultivation pattern (Karamian et al., 2022). At the farm level, another multi-objective platform identified irrigation and nitrogen schemes that reduced water use by 48%, nitrogen input by 26%, and nitrogen leaching by 51%, illustrating the potential for simultaneous productivity and environmental improvement. More broadly, sustainable decision frameworks are strongest when they incorporate uncertainty, context-specific indicators, and stakeholder priorities, since agricultural trade-offs span economic, environmental, and social domains and cannot be resolved by yield maximization alone. Overall, the application of data-driven evaluation models in Zhejiang small farms is most effective when prediction, spatial heterogeneity, and trade-off optimization are integrated within one assessment framework. In this sense, Section 5 shows that machine learning can improve performance estimation, spatial analysis can refine resource allocation, and multi-objective optimization can support sustainable production decisions that are better aligned with the realities of smallholder agriculture.

# 6 Case Study: Data-Driven Evaluation of Sustainable Agricultural Practices in a Typical Small-Scale Farm in Zhejiang Province

## 6.1 Overview of the case farm and data sources

The case farm can be defined as a typical Zhejiang smallholding with fragmented cultivated land, intensive input use, and strong dependence on household management decisions, which fits the broader structure of Chinese smallholder agriculture. This case design is also consistent with Zhejiang's own sustainability context, where resource-use efficiency across land, water, labor, material inputs, and agricultural technology has become a central basis for evaluating agricultural sustainable development (Fu et al., 2022). In practical terms, the farm-level database should therefore include plot area, cropping structure, fertilizer and pesticide application, irrigation water,

labor time, machinery services, yields, output value, and basic household characteristics so that production, resource, economic, and environmental dimensions can be assessed together.

The data sources for such a case should combine farm survey records with regional statistical and spatial data, because sustainable evaluation depends on both household behavior and local agroecological context. Where observations are incomplete, missing values can be imputed and variables standardized before modeling to ensure comparability across indicators (Gao et al., 2024). To strengthen the case analysis, farm survey data can be linked with remote or gridded information on yields, water demand, and environmental footprints, as well as village or county benchmarks, so that the Zhejiang farm is evaluated not only in isolation but also relative to surrounding resource conditions and sustainability targets (Figure 3).

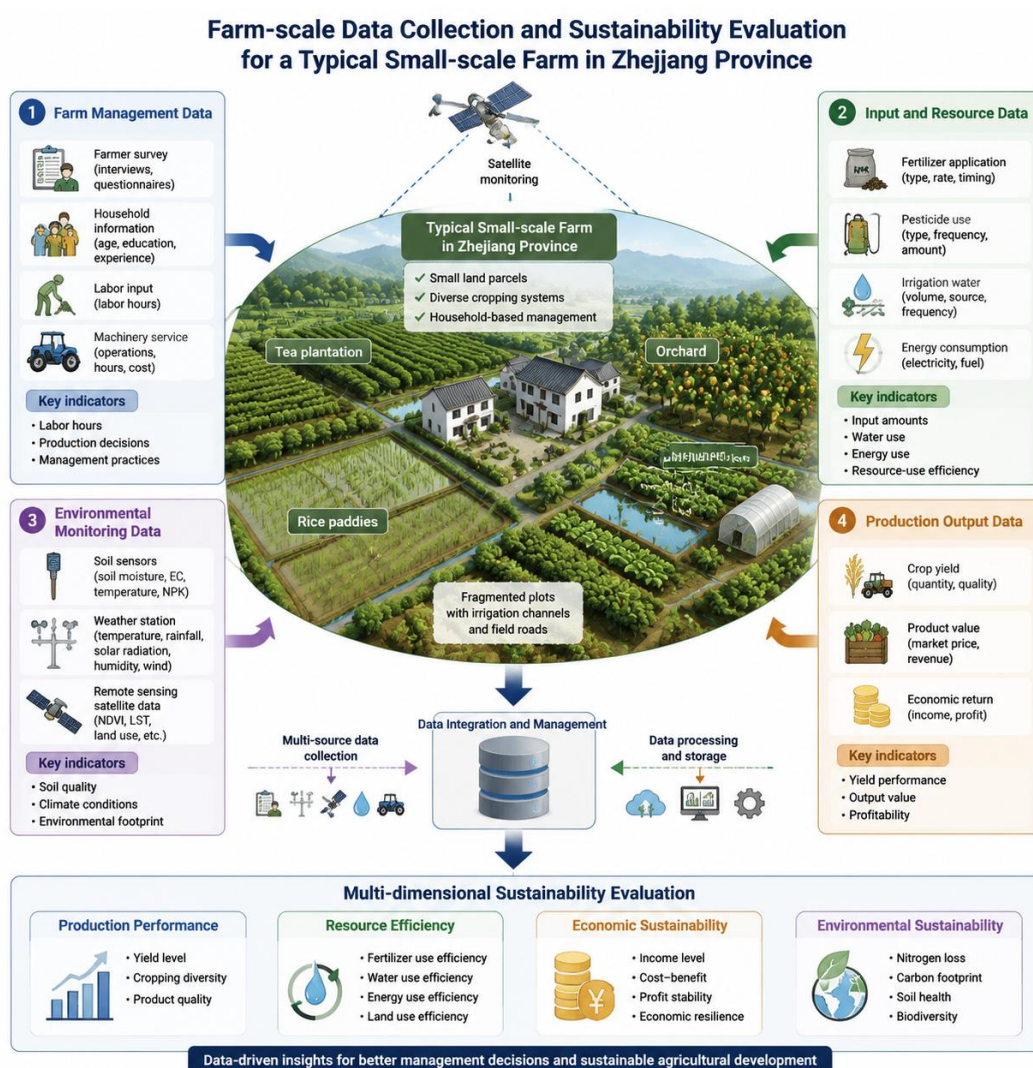


Figure 3 Conceptual framework of farm-scale data acquisition and sustainability evaluation for a typical small-scale farm in Zhejiang Province

## 6.2 Data analysis of sustainable agricultural practice performance

The performance analysis should focus on whether the case farm converts inputs into output and income with lower environmental cost than conventional smallholder practice. Evidence from millions of Chinese smallholders shows that the best-performing producers can achieve 15.3%-35.4% higher yields while using 16.0%-21.0% less nitrogen fertilizer, indicating that high productivity and lower input intensity can coexist within smallholder systems. At the same time, large-scale intervention data show that enhanced management increased yields by 10.8%-11.5% while reducing nitrogen application by 14.7%-18.1%, which makes nitrogen productivity and N-surplus reduction especially suitable indicators for judging the Zhejiang case farm's sustainability performance.

A second layer of analysis should examine trade-offs among economic return, eco-efficiency, and environmental pressure. Research using life cycle assessment and data envelopment analysis found that output-oriented eco-efficiency models can jointly evaluate yield, profit, and undesirable outputs such as carbon footprint, and that inefficient farms can still raise yield and profit while cutting emissions through better input combinations. This is important because cropping systems with the highest short-term profitability are not always the most sustainable: in smallholder comparisons, vegetable-based systems generated much greater profits but also much higher environmental pressure than wheat-maize or cotton systems, showing that the Zhejiang case should be assessed by a composite performance index rather than by yield or income alone (Guo et al., 2022).

### **6.3 Data-driven optimization strategies and application effects**

The optimization stage should identify which management adjustments produce the largest sustainability gains for the case farm under realistic smallholder constraints. Existing evidence indicates that nitrogen reduction is often the single most effective intervention, improving overall smallholder sustainability by 12%-14%, while formula fertilization and optimized sowing date and rate provide additional gains (Guo et al., 2024). More generally, multi-objective input optimization shows that pesticide use, working hours, irrigation water, and chemical nitrogen are key levers affecting food security, economic sustainability, resource sustainability, and environmental sustainability, so the Zhejiang case should prioritize these variables in its optimization scenarios.

The likely application effect is not a single maximal-yield solution but a coordinated improvement across production, income, and ecological outcomes. Scenario analysis in Chinese smallholder systems suggests that optimized planting structures and management strategies can cut global warming potential by 30%-57% while increasing profits by 102%-120%. At the broader system level, integrated optimization that redistributes crops and management under coordinated objectives can reduce water use, greenhouse gases, fertilizers, and pesticides while also increasing farmer income, which implies that the Zhejiang farm will benefit most when farm-level recommendations are connected to village-scale service support and regional planning rather than treated as an isolated household exercise (Xie et al., 2023). Overall, this Zhejiang case study supports a data-driven, multi-indicator, and optimization-oriented evaluation pathway. The central implication for Section 6 is that a typical small-scale farm can be assessed credibly only when household survey data, resource-efficiency indicators, and scenario-based optimization are integrated into one farm-level sustainability framework.

## **7 Optimization Pathways for Digitalization and Sustainable Development of Small-Scale Farms in Zhejiang Province**

### **7.1 Development of smart agriculture technology systems**

For Zhejiang's small-scale farms, the core digitalization pathway is to build smart agriculture technology systems around data collection, real-time monitoring, and precision decision support rather than simple equipment replacement. Precision agriculture research shows that data acquisition is fundamental to optimizing crop health assessment, resource allocation, and yield management, while the integration of IoT, AI, and machine vision can improve the precision and efficiency of farm operations (Marinello et al., 2023). Complementing this, smart farming studies indicate that low-cost sensors, network platforms, and real-time data systems can reduce water and energy use while supporting more targeted irrigation, fertilization, and pest control, which is especially relevant for Zhejiang's fragmented smallholder plots.

The practical design of these systems should emphasize affordability, interoperability, and farmer usability. IoT-based smart irrigation, remote crop monitoring, and decision-support systems already provide real-time information on irrigation efficiency, soil conditions, and field management, but their wider use in developing-country small farms still depends on public support and accessible service systems. More recent sensor-and-IoT reviews also show that broader adoption requires user-friendly devices, training, clear data governance, and collaboration among farmers, researchers, technology developers, and policymakers, suggesting that Zhejiang should promote digital platforms as shared service infrastructure rather than as stand-alone household investments (Mansoor et al., 2025).

## 7.2 Innovation of green agricultural production models

The innovation of green production models in Zhejiang should prioritize bundled management practices that improve yields and reduce environmental pressure at the same time. Large-scale evidence from China shows that enhanced management practices adopted by millions of smallholders increased yields by 10.8%-11.5% while reducing nitrogen application by 14.7%-18.1%, demonstrating that sustainable intensification is feasible when recommendations are locally adapted and operationally scalable. At the level of practice design, recent smallholder-system analysis further finds that nitrogen reduction has the largest positive effect on overall sustainability, followed by formula fertilization and optimized crop practices, which provides a clear sequence for Zhejiang's green-technology prioritization.

At the organizational level, green transformation should also include production models that strengthen specialization, facility access, and resource-use efficiency. Pilot evidence from the Tai Lake watershed shows that alternative farming models, including family, cooperative, and industrial forms, produced 7% higher yields with 8% less fertilizer, reducing pollutant emissions per hectare by 28% and increasing profit per hectare by 50%. This direction is reinforced by national evidence that new farming models generally perform better than traditional smallholder farming and tend to attract younger, more educated operators with stronger machinery and manure inputs, indicating that Zhejiang's green production innovation should combine ecological practices with moderate organizational upgrading (Ren et al., 2023).

## 7.3 Farmer participation and policy support mechanisms

Farmer participation is a decisive condition for whether digital and green technologies can move from demonstration to sustained adoption. Long-term evidence from the upgraded Science and Technology Backyard platform shows that technologies co-created through equal dialogue with farmers were more easily accepted and increased yields and nitrogen factor productivity in both wheat and maize, while broader diffusion became more effective when local governments, enterprises, universities, and farmers were linked through a "one-stop" multistakeholder program (An et al., 2024). Related survey evidence from Quzhou further shows that an enabling environment created through the synergy of social organizations and government support increased technology trust, willingness to adopt green technologies, and sustainable production outcomes, which is directly relevant for Zhejiang's institutional design.

Policy support should therefore move beyond uniform subsidies toward differentiated service, training, and participation mechanisms. Evidence from south China, including Zhejiang survey data, shows that agricultural socialized services significantly increase smallholders' green production behavior and encourage the adoption of organic fertilizer and soil-tested formula fertilization, supporting policies that expand joint service organizations and strengthen financial and legal service environments. At the same time, farmer motivation is heterogeneous: contract-based agri-environmental schemes work better when they are flexible and modular (Wang et al., 2026), cooperatives can help overcome participation constraints, and descriptive norms, perceived ecological value, and farmer organization all positively shape green behavior. Overall, the optimization pathway for Zhejiang small farms is to integrate digital tools, green practice bundles, and participatory policy mechanisms within one data-driven transition framework. Under this pathway, smart technology improves decision quality, green production models improve efficiency and ecological outcomes, and multistakeholder support improves the actual adoption capacity of smallholders.

# 8 Discussion

## 8.1 Advantages of data-driven evaluation in small-scale farm applications

A major advantage of data-driven evaluation is that it converts dispersed field observations into operational decisions on yields, inputs, and environmental performance, which is especially valuable in small farms where resource margins are narrow. Because precision agriculture links diagnosis, decision making, and input adjustment, it can improve resource-use efficiency while reducing production cost and environmental burden, making sustainability assessment more evidence-based than experience-only management (Marinello et al., 2023). For Zhejiang smallholders, this matters because even modest improvements in timing, fertilizer placement, irrigation, or pest response can produce proportionally large household-level benefits when adopted at plot scale.

A second advantage is that data-driven systems make sustainability evaluation more dynamic, predictive, and comparable across heterogeneous farms. Sensor monitoring, IoT platforms, and advanced analytics can provide real-time or near-real-time information that helps farmers adapt to changing soil, weather, and crop conditions rather than relying only on static annual records. Recent work also shows that farm-level decision support systems can combine multiple indicators into robust and comparable sustainability scores while still remaining usable for small and medium agricultural operators, which is important for Zhejiang's diverse small-farm structure (Falasco et al., 2025). At a broader level, predictive analytics and machine learning improve resource allocation for water, fertilizer, and energy, strengthening the value of data-driven evaluation as both an assessment method and a management tool.

### 8.2 Current limitations and challenges of data-based agriculture development

The main limitation is that the technical promise of data-based agriculture is advancing faster than the conditions needed for adoption in smallholder settings. Digital agriculture ecosystems remain unevenly developed, with rural areas often facing weaker infrastructure, lower affordability, and less support than better-connected contexts. Many smallholders still struggle with high upfront costs, fragmented land, limited awareness, weak digital skills, poor connectivity, and insufficient policy support, which slows the diffusion of precision technologies even when their agronomic value is recognized (Vijayakumar et al., 2025). This challenge is amplified by the fact that many existing digital solutions were originally designed for larger or wealthier farming systems and do not map well onto the fragmented and labor-constrained realities of small farms.

A second constraint is that data quality, interoperability, and trust remain unresolved. Data-driven agriculture requires not only collection but also cleaning, structuring, validation, and translation into useful recommendations; otherwise, raw data remain fragmented and difficult to apply in practice. In smallholder environments, reliable transmission and continuous monitoring are also difficult because devices are often deployed across remote or weakly connected areas with limited electricity and network access. Beyond technical issues, adoption is constrained by concern over who benefits from farmer-generated data, along with uncertainty about ownership, privacy, and rights of use, all of which weaken willingness to share data across the agricultural value chain (Sullivan et al., 2024). These barriers help explain why understanding of data-driven agriculture's sustainability effects remains incomplete and, in some areas, still at an early stage.

### 8.3 Future research directions

Future research should move beyond proving that digital agriculture can work and focus instead on building systems that are affordable, explainable, and context-adapted for small farms. Current reviews point to clear gaps in digital literacy, affordability, business-model innovation, and data trust, suggesting that the next stage of research should treat these as core design variables rather than external constraints (Gumbi et al., 2023). The literature also calls for more user-friendly applications that respond to diverse smallholder needs and to the social and cultural differences across farming communities, which is highly relevant for Zhejiang's varied production environments. Technically, future work should strengthen integrated datasets by fusing sensor, remote-sensing, soil, and weather data while improving AI explainability and semantic integration so that recommendations are both accurate and understandable.

A second research priority is to link technical innovation with participatory scaling and long-term validation. Evidence from collaborative smallholder programs in China shows that technologies are adopted more readily when farmers participate through equal dialogue and when government, researchers, enterprises, and farmers are connected through multistakeholder support systems. Other recent work suggests that low-cost, modular spatiotemporal data infrastructures, including citizen-generated data and affordable IoT devices, can make farm-level monitoring more inclusive while also improving local engagement. For Zhejiang, future studies should therefore test integrated evaluation frameworks over longer time horizons, compare farm types and subregions, and assess whether data-driven recommendations remain effective when scaled from pilot farms to village and county systems. Overall, Section 8 indicates that data-driven evaluation is a strong pathway for improving the sustainability assessment of Zhejiang small farms, but its success depends on whether technical sophistication is

matched by accessibility, participation, and institutional trust. Future progress in Zhejiang will therefore rely less on adding isolated technologies than on building a smallholder-oriented data ecosystem that connects evaluation, decision support, and inclusive implementation.

## 9 Conclusions

The comprehensive evaluation of sustainable agricultural practices in Zhejiang's small-scale farms reveals a system in transition, where resource-use efficiency has improved steadily but unevenly across regions and farm types. Provincial-level data from 2013 to 2019 demonstrate that Zhejiang made measurable progress in agricultural sustainable development, yet distinct spatial disparities persisted across its 11 prefecture-level cities and 25 national pilot demonstration zones, indicating that efficiency gains were real but not uniformly distributed. This unevenness reflects the broader structural heterogeneity of small-scale farming in the province, where differences in land fragmentation, household capital, and local agroecological conditions produce widely varying capacities for adopting sustainable practices. The evaluation framework must therefore account for regional and operational diversity rather than assuming a uniform trajectory of improvement across all small farms. At the farm-operation level, the strongest sustainability signals emerge from integrated management adjustments rather than isolated input reductions. Large-scale on-farm evidence shows that optimizing nitrogen application can raise yields by 10%-19% while cutting nitrogen rates by 15%-19%, increasing nitrogen use efficiency by 32%-46% and reducing nitrogen surplus by 40%, even without altering the basic smallholder operational structure. Similarly, enhanced management practices adopted across millions of Chinese smallholders increased average yields by 10.8%-11.5% while reducing nitrogen application by 14.7%-18.1%, confirming that sustainable intensification is achievable within existing smallholder systems. These findings suggest that Zhejiang's evaluation of sustainable practices should prioritize multi-indicator performance indices that capture yield, input efficiency, economic return, and environmental pressure simultaneously, rather than relying on any single metric.

Data technologies play a decisive role in the green transformation of small-scale farms by converting dispersed field observations into operational decisions that improve both productivity and environmental outcomes. Precision agriculture systems that integrate IoT sensors, remote sensing, and machine learning enable real-time monitoring of soil conditions, water use, and crop health, allowing farmers to adjust irrigation, fertilization, and pest management with greater accuracy than experience-based management alone. For Zhejiang's fragmented smallholder plots, where resource margins are narrow and agroecological heterogeneity is high, the ability to generate fine-resolution spatial and temporal recommendations is particularly valuable. Spatial optimization research demonstrates that high-resolution crop reallocation models can achieve up to 205% higher economic benefit increments and 283% greater water savings than county-scale models, showing that spatial granularity directly improves the quality of resource allocation decisions. Beyond monitoring and spatial analysis, multi-objective optimization models strengthen green transformation by making trade-offs among economic, environmental, and social objectives explicit and computable. Farm-system models that generate Pareto-optimal sets of alternative configurations allow decision makers to compare trade-offs among profit, labor demand, soil nitrogen loss, and other sustainability indicators, rather than defaulting to yield maximization alone. Applied water-energy-food nexus models have reduced water use by 2.56%, energy use by 12.71%, and environmental impacts by 6.82% while improving farmers' social conditions, and farm-level optimization platforms have identified irrigation and nitrogen schemes that reduced water use by 48%, nitrogen input by 26%, and nitrogen leaching by 51%. These results confirm that data-driven models are not merely assessment tools but active instruments for designing greener production systems. Machine learning further enhances this capacity by predicting crop performance under different management scenarios, with random forest models demonstrating strong accuracy in yield prediction and hybrid process-based emulator approaches reproducing over 90% of spatial variance in simulated yield and soil organic carbon.

The future sustainable development of Zhejiang's small-scale farms depends on building affordable, participatory, and institutionally supported data ecosystems rather than deploying isolated technologies. Current evidence shows that digital agriculture adoption among smallholders is constrained by high upfront costs, fragmented land, limited digital literacy, poor connectivity, and insufficient policy support, all of which slow diffusion even when

agronomic value is recognized. Many existing precision agriculture solutions were designed for larger or wealthier farming systems and do not map well onto the fragmented, labor-constrained realities of small farms, creating a persistent mismatch between technical promise and practical adoption. Addressing this gap requires user-friendly, low-cost, modular digital tools that respond to diverse smallholder needs and respect the social and cultural contexts of farming communities, supported by shared service infrastructure rather than standalone household investments. The second key direction is to strengthen participatory scaling mechanisms and long-term institutional support. Evidence from collaborative smallholder programs demonstrates that technologies co-created through equal dialogue with farmers were more easily accepted and increased yields and nitrogen factor productivity in both wheat and maize, while broader diffusion became more effective when local governments, enterprises, universities, and farmers were linked through multistakeholder support systems. Agricultural socialized services have been shown to significantly increase smallholders' green production behavior, including the adoption of organic fertilizer and soil-tested formula fertilization, supporting policies that expand joint service organizations and create favorable financial and legal service environments. Farmer participation is heterogeneous, with contract-based agri-environmental schemes working better when they are flexible and modular, cooperatives helping overcome participation constraints, and descriptive norms positively shaping green behavior. For Zhejiang, the central implication is that future progress will rely less on adding isolated technologies than on building a smallholder-oriented data ecosystem that connects evaluation, decision support, and inclusive implementation across farm, village, and county scales. Long-term validation studies should test whether data-driven recommendations remain effective when scaled from pilot farms to broader regional systems, ensuring that the green transformation of small-scale agriculture is both technically sound and socially sustainable.

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