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Designing an IoT– Islamic Green Finance Ecosystem: A Multi-Layer Model for Solar Smart Irrigation in Rural Indonesia

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Abstract - Climate change is intensifying droughts and increasing rainfall uncertainty, posing a direct threat to smallholder agricultural productivity in developing countries, including Indonesia. Meanwhile, the global sustainable finance agenda requires measurable and verifiable impacts to ensure that instruments such as green sukuk and Islamic green finance go beyond normative commitments. This study proposes a conceptual model of an integrated IoT–Islamic green finance ecosystem called the Shariah-compliant Irrigation and Climate-smart System (SICS), *designed for solar-powered smart irrigation in rural Indonesia. The model integrates: (1) an Internet of Things (IoT) technological infrastructure enabling real-time monitoring of soil moisture and solar pump performance; (2) a multi-layered Islamic green financing mechanism that combines green sukuk, Islamic bank financing, and Islamic social funds; and (3) a sustainability impact measurement system based on environmental, social, and economic indicators that are linked to project cash flows. A conceptual design approach is employed by synthesizing recent research on green sukuk and Islamic green finance with advancements in IoT-based smart irrigation, alongside a contextual analysis of Cigadog Village as a representative agricultural community in West Java, Indonesia. The key contributions of this article include: (a) addressing the gap in project-level (micro-level) research, which has thus far been dominated by macro-financial system perspectives; (b) proposing a replicable modular architecture applicable to clusters of rural villages; and (c) developing an impact indicator framework that can be directly aligned with reporting standards required of green sukuk issuers. Practically, the SICS model provides a scalable prototype that can be adopted by local governments, Islamic financial institutions, and green investors to structure bankable irrigation projects at the village level, while simultaneously complying with Shariah principles and advancing sustainable development goals.*

Keywords: Islamic green finance, green sukuk, Internet of Things, smart irrigation, sustainable development goals

I. BACKGROUND

Climate change and worsening water scarcity have become increasingly significant threats to agricultural productivity, particularly in Asia, which faces heightened exposure to floods, droughts, and heat waves that disrupt smallholder livelihoods and food security (LSEG & Islamic Corporation for the Development of the Private Sector, 2023; Rofik et al., 2025). In Indonesia, pressures on water resources have intensified due to environmental degradation, demographic change, and shifting rainfall patterns, leading to greater uncertainty in river flows and the performance of traditional irrigation systems relied upon by rural farming communities (Uddin & Ahmed, 2018). Reports of repeated crop failure during prolonged droughts highlight the vulnerability of smallholder farmers and underscore the need for more adaptive irrigation solutions (Uddin & Ahmed, 2018). The literature on climate-smart agriculture emphasizes technologies such as soil-moisture sensing, precision irrigation, and renewable energy as essential tools for strengthening agricultural resilience (Taghizadeh-Hesary & Yoshino, 2019). IoT-powered smart irrigation systems, especially those integrated with solar energy, offer promising opportunities for irrigation efficiency in rural Indonesia; however, adoption barriers remain high due to upfront investment costs and the absence of viable, farmer-friendly financing models (Hayati et al., 2025;Sutoyo et al., 2024;Ramdani et al., 2023). For Muslim-majority rural areas, the suitability of financing instruments also requires alignment with sharia principles. Islamic green finance therefore plays a strategic role, functioning not only as a funding source but also as a governance mechanism linking environmental, social, and economic objectives. Research by University of Muhammadiyah Yogyakarta (UMY) scholars demonstrates that aligning *"maqasid al-shariʿah"* with Sustainable Development Goals (SDGs) provides a conceptual foundation for Islamic financial innovation in sectors such as agriculture and renewable energy (Astuti & Rahmawati, 2024; Hudaefi & Beik, 2021; Wiranatakusuma & Arundina, 2011). Empirical studies in Indonesia further show that green banking practices, strong sharia governance, and transparent sustainability reporting enhance the legitimacy and performance of Islamic banks (Bose et al., 2018; Handajani et al., 2019; Sharmeen & Yeaman, 2020; Widiyanti et al., 2025; Wiranatakusuma & Firmansyah, 2022).Regulatory frameworks issued by the Financial Services Authority (OJK; 2017, 2018) and civil-society initiatives such as ResponsiBank (2014) promote sustainable finance and green disclosure, creating an enabling environment for Islamic green-finance products targeting renewable energy and climate-adaptation projects. Despite this progress, most Islamic green-finance applications remain concentrated at the institutional level, while project-level mechanisms tailored to smallholder agriculture are still limited (Bose et al., 2018).

A notable gap exists at the intersection of IoT-based irrigation technologies, sharia-compliant financing models, and measurable sustainability outcomes. Real-time data from IoT systems such as water-use efficiency, pump energy sources, and soil-moisture dynamics could strengthen impact assessment, repayment modeling, and sustainability reporting. Integrating these data streams with Islamic green-finance structures offers an opportunity to enhance credibility, reduce information asymmetry, and support compliance with national reporting standards (OJK, 2017, 2018). Against this backdrop, the present study develops a conceptual model for sharia-compliant green financing of an IoT-based smart irrigation system (SICS) in Cigadog Village. The model links the technological layer, the Islamic financing layer, and the governance and sustainability-outcome layer into a unified framework (Winarto, 2025;Taghizadeh-Hesary & Yoshino, 2019; LSEG & Islamic Corporation for the Development of the Private Sector, 2023), addressing current gaps in project-level Islamic green-finance innovation.

II. MOTIVATION

Despite technological advancements, adoption of smart irrigation systems in Indonesian villages remains limited due to three structural barriers:

a. *High upfront investment costs*

Solar panels, pumps, IoT sensors, and storage batteries require significant capital outlays that are unaffordable for most smallholder farmers.

b. *Lack of Shariah compliant green financing structures at the project (micro) level*

Existing Islamic green finance literature focuses on institutional and macro-level initiatives; green sukuk, Islamic bank green portfolios while neglecting smallholder oriented financing models.

c. *Limited integration between IoT-generated impact data and Islamic financing governance.*

Islamic banks face challenges in verifying environmental impact due to insufficient real-time, verifiable project data, resulting in risks of greenwashing and weak sustainability reporting.These gaps highlight the urgent need for a project-level, measurable, and scalable Shariah-compliant green financing ecosystem capable of supporting rural irrigation transformation.

III. OBJECTIVE

This study aims to design a conceptual model called the Shariah-compliant Irrigation and Climate-smart System (SICS), a multi-layer ecosystem that integrates:

1. IoT-based solar smart irrigation technology,
2. Layered Islamic green financing mechanisms, and
3. A comprehensive sustainability impact measurement framework,

to support climate-resilient agriculture in Cigadog Village, West Java.

Specifically, this study seeks to answer:

1. What is the technical and cost structure of SICS?
2. How can a multi-layer Islamic green financing scheme be designed for smallholder adoption?
3. How can IoT data be integrated into sustainability reporting to meet green sukuk and Islamic green finance standards?

IV. CONTRIBUTION AND METHODS

A. Contribution

This study attempts to provide four major contributions to Islamic green finance and climate-smart agriculture literature:

a. *A project-level model bridging IoT technology and Islamic green finance*

The SICS model operationalizes the link between real-time IoT irrigation data, financing design, and sustainability outcomes, an area rarely explored in prior research.

b. *A layered Islamic financing scheme (micro–meso–macro)*

The model introduces structured participation from farmers, Islamic financial institutions, technology providers, and green sukuk investors.

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c. *A standardized sustainability indicator framework*
Indicators align with OJK sustainable finance regulation and global green sukuk reporting standards.
d. *A replicable modular architecture*
SICS can be scaled to village clusters and integrated into national sustainable agriculture programming.

B. Methods

This study adopts a conceptual design methodology, comprising:

a. Systematic literature synthesis
Covering Islamic green finance, green sukuk, green banking, IoT irrigation technologies, and Indonesia's sustainable finance regulations.
b. Field observations and interviews in Cigadog Village
To capture irrigation vulnerabilities, farmer perceptions, financial constraints, and local socio-economic context.
c. Technical economic analysis of the SICS prototype
Components analyzed include solar panel capacity, sensors, pump specifications, IoT controller configuration, and cost structure
d. Development of an integrated ecosystem framework
Synthesizing technological, financial, and governance layers into a single coherent model.

V. RESULTS

A. Analyzing Systematic Literature

1. Islamic Green Finance and Islamic Climate Finance . Islamic green finance refers to the use of sharia-compliant instruments such as sukuk, *murabaḥah*, *ijarah*, and productive waqf to fund projects that deliver environmental and social benefits while upholding Islamic principles, including the prohibition of *riba, gharar,* and *maysir* (World Bank & SCM, 2019). In the context of climate finance, these instruments support mitigation and adaptation initiatives such as renewable energy, energy efficiency, and resilient infrastructure (ADB, 2022). Research in OIC countries shows that Islamic finance can directly contribute to the green economy when aligned with national sustainability policies and channeled into climate-related projects (Wardani et al., 2025). However, fragmentation among product innovation, governance capacity, and the availability of bankable projects remains a key barrier, as many regions still lack uniform reporting standards, strong institutions, and credible pipelines of green investments. From an Indonesian perspective, addressing climate vulnerability in rural communities requires integrated Islamic green-finance ecosystems that respond to local environmental conditions and livelihood dynamics, rather than macro-level financial discourse alone (Saptutyningsih, 2020).

2. Green Sukuk and Sustainable Finance in Indonesia . Green sukuk has become a central instrument in Indonesia's Islamic green-finance landscape, driven by strong government commitment and supportive regulatory frameworks (Rokhmatuloh & Wiranatakusuma, 2021). Since 2018, Indonesia's sovereign green sukuk has attracted global investor interest and financed renewable energy, sustainable transport, and other strategic green projects under the Green Bond and Green Sukuk Framework (World Bank & SCM, 2019). National policies including OJK's Sustainable Finance Roadmap Phase II and the Sharia Banking Strengthening Roadmap encourage financial institutions to integrate environmental and social risk considerations (OJK, 2023). Nevertheless, most green sukuk initiatives remain concentrated at the sovereign or corporate level, with limited mechanisms for financing small-scale rural projects (Paltrinieri et al., 2023; Prayogo et al., 2024). To build a more inclusive ecosystem, Indonesian scholarship calls for pipelines of standardized, sharia-compliant green projects that can be aggregated into investable portfolios (Darsono, 2022), supported by environmental screening and sustainability reporting that enhance institutional credibility (Johari, 2025). Evidence from UMY researchers further highlights the importance of governance quality, transparency, and investor participation for the success of green sukuk instruments (Wiranatakusuma & Firmansyah, 2022), while effective sharia governance and strong reporting practices help strengthen public trust (Syihabuddin et al., 2023).

3. Smart Irrigation Based on IoT and Solar Energy . IoT-based smart irrigation systems employ sensors, actuators, and wireless connectivity to monitor soil and environmental conditions and automate irrigation processes. Empirical studies show that integrating IoT controls with solar-powered pumps can significantly reduce water consumption and provide stable, renewable energy for irrigation activities (Al-Ali et al., 2020). Research in developing countries similarly finds that solar-powered automated pump systems can replace diesel units, leading to substantial savings in fuel costs and emissions (Yatnalli, 2023). In Indonesia, although several prototypes of sensor-based solar irrigation systems have been tested in small plots, very few have progressed into scalable village-level schemes with long-term financing mechanisms (Ardianto et al., 2025). Key challenges include high installation costs, limited local technical capacity, and uncertainty about how financial risks and future cash flows should be shared among farmers, financial institutions, and potential investors.

B. Irrigation Vulnerabilities in Cigadog Village

Observations and interviews in Cigadog Village confirmed that irrigation vulnerability is a key production problem. Most farmers still rely on a combination of rainfall and manually operated conventional pumps. Irrigation schedules are determined by experience and labor availability, rather than objective indicators such as soil moisture or plant growth phase. Consequently, several consistent vulnerability patterns emerge:

a. Inefficient water use
b. High and fluctuating energy costs
c. Heavy manual labor burden
d. Strong climate sensitivity
e. Lack of affordable Islamic financing for irrigation technology

In interviews, farmers expressed strong interest in automated and precision irrigation technologies**,** but highlighted two key barriers: (1) the perceived prohibitive initial investment costs , and (2) the lack of clear Islamic financing schemes specific to smart irrigation technologies. Thus, farmers welcome automation but emphasize cost and unclear financing as primary constraints. These contextual findings make it clear that SICS ecosystem design cannot stop at technical aspects, but must simultaneously integrate technological solutions, financing schemes, and impact governance.

C. Technical and Cost Structure of SICS

The SICS prototype developed in this research consists of several main components: (1) solar panels and inverters with capacities adjusted to the pump power and system energy requirements; (2) water pumps with certain discharge and head specifications sufficient to irrigate the target plot of land; (3) soil moisture sensors installed at representative points on the land; (4) a microcontroller-based IoT controller (e.g., ESP32) that integrates sensor data and irrigation control logic; and (5) a piping and valve system that supplies water to the plants. In general, the components that absorb the largest portion of costs are solar panels and energy storage systems (batteries), followed by pumps, sensors and IoT modules, piping infrastructure, and installation and training costs. First-year operation and maintenance (O&M) costs are relatively smaller than the initial investment costs, but must be taken into account when designing installments and financing terms. SICS investment cost structure is summarized that consists of :

a.	Solar panels + inverter	Rp 25,000,000.-
b.	Water pump	Rp 3,000,000.-
c.	IoT sensors and modules	Rp 1,000,000.-
d.	Battery storage and energy storage	Rp 3,500,000.-
e.	Irigation Pipes and infrastructure	Rp 4,000,000.-
f.	Installation and training	Rp 4,000,000.-
g.	1st year operational& maintenance cost	Rp 2,500,000.-
Total estimated investment		Rp 43,000,000.- per unit

D. Layered Sharia Green Financing Scheme

Based on field findings and a literature synthesis, this study proposes a layered Islamic green financing model involving micro, mesos, and macro levels. The design of this scheme is summarized in Table 1.

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Table 1. Design of a Layered Sharia Green Financing Scheme

Level	Main Actors	Main Sharia Contract	Financing Object	Funding Sources	Payment Mechanism
Micro	Farmer groups (Islamic microfinance institution – LKS)	Asset **Murabaha** / **Musharakah Mutanaqisah** (diminishing partnership)	SICS package (solar panels, pumps, sensors, IoT devices)	Islamic micro-financing funds from Sharia LKS	Installments aligned with harvest seasons; direct deduction from crop sales proceeds
Meso	Farmer groups / technology providers	**Ijarah** / service contract	Installation, maintenance, and system upgrades	Operating fees financed from farming business income	Service fees paid annually or every harvest season
Macro	Government / investors (Sharia financial institutions)	**Green Sukuk** / productive **Waqf**	Shared infrastructure, margin subsidies	Green sukuk, waqf funds, and ZIS (zakat, infaq, sadaqah)	Long-term return based on project performance

At the micro level, the primary relationship is between farmer groups and Islamic financial institutions through asset *murabahah* (asset sharing) or *musyarakah mutanaqisah* (asset sharing). At the mesos level, farmer groups establish contractual relationships with technology providers through *ijarah* contracts, or service agreements. The technology provider is responsible for system installation, maintenance, and upgrades; while the farmer group pays a periodic service fee. At the macro level, the government or institutional investors can use green sukuk or productive waqf to finance shared infrastructure and/or subsidize financing margins for poor farmer groups, thereby making financing more affordable.

D. Sustainability Indicators

The integration between the technology layer, green Islamic financing, governance and data, and sustainability outcomes is summarized in the "IoT–Sharia Green Finance–Sustainability Outcomes" framework shown in Figure 1. In brief, this framework describes the flow: (1) design and installation of SICS–IoT; (2) collection of IoT operational data; (3) analysis of impacts and risks by Islamic financial institutions; (4) design of green Islamic financing products; (5) implementation of financing schemes and SICS operations; (6) achievement of sustainability outcomes; and (7) feedback loop through reporting and governance.

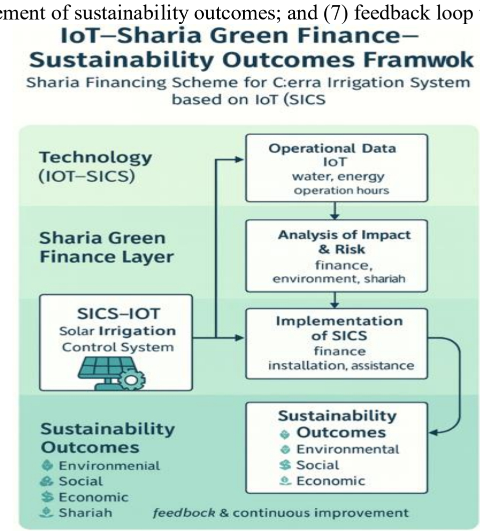

Figure 1. Framework "IoT–Sharia Green Finance–Sustainability Outcomes"

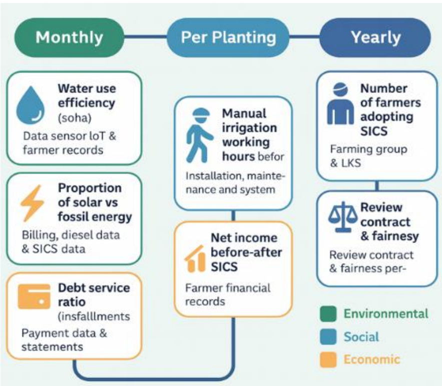

Figure 2. Roadmap for Monitoring the Impact of SICS–IoT and Sharia Financing

The figure 2 shows a roadmap for monitoring SICS–IoT and sharia green financing impacts. Monthly indicators track water efficiency, fossil fuel reduction, and cash flow. Seasonal checks assess irrigation workload and farmer income. Annual monitoring reviews beneficiaries, contract fairness, and sustainability reporting. This structured system supports informed technical, financial, and sharia governance decisions.

To operationalize *sustainability outcomes* within the "IoT–Sharia Green Finance–Sustainability Outcomes" framework, this study formulated a structured set of indicators.These indicators were designed not only to capture technical changes at the farm level, but also to capture socio-economic implications for smallholder farmers as well as the consistency of financing practices with sharia principles and the national sustainable finance framework. Indicators include:

a. Environment: water efficiency, reduction of fossil fuel use
b. Social: number of beneficiaries, workload reduction
c. Economic: farmer net income, debt service ratio
d. Sharia and Governance: contract fairness, sustainability reporting

VI. DISCUSSION

A. Integration of IOT and Islamic Green Finance

The findings indicate that SICS–IoT operates as both a resource-efficiency instrument and a governance mechanism capable of producing verifiable, real-time performance indicators. These data streams allow Islamic financial institutions to evaluate project feasibility and impact with greater precision, thereby lowering informational asymmetry and mitigating *gharar*. This aligns with scholarship emphasising that effective green banking and Islamic finance frameworks require credible impact evidence to support prudent decision-making. Empirical work on Indonesia's climate-vulnerable rural regions further underscores the need to integrate environmental outcomes into financing structures (Saptutyningsih, 2020), while research across OIC economies demonstrates that Islamic finance can advance low-carbon transitions when backed by coherent impact frameworks and policy alignment (Wardani et al., 2025). From a financial-sector perspective, sustainable investment and Islamic capital-market studies underline the need for pipelines of well-structured green projects that can feed into sukuk and other capital-market instruments (Darsono, 2022), while green banking analyses in Indonesian sharia banks emphasise the role of environmental screening and disclosure in strengthening institutional performance and legitimacy (Johari, 2025).

B. Layered Model and Ecosystem of Islamic Green Finance. The multi-layered SICS financing design reflects the broader conceptualisation of Islamic climate-finance ecosystems, in which micro-level contract arrangements, meso-level technological support, and macro-level policy instruments such as green sukuk and productive waqf must function in coordinated sequence. This is consistent with arguments that capital-market development depends on standardised contracts and structured risk-sharing (Darsono, 2022) and with studies highlighting environmental screening and disclosure obligations within Islamic banks (Johari, 2025). Positioned as a village-scale prototype, SICS demonstrates how integrated technological and financial architectures can form a pipeline of climate-smart, sharia-compliant investment opportunities. The study also describes that successful adoption requires coordinated action between farmers, technology firms, Islamic financial institutions, and regulators. In addition, SICS also aligns with OJK's Sustainable Finance Roadmap, Indonesia's Green Sukuk Framework and SDG targets for clean water, energy transition, and climate adaptation. Johari (2025) suggests that Islamic banks adopting SICS-type projects can simultaneously strengthen their sustainability profiles and comply with national sustainable-finance regulations.

C. Implications for Policy and Practice . From the standpoint of environmental and development policy, empirical work on rural climate vulnerability in Indonesia indicates that adaptation investments must be closely linked to local livelihood structures and water-resource management (Saptutyningsih, 2020). Positioning SICS within regional development and climate-adaptation programmes would therefore allow Islamic green finance to respond directly to territorially specific climate risks rather than supporting generic, top-down projects. Aligning local SICS initiatives with national green sukuk frameworks and regional adaptation plans could also create a clearer pipeline of projects for both domestic and international green investors (Wardani et al., 2025). In this regard, the integration of IoT-based indicators into sharia-compliant financing structures can support Islamic banks and Baitul Maal wa Tamwils (BMTs) / Islamic microfinance institutions in implementing the kind of green banking practices and disclosure standards discussed in Johari (2025), while ensuring that impact reporting remains grounded in real-time project performance. Consequently, SICS-type projects can function as pilot cases through which Islamic financial institutions gradually internalise sustainability considerations into their core risk-management and product-design processes.

VII. CONCLUSIONS

This study introduces a conceptual model of the Shariah-compliant Irrigation and Climate-smart System (SICS), an IoT-based ecosystem designed to support Islamic green finance for solar-powered irrigation in rural Indonesia. By integrating IoT infrastructure, a layered Islamic green financing structure, and measurable impact indicators, the model connects Islamic green finance principles with the practical needs of smallholder farmers facing climate pressures. Theoretically, SICS advances Islamic green finance literature by embedding real-time technical data into financing design and impact reporting. Practically, it offers a roadmap for governments, Islamic financial institutions, and investors to develop bankable village irrigation projects aligned with green sukuk and sustainable-finance standards. Realizing this model requires coordinated actor participation, strengthened technical and institutional capacity, and enabling policies for small-scale Islamic green financing, while future field testing, financial modelling, and IoT-based reporting standards will be essential for maturing SICS into an implementable project framework capable of supporting irrigation transformation and rural food-security goals.

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