Solar Photovoltaic Portable Cold Storage Systems with IoT Control and Automation: A Review

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Abstract. Post-harvest losses of perishable agricultural commodities remain high in world with limited cold-chain infrastructure and unreliable electricity supply. Solar photovoltaic-powered portable cold storage systems provide an off-grid solution by maintaining low temperature and suitable relative humidity conditions that slow respiration, moisture loss, ripening, and microbial growth in stored produce. This review examines major refrigeration technologies used in portable cold storage. The energy storage approaches i.e., phase change material (PCM)-based cold thermal energy storage maintains near-isothermal conditions and reduces compressor runtime and energy consumption were discussed. The structural design factors play key role in form of insulation materials, storage geometry, and vacuum insulated panels where are evaluated because they reduce heat transfer and improve thermal stability. The environment inside the structure play a key role where sensor network, automation control, Integration of Internet of Things (IoT) networks and artificial intelligence (AI)-based control systems supports real-time monitoring and adaptive cooling management. The current limitations of low thermal conductivity and sub-cooling behaviour of PCMs, high system cost, and limited long-term field validation also discussed. Future work should focus on high thermal conductivity PCM composites, machine learning-based performance prediction, and low-cost modular system development to improve large-scale adoption and operational reliability of clean-energy postharvest preservation systems.
Keywords: Solar-Powered Cold Storage; Refrigeration Technologies; Phase Change Materials; Internet of Things; Control and Automation

1. Introduction

A considerable amount of perishable agricultural commodities deteriorates before reaching to the consumers. Global post-harvest losses are estimated near 30 %, while losses in developing and emerging economies may reach 40–60 % because of inadequate post-production infrastructure, improper on-farm handling, excess produce moisture, and unreliable electricity supply [1,2]. Commodity losses remain particularly severe in Africa (30–50 %), South Asia (20–44 %), and Latin America (>40 %) [3]. Cold storage systems reduce these losses by maintaining low temperature and high relative humidity, which slow respiration, ripening, dehydration, and microbial growth while preserving nutritional quality of stored produce [4,2,5]. Current studies developed on-grid solar-powered cold-storage systems integrated with Internet of Things (IoT) technologies for storage of perishable agricultural commodities. Prototype solar cold-storage systems were integrated with multiple sensors and microcontrollers for monitoring and control of temperature and relative humidity during storage. IoT-based control systems also generated emergency alerts when temperature and relative humidity deviated from selected storage conditions. Integration of sensors, monitoring systems, and automated control reduced manual handling and improved operational efficiency during storage management. Current developments also indicate future prospects in portable cold-storage technologies, including use of renewable-energy sources, intelligent sensors, and Internet of Things (IoT)-based monitoring and control systems for agricultural applications [7]. Portable and decentralized solar-powered cold storage systems are increasingly important for small-scale farming operations and remote regions where reliable grid electricity is limited [3,5,6-7]. Solar-powered off-grid storage units reduce spoilage losses by nearly 60–80 % and improve farmer income by 30–50 % through better product quality and market price [1,2,5]. Mobile micro cold storage (MCS) systems combine solar photovoltaic (PV) energy harvesting, thermoelectric refrigeration, and electric vehicle-based mobility to achieve grid-independent operation [8]. Other hybrid systems integrate solar PV, grid electricity, and phase change material (PCM)-based cold thermal energy storage (CTES) with vapor compression refrigeration cycles to improve operational reliability and cooling continuity [9]. Further expansion of CTES-based cold storage systems requires integration with smart farming platforms, rural micro-grid systems, and sustainable cold-chain infrastructure [10]. Long-term field validation under practical operating conditions is still limited. Future studies should improve state-of-charge estimation methods and develop durable PCM materials prepared from locally available and environmentally safe resources to reduce cost and improve accessibility in regions such as Africa and South Asia [10-11]. This review highlights the conventional, present technologies and future outlooks for improvement in portable cold storage systems. This review also covers recent advancements in solar photovoltaic-driven portable cold-storage technologies with emphasis on integration of Internet of Things (IoT)-based monitoring and automation systems. The review evaluates thermodynamic performance, different cooling systems, for reduction of post-harvest agricultural losses in off-grid rural conditions. The study also examines the feasibility of emerging smart-farm technologies for optimization of energy utilization and improvement of resilience in decentralized cold-chain infrastructure systems.

2. Methodology

This review used a systematic approach for synthesis of academic literature, policy reports, and empirical case studies published between 2020 and 2026. Information was collected through searches in Google Scholar, Springer, ResearchGate, Frontiers, and Scopus using keywords related to portable cold storage, phase change materials (PCMs), Internet of Things (IoT)-based monitoring, and solar-energy integration. The study selection was limited to research with relevance to agricultural post-harvest transportation, energy efficient in remote areas and advanced technology and its applications accordingly. The information collected was previous reviews-based information regarding the performance parameters, the challenges, and future prospects of the hybrid solar-powered cold-storage systems was extracted.

3. Cooling System in Portable Cold Storage

The internal storage environment and space for preservation effectiveness of cold storage systems is determined by cooling mechanisms. The phenomenon used was vapor-compression refrigeration systems are systems that use refrigerant fluids to lower the temperature by exposing them to a phase transformation under pressurized conditions. These systems are effective for the temperature control, but, due to the fact that they must be powered at all times, these systems cannot be used outside of the home in a portable off-grid manner [7]. Evaporative cooling systems (ECYS) rely on the use of the latent heat of the evaporation of water to cool the ambient air, due to which these systems need no external energy. The system approch requires the humidification to a matter state where the ambient air has a relatively high level of moisture, between 90 and 100 % relative humidity (RH), which is best achieved when ambient humidity is low, before humidification [12]. In anorther system, thermo-electric cooling systems, direct current flow through a P-type semiconductor and an N-type semiconductor which creates a cooling effect, known as the Peltier effect.. These solid-state systems maintained produce quality for more than one week during transportation and market storage conditions [1,13]. Phase change materials (PCMs) are also integrated into cold storage systems as passive thermal storage materials. PCMs absorb latent heat during solid-to-liquid phase transition and help maintain stable chamber temperature with lower energy fluctuation [14]. Stable thermal conditions improve temperature regulation and reduce cooling energy demand. Effective preservation of perishable commodities generally requires storage temperature between 0 and 13 °C together with relative humidity between 80 and 95 %. These conditions slow metabolic activity, respiration, and transpiration processes, thereby reducing weight loss and preserving appearance, flavor, and nutritional quality of stored produce [1].

4. Cold Storage Parameters

4.1 Factor Affecting Storage Efficiency

The efficiency of solar photovoltaic (PV) portable cold-storage systems depends on environmental conditions, system design, and material properties. Operating temperature of PV modules directly affects system efficiency because higher temperatures caused by intense solar radiation reduce electrical output and power-generation efficiency of PV cells. Cooling performance of these systems also depends on integration of thermal-energy-storage units, particularly the configuration and type of phase change materials (PCMs) used. Studies reported and as shown in Fig. 2, respectively that placement of PCM modules, including their arrangement relative to insulation panels, and selection of PCMs with suitable phase-change temperatures are important for extending cooling duration and maintaining temperature uniformity inside storage systems [9, 10].

4.2 Performance Parameters in Portable Cold Storage

The operational performance of cold storage systems depends mainly on cooling behavior, energy efficiency, and humidity control, which together determine preservation quality of perishable commodities. Cooling time is commonly defined as the duration required for the storage chamber to reach the target preservation temperature, such as 8 °C, and is used as an indicator of thermal response performance [15]. System dynamics also show a positive relationship between increasing cold chamber temperature and hot side heat removal rate [8]. Stable cabinet temperature is important for reducing compressor operating duration and extending compressor OFF-cycle periods, which lowers overall energy consumption during storage operation [14]. Phase change material (PCM) integration improves thermal stability inside cold storage systems by increasing thermal inertia. PCM incorporation extended temperature retention duration by nearly 4 h and reduced compressor ON-time by 4.86 % [9]. Solar-powered PCM-integrated systems also reduced total energy consumption by 17.9 % compared with conventional refrigeration systems [6]. Refrigeration efficiency is commonly evaluated using the coefficient of performance (COP), which represents the ratio between removed heat ($Q_{cooling}$) and supplied energy input (W_{in}) [13,16]. Daily energy consumption of cold storage systems generally ranged from 9.18 ± 1.23 kWh/d to 12.88 ± 2.21 kWh/d depending on refrigeration configuration [16]. Hybrid solar-battery PCM systems improved overall COP by 16.7 %, increasing the value from 1.80 to 2.10 [9]. Additional operational parameters include PCM discharging efficiency, which indicates the effectiveness of stored cold energy delivery from PCM to the storage chamber [15]. In evaporative cooling systems, cooling efficiency is evaluated psychrometrically by measuring how closely the leaving air dry bulb temperature approaches the entering air wet bulb temperature [12]. Relative humidity control remains equally important during storage because inadequate humidity accelerates wilting, softening, and moisture loss in stored produce. High humidity conditions help maintain saleable weight, flavor, texture, appearance, and nutritional quality of agricultural commodities [3,4]. Overall system effectiveness is evaluated using both electromechanical and biological performance indicators. Mechanical assessment includes compressor ON–OFF cycles, grid energy savings, and refrigeration efficiency parameters [9]. Biological analysis comprises of the following during storage of crops i.e., weight reduction (%), physiological loss in weight, the texture stability, colour retention and decrese in the microbial load [5,8].

5. Solar PV Integration in Portable Cold Storage

5.1 SPV Components

The solar PV system for cold storage systems used in portable consist of solar panels, charge controller, battery storage unit, the inverters. Solar panels convert solar radiation into electrical energy. The charge controller regulates electrical flow from the panels and protects batteries from overcharging and deep discharge conditions. The inverter converts direct current into usable alternating current for refrigeration units, sensors, and control systems as shown in Fig. 1, respectively. Battery storage units supply backup power during night-time operation and periods of low solar irradiance to maintain continuous cooling inside the storage chamber. Solar photovoltaic (PV) panels generate electrical energy from sunlight, although conversion efficiency decreases as panel operating temperature rises [17-19]. Flat roof mounting gives surface shading and reduces heat flow into the cold storage chamber, which lowers refrigeration load. A 23.5° north-facing tilt improved winter peak power output by 34 % due to better solar incidence angle [18]. MPPT solar charge controllers regulate electrical flow to batteries and protect them from overcharging [20,8]. A variable speed drive (VSD) converts DC output into variable-frequency AC supply for compressor operation, whereas hybrid inverters use stored battery energy during night-time operation [18]. Lead-acid batteries exposed to ambient temperature between 40–60 °C show major reduction in service life, therefore accurate battery sizing and thermal management remain necessary [18,8]. PV arrays should handle compressor start-up surge conditions using a 1.2 power factor during system sizing [17,12]. Series and parallel panel arrangements remain limited by charge controller voltage and current capacity, together with safety factors between 1.2 and 1.3. VSDs and inverters should also match the maximum refrigeration compressor load to maintain stable cooling conditions [18,17]. Battery size and storage cost may be reduced by improving thermal insulation of the cold storage structure or by using latent thermal storage materials such as phase change materials (PCMs) [18,19].

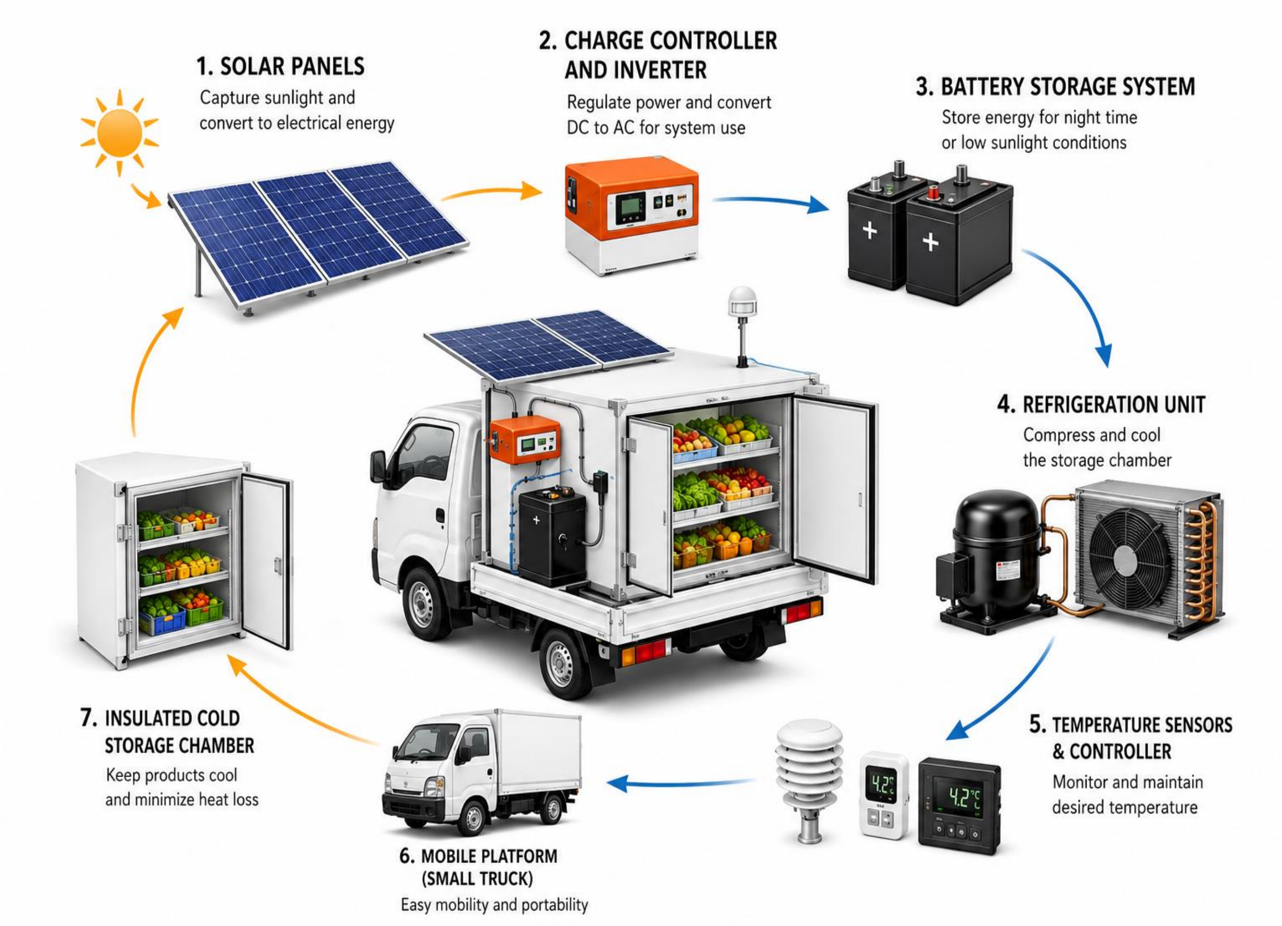

Fig. 1: Solar photo voltaic components for portable cold storage systems [1-25]

5.2 Energy Requirement

The power consumption of cold storage units is highly dependent on local weather conditions, as structural heat gain through cabinet walls increases linearly with ambient temperature [17,6]. Higher ambient temperature extends compressor operating time and increases the biological heat of respiration in stored agricultural commodities, which raises total energy demand. Low relative humidity also causes produce to absorb ambient heat and accelerates metabolic respiration and ethylene (C_2H_4) generation, reducing storage life [12]. Therefore, the total daily cooling load (Q) includes conduction through insulated walls, product sensible cooling, respiration heat, door infiltration, and auxiliary thermal loads [12,17]. After summing product load, transmission load, respiration heat, fan load, lighting load, and defrosting load, a 20 % safety factor is generally applied to account for unconsidered parameters and operational fluctuations [17]. The required electrical power is then obtained by dividing the total thermal demand by the refrigeration system's Coefficient of Performance (COP) [18, 20]. To satisfy the electrical demand, the nominal power of the solar photovoltaic system is estimated as:

$$P_{PV.nom} = N_{PV} \times P_{mod.nom}$$

which ensures that the PV array can accommodate compressor startup surge conditions. Finally, the required energy storage capacity (E_{sto}) depends on the total daily energy consumption and the required days of operational autonomy [16].

5.3 Energy Storage

Electrochemical battery storage is commonly used in photovoltaic (PV) systems to overcome the intermittent nature of solar radiation and maintain system operation during low irradiance periods. Excess daytime electrical energy is stored in battery banks and later used during night-time or cloudy weather conditions. In hybrid systems, stored battery energy can operate the refrigeration compressor through a variable speed drive (VSD) and inverter arrangement [18,17,6, 21]. Battery storage also supports additional farm electrical loads when solar power generation decreases. However, large battery dependence increases system cost and introduces limitations related to shorter service life and environmental concerns linked with material extraction and disposal processes [10]. Phase change materials (PCMs) are used as an alternative thermal energy storage method to reduce dependence on electrochemical batteries. When the material in in melting condition, PCMs can absorb heat from their environment due to the latent heat of melting, and when it gets solidifying, the heat absorbed in the melting process is released to the environment. High thermal storage density with comparatively lower storage volume requirements have resulted from the transfer with a stable thermal behaviour during phase transition. When solar irradiance is low or unavailable, the latent energy stored in the chambers helps keep the temperature of the chambers cool thereby longer the cooling time in storage. By integration with PCM, thermal stability was also increased resulting in lesser fluctuation in the chamber temperature for internal trials from ±2.8 °C to ±0.6 °C [19].

6. Design and Automation in Portable Cold Storage

The portable cold store system were powered by solar energy which combines power generation, energy storage, refrigeration, insulation and IoT monitoring parameters for uninterrupted cooling effect even in varying environmental conditions. PV modules produce electricity, and MPPT charge controllers are used to manage electricity flow and have an advantage in optimizing the charging efficiency. During periods of no solar insolation at night, the solar thermal storage system with the use of phase change material (PCM) ensures a continuous cooling process. Refrigeration units provide controlled low-temperature storage, whereas structural insulation reduces external heat gain into the storage chamber. Sensor networks and automated control systems continuously monitor storage parameters and regulate cooling performance to improve energy efficiency during transportation and field-level storage operations. Designing portable cold storage requires a balance between compact, lightweight structure and sufficient storage space for agricultural commodities during transport and handling [7,14,15]. Portable units are generally designed for manual movement or four-wheeled transport while maintaining suitable internal storage volume. Structural geometry also affects thermal behavior. Cylindrical configurations show lower heat transfer than cuboid structures because of their smaller surface area-to-volume ratio, which reduces thermal permeability and improves heat retention inside the chamber [14]. To reduce external heat gain, portable cold storage structures commonly use polyurethane sandwich panels (PUSP). These panels generally consist of high-density polyurethane foam, such as 0.10 m thick insulation, placed between corrugated aluminium sheets [13,17]. Multi-layer wall structures containing air gaps, fiberglass, aerogels, and multi-foil layers further reduce solar heat penetration and lowered thermal impact of solar radiation by nearly 27 % [7]. Replacement of conventional polyurethane insulation with vacuum insulated panels (VIP) also lowered thermal conductivity and reduced heat transfer from ambient surroundings. Lower heat gain extended the phase transition duration of integrated phase change materials (PCMs) up to 46.5 h [15]. Use of advanced insulation materials therefore decreases cooling load, improves energy efficiency, and increases operational economy of portable cold storage systems [7, 22].

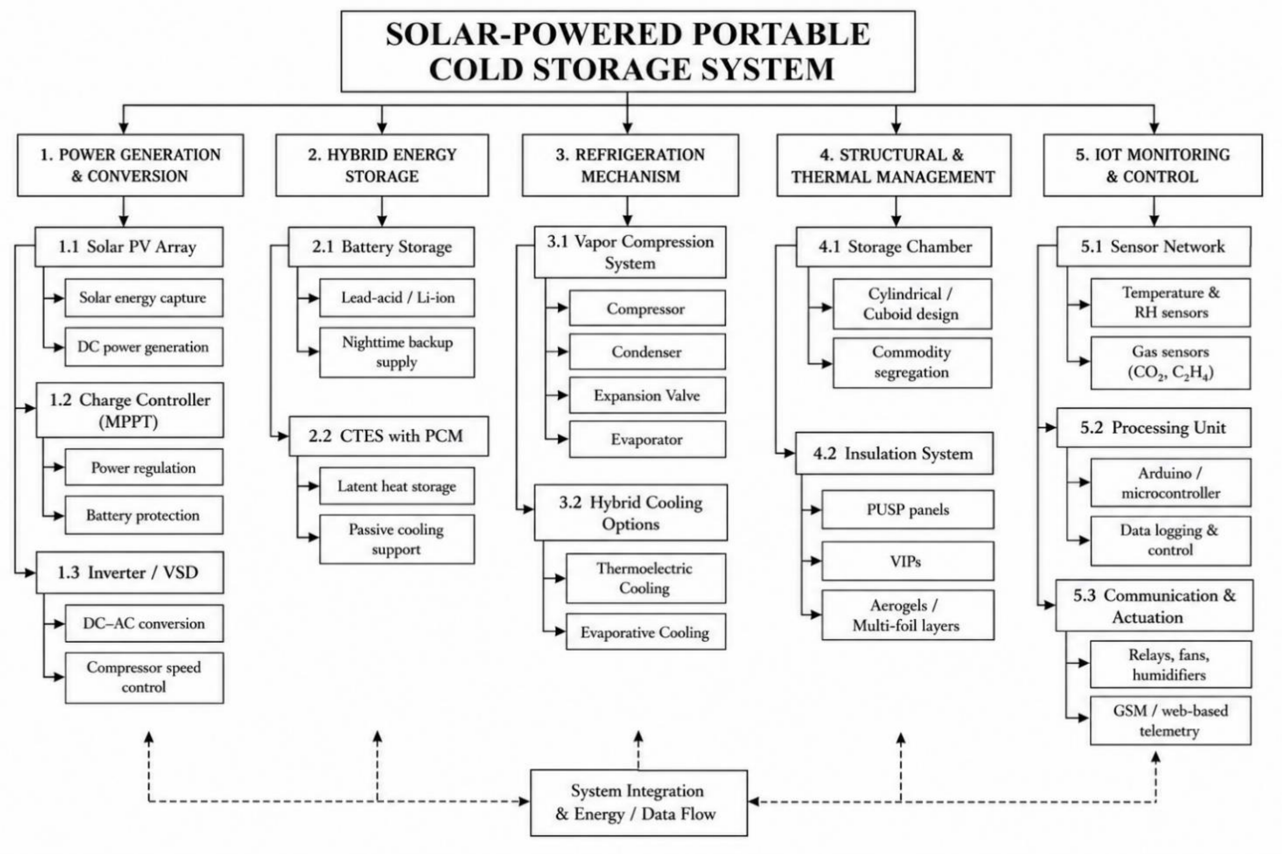

Fig. 2: Mechanism of solar powered cold storage systems [1-25]

Table 1: Comparison of Refrigeration Technologies Used in Portable Cold Storage systems

Refrigeration technology	Cooling principle	Energy source	Power consumption	Key advantages	Limitations	References
Vapor-compression systems	Refrigerant phase change during evaporation and condensation	Grid electricity, Solar PV, Battery, Diesel	75 W–5 kW; commonly 100–200 W in mini units; up to 2.2 kW in large systems	Precise temperature and 80–90% RH control; suitable for frozen storage	High energy demand; refrigerant leakage risk; high particulate emission	[10,12,19]
Phase-change material (PCM) systems	Latent heat storage during solid–liquid transition	Pre-charged thermal energy	Zero during operation; 5.6–18.6% energy saving in hybrid systems	Stable cooling without continuous power	High material cost; long charging time	[15,22]
Solar-integrated systems	Solar PV-driven refrigeration with PCM or ice storage	Solar photovoltaic	336.76–447.61 W; energy yield 2.4–5.1 MJ m^{-2} day^{-1}	Off-grid cooling; low carbon emission	Cooling capacity reduced by 7.15% during cloudy weather	[16,18,6,23]
Thermoelectric systems	Peltier effect creates temperature gradient	12 V DC, Solar PV, Battery	9–180 W; typically 30–75 W in mobile units	Compact; lightweight; no refrigerant use	Low COP; limited cooling volume; high battery drain	[17,8]
Evaporative cooling systems	Heat removal through water evaporation	Ambient heat, Solar PV, Battery	0 W in passive units; up to 25.4 W in active systems; 427.2 Wh day^{-1}	Low operating cost; eco-friendly	Poor performance at high humidity;	[12]

7. Internet of Things System and Control in Portable Cold Storage

The IoT monitoring system in portable cold storage integrates components i.e., sensor networks, data processing units, and automated control systems for real-time storage management as presented in Fig. 3, respectively. Temperature, relative humidity, CO_2, and ethylene sensors continuously monitor internal storage conditions and transmit data to microcontrollers such as Arduino UNO for processing. Logic-based control algorithms and machine learning models analyze sensor data and regulate compressor operation, humidification, and ventilation according to storage requirements. GSM modules and wireless telemetry systems support remote monitoring, closed-loop control, and continuous adjustment of storage conditions during transportation and field-level operation. Integration of Internet of Things (IoT) networks into portable cold storage systems supports real-time monitoring of storage conditions through continuous wireless data transmission. These systems reduce infrastructure cost and decrease the need for repeated manual inspection during storage operation [4,24,7]. Important storage parameters such as temperature, relative humidity (RH), ambient light intensity, and spoilage gas concentration are monitored continuously using different sensors as shown in Fig. 2, respectively. DHT11 and DHT22 sensors are commonly used for temperature and humidity measurement, whereas BH1750 sensors monitor light intensity. Ethylene (C_2H_4) and CO_2 concentrations are detected using MQ-series sensors or Senseair-S8 sensors [17,25]. Collected sensor data is processed through programmable microcontrollers such as Arduino UNO and transmitted to remote web servers using GSM communication modules including SIM800A for centralized monitoring and storage [4]. Continuous environmental data allows automated IoT control systems to regulate humidification, ventilation, and refrigeration compressor operation according to storage conditions. Controlled atmospheric conditions reduce contamination risk and help maintain postharvest quality of stored agricultural commodities [17,25].

8. Thermal Effect in Portable Cold Storage

Refrigeration technologies used in portable cold storage differ in cooling mechanism, energy requirement, operational efficiency, and storage suitability. The comparative approach is presented in Table 1 for different cooling systems used in portable cold storage systems. Vapor-compression and solar-assisted refrigeration systems provide precise temperature control and higher cooling capacity for perishable commodity storage. Phase change material (PCM)-based, thermoelectric, and evaporative cooling systems reduce energy consumption and improve suitability for off-grid operation. However, each technology has specific limitations related to power demand, climatic dependence, cooling rate, system weight, or installation cost, which affect their practical application in agricultural cold storage systems. Ambient temperature strongly affects the thermal behavior of cold storage systems, where higher external temperature increases heat gain through storage walls and extends refrigeration compressor operating time, leading to greater power consumption. This external heat load also influences the performance of integrated phase change materials (PCMs). PCMs regulate chamber temperature by absorbing latent heat during solid-to-liquid phase transition while maintaining nearly constant temperature conditions [17,14]. Large changes in ambient temperature reduce PCM cooling duration considerably. Increase in ambient temperature from 15 °C to 50 °C reduced the time required to reach critical threshold temperature by nearly 68 % [22,14]. Thermal performance of PCM systems also depends on thermophysical properties such as thermal diffusivity and thermal conductivity. Higher thermal diffusivity reduced threshold duration, whereas naturally low thermal conductivity of many PCMs limits practical heat transfer performance [22,11]. Improvement in thermal conductivity through encapsulation methods increased overall heat transfer efficiency. Encapsulation of water within graphite spheres increased effective thermal conductivity nearly twelvefold and reduced freezing and melting time by 53.7 % and 44.4 %, respectively [11]. Vacuum insulated panels (VIPs) further reduced ambient heat transfer because of their much lower thermal conductivity compared with conventional polyurethane insulation. Reduced external heat gain extended PCM phase transition duration up to 46.5 h [15]. Structural geometry also affected thermal management. Cylindrical storage units had less surface area/volume and had a lower thermal permeability as compared to cuboid systems, contributing to the extendability of heat storage within the storage space [14].

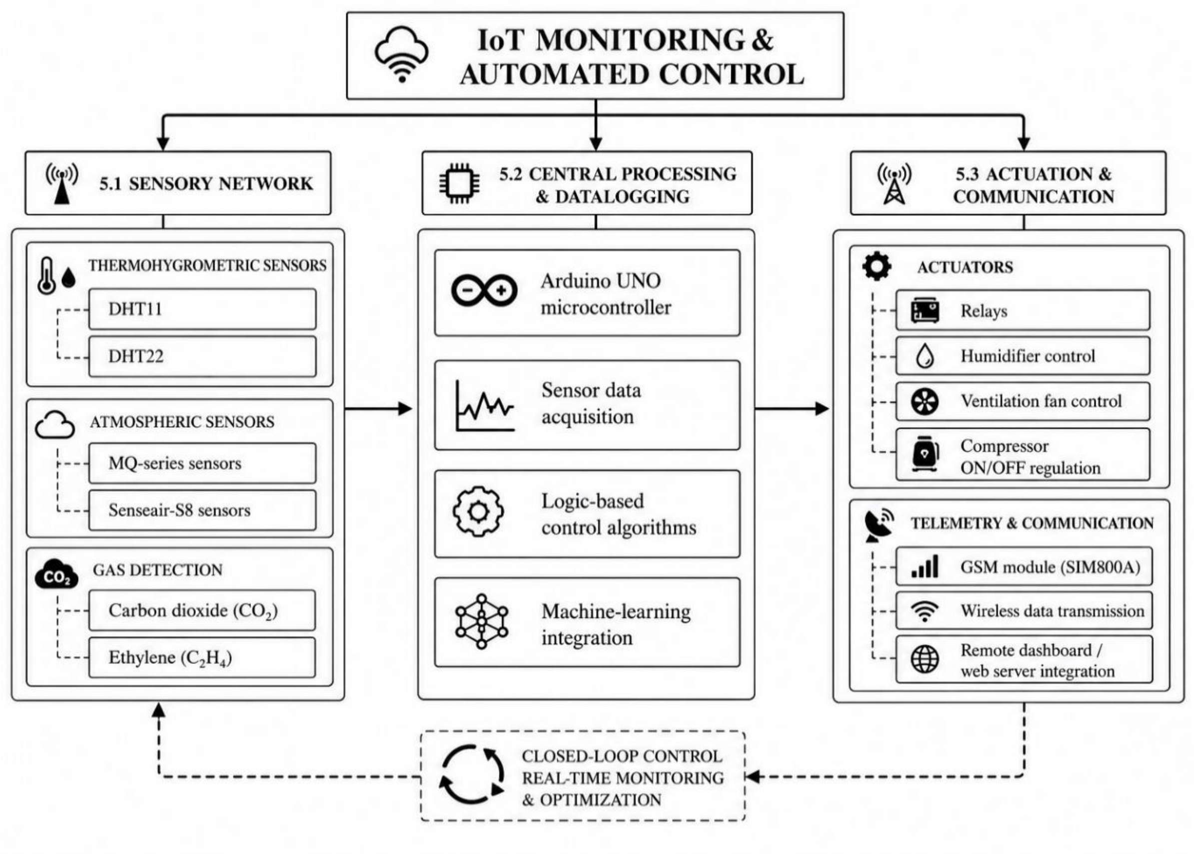

Fig. 3: Various **c**omponents in IoT network system with automation control and real time monitoring [1-25]

9. Technical Challenges

There are various operational and technical constraints associated with portable cold storage systems. The continuity of electricity is essential to most systems, limiting their use in areas where the power grid is unreliable and solar power is unable to meet its needs. The solar-powered operation involves a rapid variation in solar intensity conditions that have to be precisely controlled by advanced DC-DC converter [8,7]. Different refrigeration techniques have differing performances in terms of cooling efficiencies. The coefficients of performance (COP) of such sorption cooling systems are normally less than those of the vapor compression systems, and their cooling time is also less compared to vapor compression supercharging [7] while evaporative cooling is dependent on weather and ambient heat availability. System is also affected by extreme ambient conditions. When the external temperature is above 35 °C, storage walls gain heat, efficiency decreases in the insulation and the efficiency of the compressor decreases. Low operating ambient temperature also makes refrigeration more complex systems, and it affects the efficiency of the overall systems as well [10,18]. Despite the low thermal conductivity, the subcooling phenomenon of phase change material restricts the possibilities of certain fields in which phase change material integration is considered. Most of the PCM also have a thermal conductivity between 1 to 2 orders below the common heat transfer fluids, hence the charging and discharging duration is longer in thermal storage operation [11]. The reliability of the sensor may also deteriorate under suddenly changing storage conditions. The different sensors, for instance, DHT22, presented errors in measurement in front of significant temperature changes [4]. There are still a number of deficiencies to learn about the PCM-based portable cold storage systems. Standardized of PCM testing processes are limited; there are different studies that have not been conducted on a field scale; and there are still more PCM formulations that continue to drive overall system expenses [11]. Thus, development of high thermal conductivity PCM composites and low-cost materials of bio-origin based PCM materials should be further researched in the future. Extended field testing is also necessary to assess durability, lifecycle performance and economic viability in actual storage applications [10,7]. Further operational increase in system stability and post-harvest preservation efficiency of portable cold storage applications can be achieved by using AI-based adaptive control systems, coupled with improved thermal modelling.

10. Future Prospects

There are still some research gaps to be filled regarding modelling, multi-scale optimization and adaptive artificial intelligence (AI)-based control strategies of portable cold storage systems. State-of-charge (SOC) estimation methods for batteries are also significant for better utilization of the batteries and their general system reliability [10]. In addition, machine learning (ML) models should be integrated with component degradation studies to interpolate the continuous performance degradation of photovoltaic (PV) panels and electrochemical batteries when operating in real field conditions [16]. The precise use of Internet of Things (IoT)-based monitoring systems combined with ML algorithms and advanced food sensing technologies can help in consistently monitoring the surrounding environment and automatically controlling the surrounding inside storage chambers. Operational efficiencies and quality post-production can be achieved with real-time control of storage conditions [17,8]. Future of off-grid cold storage systems should also have been the better coupling of Phase Change Materials (PCMs) and hybrid renewable energy systems. The operation can be made more stable when using of combined modes when a solar photovoltaic system is coupled with solar heat collectors and, optionally, with other secondary renewable energy systems like wind or biomass respectively, under variable environmental conditions [8,11]. Another large area of research to be carried out is material development. The thermal conductivity, melting temperature of the PCM composites and the thermal energy storage density needs to be improved in the future's PCM studies [14, 10]. Preparation of PCMs using local materials with low cost and environmentally friendly methods could overcome the barriers of adopting PCMs in developing countries like Africa and South Asia [14,11]. Other charging solutions, such as industrial waste heat recovery, need to be explored. The usual test method of the PCM thermal properties and repeated thermal cycles under real working conditions are still few in number. There is a need for common testing protocols that would allow comparing materials, while enabling industrial-scale development of modular cold thermal energy storage (CTES) systems [10,11].

10. Conclusion

In conclusion, perishable agricultural commodity degredation after harvest is still a big problem especially in rural areas of developing countries where there is poor cold chain delivery and loss of electricity. Portable cold storage units powered by solar photovoltaic (PV) emerge as effective low-carbon solution to minimize these losses and to help improving the conditions on agricultural storage practices in rural areas. Such systems provide a regulated temperature and relative humidity, which retards the spoilage, moisture evaporation and microbial development in stored vegetable products. Proper structure choice and energy management is key to the efficient operation of portable cold storages. The use of compact storage geometry and vacuum insulated panels (VIPs) creates external heat transfer reduction and the heat stability. In approaching the traditional electrochemical battery dependence, phase change material (PCM) based cold thermal energy storage (CTES) systems are gaining in popularity for their near-isothermal cooling rate, extended cooling time, decreased ON-time of the compressor operation and an overall improvement of the coefficient of performance (COP). Monitoring and automatic regulation of the conditions inside the storage room are further assisted by the integration of Internet of Things (IoT)-based sensors. Integration of Internet of Things (IoT)-based sensors further supports real-time monitoring and automatic regulation of internal storage conditions. Several technical limitations still affect large-scale deployment of these systems. Low thermal conductivity and subcooling behavior of PCMs reduce thermal storage efficiency, while high ambient temperature decreases photovoltaic system performance and refrigeration efficiency. Future research should therefore focus on development of high thermal conductivity bio-based PCM composites and machine learning-based predictive control systems for adaptive operation and component degradation analysis. Long-term field studies under practical operating conditions are also required to improve reliability, economic feasibility, and wider adoption of solar-powered portable cold storage systems in sustainable agriculture.

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