Kampot Cooling

Innovative Technology Solution to Save Cambodia's World-Famous Pepper

PERFORMANCE ANALYSIS OF INNOVATIVE SOLAR-POWERED COOLING AND IRRIGATION SYSTEM FOR IMPROVING PEPPER FARMS

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Implemented by:

People in Need

Banteay Srei

Fair Farms

SOGE Solar Green Energy Cambodia

This project is supported by the Asian Development Bank (ADB) through the Innovation Hub and High-Level Technology (HLT) Fund.

Executive Summary

The project aimed to assess how effectively a solar-powered cooling and irrigation system could reduce heat stress, improve water-use efficiency through modern irrigation practices, strengthen the resilience of pepper producers—especially women workers—and generate evidence to support future scale-up. Data was collected through soil sampling, climate analysis (2022–2025), baseline surveys on cultivation and irrigation practices, installation of temperature-monitoring systems in test and control plots, technical assessments of cooling, fogger, solar, battery, and drip irrigation components, user interviews, and an economic analysis based on avoided losses.

Results show that both farms faced severe heat stress, with peak temperatures reaching 40–44°C—far above the optimal 32–33°C for pepper. These extremes led to major yield reductions: Fair Farm lost around 30–40% of vines and 6–7 tons in 2022, while Reaksa Farm's yield fell from 1 ton to 300–400 kg in 2023. Soil tests identified sandy loam soils with low organic matter and nitrogen, and both farms relied mainly on visual assessment for irrigation. Shifting from manual to drip irrigation can reduce water use by roughly 50%.

The cooling system performed strongly, lowering canopy temperatures by 8.2°C at Fair Farm and 7.4°C at Reaksa Farm, while foggers-maintained humidity and limited heat stress during peak hours. Solar power met most of the system's energy needs. Farmers reported easier operations, cooler working conditions, and overall satisfaction. Fair Farm's system ran smoothly, while Reaksa Farm experienced minor power interruptions but received adequate support.

The economic analysis indicates significant financial benefits: avoided losses per heatwave (USD 42,000–53,000 per hectare) exceed the system cost of USD 18,667 per hectare by a factor of 2.3–2.9. One major avoided heatwave can fully repay the investment in a single season, with larger coverage areas reaching break-even even faster. Overall, the system effectively reduces heat impacts, improves water efficiency, and protects farmers from severe losses. Its strong technical performance, positive user feedback, and compelling economic returns support scaling up the system across Kampot pepper farms to enhance climate resilience and safeguard Cambodia's PGI-certified pepper industry.

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1. Introduction

The Kampot Cooling: Innovative Technology Solution to Save Cambodia's World-Famous Pepper is a one-year ADB funded project. The Kampot Cooling project featuring innovative solar powered cooling solutions is being designed and tested on Cambodia's world-famous Kampot Pepper cultivation to mitigate climate change impacts, including severe heat episodes and prolonged drought conditions, which have had devastating impact on the 2024 harvest. The project will design and install a cost-efficient cooling solution to ensure the long-term sustainability of one of Cambodia's key agricultural products in the face of climate change impacts, while also building the resilience and capacity of women workers in the peppercorn value chain to mitigate current and future climate change impacts.

PIN in collaboration with SOGE company, Banteay Srei organization and Fair Farm, has piloted the technology at two Kampot Pepper farms located in Kampot and Kep Provinces, with the objective of understanding the technology's impact on cultivation, operations and its ability to mitigate extreme heat and prolonged drought conditions. Additional project activities include a gender empowerment training series and awareness-raising activities aimed at fostering local buy-in and supporting the scalability of the technology.

2. Background

Solar-powered cooling solutions are currently being developed and tested in Cambodia's Kampot pepper cultivation. This initiative aims to address the pressing challenges posed by climate change, such as severe heat and prolonged drought, which significantly impacted the 2024 harvest. The primary goal of this project is to create a cost-effective cooling system that not only ensures the sustainability of this vital agricultural product but also enhances the resilience of women workers involved in the peppercorn value chain.

The technology being explored focuses on several key strategies:

- Lowering ambient air temperatures through the use of misting systems or sprinklers, which can help create a more favourable microclimate for the pepper plants.
- Implementing water-efficient ground-level irrigation techniques to optimise water resources, thereby reducing waste and ensuring that crops receive the necessary hydration even during dry spells.

Currently, this innovative technology is being piloted at two farms, i.e., Fair Farm and Reaksa Farm, in Kampot and Kep Provinces. The current assignment aims to evaluate its impact on the pepper cultivation practices, operational efficiency, and overall effectiveness in mitigating the impacts of extreme heat and prolonged periods of drought.

3. Objective

The primary objective of this report is to provide a thorough and comprehensive assessment of the pepper cultivation practices employed at the two farms, along with an evaluation of the effectiveness of the innovative solar-powered cooling and irrigation system that have been piloted in these two farms.

Specifically, this final evaluation report will serve as a crucial reference point for future comparisons and assessments following the implementation of the solar-powered cooling and irrigation systems. Additionally, this report presents the findings from the assessment of the performance of the piloted technology. Furthermore, it includes targeted recommendations for areas that require improvements, ensuring that future initiatives can build on the lesson learned from this pilot project.

4. Literature Review

4.1. Best Practices in Pepper Production

Pepper (*Piper nigrum L.*) thrives in humid tropical regions situated between approximately 20° N and S latitude, where it enjoys optimum temperatures around 28°C and an annual rainfall ranging from 1,250 to 2,000 mm (ICAR-IISR, 2019). For optimal productivity, it is crucial that pepper is cultivated in areas that receive at least 1,750 mm of rainfall each year, with the best performance typically observed in regions receiving between 2,000 and 3,000 mm of rainfall annually. A distinct dry season is particularly advantageous for flower induction, while supplemental irrigation becomes necessary during extended dry spells to ensure consistent growth and yield (IPC, 2007). Additionally, maintaining a relative humidity level above 70% is essential for promoting vigorous vine growth.

The soils best suited for pepper cultivation are sandy loam to clay loam, characterised by being well-drained and porous, with a slightly acidic reaction. The recommended soil pH range for optimal growth is between 5.5 and 6.5, as this range ensures maximum nutrient availability and encourages healthy root systems (IPC, 2007). It is vital to avoid waterlogging through adequate drainage systems, and mulching is highly recommended to help conserve soil moisture, particularly during drier periods (ICAR-IISR, 2019). Good Agricultural Practices (GAP) also emphasise the importance of water-use efficiency, advocating for methods such as drip or pitcher irrigation, proper scheduling of irrigation, and the utilisation of uncontaminated water sources to maintain crop health (IPC, 2007).

In terms of field establishment, it is recommended to follow a spacing of 1,100 to 1,600 vines per hectare. This process should include the preparation of planting pits through methods such as solarisation and the incorporation of organic amendments to enrich the soil. Around each vine, a weed-free zone with a radius of about 60 cm should be maintained, which, when combined with mulching, helps suppress weed growth and preserves soil moisture (IPC, 2007). Furthermore, live supports for the pepper vines must be pruned regularly to allow filtered light to reach the plants and to minimise the incidence of diseases. Best practices suggest conducting at least two pruning cycles per year to maintain optimal growth conditions (ICAR-IISR, 2019; IPC, 2007). A summary of Good Agricultural Practices for peppercorn is given in Table 1.

Table 1. Summary of Good Agricultural Practices for peppercorn (IPC, 2007)

Parameter	Required Practice	Recommended Practice
Land Slope	The slope for any land to be planted with pepper should be less than 25°.	A slope not exceeding 10° is recommended for better soil conservation, easier harvesting, and farm management.
Altitude	Pepper holdings should not be planted on land higher than 1,200 m above mean sea level.	Land with altitude less than 1,000 m above mean sea level is preferred for good pepper cultivation.

Rainfall	Pepper should be planted in areas that receive at least 1,750 mm of rainfall annually.	Pepper cultivation is best under rainfall of 2,000–3,000 mm. A clear dry season is advantageous for flower induction. Where there is a prolonged dry period, irrigation may be required.
Temperature	Pepper should not be grown in areas where temperatures can fall below 10°C or rise above 40°C.	Generally, temperatures should be within the range of 23°C to 32°C, with low variation within a day.
Humidity	Pepper should be grown in areas where humidity is high.	Relative humidity should be over 70%.
Soil Depth	The soil depth should be at least 0.75 m.	Soil depth may be 1.0 m or more.
Soil Characteristics	Soils should be analysed to determine pH, nutritional status, and physical properties, with soil amelioration based on analysis.	Recommended soils are sandy loam, clay loam, or lateritic with adequate nutrients and suitable pH.
Nutritional Status of the Soil	Nutrient addition should be based on soil analysis and crop requirements.	Organic matter (farmyard manure, compost, leaf litter) should form a major part of soil nutrients.
Physical Properties	Soils should be sandy loam to clay loam or lateritic, porous, with good water-holding capacity, but not waterlogged.	Soil amelioration using organic matter and minimum tillage should be practiced to improve soil structure and texture.

4.2. Pepper Production in Major Countries

Black pepper cultivation practices vary significantly across major producing countries, leading to wide differences in yields (Jim, 2025). Cambodia achieves exceptional pepper yields of 3.5 ton/ha that rank second globally among major producing countries, surpassed only by Malaysia of 4 ton/ha, the world leader (ASEAN AgriFood, 2025). Based on surveys of pepper trade and promotion bodies across seven major producing nations, Cambodian yields significantly outperform most competitors including Vietnam, India, and others.

Cambodia's competitive advantage stems from optimal climate conditions with temperatures of 22-32°C and annual rainfall of 1,500-2,500 mm, combined with well-drained, lightly sloping soils ideal for pepper cultivation.

Farmers in Tboung Khmum and Kampot maintain best practices with 1,800-2,000 poles per hectare, proper irrigation, and fertilization, producing high yields on relatively small land areas compared to other countries. Beyond yields, Cambodian pepper excels in quality metrics, with density measurements placing Cambodia near the top of the range with exceptional consistency compared to other major producers. Piperine content—the compound providing characteristic flavor and health benefits—exceeds that of Vietnamese, Indian, and Sarawak pepper, with some estimates reaching 6%. These superior yields directly enhance profitability and help offset higher production costs, demonstrating both farmer expertise and Cambodia's natural suitability for pepper cultivation.

Despite these yield advantages, the sector faces constraints from international price volatility since 2017 and climate change impacts in 2024, which require investment in irrigation, shading, and vine replacement. Additionally, harvest timing, primarily occurring in March-May, coincides with peak global supply from Vietnam and India, intensifying price competition where quality differentiation becomes crucial.

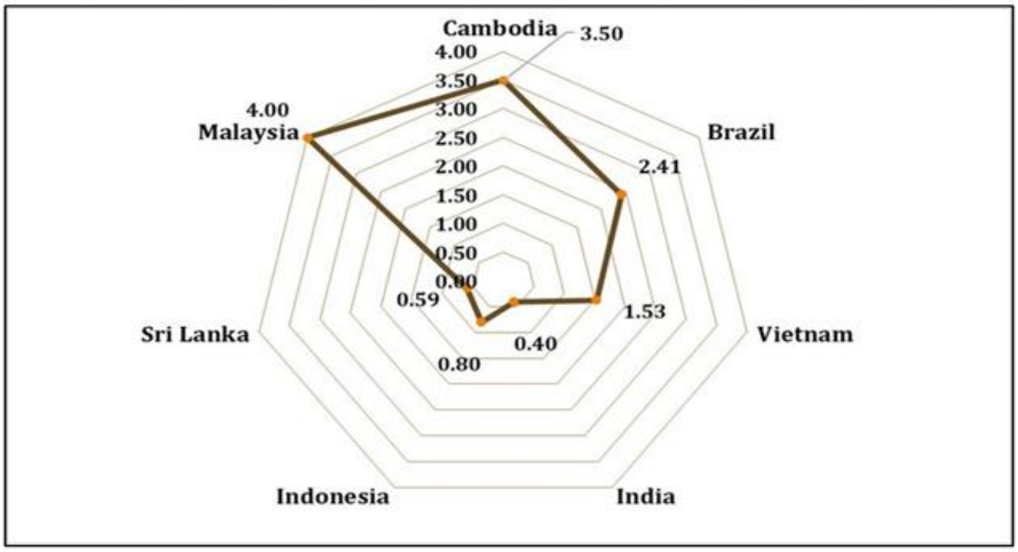


Figure 1. World pepper annual yield production (Jim, 2025)

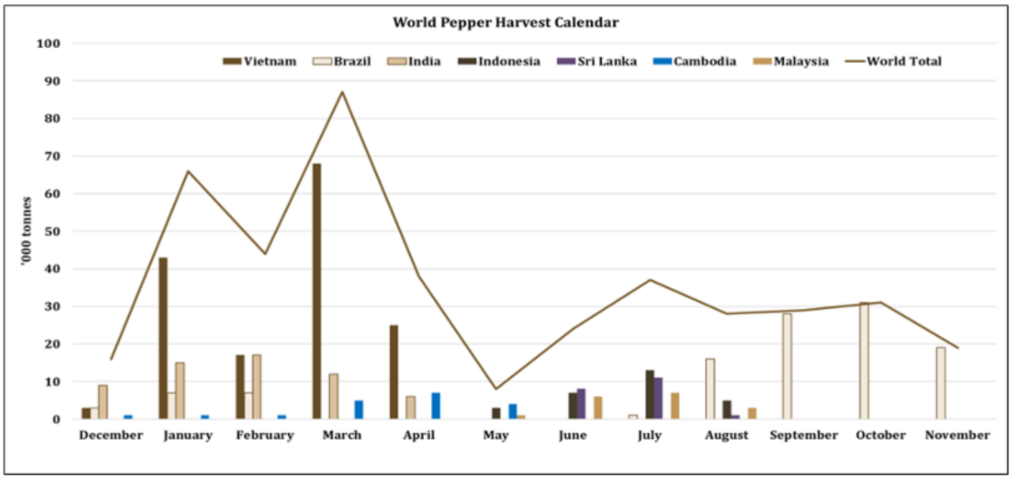


Figure 2. World pepper annual yield production (Jim, 2025)

4.3. Pepper Production in Cambodia

Cambodia's agro-ecological conditions, characterised by a favourable climate and fertile, well-drained soils, have positioned the country as one of the most suitable regions globally for the cultivation of high-quality peppercorn (EuroCham Cambodia, 2022). In 2020, the total national production of pepper was estimated at approximately 17,000 tonnes, cultivated across an area of 6,822 hectares. During this period, exports were recorded at around 3,500 tonnes (MAFF, 2021).

Within this sector, Kampot pepper holds particular significance, being the first pepper variety in the world to be granted Protected Geographical Indication (PGI) status by the European Union (European Commission, 2016). This designation underscores the unique qualities of Kampot pepper, which derive from the region's unique combination of climate, hydrological characteristics, and soil composition. Together, these factors create a distinctive terroir that is ideal for peppercorn cultivation. In accordance with the Kampot

Pepper PGI specifications, production must be entirely organic and restricted to two specific subspecies of *Piper nigrum*: Kamchay and Lampong (also known as Belantoeung). Since receiving this GI certification, the prices for Kampot pepper have surged dramatically; for instance, the price of black pepper increased from USD 5.75/kg in 2010 to USD 10/kg in 2020, reflecting a notable rise of 74%. Similarly, red pepper prices jumped from USD 10/kg to USD 25/kg (+150%), and white pepper prices rose from USD 12/kg to USD 28/kg (+133%) during the same period (FAO, 2022). The area allocated to Kampot peppercorn cultivation has expanded significantly, growing from just 1 hectare in 2010 to 264 hectares at present, with cultivation concentrated exclusively in Kampot and Kep provinces.

According to data from the Kampot Pepper Promotion Association (KPPA, 2024), the annual production of Kampot peppercorn has seen remarkable expansion, increasing thirteenfold from a modest 11 tonnes in 2009 to an impressive 143 tonnes in 2023.

4.4. Emerging Issues of Drought and Heat Wave in Kampot Pepper Production

Despite its international recognition and a decade of steady growth, the Kampot peppercorn sector is currently facing severe challenges that could potentially threaten its productivity. In 2024, the region experienced extreme heat and prolonged drought conditions (Figure 3), which led to widespread crop damage and significant yield losses across various production areas. Annual output, which had reached 143 tonnes in 2023, was estimated to have fallen by about 66 tonnes, resulting in a sharp decline of approximately 46% (KPPA, 2024, EU-German CAPSAFE, 2025; ASEAN AgriFood, 2025; *South China Morning Post*, 2024).

Figure 3. Kampot farmer inspects withered pepper vines severely affected by the 2024 heatwave and prolonged drought. (Photo credit: TANG CHHI Photo credit: TANG CHHIN Sothy / AFP (published via YEN.com.gh)

4.5. Contributing Factors

Recent climatic shocks have placed considerable stress on pepper cultivation in Cambodia, particularly in the renowned Kampot region. A record-breaking heatwave in late April 2024 brought peak temperatures soaring to an alarming 43°C. Such extreme temperatures created severe physiological stress in pepper vines, leading to significant disruptions in normal growth processes. This heat stress resulted in reduced flowering and a lower fruit set (ICAR-IISR, 2019; South China Morning Post, 2024).

The adverse impacts of the heatwave were further compounded by a prolonged six-month drought that followed, exacerbating existing water shortages and severely restricting the use of irrigation. Pepper plants are particularly sensitive to soil moisture stress; prolonged dry conditions diminish vine vigor, increase susceptibility to pests and diseases, and ultimately undermine overall yield potential (IPC, 2007; EU-German CAPSAFE, 2025).

Local farmers have also expressed concerns regarding broader environmental changes, which they identify as critical threats to the future of peppercorn cultivation. They increasingly recognise that climate change is contributing to irregular rainfall patterns, declining soil fertility, and more frequent extreme weather events. These factors are collectively eroding the resilience of their crops and threatening the long-term sustainability of Kampot peppercorn production (ASEAN AgriFood, 2025; KPPA, 2024).

4.6. Impact of Drought and Heat Stress on Kampot Peppercorn

The 2024 drought and extreme heatwave had devastating effects on Kampot pepper production. Farmers reported yield losses of 60–70% compared to the previous year, with total harvests falling to just 30–40 tonnes, a sharp decline from 120–130 tonnes in 2023 (Kampot Pepper Promotion Association, 2024; South China Morning Post, 2024).

This production collapse was accompanied by significant price increases after nearly a decade of stability. In 2023, Kampot black pepper was priced at around USD 15/kg, red pepper at USD 25/kg, and white pepper at USD 28/kg. By 2024, these rose to USD 18/kg, USD 28/kg, and USD 31/kg, respectively (EU-German CAPSAFE, 2025; ASEAN AgriFood, 2025). While higher prices might appear beneficial, they failed to offset farmer losses due to the drastic fall in yield.

In addition to reduced output, plant mortality was widespread, with many vines dying under prolonged drought and temperatures exceeding 40°C. Surviving plants produced lower-quality pepper, with smaller berries and reduced flavor intensity, directly linked to adverse weather conditions (ICAR-IISR, 2019; IPC, 2007).

The economic and social consequences were severe. Farmers faced financial hardship, as Kampot pepper plants require 3–4 years to reach maturity, making recovery from such large-scale losses extremely slow and costly (KPPA, 2024). These stresses raised serious industry concerns, with stakeholders warning that climate-induced declines threaten the sustainability of Kampot pepper, a globally recognized product with EU Protected Geographical Indication (PGI) status (European Commission, 2016).

4.7. Irrigation Systems

Peppers require regular watering throughout their growing cycle. Adequate water supply is crucial for healthy plant growth and fruit development. Water is a vital resource for pepper plants and efficient irrigation methods are crucial to ensure optimal growth and yield. There are some modern irrigation techniques that promote water sustainability, one of which are drip irrigation and sprinkler irrigation. Drip irrigation is a highly efficient method that delivers water directly to the base of the plants. It minimises water loss due to evaporation and ensures that water reaches the root zone where it is needed the most. Drip irrigation also helps in reducing weed growth and prevents foliar diseases by keeping the leaves dry.

Sprinkler irrigation is another effective method for watering peppers. However, it is important to ensure that the sprinklers are properly calibrated to minimise water wastage. Pepper plants have certain sensitivities; young plants are delicate; water logging or constant wet foliage be able to cause disease and also often planted in rows, with canopy structures. Cambodia is tropical region, hot and rainy season, therefore, micro-sprinklers are often a better option, especially once plants are established. They allow localized watering, less wet foliage, better soil moisture control. In addition, micro sprinklers work with lower pressure which is comfortable with smaller pumps. In addition, this type of sprinkler is high water efficient as well as required less electricity to operate pump systems.

5. Methodology

5.1. Soil Data

To achieve a comprehensive understanding of the pepper cultivation practices and the impact of the solar-powered cooling systems, various types of relevant data were collected systematically. Soil samples (Figure 4) were taken from two selected Kampot pepper pilot farms, with specific details outlined in Table 2. For each site, two samples were collected from both a test plot and a non-test plot, resulting in a total of four samples across the two farms.

- **Soil Profile Analysis**: To characterise the soil horizons and properties effectively, a pit measuring 0.5 m x 0.5 m x 0.5 m was excavated on each farm. This allows for sampling at various depths to gain insights into the different layers of the soil and their respective characteristics. Soil profiles of Fair Farm and Reaksa Farm are given in Figure 5 and Figure 6, respectively.

- **Soil Physical Property Analysis**: The collected soil samples underwent rigorous analysis to determine their physical properties. This includes assessing the soil texture, which was done using hydrometer or sieve analysis techniques at the laboratory of the Institute of Technology of Cambodia (ITC). Additionally, infiltration rates were measured using K-SAT apparatus at the ITC to evaluate how well water permeates through the soil, which is critical for understanding irrigation efficiency.

- **Soil Chemical Property analysis**: The soil samples were also assessed for essential chemical properties such as pH, nitrogen (N), phosphorus (P), and potassium (K). These analyses were conducted using standard laboratory methods, including colorimetric analysis for nitrogen and phosphorus, at the ITC laboratory.

Furthermore, Soil Organic Matter (SOM) content was determined using either the Loss of Ignition method or the Walkley-Black method, depending on the specific conditions of the soil in the targeted areas.

Table 2. Proposed soil data to be collected

Data/Analysis	Parameter	Description
Soil Profile		A 0.5m x 0.5m x 0.5m drilled pit on each farm
Soil Physical	Soil texture	Hydrometer or sieve analysis at the laboratory of ITC.
	Water-holding	Pressure plate analysis at the laboratory of ITC.
	Capacity infiltration	K-SAT apparatus at ITC.
Soil Chemical	pH	Standard laboratory methods (e.g., colorimetric analysis for N and P) at the laboratory of ITC.
	Nitrogen (N)	
	Phosphorus (P)	
	Potassium (K)	
	Soil Organic Matter (SOM)	Loss of Ignition or Walkley-Black Method depending on the actual soil condition at targeted areas.

Figure 4. Soil sampling activities

Figure 5. Soil profile at Fair Farm

Figure 6. Soil profile at Reaksa Farm

5.2. Cultivation Practices

Furthermore, a structured questionnaire survey was administered to target farmers and farm workers to collect both qualitative and quantitative data on several critical aspects of peppercorn cultivation. This survey aims to gain deeper insights into the following areas:

- Irrigation management practices
- Water needs specific to Kampot pepper crops
- Sources of available water (e.g., wells, etc.)
- Soil management techniques
- Strategies for weed and pest management
- General crop management practices
- Economic return analysis (costs vs. revenues)
- Historical yield data
- Challenges faced in cultivation and resource management

5.3. Data Collection Methods

The necessary data outlined above were collected through a variety of methods, with a strong emphasis on gender considerations to effectively address issues related to gender equality and women's empowerment. The methods employed will include:

- **Surveys**: Conduct face-to-face interviews with farmers using the prepared questionnaire.
- **Field Observations**: Make direct observations of farming practices, irrigation systems, and crop conditions to complement the survey data.

On May 18, 2025, the survey was conducted at the two farms to assess baseline conditions. This assessment specifically focused on several critical factors, including heat stress, current irrigation practices, soil management techniques, pest management strategies, and economic yield.

5.4. Monitoring System

Additionally, monitoring systems were installed in both test and non-test areas of each farm, to measure and record the on-site temperature using Precision Temperature and Humidity Sensor RS485 Interface Environmental Real Time Monitoring High Precision Wall Mounted from Guangzhou Finru Trading Co., Ltd. A simple diagram of the proposed monitoring system is given in Figure 7.

Each testing and non-testing area has a controller connected to temperature, humidity, and moisture sensors. These sensors recorded data every minute (logging interval), which was then transmitted from the controller to a WIFI router and subsequently to the Cloud. This allows for real-time data access via mobile devices or computers for performance analysis.

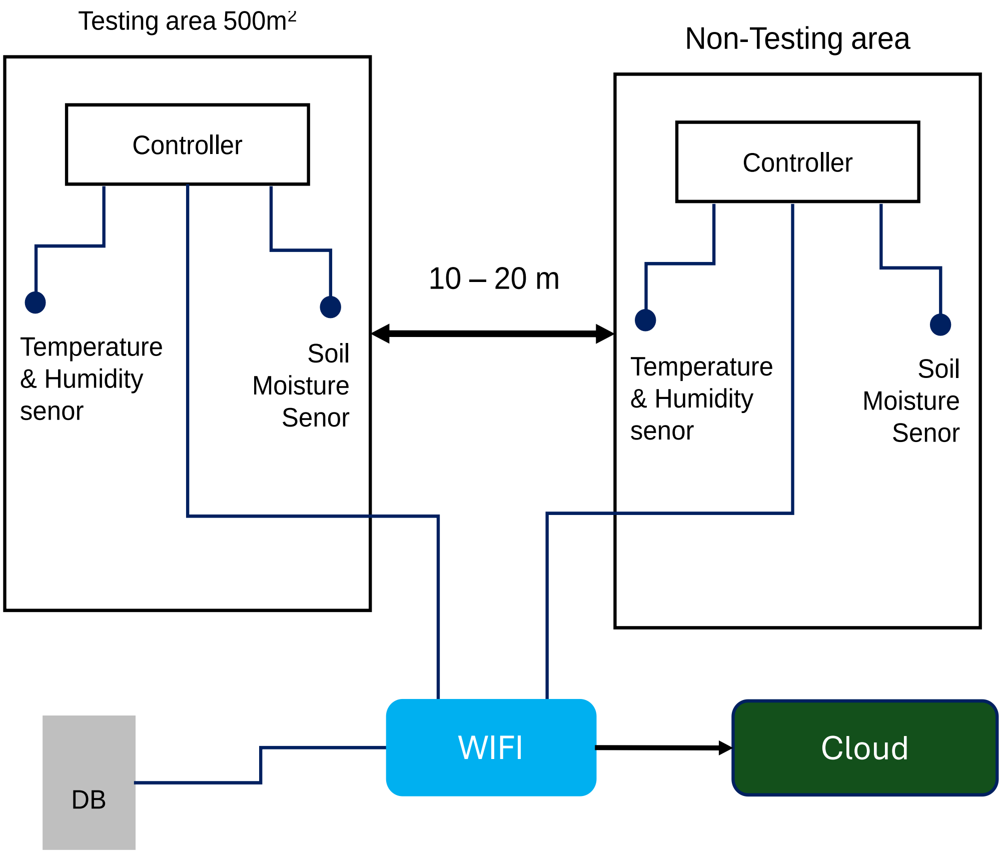


Figure 5. Monitoring system for data collection

6. Findings

6.1. Baseline Survey

6.1.1. Demographics

The baseline analyses were carried out at two pepper farms. The first, Fair Farm (Figure 8), was established in 2015 with the total area of 10 ha. The second farm, Reaksa Farm (Figure 9), was established in 2015. A summary of demographics for both farms is provided in Table 3.

Table 3. Demographics of the two farms

	Fair Farm	Reaksa Farm
Established year	2015	2015
Major crops	Pepper	Pepper
Total area	10 ha	1.5 ha
Total area for testing the Kampot cooling system	500 m^2	500 m^2
Average Year Yield	~650 kg / ha	~666.7 kg / ha

Figure 8. Fair Farm

Figure 6. Reaksa Farm

6.1.2. Irrigation Management Practices

The two farms have slightly different irrigation management practices. Fair Farm did not record the irrigation used per day or month. During the dry season, they watered the pepper every 2-3 days. Before 2025, manual watering was employed, involving 10 workers and taking 2-3 days to complete one cycle. However, in 2025, an automated drip irrigation system was installed by a local company (see Figure 10), reducing the need for labour to just one person. Currently, there are no specific controlled variable, such as soil humidity or air temperature, to manage the irrigation system. Instead, the dryness of the soil is visually assessed. The installation company recommended irrigating the pepper for 12 minutes each time. The main water source for irrigation is the underground water. However, during the dry season, the water level in the well is significantly low, preventing the farm from pumping at full capacity and adequately irrigating the peppercorn, which has led to some plants dying. Water is pumped by an electric water pump. In the dry season, the farm spends approximately $200 per month on water pumping, while in the rainy season, the cost drops to about $125 per month.


Figure 7. Drip irrigation system at Fair Farm

At Reaksa Farm, the precise water demand for irrigation is not monitored; instead, they rely on visual assessments of soil dryness and adhere to local traditional practices. Manual watering is conducted, taking about 1 minute to irrigate 5 plants, with a total of 3 hours required for 1.5 hectares divided into 3 blocks. During the dry season, they water the peppercorn every 3 days, while no irrigation occurs in the rainy season. The main water source for irrigation is a pond (Figure 9). However, the water is not directly pumped to irrigate the peppercorn; it is first stored in a pond before being used for irrigation. Since 2022, a solar water pump was introduced at the farm. Prior to that, they relied on a 12 HP gasoline water pump for irrigation. The estimated annual cost of gasoline for water pumping was approximately $225. The summary of irrigation management practices of these two farms is given in Table 4.

Table 4. Irrigation management practices of the two farms

	Fair Farm	Reaksa Farm
Water demand for irrigation	Not monitored	Not monitored
Technology	Drip	Manual
Method for monitor	Visual check of soil dryness	Visual check of soil dryness
Frequency	Every 2-3 days	Every 3 days
Source of water	Well	Well and pond
Pumping technology	Electric pump	Then: gasoline water pump, Now: solar water pump
Cost for water pumping	$200/month in dry season, $125/month in rainy season	Gasoline: $225/year

Figure 11. Pond water source for irrigation at Reaksa Farm with solar pump

As there were no recorded irrigation data from either farm, water use for manual pepper irrigation can be estimated from the literature.

6.1.3. Soil, Weed, and Pest Management

Fair Farm has implemented cover cropping (Figure 10) for soil management, a technique introduced by a French NGO in 2022. However, their General Manager and technical staffs noted a decline in plant growth and health, possibly due to competition for water and nutrients with the cover crops. Consequently, it was advised that the farm owners discontinue this practice. In contrast, Reaksa Farm does not employ any specific soil management techniques, relying instead on traditional methods such as manual weeding and maintaining bare soil (Figure 11).

Notably, neither farm checked soil moisture levels before irrigation. Both farms continue to use manual weeding techniques, with workers regularly monitoring weeds and caring for the peppercorn plants.

Additionally, both farms are adopting organic farming practices, utilising only biological controls for pest management. A summary of soil, weed, and pest management practices for these two farms is provided in Table 5.

Table 5. Soil, weed, and pest management of the two farms

	Fair Farm	Reaksa Farm
Soil management	Cover cropping technique	Traditional technique
Soil moisture assessment	No	No
Weed management	Manual weeding	Manual weeding
Pest management	Biological controls	Biological controls

Figure 12. Cover crop in Fair Farm

Figure 8. Bar soil for pepper in Reaksa Farm

6.1.4. Heat Stress, Crop Management, and Yields

Fair Farm has identified the optimal temperature range for peppercorn cultivation as 32-33°C. In contrast, Reaksa Farm is unaware of the ideal temperature conditions for growing peppercorns. The peak harvest period occurs between April and May.

Fair Farm experiences heat stress annually during the hot months of April and May. The years 2023 and 2024 were particularly severe, marked by a combination of extreme heat and water shortages. Temperatures reached 40-41°C, especially between 9 AM and 3 PM, leading to the death of approximately 30-40% of peppercorn plants due to previous heat stress events. The farm is still in the recovering phase from events. In 2022, it lost 6-7 tons of peppercorn yield due to heat stress, which has led to a reduction in the labour force available for farm operations and harvesting.

Similarly, Reaksa Farm also faced severe heat stress during 2023 and 2024, with 2023 being the most challenging year. In that year, peppercorn yields dropped sharply, falling from around 1 ton to only 300–400 kg. However, by 2024, production returned to normal levels. The exact number of peppercorn plants lost due to heat stress remains unknown.

To mitigate the impacts of heat stress on peppercorn, both farms have implemented several strategies, such as providing shade for the plants and manually spaying water to cool them down. However, these methods have proven to be largely ineffective. A summary is given in Table 6.

Table 6. Impact of heat stress on pepper cultivation at both farms

	Fair Farm	Reaksa Farm
Ideal growing conditions	32-33°C	Based on traditional practice
Experienced heat stress	Yes, 2023-2024	Yes, 2023-2024
Plants lost due to heat stress	30-40% around 6000 to 8000poles (Assuming 2000 poles/ha and 20,000poles/10ha)	No lost due to heat stress except yield reduction
Peppercorn yield lost due to heat stress	6-7 tons in 2022 reduced to 700 kg per year in 2024	1 ton in 2022 to 0.3-0.4 tons in 2023

Heat stress mitigation	Shading and manual water spraying	Shading and manual water spraying
Revenue loss	79,500USD to 94,500 USD (Assuming the same price with Reaksa farm 15USD/kg) in 2024	700kg x 15USD/kg=1,050USD in 2023
Cost of replacing vines	18000 USD to 24000 USD (Assuming 3USD/pole of vine cost from Reaksa farm) in 2024	No replacement of vines

6.1.5. Economic Return Before the Kampot Cooling

Reaksa farm shared the economic return analysis.

<u>Normal Operation Economics</u>

Initial Startup Costs

On Kampot pepper farms, planting is generally organized with support poles approximately 4 meters in height, spaced at 2 meters apart. This arrangement provides an average planting density of around 2,500 pepper vines per hectare. The cost of each pole is about USD 2, while the cost of vines is about USD 3 per pole. Considering only poles and vines, the estimated initial startup cost amounts to approximately USD 12,500 per hectare, not including additional expenses such as labor, shading structures, and other farm inputs that the total cost can reach to 37,773 USD/ha (Jim, 2025).

Table 2. Initial startup costs of peppercorn cultivation at Reaksa farm in 2015.

Initial Startup Costs	Unit Price	Quantity	Total (USD)
Pole	2	2500	5000
Vine	3	2500	7500
Total (USD)			12500

Operation Labour Cost

Based on Reaksa Farm's experience, routine operations during the dry season require about five laborers, engaged three days per month during the dry season (around six months). During the rainy season, they reduce the operation to once per month. Each laborer earns USD 10 per day. Their main tasks include irrigating the pepper vines, weeding, and applying protective sprays to ensure proper crop maintenance.

Table 3. Operation labour cost of peppercorn cultivation at Reaksa farm

Operation Labour Cost	Num ber	Wage/day (USD/day)	Total days per year in dry seasons	Total days per year in rainy season	Total (USD)
Labourers	5	$ 10	60	6	$ 3,300

Economic Return

The owner of Reaksa farm mentioned that the pepper products were sold to Fair Farm at prices ranging from USD 15 to USD 19 per kilogram, generating an estimated annual income of approximately USD 11,900 to USD 17,000.

Table 4. Income generation of peppercorn cultivation at Reaksa farm

Income generation	Reaksa Farm
Annual yields (kg) (For normal year)	10000
Saling price (USD/kg)	15 -19
Total Annual Revenue (USD)	11,900 USD to 17,000 USD

6.2. Soil Data Analysis

6.2.1. Soil Physics

The soil analysis results from Kampot pepper farms, taken from Fair Farm and Raksa Farm under both testing and non-testing plots is show in Table 10.

The soil physical analysis indicates that the soil is predominantly sandy loam, a texture that provides both good aeration and moderate water-holding capacity. This composition allows water to infiltrate and drain effectively while still retaining enough moisture to sustain pepper growth. The bulk density measurement shows that the soil is not overly compacted, which corresponds to good porosity and facilitates healthy root penetration, microbial activity, and efficient circulation of water and air within the soil profile. The soil's moisture retention capacity is moderate: while the sandy fraction promotes rapid drainage, the finer silt and clay particles ensure that sufficient water is stored between irrigation events.

The soil's infiltration capacity, represented by the saturated hydraulic conductivity (Ksat), is relatively high due to the sandy loam structure. This means water quickly infiltrates into the soil during rainfall or irrigation, reducing the risks of surface runoff and waterlogging. However, rapid infiltration also means that water may move beyond the root zone if not managed properly, which could lead to drought stress during dry periods. To optimize water availability for pepper plants, careful irrigation scheduling—such as drip or sprinkler systems—should be applied, together with organic amendments that enhance water-holding capacity.

Overall, the soil's physical properties are well-suited for Kampot pepper production. The combination of sandy loam texture, moderate bulk density, good porosity, and favorable infiltration capacity supports healthy root development and efficient water management. With proper irrigation practices and the addition of organic matter such as compost or vermicompost to improve water and nutrient retention, the soil can provide an excellent foundation for sustainable and high-quality pepper cultivation.

Table 5. Soil physic properties

Location	% Sand	% Silt	% Clay	Type of Soil	Ksat (cm/min)	Bulk Density (g/cm3)
Fair farm (testing plot)	58.7	30.6	10.7	Sandy Laom	0.03	1.53
Fair farm (non-testing plot)	59.9	23.2	16.9	Sandy Laom	0.02	1.59
Raksa farm (testing plot)	61.2	23.2	15.5	Sandy Laom	0.03	1.46
Raksa farm (non-testing plot)	61.5	26.2	12.3	Sandy Laom	0.01	1.50

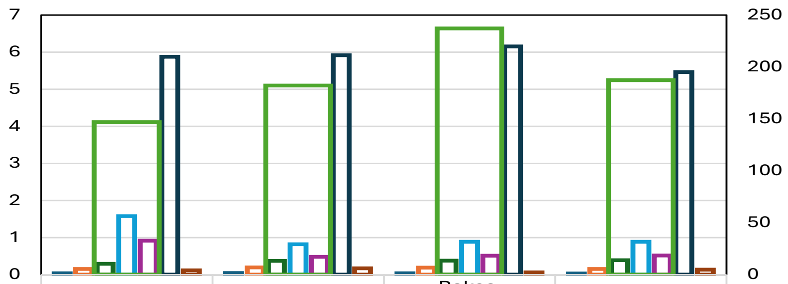
6.2.2. Soil Fertility

The soil analysis results from Kampot pepper farms, taken from Fair Farm and Raksa Farm under both testing and non-testing plots, show several important fertility characteristics (Figure 14). The total nitrogen content is very low, ranging from 0.031% to 0.041%, which indicates a deficiency that may limit pepper vine growth and yield unless supplemented with additional nitrogen through organic or inorganic fertilisers. Available phosphorus, however, is extremely high, ranging from 146 ppm to 237 ppm, far above the optimal range, which suggests that phosphorus fertilisers have been applied excessively in the past. This buildup means no further phosphorus should be added, as it could cause nutrient imbalances and environmental risks such as runoff and eutrophication. Exchangeable potassium is in the medium range (0.150–0.196 meq/100g), which is not critically low but still indicates the need for supplementary potassium inputs to optimise crop performance. Exchangeable sodium is low (0.289–0.390 meq/100g), which is favourable, as it avoids soil salinity problems.

Soil organic matter and soil organic carbon are both very low, with SOM values between 0.822% and 1.579% and SOC ranging from 0.477% to 0.916%. These levels point to weak soil structure, limited microbial activity, and low nutrient retention, which reduce overall soil fertility and resilience. Therefore, organic amendments such as compost, vermicompost, biochar, or cover crops are highly recommended to improve soil health.

In terms of soil reaction, the measured pH is 6.40, which is within the slightly acidic range. This condition is generally favourable for pepper cultivation, as it supports good nutrient availability, though maintaining pH stability will be important to avoid future nutrient lock-up. The electrical conductivity (EC) is 0.187 dS/m, which indicates very low soil salinity and is considered safe for Kampot peppercorn production.

Overall, the soils of Kampot pepper farms are characterised by critically low nitrogen, excessive phosphorus, medium potassium, safe sodium, very low organic matter, a slightly acidic pH of 6.40, and low salinity with EC at 0.187 dS/m. These results suggest that management should focus on replenishing nitrogen and potassium, avoiding additional phosphorus inputs, and improving organic matter content to enhance soil fertility and sustainability. Maintaining the current pH and EC conditions will help ensure a suitable environment for pepper growth.



	Fair farm(Testing plot)	Fair farm(Non-testing plot)	Raksa farm(Testing plot)	Raksa farm(Non-testing plot)
Total Nitrogen (%)	0.036	0.041	0.035	0.031
Exchangeable K (meq/100g)	0.153	0.196	0.186	0.15
Exchangeable Na (meq/100g)	0.289	0.373	0.378	0.39
Soil Organic Matter (%)	1.579	0.822	0.884	0.886
Soil Organic Carbon (%)	0.916	0.477	0.513	0.514
pH	5.88	5.92	6.15	5.46
EC (ms/cm)	0.11	0.17	0.06	0.13
Available P (ppm)	146.803	182.135	237.142	187.268

Figure 9. Soil chemical properties of the farm testing plot

6.2.3. Climate data

The Figure 15 illustrates daily temperature fluctuations across four consecutive years (2022, 2023, 2024, and 2025). The graph enables comparison of seasonal changes and inter-annual variability, which are critical for understanding crop stress dynamics.

The temperature data from 2022–2025 show a clear seasonal cycle. During the cool season (December–February), providing relatively mild conditions though still near the crop's optimum range. The hot season (March–May) records the highest values, and represents the most critical period of heat stress risk, particularly in April and May. In 2024, the data recorded the highest frequency of hot peaks, with multiple instances exceeding 36°C, confirming it as a particularly harsh year for temperature extremes. Across all years, the April–May period consistently emerged as the critical heat window, with temperatures reaching 36–38°C. These values are well above the optimal growth threshold and significantly intensify crop stress during this sensitive stage. By contrast, in 2025, temperatures clustered more consistently within the 32–35°C range for most of the year, with fewer sharp dips or peaks, reflecting a comparatively stable and less extreme pattern.

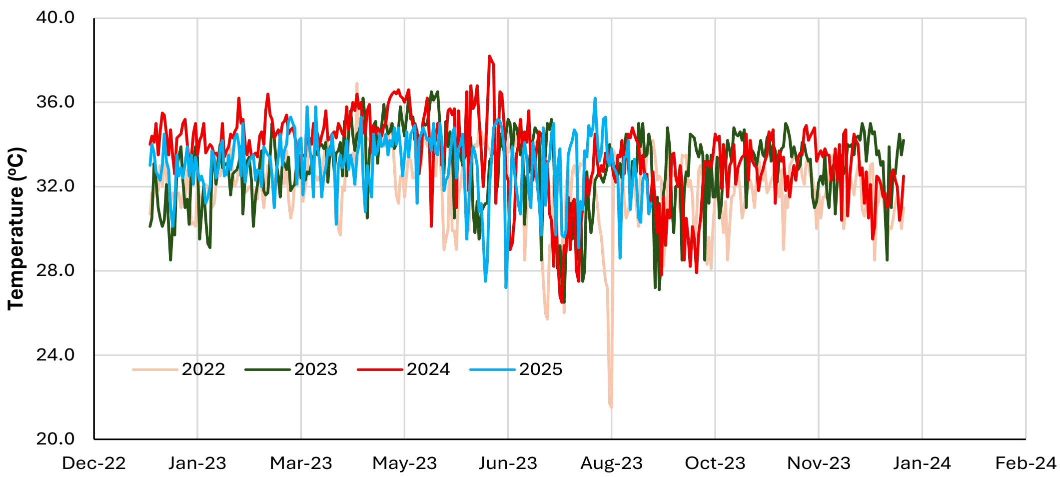


Figure 10. Daily Maximum Temperature from 2022 to 2025

The Figure 16 illustrates daily rainfall distributions across the years 2022, 2023, 2024, and 2025. The rainfall data confirms a distinct wet and dry seasonal cycle but also reveals significant inter-annual variability. While 2022 and 2025 had relatively moderate distributions, 2023 and 2024 demonstrated unusual and extreme rainfall patterns.

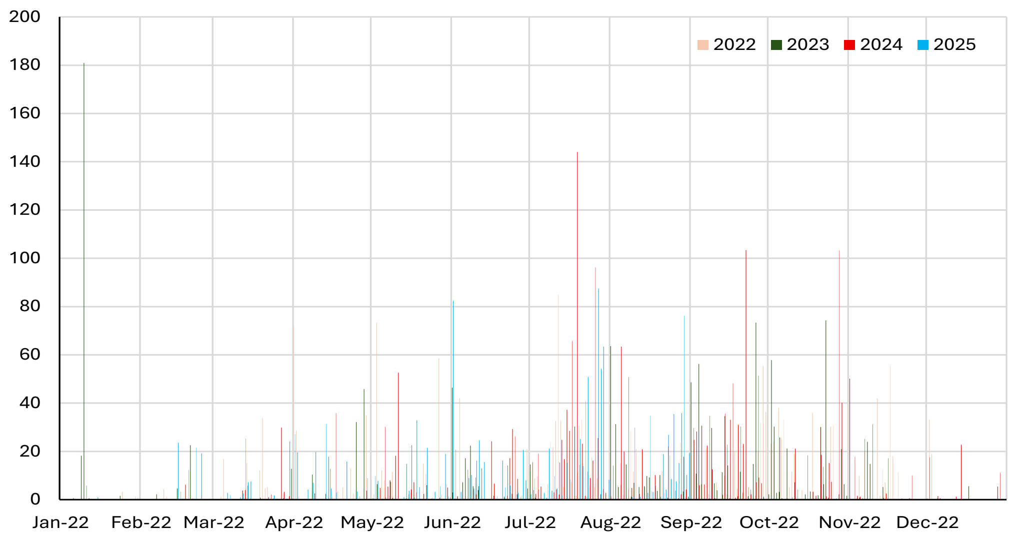


Figure 11. Daily Rainfall from 2022 to 2025

Figure 17 presents accumulated rainfall totals comparing four years (2022, 2023, 2024, and 2025). In 2024, the dry season (January–May) was marked by a significant rainfall deficit compared to other years. Accumulated rainfall remained below 200 mm by May, far lower than 2022 (~500 mm), 2023 (~250 mm, due to an unusual February spike), and 2025 (>600 mm). This delayed onset of rainfall left soil moisture reserves depleted during the critical early growth stages.

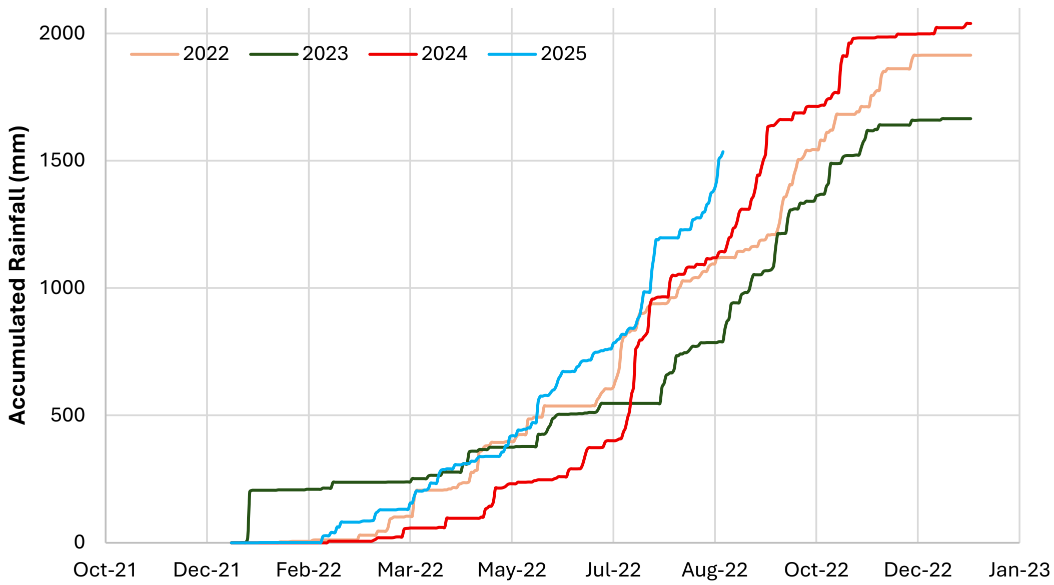


Figure 12. Accumulated Rainfall from 2022 to 2025

The overlap of reduced rainfall and extreme heat in early 2024 created a compounded stress effect. Plants were exposed to high evaporative demand without adequate rainfall to replenish soil moisture, while the extended dry spell further intensified heat stress, heightening the risk of wilting and yield loss. Compared to other years, 2024 stands out as having the harshest early-season conditions, where both temperature and rainfall patterns aligned to magnify stress. This combination of low rainfall and extreme heat made 2024 a particularly challenging year for pepper production, unlike 2025, which benefited from early rainfall that partially offset the impacts of high temperatures.

6.3. Description of Piloted Technology

6.3.1. Cooling System

The cooling system is a modified refrigeration cycle system, functioning as an air-conditioning unit with 4 HP capacity. The cooling system consists of key components: a compressor, condenser, evaporator, cooling water storage tank, and pump, etc. This air conditioning system is operated to lower the water temperature to around 15°C, which is then pumped into storage tanks (two tanks, each with a capacity of 1 m³), as indicate in Figure 18 and Figure 19. In the testing area, the temperature is set at 35°C, meaning that when the ambient air temperature exceeds 35°C, water at 15°C is supplied to the testing area through a pre-installed piping system and sprayed with a nozzle.

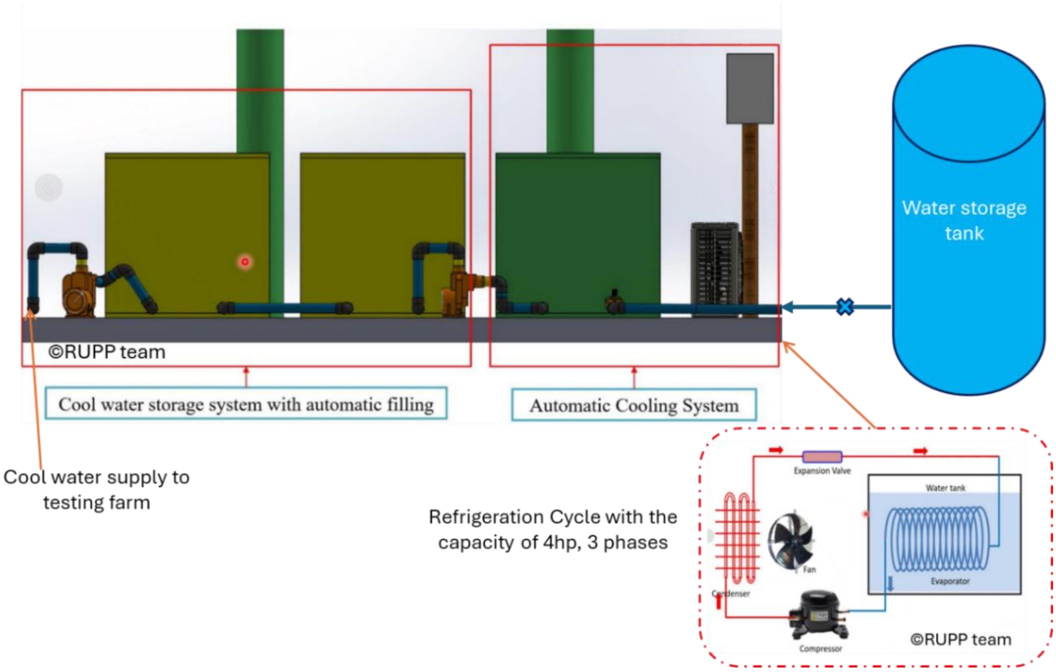


Figure 13. Schematic diagram of cooling system

Figure 14. Photo of actual cooling system supply to testing area

Water for the cooling system is sourced from a 20,000-litre storage tank (Figure 20) and is utilised by a 4 horsepower, 3-phase cooling system (Figure 21) designed for agricultural microclimate control. This system features a compressor and refrigerant circuit that circulates refrigerant through copper coils for effective heat exchange, a large finned aluminium condenser paired with a high-capacity fan to dissipate heat, and an integrated electrical and control panel for operation and protection. Its primary application is to supply cooled water for the fogging and spraying system, ensuring that canopy temperatures in pepper farms remain below 35 °C during periods of heat stress.

Figure 15. Water tank

Figure 16. Evaporator of the cooling system

A copper coil heat exchanger, Figure 22 (a), submerged in a stainless-steel water tank (SUS 304), is an integral part of the refrigeration circuit connected to the cooling unit. Made from copper tubing for its high thermal conductivity, the coil circulates refrigerant that absorbs heat from the surrounding water, lowering the water temperature as the refrigerant evaporates and creating a cold-water supply. The water-cooling system operates automatically based on sensor and controller. There are water level sensors, Figure 22 (b), to detect the water level in the tank and temperature sensors to measure the temperature of water.

Figure 22. Heat exchanger of the cooling system (a) and sensor for controlling water temperature (b)

6.3.2. Spraying System

The spray (fogger) cooling system (Figure 23) employs a network of overhead foggers installed beneath shade nets to regulate the microclimate of the pepper farm. Fogger spray lines are suspended above the crop rows, evenly distributing fine-mist foggers that create a micro-spray to lower canopy temperatures and increase humidity. This system is controlled by a smart controller equipped with temperature sensors, which automatically activates the spray when ambient temperatures exceed 35°C and halts it when temperatures drop below 32°C. Designed to cover approximately 500 m² of testing area, the system aims to prevent heat stress, reduce leaf scorch, and maintain optimal humidity levels (60–70%) for pepper growth during hot, dry seasons.

The spray system, featuring fogger nozzles (Figure 24) for applying cooling water to the pepper plants, consists of 18 foggers per line with a total of 9 lines installed across the test plot. This configuration is designed to effectively cool an area of 500 m². The fogger nozzle specification includes a 4-way cross-type nozzle made from durable, UV-resistant plastic, featuring four outlets for uniform 360° spray coverage. It produces a fine mist to effectively cool and control humidity, operating at a pressure typically ranging from 1.5 to 3 bar (15 to 45 psi). The discharge rate is approximately 20 to 30 litres per hour per nozzle set, depending on the model and pressure. These nozzles are installed on overhead spray lines beneath shade nets to reduce canopy temperature and maintain humidity levels in pepper farms and greenhouses.

The fogging system is managed by a smart controller (Figure 25) that automates spraying based on temperature thresholds: spraying activates when the temperature reaches 35°C or higher and deactivates when it drops to 32°C or lower. Additionally, temperature and system data are monitored and recorded at 5-second intervals to ensure responsive control.

Figure 17. Spraying system

Figure 18. Fogger of the spaying system

Figure 19. Controller for spraying system

6.3.3. Solar Photovoltaic System

Both farms are equipped with a solar photovoltaic system (Figure 26) consisting of 9 panels (360 W each), connected to a 6 KVA inverter and supported by a KNYEE 15.36 kWh $LiFePO_4$ battery for energy storage. The SOGE Solar Photovoltaic Module (Model ZY360Q12PH-72), Figure 27, delivers a peak power of 360 W with a maximum power voltage of 42.25 V and current of 9.05 A. It has an open-circuit voltage of 50.04 V and a short-circuit current of 9.62 A. The panel weighs 19.4 kg, measures 1978 × 990 × 35 mm, and supports system voltages up to 1500 V DC with a maximum overcurrent protection of 20 A.

For inverter, the RiO Sun II 6KVA all-in-one solar inverter (Figure 28) supports DC input 48V / 150A and provides AC output 230V, 50/60Hz. It also functions as an AC charger (230V input, 50/60Hz, 60A) and solar charger with PV open-circuit voltage 250V, PV input current 40A, and MPPT voltage range 120–240V. Rated DC output is 48V / 100A.

The KNYEE Floor Type Storage Battery (Model KNYE15K), Figure 9, has a rated capacity of 15.36 kWh with a nominal voltage of 51.2 V and energy density of 132 Wh/kg. It supports a maximum charging/discharging current of 100 A, operates within -20°C to 55°C, and uses $LiFePO_4$ chemistry for long cycle life and stability.

Figure 20. Solar system

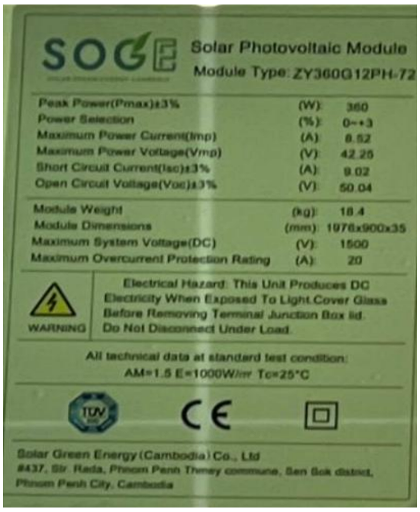


Figure 27. Solar photovoltaic module

Figure 28. Inverter

Figure 29. Specification of battery

6.3.4. Drip Irrigation System

Fair Farm

The drip irrigation system at Fair Farm (Figure 30) features a head unit equipped with a Rivulis disc filter, which effectively removes particles to prevent emitter clogging. It includes multiple pressure gauges for monitoring inlet and outlet pressure, along with PVC and HDPE pipeline fittings and valves for flow regulation. Ball valves with red handles facilitate isolation and control of water flow, while bypass and venturi injector lines are visible for fertigation, allowing fertilizer injection through the irrigation water. The mainline and manifold are constructed from durable PVC and HDPE pipes, supported by bolted flanges and a steel frame. The operation process involves water passing through the filter, being regulated by valves, distributed into mainlines, and then fed into drip laterals throughout the pepper plantation.

The pump and pressurised system (Figure 31) comprise an electric centrifugal pump, visible in the setup, and is coupled with LEO Pressurised Membrane Tanks (36L) to stabilise water pressure. Two LEO membrane tanks are installed to minimise pump cycling, maintain constant pressure, and protect the system from surges, with a maximum working pressure of approximately 10 bar, as indicated on the label. This system is integrated with the drip irrigation head unit, featuring a Rivulis filter for a clean water supply, and is equipped with pressure gauges, valves, and fertigation lines for effective control. It ensures a steady flow to both the drip laterals and the fogger spray system.

Figure 21. Drip system head unit at Fair Farm

Figure 31. Pump and pressurised system at Fair Farm

The automatic controller (Figure 32), a Hunter X2 model, serves as an irrigation timer with a dial-based programming system and a digital display, allowing for multiple start times and run times per day, along with manual start and seasonal adjustment functions. It features smart capability, being compatible with the Hydrawise Wi-Fi module for potential upgrades enabling remote control via smartphone or PC. Typically, it supports 4 to 14 stations, depending on the model configuration, and operates on standard AC power, providing output for irrigation valves and a pump start relay. This controller is used to manage both drip irrigation and fogger spray systems by scheduling automatic operations based on time or seasonal requirements.

Figure 22. Controller for irrigation system at Fair Farm

The automatic valve, Figure 33 (a), is a solenoid-controlled irrigation valve made from heavy-duty plastic with reinforced fittings, designed for durability in agricultural environments. It features pressure gauges on both sides to monitor inlet and outlet pressure, ensuring stable operation. This valve automatically opens and closes water flow based on signals from the Hunter X2 irrigation controller or a similar smart controller, maintaining regulated pressure and flow to the drip laterals and fogger systems. Additionally, it can be manually overridden using a red-handled valve for maintenance or emergency control.

The drip lateral, Figure 33 (b), specifications include flexible polyethylene (PE) tubing with a typical diameter of 16 mm, which is standard for farm drip irrigation. The layout runs close to the base of the pepper vines and is secured near the support pole. Integrated or attached button-type emitters deliver water directly to the root zone, ensuring low-pressure, uniform water distribution to individual plants. This setup reduces water loss through evaporation and promotes efficient irrigation, making it particularly optimized for perennial crops like pepper, where precise water delivery at the root zone is essential.

Figure 23. Automatic vale (a) and drip lateral (b) at Fair Farm

Reaksa Farm

The drip irrigation system at Reaksa Farm features lateral lines (Figure 34) made from flexible polyethylene (PE) tubing, typically with a diameter of 16 mm. These lateral lines run along the plant rows, with branch tubes directing water close to the base of each pepper vine. Each lateral is connected to the mainline through fittings and supplies water to button-type drip emitters. This setup ensures low-pressure, localized water delivery directly to the plant root zone, promoting efficient irrigation and minimising water loss.


Figure 24. Drip lateral at Reaksa Farm

The drip irrigation head unit (Figure 35) specification includes key components such as a sand/media filter (black canister) with a pressure gauge, a heavy-duty PVC pipeline manifold (blue, approximately 2–3 inches in diameter), and a fertigation/venturi injector system. This unit filters water to prevent emitter clogging, provides fertigation capability through the venturi injector (white transparent tube), and regulates pressure while distributing water through the mainline to the sub-main drip laterals.


Figure 25. Drip irrigation head unit at Reaksa Farm

The emitter Figure 36 specification for the drip irrigation system features a button-type drip emitter made from durable, UV-resistant plastic, typically color-coded blue to indicate the flow rate class according to emitter standards. The flow rate ranges from approximately 2 to 8 L/h, depending on the model and water pressure, with the marking "DD-16S" suggesting a 16 L/h pressure-compensating type. It operates within a standard pressure range of 1 to 2 bar (15 to 30 psi) and is designed with a circular outlet that includes multiple cross-slots to regulate and stabilise the flow.

Figure 36. Emitter for drip irrigation system at Reksa Farm

Water Use Efficiency

Since the irrigation system was installed during the rainy season, a direct investigation of drip irrigation efficiency was not conducted; however, its potential benefits can be estimated from existing literature.

Irrigation by hand

During the dry season, irrigation is essential to maintain pepper vine health, with hand irrigation of approximately 15 liters every three days, or about 10 applications per month. In Kampot pepper farms, planting typically involves poles around 4 meters high, spaced 2.4 meters apart, with pits of 30 × 40 × 50 cm dug 15–20 cm from each pole, resulting in an average density of 2,000 plants per hectare. Based on these parameters, the total ideal water requirement is estimated at 15 liters × 60 applications per year × 2,000 poles per hectare, which equals 1,800,000 liters per hectare per year, or approximately 1,800 m^3/ha/yr.

Figure 26. Traditional method to irrigate peppercorn plants (Kampot Pepper, n.d.)

Drip Irrigation Method

Drip irrigation's high efficiency stems from two main factors: a) it delivers water directly to plant roots, minimizing evaporation and soil infiltration; b) it distributes water based on daily crop needs rather than a fixed cycle. Additionally, drip irrigation offers several advantages: 1) targets specific soil areas; 2) operates with low quantities and pressure; 3) keeps plant leaves dry; 4) allows for fertilization through irrigation; 5) supports automation; 6) reduces water evaporation; and 7) enhances the quality and quantity of production.

Figure 38 illustrates that drip irrigation provides the highest field-level efficiency because most of the water reaches the plant roots with minimal losses between 85 to 95%. In contrast, surface or traditional irrigation is the least efficient due to higher losses from evaporation and infiltration.

According to FAO (2017), soil moisture–based scheduling can reduce irrigation water use by 20–40% compared to fixed-interval methods. Maintaining stable soil moisture also helps reduce stress on pepper vines, thereby improving flowering and berry development, which enhances both yield and quality. In addition, reduced pumping requirements translate into lower fuel or electricity costs, contributing to energy and cost savings. Most importantly, improved water use efficiency supports long-term sustainability by conserving scarce water resources, a factor especially critical during the dry season in Kampot when water availability is limited.

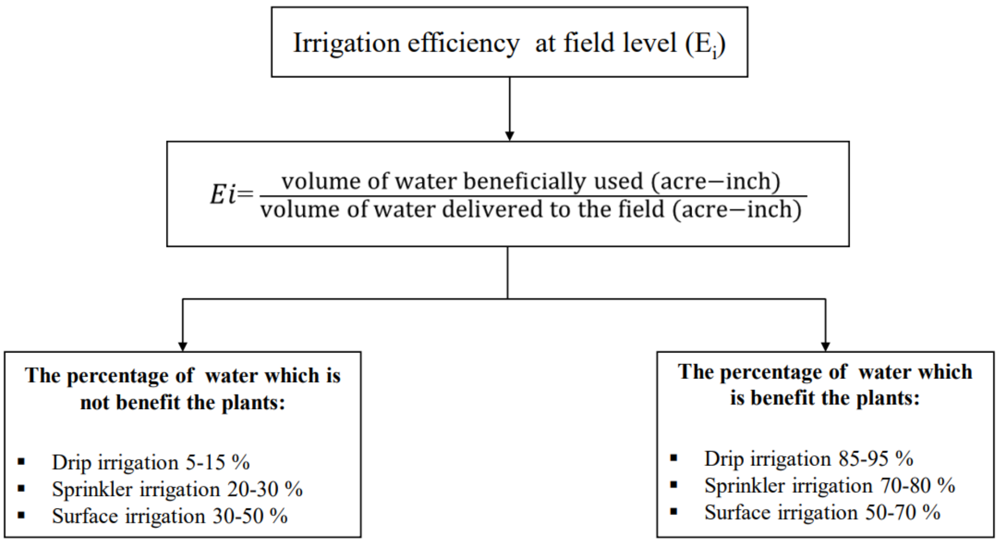


Figure 27. Irrigation efficiency (Doe Smith, 2021)

Table 6. Water Use Efficiency of Irrigation Methods in both farms

	Reaksa Farm	Fair Farm
Irrigation Methods	Estimated annual total water use (m^3/yr)	Estimated annual total water use
Hand or traditional irrigation	1,800	1,800
Drip Irrigation System	900 (Assuming 50% improved compared to traditional irrigation)	9000 (Assuming 50% improved compared to traditional irrigation)

By this analysis (Table 11), we can conclude that 50% of reduction in water consumption due to drip irrigation systems between pilot and non-pilot plots.

6.4. Assessment of System Performance

6.4.1. Solar Photovoltaic System

Daily energy generation from solar PV system and daily energy consumption data for the two cooling systems was obtained from the technology provider, Solar Green Energy Cambodia (SOGE). The two datasets span the period from 01st April to 15th September of 2025. Each dataset includes total daily energy generation, total daily energy consumption, daily energy consumption directly from solar PV source, and daily energy consumption sourced from battery storage. The daily energy generation and consumption figures for Fair Farm and Reaksa Farm are illustrated in Figure 39 and Figure 40, respectively. However, it was noted that there were gaps in the two datasets where daily energy consumption was recorded as zero, and the reasons for these gaps remain unclear. To facilitate a more accurate analysis of the data, all observations with daily energy consumption equal to zero were excluded from further examination. A summary of the key metrics from the two datasets is provided in Table 12.

On average, the solar PV system at Fair Farm generated 8.37 kWh per day, with a standard deviation of ± 4.97 kWh. Meanwhile, the solar PV system at Reaksa Farm produced an average of 6.08 kWh per day, with a standard deviation of ± 5.21 kWh.

Regarding energy consumption, the cooling system at Fair Farm consumed 7.75 kWh per day, with a standard deviation of ± 4.91 kWh, and the peak consumption recorded reached 26.00 kWh in a single day. In comparison, Reaksa Farm had an average daily energy consumption of 6.02 kWh, with a standard deviation of ± 5.16 kWh. Notably, the peak consumption at Reaksa Farm was slightly lower, at 19.40 kWh per day. Additionally, a t-test was conducted to assess the differences between the daily energy generation produced by the solar photovoltaic (PV) system and the daily energy consumption recorded at the two farms. The results indicate that there is no significant difference between the daily energy generation from the solar PV system and the daily energy consumption observed at both farms, as evidenced by a p-value greater than 0.05 in each case.

Table 12. Summary of solar photovoltaic data

	Fair Farm	Reaksa Farm
Total daily generation from solar (kWh)	8.37 (4.97) 0.00, 19.00	6.08 (5.21) 0.00, 20.00
Total daily consumption (kWh) **Mean (SD)** **Min, Max**	7.75 (4.91) 0.10, 26.00	6.02 (5.16) 0.20, 19.40
Daily consumption from solar (%) **Mean (SD)** **Min, Max**	62.93 (28.20) 0.00, 100.00	28.00 (26.65) 0.00, 90.00
Daily consumption from battery (%) **Mean (SD)** **Min, Max**	37.08 (28.19) 0.00, 100.00	72.01 (26.64) 10.00, 100.00

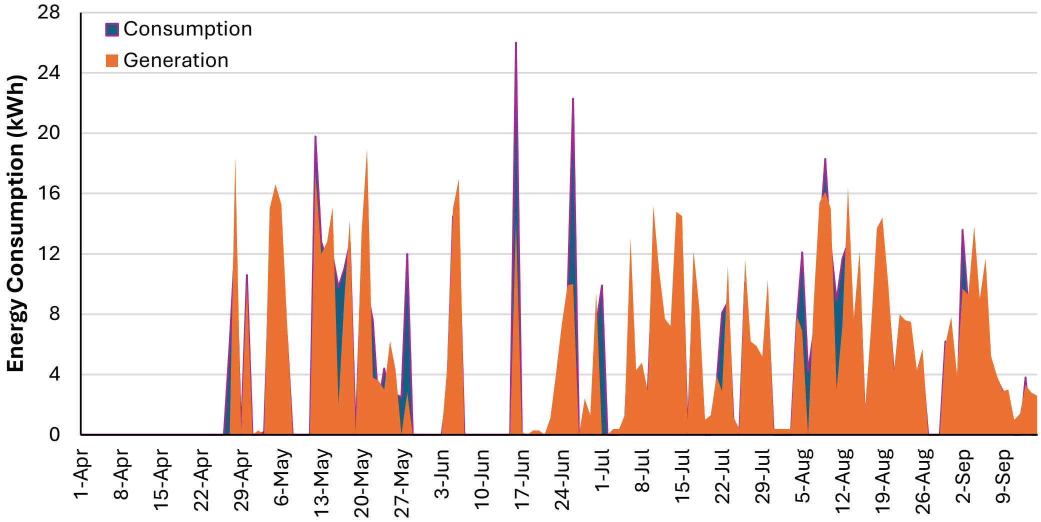


Figure 28. Daily energy consumption at Fair Farm

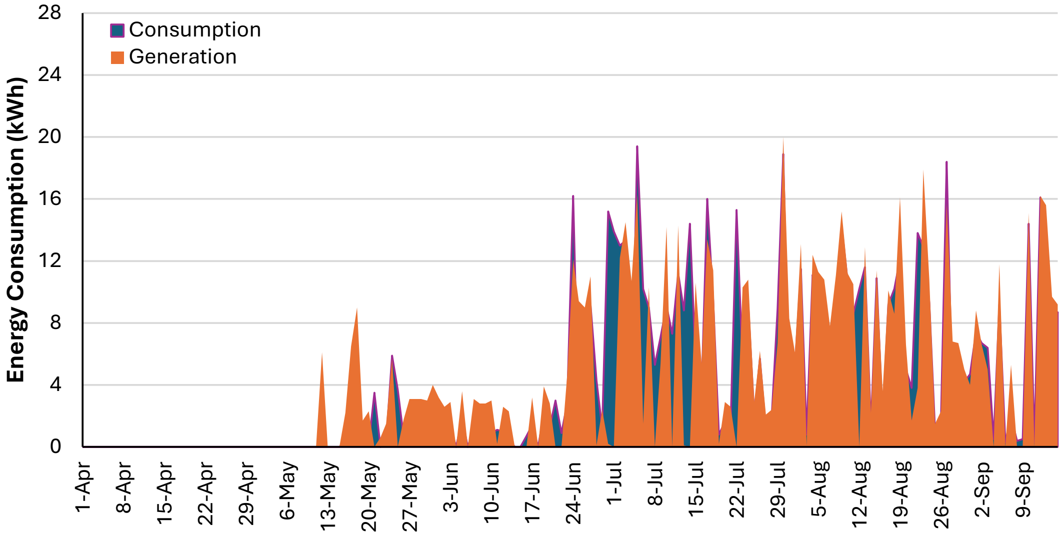


Figure 29. Daily energy consumption at Reaksa Farm

To gain a more comprehensive understanding of the performance of the solar photovoltaic system, an assessment was conducted on the percentages of energy consumption derived directly from the solar PV system as well as from the battery storage. The percentages of daily energy consumption for the cooling systems at Fair Farm and Reaksa Farm, separated into those sourced from the solar PV system and the battery, are depicted in Figure 41 and Figure 42, respectively.

It was notably observed that the cooling system at Reaksa Farm relied heavily on energy from battery, with an average daily energy consumption sourced from the battery reaching 72.01% (± 26.64%). In contrast, the cooling system at Fair Farm demonstrated a different energy consumption pattern, utilising only 37.08% (± 28.19%) of its daily energy needs from the battery.

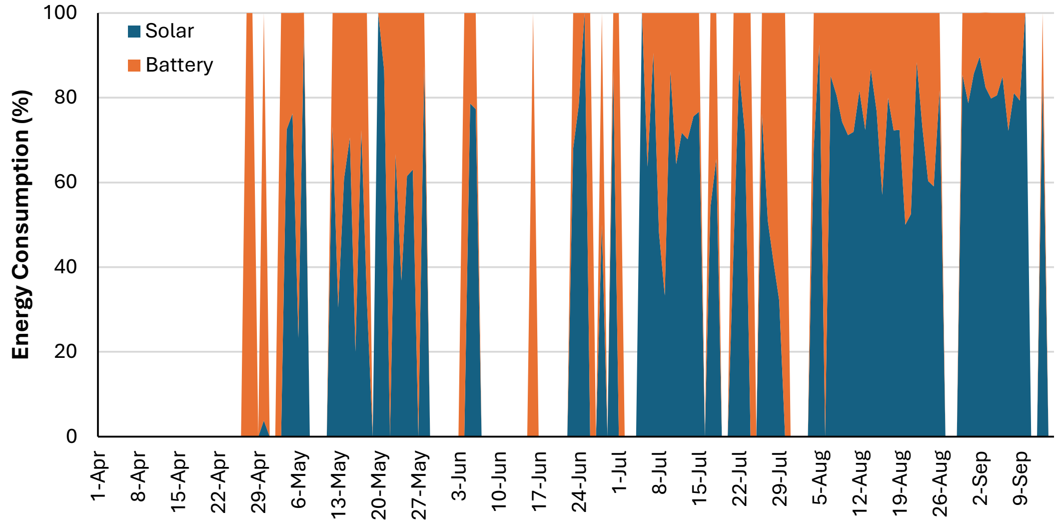


Figure 30. Percentage of daily energy consumption at Fair Farm

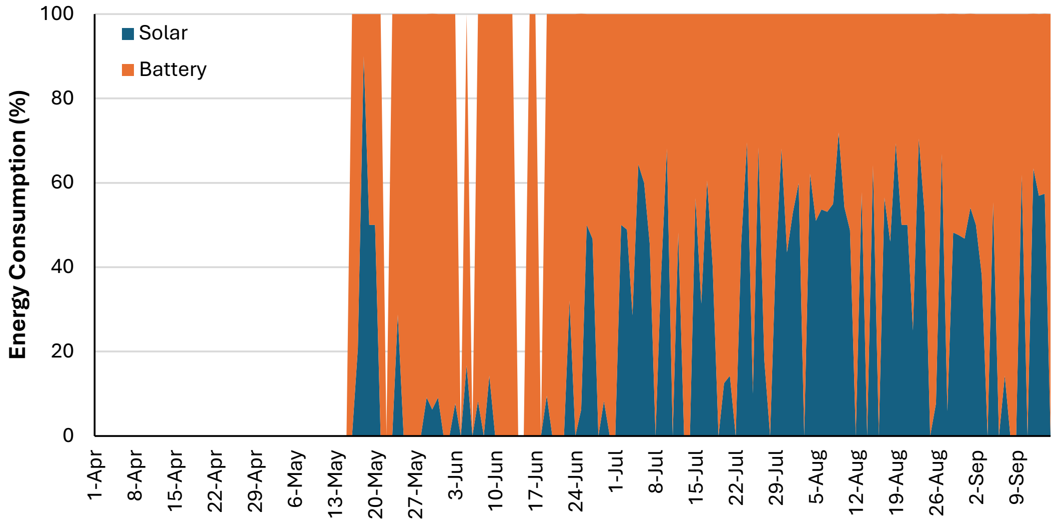


Figure 31. Percentage of daily energy consumption at Reaksa Farm

6.4.2. Cooling System

As previously mentioned, several sensors were installed at both farms to continuously record temperatures at one-minute intervals. These sensors were placed in both the non-test area and the test area to ensure accurate data collection. The recorded temperature data for the non-test area and test area of Fair Farm is presented in Figure 43 and Figure 44, respectively. Similarly, the temperature readings for the non-test area and test area at Reaksa Farm are illustrated in Figure 45 and Figure 46, respectively.

It was observed that the temperatures recorded in both the non-test area and the test area at Reaksa Farm were slightly higher compared to those at Fair Farm, as detailed in Table 13. Specifically, the average temperature in the non-test area at Fair Farm was recorded at 29.68°C (± 3.92°C), while the average temperature in the test area at Fair Farm was slightly lower at 28.95°C (± 3.25°C). In contrast, the average temperature in the non-test area at Reaksa Farm was found to be 30.34°C (± 3.51°C), indicating a notable increase. Furthermore, the average temperature in the test area at Reaksa Farm was measured at 29.71°C (± 2.96°C).

Table 7. Temperatures in non-test area and test area at the two farms

	Non-Test Area	Test Area
Fair Farm (oC) **Mean (SD)** **Min, Max**	29.68 (3.92) 23.80, 40.30	28.95 (3.25) 21.63, 40.26
Reaksa Farm (oC) **Mean (SD)** **Min, Max**	30.34 (3.51) 24.70, 44.30	29.71 (2.96) 23.27, 39.31

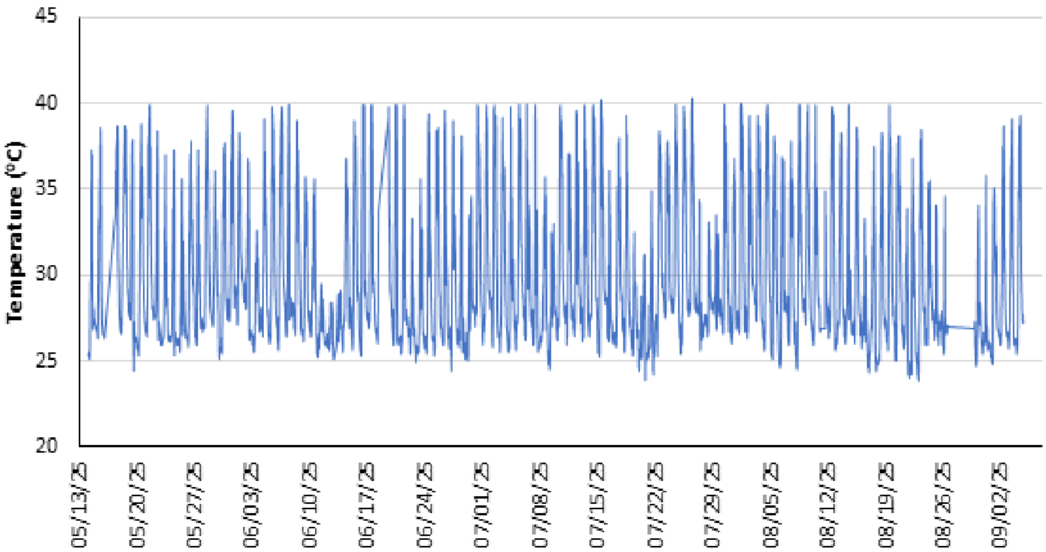


Figure 32. Temperature in non-test area at Fair Farm

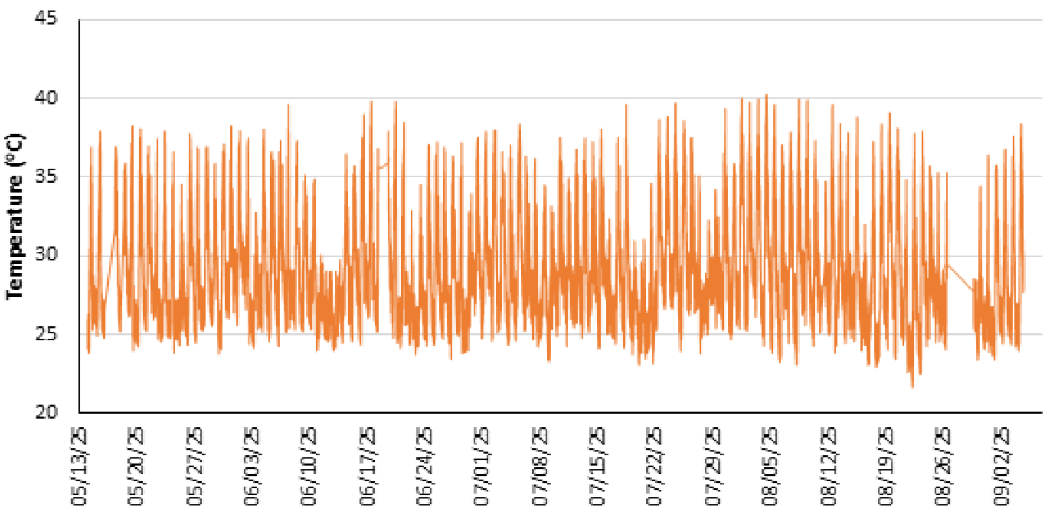


Figure 33. Temperature in test area at Fair Farm

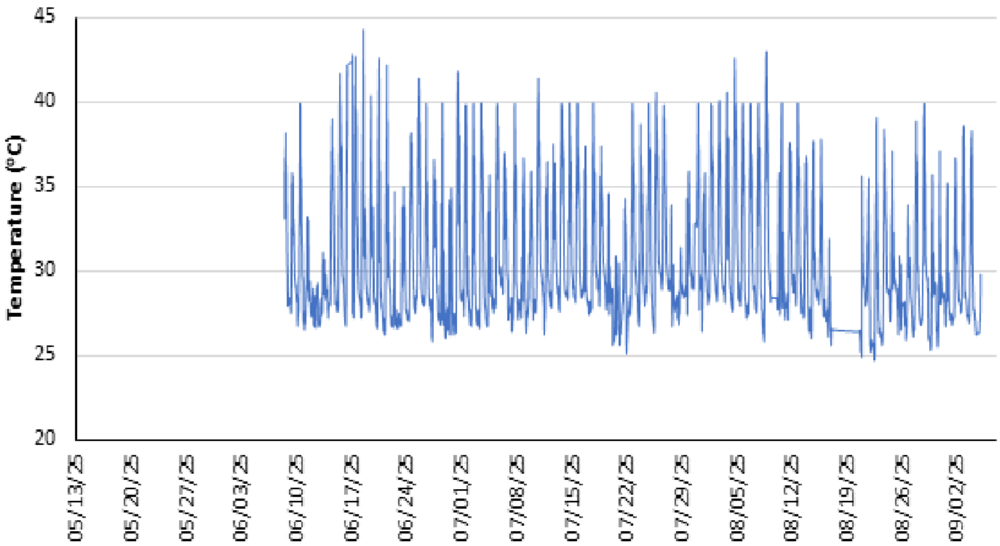


Figure 34. Temperature in non-test area at Reaksa Farm

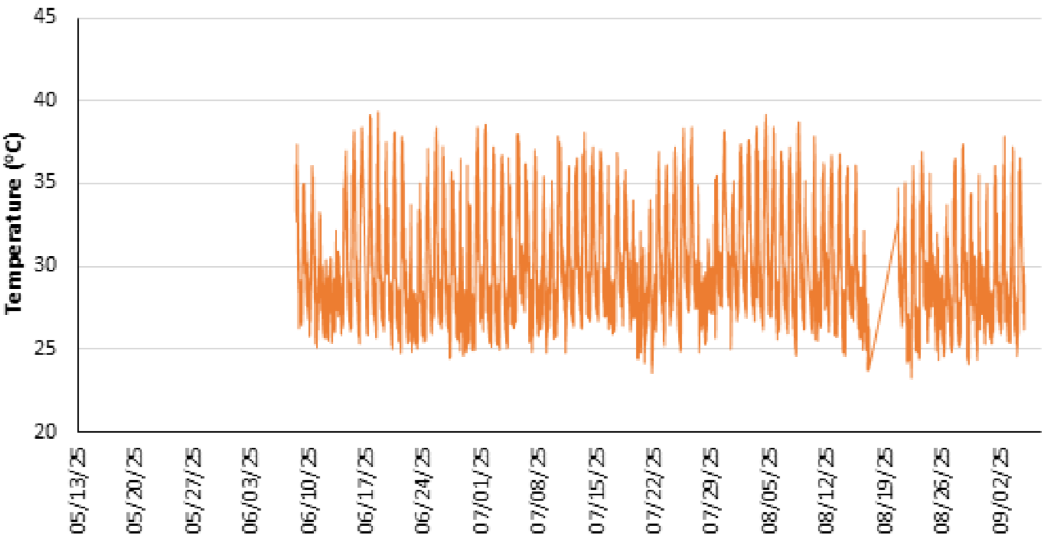


Figure 35. Temperature in test area at Reaksa Farm

The cooling systems at both farms were programmed to activate when temperatures exceeded 35°C. In order to evaluate the performance of these cooling systems at these two farms, the datasets were systematically trimmed. Specifically, any observations where the temperature in the non-test area fell below 35°C were excluded from the analysis. The results of this analysis, which compare the temperatures in the non-test area to those in the test area, are illustrated in Figure 47 for Fair Farm and Figure 48 for Reaksa Farm. The results presented in Table 14 clearly indicate that the temperatures in the test areas were consistently lower than those in the non-test areas across both farms, with a statistically significant difference ($p < 0.001$). Specifically, the average temperature recorded in the non-test area at Fair Farm was 37.12 (± 1.31°C), while the average temperature in the test area was significantly lower at 28.95 (± 3.25°C), resulting in a notable difference of 8.2°C. Similarly, at Reaksa Farm, the average temperature in the non-test area was measured at 37.16 (± 1.59°C), whereas the average temperature in the test area was found to be 29.71 (± 2.96°C), leading to a difference of 7.4°C.

Table 8. Comparison of temperatures in non-test area and test area at the two farms

	Non-Test Area	Test Area	Difference[1]	95% CI[1,2]	p-value[1]
Fair Farm (oC) **Mean (SD)** **Min, Max**	37.12 (1.31) 35.00, 40.30	28.95 (3.25) 21.63, 40.26	8.2	8.2, 8.2	< 0.001
Reaksa Farm (oC) **Mean (SD)** **Min, Max**	37.16 (1.59) 35.00, 44.30	29.71 (2.96) 23.27, 39.31	7.4	7.4, 7.5	< 0.001

1 Two sample t-test

2 CI = Confidence Interval

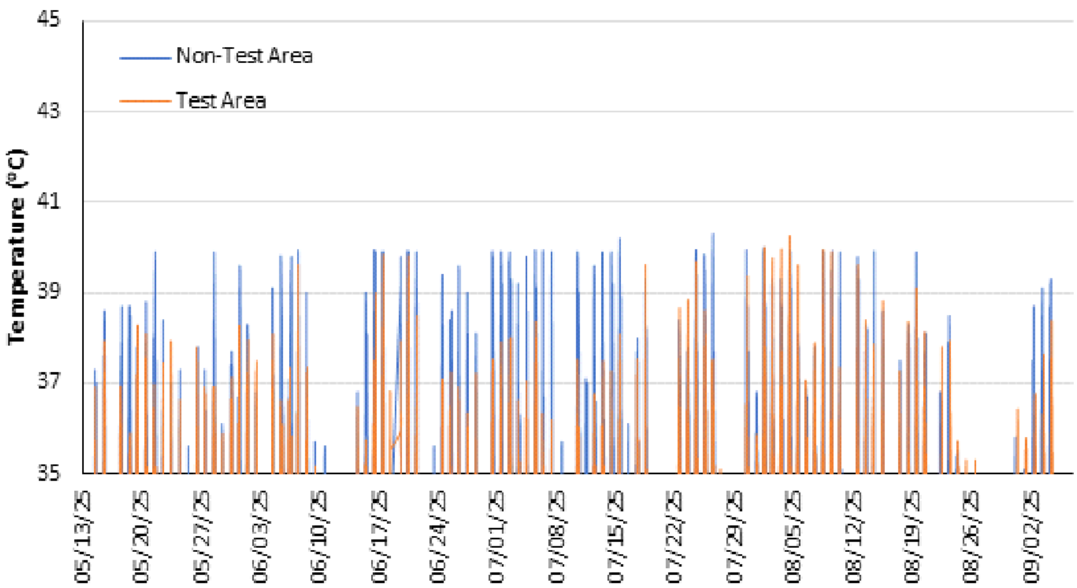


Figure 36. Temperature comparison between non-test area and test area at Fair Farm

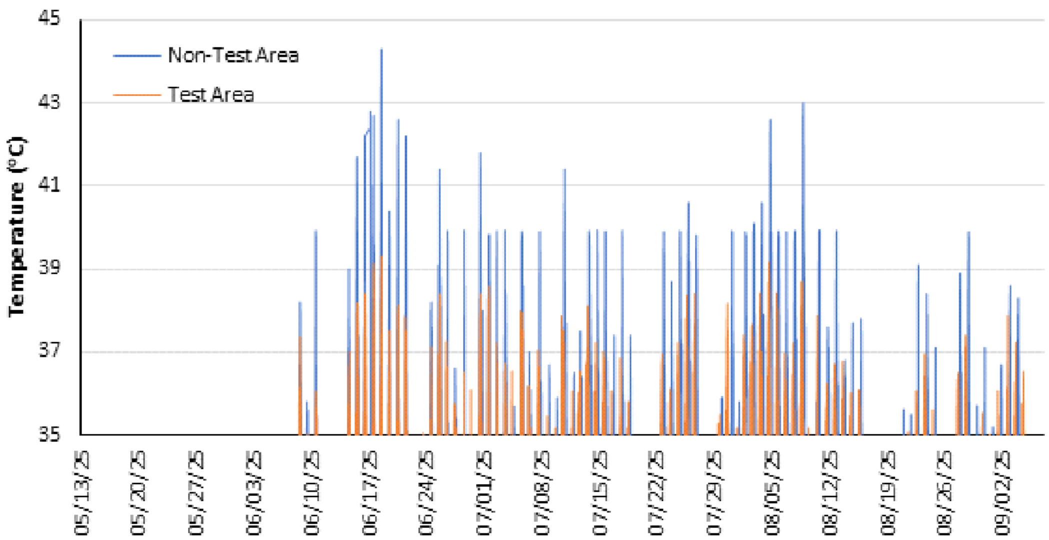


Figure 48. Temperature comparison between non-test area and test area at Reaksa Farm

6.4.3. User Feedback

The questionnaires survey was conducted (Figure 49) to collect user feedback on the operational cooling systems at both Fair Farm and Reaksa Farm. The survey focused on system operation, ease of use, and maintenance. At Fair Farm, observations indicated a noticeable reduction in temperature following the installation of the cooling system. In the absence of the system, the plantation experienced higher heat levels, making working conditions less comfortable. The cooling system was reported to reduce heat and improve working conditions, resulting in user satisfaction. In contrast, at Reaksa Farm, farmers were unable to effectively observe temperature reduction because the onset of the rainy season coincided with the system's readiness. Farmers at Reaksa Farm expressed hope that the system would continue to operate in the following year, allowing for further observation and evaluation.

Additionally, at both Fair Farm and Reaksa Farm, the technical team provided training on system operation and maintenance to facilitate ease of use to the famers, as the system operates automatically. Farmers expressed high satisfaction with the training received. During operation at Fair Farm, the system functioned properly without major issues. However, Reaksa Farm experienced recurring problems with the solar power supply and required assistance from the technology provider, SOGE. Farmers at both sites indicated that expanding the installation of the cooling system across the entire farm would be highly beneficial.

Figure 37. Interview with farms' workers to collect their feedback for cooling system

6.4.4. Technology Economic Return

The economic return of the solar-powered cooling and irrigation system was assessed using an avoided-losses model, which reflects the reality of pepper cultivation under extreme heat and drought (Table 15). Rather than relying on increased profits, the return is derived from the losses that the technology helps farmers avoid—losses that have recently become severe and recurrent.

The cooling system has demonstrated the ability to reduce canopy temperatures to ideal growing conditions, preventing heat-stress damage during peak temperature periods. Likewise, the drip irrigation system provides consistent moisture levels and has strong theoretical evidence for improving water-use efficiency and protecting vines during prolonged drought. When combined, these technologies stabilize the microclimate, maintain vine health, and can shorten the payback period through avoided crop losses.

The calculation therefore estimates the economic value of losses avoided in three key areas:

i) *Avoided Yield Losses:* Preventing the assumed 80% yield reduction typically observed during heatwave years.

ii) *Avoided Plant Replacement Costs:* Avoiding the 35% mortality rate, which requires farmers to replant poles and vines at significant cost.

iii) *Avoided Future Lost Productivity:* Newly replanted vines require 4 years to reach full maturity, producing 80% lower yields during this period. Preventing vine death avoids this prolonged productivity gap.

Table 9. Economic Return of Solar-Powered Cooling & Irrigation System

Category	Value (per 1 ha)	Formula Used
Baseline Yield (Excel Data)	650–667 kg/ha	–
Heatwave Yield (2024)	200–260 kg/ha	–
Yield Loss per Heatwave	390–450 kg/ha	= Baseline yield – Heatwave yield
Value of Yield Loss	USD 5,850–8,550 per ha	= (390–450 kg) × (USD 15–19/kg)
System Cost (1 ha)	USD 18,667	= USD 14,000 ÷ 0.75 ha
Key ROI Assumptions	80% yield loss avoided; 35% mortality avoided; USD 2/plant; 4-year maturity; 80% juvenile yield reduction	–
Avoided Yield Loss	USD 9,750–12,350 per ha	= (Yield loss per ha × 80%) × (USD 15–19/kg)
Avoided Plant Replacement	USD 1,400 per ha	= (2,000 plants × 35%) × USD 2
Avoided 4-Year Juvenile Yield Loss	USD 31,200–39,520 per ha	= (650 kg × 80% × 4 years) × (USD 15–19/kg)
Total Avoided Loss per Heatwave	USD 42,350–53,270 per ha	= Avoided yield loss + Avoided replacement + Avoided juvenile loss
Return vs. System Cost	Avoided losses = 2.3–2.9× system cost	= Total avoided loss ÷ USD 18,667
Payback Trigger	1 major heatwave fully repays investment	= If avoided loss ≥ USD 18,667

Heatwave Avoidance Required for Investment Payback

The economic return of the solar-powered cooling and irrigation system is best assessed through an avoided-loss framework, which measures how many heatwave or drought events must be prevented to recover the investment (Table 16). Because the system protects a defined cultivation area, the return varies by coverage size: smaller areas avoid fewer losses and therefore require more extreme events to reach break-even, while larger areas recover costs more quickly. Based on current yield, mortality, and replacement cost assumptions, a 500 m² pilot area would require approximately 15 avoided events, whereas the full 7,500 m² system coverage needs only one major heatwave to fully repay the USD 14,000 investment. This demonstrates the strong economic justification for deploying the system at scale.

Table 10. Break-Even Analysis Based on Coverage Area

Category	Value (per 1 ha)	Formula Used		
500 m² (pilot)	USD 3,733	USD 2,118–2,664	≈ 15 events	Cost ÷ Avoided loss
2,500 m²	USD 9,333	USD 10,588–13,318	≈ 3 events	Cost ÷ Avoided loss
5,000 m²	USD 12,444	USD 21,175–26,635	≈ 1.5 events	Cost ÷ Avoided loss
7,500 m² (system coverage)	USD 14,000	USD 31,762–39,952	≈ 1 event	Cost ÷ Avoided loss
10,000 m² (1 ha)	USD 18,667	USD 42,350–53,270	≈ 0.75 events	Cost ÷ Avoided loss

Note:

- System cost is proportionally scaled according to the land area covered by the technology.
- Avoided losses are calculated using Excel-based baseline yields, documented heatwave-related yield reductions, and an assumed 80% yield protection, together with avoided plant mortality and the four-year productivity gap associated with juvenile vines.
- The system reaches break-even once avoided losses exceed the investment cost for the corresponding coverage area.

This analysis adopts a conservative approach. It does not yet account for several additional benefits that would further strengthen the economic case for the technology, including:

- Energy savings from full solar substitution for pumping and cooling;
- Water savings from improved drip irrigation efficiency;
- Labor savings from automated irrigation and cooling;
- Potential yield gains resulting from stabilized, optimal microclimatic conditions.

These additional benefits are expected to further enhance overall returns and shorten the payback period.

7. Conclusions

This report provides a comprehensive assessment of the peppercorn cultivation practices implemented at Fair Farm and Reaksa Farm, while also evaluating the effectiveness of the innovative solar-powered cooling and irrigation systems that have been piloted at these two farms. Through data analysis and observation, several key conclusions can be drawn from the findings.

- Traditional cultivation practices continue to be utilised at both Fair Farm and Reaksa Farm, encompassing essential components such as soil management, weed management, and pest management. While irrigation management practices were introduced to enhance water efficiency and support crop growth, both farms have still faced challenges due to prolonged periods of drought. This ongoing drought has led to significant heat stress, which has adversely impacted the health of the peppercorn plants and ultimately reduced their yields.

- Soil analysis revealed that both farms possess soils generally suitable for pepper cultivation, but with critical limitations. At Fair Farm, soils showed moderate fertility with relatively balanced pH yet low organic matter, restricting water retention and nutrient availability. At Reaksa Farm, the soils were found to be more compact with higher acidity, conditions that can reduce root penetration and exacerbate nutrient deficiencies. Across both farms, insufficient organic matter and fertility management reduce the natural buffering capacity of soils against drought and heat extremes, underscoring the need for improved soil management practices such as compost application, mulching, and cover cropping.
- Climate data further highlighted the vulnerability of pepper cultivation. Prolonged droughts and recurring heatwaves, particularly during April–May 2024, coincided with severe rainfall deficits. Temperatures frequently exceeded the optimal 32–33°C range for pepper growth, with peaks above 36°C, while accumulated rainfall during the dry season was less than 200 mm—significantly lower than in other years. These combined stresses contributed to marked yield declines and highlighted the limited capacity of traditional management practices to cope with climatic extremes.
- The design of the solar PV system is adequate for operating the cooling systems at both farms. Based on the data collected regarding energy generation from the solar PV systems and the corresponding energy consumption of the cooling systems, it is evident that these two figures align closely. Additionally, the choice of inverter is commendable, as it is well-suited to accommodate the maximum power requirements of the load.
- The piloted cooling systems have proven to be effective in significantly reducing temperatures within the designated test areas. Results indicate that, across both farms, the temperatures in these test areas were consistently lower than those recorded in the non-test areas, demonstrating the cooling systems' capability to mitigate heat. Despite this impressive reduction, the temperatures in the test areas remain relatively high, potentially exceeding the ideal conditions necessary for optimum growth of peppercorn plants.
- Farmers expressed strong interest in expanding the cooling systems across their farms, recognizing their innovative features in automation, reliance on green energy, and ease of operation and maintenance. However, a detailed assessment of investment requirements and return on investment is still necessary before large-scale adoption can be justified.
- Return on Investment (ROI) analysis shows that the system provides substantial economic value by preventing climate-induced losses. When evaluated through an avoided-loss framework using baseline production data and heatwave impacts, the solar-powered cooling and irrigation system demonstrates a strong economic justification. For a 1-hectare equivalent system cost of USD 18,667, avoided losses from a single severe heatwave—comprising yield loss prevention, avoided plant mortality, and avoidance of four years of reduced juvenile yield—range from USD 42,350 to USD 53,270. This means that one major heatwave event is sufficient to fully repay the investment, and additional events translate directly into net economic gain. The analysis is conservative and does not yet include energy

savings, labor savings, water-use efficiency gains, or yield increases from improved microclimatic stability, which would further strengthen the economic return and shorten the payback period.

8. Recommendations

Several recommendations can be put forward to enhance the existing cooling systems at the two farms, as well as for future installations. The following points outline key areas for consideration and improvement:

- The testing period coincides with the rainy season, when there is no heat stress and rainfall is frequent. Given these conditions, it would be prudent to also conduct tests during the dry season. This additional testing is essential to ensure that the solar system design is capable of generating sufficient power to support the cooling system, especially since the dry season will require increased energy for spraying and other cooling activities.
- It is strongly recommended to extend the assessment period for at least one full year. This extension to a full year would provide sufficient time to capture and analyse the long-term impact of the piloted cooling system on the growth and yields of peppercorn plants. Therefore, a more comprehensive understanding of how the cooling system influences plant health and productivity can be obtained. Furthermore, this extended assessment will enable a thorough evaluation of the economic return on investment for the cooling system, allowing for informed decisions regarding its viability and potential for broader implementation.
- The pilot cooling system utilising solar panels offers an eco-friendly method for cooling water. However, it necessitates a larger investment in both the solar PV system and the cooling technology. More affordable alternatives, like evaporative cooling, should also be considered. Evaporative cooling systems can function effectively in Cambodia’s climate. This method cools the surrounding air through water evaporation, eliminating the need for additional cooling systems or solar PV installations, thus reducing overall costs.
- From a technical standpoint, it is highly recommended to integrate advanced smart control systems that encompass soil moisture sensors as well as sensors that measure the relative humidity of the surrounding environment within the test area. The incorporation of these additional sensors will facilitate a more precise management of the growing conditions for the peppercorn plants, ultimately leading to healthier and more productive crops. Furthermore, it would be beneficial to consider the implementation of remote monitoring capabilities for these critical variables, allowing for real-time data collection and analysis to optimize plant growth more effectively.

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