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## OFF-GRID MILK PRESERVATION SOLUTIONS FOR SMALLHOLDER FARMERS IN SUB-SAHARAN AFRICA

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## ABSTRACT

Milk production in sub-Saharan African countries has increasingly gained attention from both private and public sectors due to its role in food security, nutrition, and rural livelihoods. The emphasis has been on devising strategies to increase production and efficiency within the dairy value chain, with a particular focus on minimizing post-harvest milk losses among smallholder farmers. One of the interventions for reducing these losses is the preservation of milk freshness overnight. Considering that most smallholder dairy farms are located in rural areas with limited or no access to grid electricity, effective solutions need -to rely on renewable energy sources, such as solar or biogas-powered cooling systems. Current milk preservation solutions available in the market vary significantly in terms of storage capacity, ranging from 2.5 liters to 500 liters. Many of these solutions fail to meet the specific needs of smallholder farmers in Uganda and other sub-Saharan African countries, where dairy farming structures and management practices are relatively uniform. A typical smallholder farmer in Uganda, for instance, owns approximately 10 dairy cows and operates on about 2 hectares of land. Despite the availability of various milk preservation technologies, many of these solutions are either too costly or do not align with the production capacities and financial constraints of smallholder farmers. Consequently, post-harvest milk losses remain a persistent challenge, leading to economic losses and reduced profitability for farmers. This study followed an integrative review approach to assess the existing body of literature on existing developed off-grid milk preservation systems piloted in sub-Saharan Africa. Data sources included project websites, published literature, and technology reports. The review aimed at profiling existing technologies, their efficacy and accessibility, and key bottlenecks that hinder the technology adoption in low-resource settings. This review also established a representative price point that aligns with the financial capabilities of smallholder farmers based on prevailing farming practices. By evaluating these factors, the review provides recommendations for solution developers to design context-tailored technologies that can better serve these farmers. Addressing these challenges is crucial for the overall sustainability of the dairy value chain development in sub-Saharan Africa.

**Key words:** Smallholder dairy, milk losses, freshness preservation, renewable energy, low-resource engineering

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## INTRODUCTION

Smallholder farmers of sub-Saharan Africa, cultivate 2-5 hectares, producing 70% of the food calories consumed by sub-Saharan Africans [1]. The world population is projected to increase by 34% to 9.7 billion by 2050 and most of the increase will occur in developing countries [2]. Food production will have to increase by 70% to meet the demand [3]. A similar projection has been published by the Food and Agricultural Organization [4]. The United Nations sustainable development agenda for 2030 has targeted to end hunger and all forms of malnutrition as goal 2 [5]. Among proposed interventions is promoting sustainable food production systems among small-scale farmers [5]. Smallholder farmers are increasingly practicing mixed agriculture – mixing crop and livestock. Adding livestock production to crop farming enhances household resilience through diversification of products from animals such as milk, beef, butter, hide and skins and manure for crop fertilizer. To accelerate mixed agriculture, governments in developing countries are putting in place incentives such as subsidies [6].

The incentives are producing the desired outcomes. For example, in Uganda milk production has increased from 395 million liters in 1986 to 1.08 billion liters in 2010; with an annual growth of 4.9% [7]. However, the increase would be even higher, but these farmers experience unacceptable post-harvest losses. The Food and Agricultural Organization (FAO) reported that Uganda, Kenya and Tanzania, have losses estimated at \$23, \$22.4, and \$14.7 million per year, respectively. The highest percentage of about 5.8% and 11% is directly incurred by smallholder dairy farmers at the farm level and during transportation, respectively [8]. Some of their milk (mostly the evening milk) is wasted just because they don't have an on-farm means preserve it. In sub-Saharan Africa, most farmers live in rural areas with no access to grid electricity. Also, these farmers stay far from town centers with collection points housing cooling facilities; they cannot transport the milk in the night because it becomes unsafe and in addition the roads become impassable in the rainy season when production is at the peak [8]. As such, these farmers end up processing the milk into low value products such as ghee or consume it [9].

Off-grid preservation technologies developed for these smallholder farmers do not usually fit within their income flow. Smallholder farmers are likely to adopt technologies that are consistent with their cash flows. In view of the projection by the Food and Agricultural Organization for milk demand [4] and certainly driven by the need to address SDG goal # 2 by the year 2030, several interventions have been developed to eliminate the post-harvest loss in the milk value chain in the developing world. This review assesses the several solutions or technologies commercialized or ready for commercialization to highlight the critical factors to consider by solution developers towards improving technology up-take.



## Who is a smallholder dairy farmer?

Smallholder farmers can be defined in several ways depending on the context, country and/or ecological zone. In the context of dairy production in a country like Uganda, smallholder farming has been grouped based on production systems [10]. There are two production systems: 1) Intensive, which is further subdivided into smallholder intensive, medium-holder intensive and large-scale intensive; and 2) extensive, which is further subdivided into smallholder extensive, medium holder extensive, pastoralists and agro-pastoralists. The intensive production systems are mainly common in the peri-urban areas while the extensive production systems are commonly found in the rural areas [10]. However, typical dairy farms in Uganda are mainly smallholder extensive types [11]. Farmers who practice smallholder extensive farming usually owns about 2 hectares of land with about 10 local dairy cows, but they also have an option of grazing from larger public lands [11]. These farmers usually sell their milk locally to vendors/middlemen who collect from the farms once a day because they are far from the major cities with markets. The analysis considers this typical farmer and examines how the developed technologies can be appropriate in terms of capacity and cost. Similar production systems can be found in numerous sub-Saharan African countries and as such we consider Uganda to be an excellent representative model.

## Technologies

Solutions can be subdivided into two categories: devices powered by solar energy and others powered by biogas or other off-grid energy sources. Solar energy can be utilized through photovoltaic (PV) sun energy to electric energy conversion that operate conventional vapor-compression refrigeration system [12] or through direct use of concentrated sun heat that operate ammonia-water refrigeration systems [13]. The trend of decreasing PV panel prices is fueling increased use of vapor-compression systems [14, 15], especially in places where grid-electricity is expensive or in short supply or unreliable [16, 17]. Biogas-powered milk freshness preservation is achieved through two methods: mild heat treatment of milk followed by low-cost evaporative cooling or direct heating to drive ammonia-water refrigeration. Following are brief descriptions of currently commercialized or developed and piloted systems:

### Solar PV-based energy systems

#### Solar farm milk chillers

Sundanzer Refrigeration Inc. (<https://sundanzer.com>) developed a solar-powered farm milk chiller (FMC). The device uses a vapor compression cycle powered by electricity from PV panels. A micro-processor control allows the solar panels to connect directly to a DC compressor. The technology behind FMC was originally developed by scientists at NASA to transform space technology to earth use [18].



The solar panels are exposed to at least five hours of sunlight a day and form ice is stored in the walls of the refrigerator. Water is used as a phase change material that is integrated in the insulated refrigerator walls. The quantity of ice formed is enough to maintain low temperatures (between 10 and 4°C) to run the chiller overnight with a load of 40 liters of milk. Brine bags that do not freeze at 0°C [18] are placed close to milk cans in the cooling chamber to increase heat transfer. Farm Milk chiller devices have been field tested in Kenya and Rwanda. Over 82 units are in operation in these two countries. Each unit is estimated to cost USD 1,850 including complete installation [18].

### **Rapid milk chiller**

Promethean Power Systems manufactures and markets the rapid milk chiller (<https://cooelectrica.com>). The system uses a phase change material to store thermal energy in form of ice that is used in times of low electricity. When connected to grid electricity, the systems form ice as a “thermal battery.” When the grid electricity operation is interrupted, the formed ice is used for chilling to below 4°C. A fully charged thermal battery is achieved in five hour of grid-electric operation and can chill 500 liters of milk [12]. Promethean Power Systems has deployed about 3000 units in various parts of rural India through major dairy processors like Amul and Chitale [12]. In 2013, each unit was costing USD \$7,000. Promethean Power System is dedicated to developing a device that will be off-grid and be fully solar energy-powered.

### **Hohenhein solar cooling system**

The Institute of Agricultural Engineering of the University of Hohenhein developed and has field-tested the Hohenhein solar cooling system (<https://www.uni-hohenheim.de/en>) in Kenya [19]. The system uses a solar powered DC- freezer. The freezer has a volume of 166 liters and can generate up to 13 kg of ice required for preserving 60 liters of milk per day (total system capacity). The freezer is equipped with a control unit to customize use of the available solar energy. The system comes with 25 reusable plastic blocks of 2 kg and two 30-liter insulated milk cans with a removable ice-holding component. Therefore, the freezer can produce 50 kg of ice for use in 5 days of low solar radiation [20]. To operate the system, milk is placed in an insulated traditional 30-liter can and the ice-holding compartment with the ice blocks is inserted into the milk and covered. Stainless steel material is used for the cans and ice-holding component to maintain food grade surface in contact with the milk. The system can be operated in two modes; the 6-hour mode is for milk transportation purposes; the 12-hour mode is for storage of evening milk purposes. In the 6-hour mode, the 6 kg of ice are used to lower milk temperature from 35 to <19°C. In the 12-hour mode, 8 kg of ice are used to lower the milk temperature to



<13°C [20]. The cost of the system is USD 1,560 based in Kenya, but can cost up to USD 2245 when directly imported as a finished product [19].

### **Solar thermal refrigeration system**

#### **The intermittent solar ammonia absorption cycle Solar ice maker**

The intermittent solar ammonia absorption cycle (ISAAC) device was developed by Energy Concepts Inc. (<http://eci-info.com/wordpress2>) to operate purely without electricity [20]. It is based on the intermittent ammonia/water absorption refrigeration technology, which is driven by heat rather than electricity. The device is composed of a parabolic trough that captures solar energy that is used to generate ammonia refrigerant during day. The refrigerant is then cycled back to the generator and ice is made in the night. The generated ice is then placed in the ice bags and can be used to cool milk. Milk is chilled to by immersing milk cans containing milk into the ice bath. On a sunny day, the daily production per square meter of solar collector is 5 kg. The cost of production of the 11 square meters ISAAC, is approximately USD 7,000 in low-wage places like sub-Saharan Africa. In a pilot study at the Kenyan coast, 50 kg of ice cooled 100 liters of milk [21].

### **Biogas powered systems**

#### **CoolChurn**

The Coolchurn is a modification of an existing evaporative cooling technology originally developed for beer consumers in Europe and Asia. The cool system developed in Germany was re-engineered by researchers from the University of Georgia to provide a cooling system for off-grid smallholder farmers. The CoolChurn has a capacity of 15.5 liters and weighs about 22 kg when empty and can chill milk from 34°C to 4°C in under 4 hours [8]. The CoolChurn is based on evaporative cooling principles. It is a three-chamber device. The center chamber is where the product to be cooled is housed. Next to the product chamber is the “refrigerant” water chamber connected by a pressure sensitive valve to the outer most chamber that houses a water adsorber like zeolite. The zeolite chamber is maintained under sealed vacuum. The valve is operated by a switch, which exposes the zeolite chamber vacuum to the water in the water chamber. At this vacuum and room temperature, the water vaporizes and the vapor is adsorbed by the zeolite. The heat of vaporization is provided by the warm product, whose temperature drops. To be used again the device needs to be regenerated. Regeneration involves closing the valve followed by heating the whole unit to approximately 200°C. The heat causes the adsorber or zeolite to free the water, which returns to the water chamber via the pressure sensitive valve. Cold water in the product chamber is used to condense the returning vapor from the adsorber [22]. Regeneration can be achieved with electricity or biogas or charcoal heating. Use of the biogas powered brick oven for regeneration has been demonstrated successfully [22]. The device was deployed in a pilot study



in the southwestern Uganda [22]. The price per unit was a little over USD 2,000. Feedback from the pilot study user participants informed the development of the EvaKuula, described below.

### **Biogas milk chiller**

Simgas B.V. (<https://simgas.org>) based in the Netherlands developed the biogas milk chiller. The chiller utilizes the standard ammonia-water cycle to cool milk from approximately 35°C to 4°C within 3 hours using biogas as an energy source. The biogas is used to provide the heat needed to evaporate the refrigerant. The cold is generated during the day and is stored in form of ice in the compact system. The ice is then used in the night for cooling. The chiller can hold two, five liter cans and therefore has a capacity ranges between 2.5 to 10 liters. The technology has been pilot tested in Tanzania, Kenya and Rwanda. Unfortunately, at the time of writing, the company had filed for bankruptcy in Amsterdam under insolvency number F.13/18/359.

### **EvaKuula**

The EvaKuula process combines thermization and evaporative cooling to preserve milk freshness. Thermization is a gentle heat treatment applied to milk and involves temperatures between 57°C and 68°C for durations ranging from 5 seconds to 30 minutes. The process is known to lower the count of spoilage microorganisms by about 3 or 4 logs, thereby extending the milk's shelf life prior to undergoing additional processing [23]. The EvaKuula kit consists of two main components; the thermization drum, which is made up of a deep round aluminum pan and wooden insulation; and an evaporative cooling unit made up of a wind-powered mechanical air extraction fan, water troughs surrounded by jute pads on each side of the cooling chamber [24]. Thermization is achieved by heating water in the deep pan over a biogas burner to boiling (approximately 96 °C). The deep pan is then quickly transferred to the wooden insulation drum and a can filled with a desired quantity of milk is placed inside the drum that is covered. Milk is kept in the drum for 45 minutes to attain a temperature of 63°C and then transferred to the evaporative cooler for cooling to approximately 10 to 14 °C, below room temperature (about 19°C) and stored until the next day. The thermization drum can accommodate one 20-liter milk can at a time, but the evaporative cooler can accommodate four 20-liter cans at a time. Therefore, the maximum EvaKuula capacity is 80-liters [24].

In the initial field deployment studies, it was noted that the need to invest in both a domestic biogas plant and EvaKuula at the same time was limiting up-take [24]. To overcome this problem, thermization has been accomplished with woody biomass in efficient stoves with the goal of transitioning to biogas, once the EvaKuula has been paid off. In comparison to devices described above, EvaKuula is unique and as such more studies are needed to support inclusion in established fresh milk standards for



regulatory purposes. The production cost of the EvaKuula unit piloted in Uganda was USD 790 [24]. Although the EvaKuula is promising in terms of cost and capacity, in comparison the other devices described above, lowering the production cost further will greatly improve affordability and subsequently technology up-take.

### **Price-point for off-grid milk freshness preservation solutions**

Taking an assumption that the Ugandan smallholder farmers are an accurate representation of other sub-Saharan African smallholder farmers with similar milk value-chains, such as Rwanda, Kenya and Ethiopia. On average, such farmer households possess five milking cows at any one time. Conservatively, each cow produces 7.7 liters of milk [25]; 54% and 46% of this milk is morning and evening milk, respectively [26] or 4.2 liters in the morning and about 3.5 liters in the evening. Assuming all the morning milk sales income is used for financing the daily household needs and the evening milk sales income is used for servicing payment of a milk freshness preservation technology, the total evening daily production will be approximately (0.46x7.7x5 cows = 17.7 liters). This estimate is consistent with literature values of 16 and 11.1 liters of morning and evening milk, respectively [8, 24] for smallholder farmers. According to the Dairy Development Authority (DDA) of Uganda, the southwest and central contribute about 50% of Uganda's national production. For an average farm-gate price of 700 Uganda shillings per liter (central and southwest average), the total evening milk sales per day come to 12,390 UGX (USD 3.69) translating to 371,700 UGX (USD 110.63) per month.

From the analysis, the minimum capacity for an average typical farmer is about 18 liters and the available extra monthly income to make payments for a cooling technology is USD 110.63. There are two possible ways farmers can finance the devices. Either through rent-to-own or direct purchase. Most smallholder households cannot pay cash up-front for devices in the ranges shown above. Rent-to-own is preferred because it allows small payments consistent with smallholder household cash flow. Smallholder farmers are hesitant to acquire loans, especially if the payments are extended over two or more growing seasons. They have experiences of unpredictable poor growing seasons, putting them in situations where they are unable to pay and financial institutions (For example, microcredit finance) going for their assets [27].

At the time of writing, most of the devices featured above had no established retail prices in the Ugandan market. This is because most of the device developers were concluding pilot studies and pricing reported was for the regions in which the devices were being piloted. However, the above analysis demonstrates that the extra income available to pay for an off-grid milk freshness preservation device by a typical Ugandan farmer is not more than USD 110 per month, with preferably shorter pay-back period of less than a year in a rent-to-own business model. Considering half a



year (one growing season) as the target payback period, an ideal market price for product should not go over USD 600 as the total retail price. The half a year period is based on the production seasons that are on average 6 months. Within a production season, production of milk is sustainable and therefore income to sustain pay back will readily be available.

Based on the technology's milk holding capacity, the Solar ice maker, Hohenhein solar cooling system, EvaKuula and the solar farm milk chillers have capacities that meet the cooling needs of a typical smallholder farmer (Table 1). However, as farmers increase their production above 100 liters, these devices fall short. Devices such as the larger solar farm milk chiller or rapid milk chiller are applicable at this level of production and may be affordable. At this level, these farmers can be either medium holder extensive or pastoralist or agro-pastoralists.

Because the cost of a product can be limiting in the low settings, other alternative approaches to manufacturing can be explored to lower the manufacturing cost and promote local manufacturing. These can include manufacturing techniques like digital fabrication. In modern technology, 3D printing, laser cutting and CNC (Computer Numerical codes) are the digital tools commonly used for digital fabrication. 3D printing has been applied in several applications not only in the developing world but also in the developed world. Examples include, in managing humanitarian work, 3D printing has been used to print on site logistical supplies like; manufacturing pipe connections and cost-effective medical supplies [28, 29]. Applications like these demonstrate that 3D printing can be a cost-effective tool among the available digital printing tools for low-resource manufacturing.

Although 3D printing technology offers the benefits of the ability to create customized products rapidly, lower transportation costs by producing goods on-site, and enable decentralized manufacturing, the generated products have been reported to be limited in strength and durability compared to conventionally manufactured components; especially when using low-cost printers and materials [29]. In addition, the initial investment for quality 3D printers, ongoing maintenance, material availability, and the need for technical expertise can pose significant barriers in low-resource settings [30]. Therefore, technology developers aiming to lower product prices to affordable limits should consider exploring 3D printing as a cost-effective local manufacturing approach while being mindful of its potential limitations.

## CONCLUSION AND RECOMMENDATIONS FOR DEVELOPMENT

The current off-grid milk freshness preservation technologies have the potential to address the evening milk problem in rural sub-Saharan Africa. However, wide uptake will only be possible if the technology developers address several roadblocks. First, our analysis suggests that a device priced higher than the price-point of USD



600 is not likely to be sustainable. Solution developers should strive to produce below the price-point to leave room for operational costs for those in the value chain such as distributors. Secondly, solution developers should consider an integrated approach, where smaller affordable solutions are deployed on the farm, and larger capacity solutions are placed at trading center as bulking points at the co-operative/group level. The smaller units would then be used for on-farm storage, and the large capacity technologies are then used for aggregating at higher levels within the production system particularly at the co-operative/group level. Using larger capacity units for bulking allows for co-ownership by farmers through co-operatives or bulking groups, hence improving affordability by cost-sharing. With this approach, farmers can keep their milk fresh for prolonged hours in times when collection is not done on time.

Future studies should focus on understanding the farmers' willingness to pay the established USD 600 price-point, to support solution developers align product pricing with market realities. More still, a comprehensive cost-benefit analysis of a tiered cold chain model that comprises of the small on-farm units and larger units at the cooperative level is required to inform the economic viability and long-term sustainability of such systems. Because most of the technologies were at pilot stage at the time of writing, a follow-up assessment of each technology under real-world rural conditions is also critical to assess energy efficiency, durability, and usability of the technologies within the target settings.

### **Limitations of the work**

At the time of writing, most of the devices mentioned above had not been introduced/piloted studied on the Ugandan Market. Therefore, the retail prices of the devices reported in this paper were as quoted for the regions in which the devices were being piloted. Therefore, depending on the region where the product was developed, the cost may be higher or lower at the time marketing to the target region.

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### **List of abbreviations**

FAO – food and Agricultural Organization  
PV – Photovoltaic  
FMC – Farm Milk Chiller  
DC – Direct current  
NASA – National Aeronautics and Space Administration  
USD – United States dollars  
ISAAC - Intermittent Solar Ammonia Absorption cycle  
DDA - Dairy Development Authority



**Table 1: Off-grid milk freshness preservation technologies**

Technology	Energy Source	Capacity (Liters)	Cost (USD)	Deployment Region	Key Features	References
Sun-Danzer Farm Milk Chiller	Solar PV	40	1,850	Kenya/Rwanda	Ice storage for overnight use	[18]
Promethean Rapid Milk Chiller	Grid/Solar Hybrid	500	7,000	India	Thermal battery for interruptions	[12]
Hohenhein Solar Cooling System	Solar PV	60	1,560–2,245	Kenya	Ice blocks for milk preservation	[19, 20]
ISAAC Solar Ice Maker	Solar Thermal	100	7,000	Kenya	Ammonia absorption refrigeration	[21]
Cool-Churn	Biogas	15.5	2,000	Uganda	Evaporative cooling principles	[8, 22]
Biogas milk chiller	Biogas	10	-	Kenya	Ammonia absorption refrigeration	[31]
EvaKuula	Biogas/Wood Biomass	80	790	Uganda	Thermization + evaporative cooling	[24]



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