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Energy Assessment and Renewable Energy Opportunities in Post-Harvest Food Systems: A Comprehensive Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Energy efficiency and renewable sources are highlighted in this manuscript which discusses the use of energy in food systems after harvesting. Methodology provided aids in optimizing energy use in food processing. By highlighting both conventional and renewable energy technologies, such as

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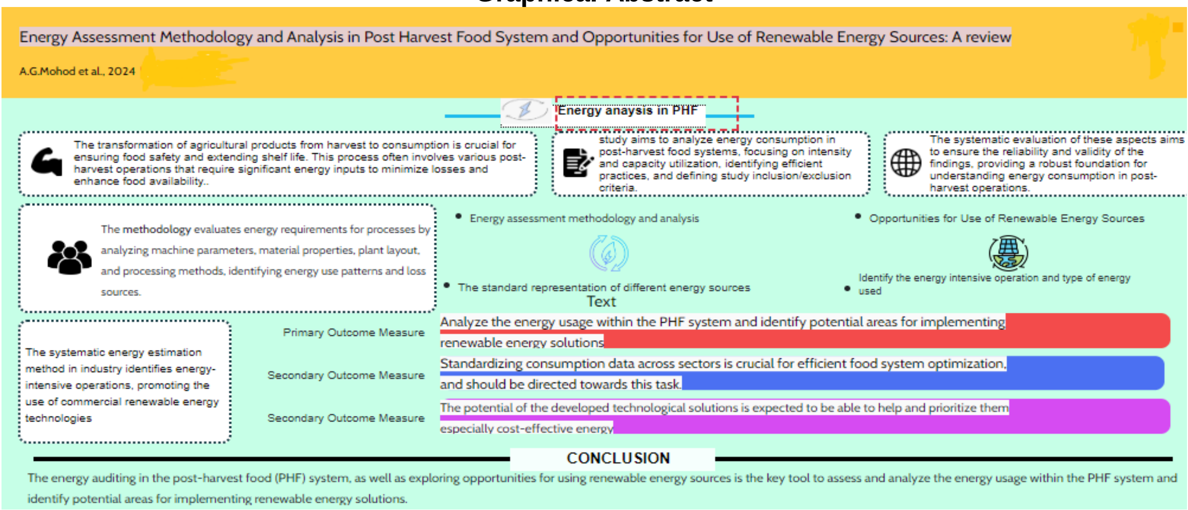
solar PV and biomass, the manuscript proposes sustainable solutions that are timely and essential for combating climate change and food security challenges. The importance of standardizing energy data and improving energy efficiency within the PHF system aligns well with current global efforts to promote sustainable agricultural practices, making this research highly relevant to the scientific community. The focus on reducing fossil fuel dependence in post-harvest operations is particularly significant as it addresses both environmental concerns and long-term cost savings for the industry. Additionally, the inclusion of real-world case studies, such as solar drying in turmeric processing, strengthens the manuscript's practical applicability. This review also highlights the practical benefits of renewable energy sources, including reduced carbon emissions and energy independence, while emphasizing the critical role of energy auditing in optimizing efficiency and sustainability. By integrating these approaches, we can enhance energy management and support a transition towards a greener future. Overall, the paper provides a robust foundation for future research and policymaking in sustainable food processing systems.

Graphical Abstract



Keywords: Energy; energy consumption; energy audit; post-harvest food.

1. INTRODUCTION

1.1 Importance and Scarcity of Energy in Post Harvest Food (Phf) System

The growing demand for food, coupled with the need for sustainable practices, underscores the vital role of energy in postharvest food systems. Inefficient energy use leads to substantial waste and higher costs while also contributing to environmental issues, like increased carbon emissions. This paper aims to evaluate current energy consumption patterns and explore renewable energy opportunities that can improve efficiency and sustainability. By tackling these critical aspects, we can foster more resilient food supply chains and contribute to global efforts for a greener future [2-4].

"A significant part of agricultural production goes through some degree of transformation between harvesting and consumption to make food edible and digestible. Energy is required to preserve food, reduce post-harvest losses, and extend its availability over a longer period of time. The energy consumption as well as employment and value added by the PHF system is several times greater than the farm-level activities. The total food system uses around 17 to 20% of total energy use in the economies. Of this, usually around one-fifth to one-quarter only is spent on production on the farm, and the remainder goes into post-harvest operations" [36,37,52].

"Postharvest handling of agricultural produce is crucial for food security and supporting farmers in developing countries. Postharvest systems deliver sorted, segregated, packaged, and market-appropriate products to consumers in distant locations. These systems consume resources and internal patterns, delivering outputs such as energy, information, data, wash water, chemicals, packaging materials, and skilled people. These systems produce prepared products, information, worker pay packets, waste water, and packaging waste, all of which are open systems, as shown in Fig. 1" [9,11,12].

Fig. 1. Post harvest open system

The components of the PHF system are: food processing, transportation, storage, and cooking. The post-harvest food system requires 2 to 4 times more energy than the energy on farms. Commercial energy is often used for food processing, such as milling, crushing, forward transport, and, to some extent, cooking [18,20]. The share of commercial energy in total energy used in the PHF system ranges from 22% in Africa to 80% in the Near East. The PHF system's energy consumption is influenced by income, urbanization, availability of fossil fuels or forests, and various parameters like cropping, dietary patterns, food export or import, and urban location. This information is discussed for four world regions and 90 developing countries, with country-specific insights provided graphically due to limited space for individual data reporting [13,14,15,17].

"Limited energy access is a significant challenge for small and medium-sized enterprises in rural areas. Food losses in developing countries are primarily during harvest and storage, making post-harvest activities a priority for increasing farmers' income. This includes inadequate energy access for post-harvest operations, transportation, and distribution. Additionally, managing industrial by-products, residues, and wastes in an environmentally sound manner is crucial for the agrifood industry's development" [31,51]. "One management option is to use industrial wastes to produce energy. In addition, rising energy prices affect the competitiveness of existing food processing enterprises and highlight the need for the food processing sector to reduce energy consumption. Profit is generally one of the most common and accepted criteria for determining the success of an economic activity. Integrated food-energy systems must be profitable in the long term for their practices to be adopted by all the stakeholders" [6,7,8,10].

"Lack of linkages between industry, government, and institutions, lack of technology and advanced technique in food processing, and lack of linkage between farmers and processing units are the most significant factors responsible for the scarcity of energy in the PHF system. In Post-harvest loss can be defined as the degradation in both quantity and quality of a food production from harvest to consumption. Quality losses are intrinsic in nature, leading to internal and external biochemical changes leading to changes in colour, flavour, nutritive value of food, calorific value, etc. without significant change in weight or volume. Quantitative loss is more serious in nature, leading to value loss to the actors in the supply chain. It is mainly caused by poor post-harvest management practices such as loss in weight due to moisture loss, physical damage, insect pest infestation, spoilage or rotting due to senescence, bacterial/fungal infections, etc." [18,20,21,22,27].

1.2 Energy Sources in Post-Harvest Systems

"The food industry is heavily dependent on fossil fuels and significantly contributes to GHG emissions. The global population is also growing, and food demand is expected to increase by 60% by 2050. To combat environmental pollution and create a more sustainable food sector, energy use during manufacturing needs to be reduced" [38].

Energy is a crucial parameter in agri-food industries, accounting for profit and operating expenses like material, labor, and water. It plays a fundamental role in food systems, consumed in primary production and secondary activities like drying, cooling, storage, transport, and distribution [63]. Agri-food systems account for 30% of the world's total energy consumption, requiring energy at all stages of the chain, including production, processing, transport, and manufacturing of fertilizers, agro-chemicals, and machinery [23,24,26]. Electrical energy is the most convenient for PHF systems due to its ease of transportation, control, and conversion into other energy forms, with a 100% efficiency rate.

Agro-industries have both direct and indirect energy sources. [38,39].

"The direct energy includes electricity, mechanical power, and solid, liquid, and gaseous fuels. Indirect energy, on the other hand, refers to the energy required to manufacture inputs such as machinery, farm equipment, fertilizers, and pesticides [42,46]. The type of energy we use in the agrifood chain and how we use it will in large part determine whether our food systems will be able to meet future food security goals and support broader development objectives in an environmentally sustainable manner. The agrifood systems not only require energy; they can also produce energy. For this reason, agrifood systems have a unique role to play in alleviating 'energy poverty in Fig. 2" [27,35,41].

Indirect sources of energy include seeds, manures, chemicals, fertilizers, and machinery, which release energy through conversion processes rather than directly, such as in farm yards and poultry [38,49,50,53].

The direct/indirect energy may be further classified as renewable and non-renewable sources of energy depending upon their replenishment. To increase energy efficiency in the food industry, specific energy consumption reduction is needed [55,58,59].

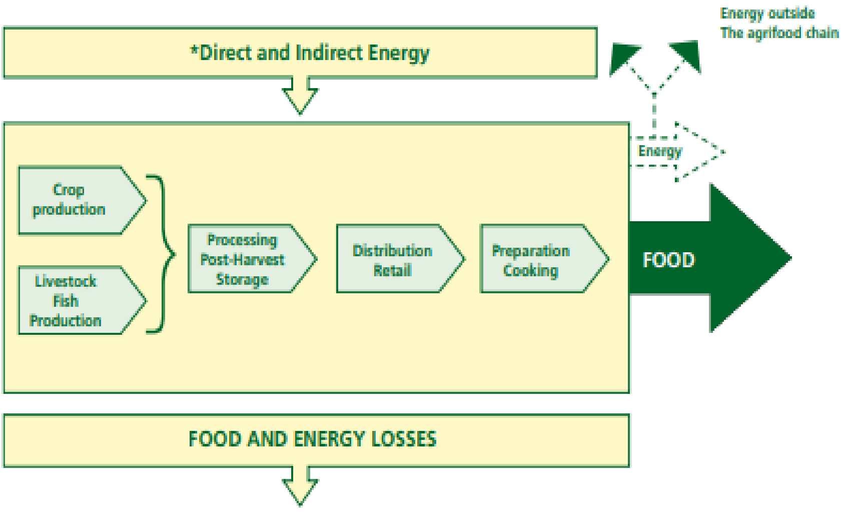


Fig. 2. Energy "for" and "from" the agrifood chain indirect sources of energy

Table 1. Differences between renewable and non-renewable Energy [66, 56].

Sr. No	Renewable sources of energy	Non-Renewable sources of energy
1	Renewable energy is generated from natural, sustainable resources such as the sun, wind, and water.	Non-renewable energy is generated from finite resources such as coal, oil, and natural gas.
2	Renewable energy is generated from natural, sustainable resources that are replenished regularly.	Non-renewable energy, on the other hand, is generated from finite resources that will eventually run out.
3	These resources include the sun, wind, water, and geothermal heat.	These resources include coal, oil, and natural gas.
4	Development of models for renewable energy, waste heat, solar energy, efficient heat pumps.	Not highly efficient
5	Renewable energy is cleaner, eco-friendly, and doesn't emit harmful pollutants harming environment.	Non-renewable energy sources harm environment with emissions.
6	Additionally, renewable energy has much lower operational costs and does not rely on finite resources that can fluctuate in price.	upfront cost of Non-renewable energy can be higher than nonrenewable energy.

Benchmarking energy consumption internally and externally is crucial for assessing and improving performance. Historical data identifies trends, while trend analysis reveals capacity utilization effects on efficiency and costs. External benchmarking compares similar units to avoid misleading findings. Both methods help understand capacity utilization effects on a broader scale. [16,69,72]. A few comparative factors that need to be looked into while energy benchmarking externally is: • scale of operation; • vintage of technology; • raw material specifications and quality; and • product specifications and quality.

2. METHODOLOGY FOR ENERGY ESTIMATION OF UNIT OPERATIONS

The energy estimation in the unit operations of the post-harvest food industry required the systematic approach [33,34,38]. The step-by-step methodology to begin the energy estimation processing unit should be planned as

- Decide an objective of analysis to quantify the energy accounted in unit
- Choose a system boundary of energy utilization
- Draw a flow diagram of process
- Identify all mass and energy input
- Quantify all mass and energy input
- Identify all mass and energy output
- Quantify all mass and energy output
- Analyze the recorded data
- Draw graphical representation of energy use in unit.
- Identify energy intensive operations in the unit
- Explore the possibility of energy conservation
  - Retrofitting of existing system with possible renewable energy systems

The Data recorded during the energy audit for unit operations should be averaged over the period of the season or on the basis of yearly data to avoid the fluctuations and errors in energy consumption. The following imperial equations could be used to calculate energy consumption using various sources in post-harvest food industries. [32,33,39,52].

The mathematical conversions used for computation of different energies for unit operations are as follows:

Electrical energy: $E_p = K.P.t_e$ (kWh) (1)

Thermal energy: $E_f = C_f.W_f$ (J) (2)

Manual energy: $E_m = 0.075N.t_m$ (kWh) (3)

Solar energy : E_s= Isc. A. t_s (J) (4)

The total energy, E_T for unit operations in processing is computed as

$$E_T = E_P + E_f + E_m + E_s \quad (5)$$

E_T = Total energy requirement for all processing operations (J)
T = Time taken for a particular operation (h)
C = Lower heating value of fuel used for a particular operation (J kg^{-1} or J l^{-1})
I_{sc} = Average solar energy availability (J s^{-1} m^{-2})
W= Quantity of fuel used for a particular operation (l or kg)
P= Electrical power consumed for a particular operation (kW)
N=Number of persons involved in a particular operation
K =Efficiency of the electric motor used for a particular operation
A= Open sun drying area, m^2

The assessment of energy in agro processing operations involves assessing various factors, such as machine parameters, material properties, plant layout, capacity, and processing methods. This information is crucial for developing energy-efficient units, which can reduce costs and energy loss due to mismatch between prime mover and machine or transmission losses. The main purpose is to determine energy use patterns, sources, and excess points [39].

The energy consumption in eight-unit operations of cashew nut processing using data from nine mills. Equations were developed to calculate electricity, fuel, and labor requirements for each operation. Results showed total energy intensity varied between 0.21 and 1.161 MJ kg1, with electrical energy intensity ranging from 0.0052 to 0.029 MJ kg1 and thermal energy intensity ranging from 0.085 to 1.064 MJ kg1. These equations were useful for budgeting, forecasting, and planning plant expansion [33].

The study evaluated energy consumption in nine Nigerian palm kernel oil (PKO) mills using mathematical expressions and empirical equations. Mathematical expressions were used to evaluate energy requirements for seven-unit operations, while empirical equations were used to relate energy requirements to palm-nut/kernel input [33].

Table 2. Unit operations and form of energy used in agro-processing industries. [38]

SN	Processing Industries	Unit operations	Energy Used
1	Cashew Processing	Distillation	Electricity
2	Juice/Candy production	Milling	Diesel
3	Rice Processing	Cleaning	Petrol
4	Edible Oil Expression	Sorting	Furnace Oil
5	Gur Making	Cutting	Gasoline
6	Tamarind Processing	Peeling	Kerosine
7	Timber processing	Drying	LPG
8	Palm Kernel oil processing	Boiling	LDO
9	Paper and Pulp Processing	Steaming	Wood
10	Grain Mills	Sterilization	Shells
11	Dal Mills	Tampering	Processes Waste
12	Poultry and Meat processing	Cooling	Coal
13	Fish Processing	Shelling	Charcoal
14	Kori-tofu processing	Chopping	Pit
15	Tea processing	Pasteurization	Lignite
16	Cassava processing	Heating	RDF
1	Kokum processing	Blanching	Bruqietted fuel
18	Bakery processing	--and many more	Agri. Residues
19	Milk Processing		Animal Waste
20	Canned food processing		Human Power
21	Vegetable processing		Animal Power
22	Jute processing		Wind Energy
23	Grain processing		Solar Energy
24	Sugar cane processing		Biogas
25	---- and many more		Landfill gas etc…

3. ANALYSIS OF ENERGY DATA AND REPRESENTATION

The recorded data with the help of mathematical expressions in the food industries could be presented in different form to compare with the similar industries [34,28,29,30]. The energy use patterns and energy use efficiency indicators viz;

i. Energy intensity (E_I)
ii. Energy cost per unit product ($E_{C/P}$)
iii. Energy ratio (E_R)
iv. Food energy ratio (F_{ER})
v. Percentage yield by weight.

The analysis of energy consumption and production in industries is crucial to determine disparities in energy consumption for producing the same quantity of product, considering factors like installed capacity, production, and energy intensity [51,37,40].

3.1 Installed Capacity (P)

The installed capacity of the industry was determined by considering the capacity, number of batches performed per day and average working days in a year.

Installed capacity, P (kg) = capacity x no. of batches/day x working days (6)

3.2 Production (P_r)

The industry's production is determined by analyzing the average actual raw material processed per kg yr-1, taking into account the average of the last three years' production data.

3.3 Percent Production Capacity Utilization (P_{PCU})

The percent production capacity utilization of the industry has to be calculated as the ratio of actual production to the total installed capacity of the industry.

Percent production capacity utilization (P_{PCU}), % = (P_r/P) x100 (7)

3.4 Total energy (E_n)

The industry's energy consumption for unit operations and lighting must be estimated using the maxi energy audit method and cross-checked from electrical bills annually, while the quantity and type of biomass used for raw material processing must be measured. All the forms of energy sources were converted in to the common unit of energy i.e MJ Yr^{-1}.

3.5 Energy Intensity (E_I)

The energy intensity of industry has to be calculated as the ratio of Total energy consumption (E_n) and Production (P_r).

Energy intensity (E_I), MJ kg^{-1} = Total energy (E_n)/ Production (P_r) (8)

Another way to represent the flow of input and output energies in the plant is with the help of symbols (Fig. 3.). Different symbols for energy accounting of food processing operations are used for development of energy flow diagram in Fig. 3 [16,37].

4. ENERGY ASSESSMENT/ ACCOUNTING IN POST- HARVEST INDUSTRIES

The fundamental goal of energy management in the processing industry is to produce value-added goods and provide services with the lowest cost and least environmental effect. It is defined as *"the strategy of adjusting and optimizing energy, using systems and procedures so as to reduce energy requirements per unit of output while holding constant or reducing total costs of producing the output from these systems.* [16,51,67]

The objective of energy management is to achieve and maintain optimum energy procurement and utilization throughout the organization and:

1. To minimize energy costs and waste without affecting production or quality
2. To minimize environmental effects.

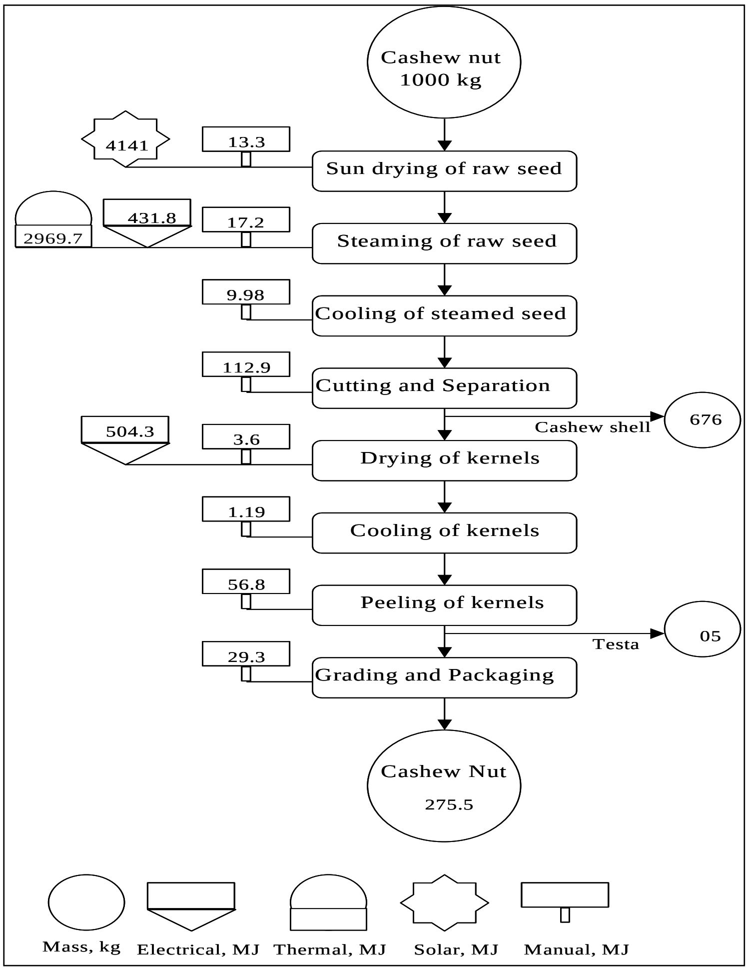


Fig. 3. Representative process flow diagram with symbols for energie

Energy audit is the key to a systematic approach for decision-making in the area of energy management. It is an effective tool for:

- Explore the relationship between energy and production
- Identify the pattern, type, level, and efficiency of energy use.
- Provide baseline information for energy consumption.
- Help to identify energy conservation opportunities.
- Help identify measures for efficiency improvements.
- Help to reduce disparities among similar processes and provide ecological perspective [43].

4.1 The Proposed Energy Audit Framework

Conventional energy audits often overlook the unique characteristics of buildings by only measuring energy consumption through utility bills, treating the entire building as a single entity. As a result, as shown on the left side of Fig. 4, energy consumption profiling and benchmarking can only be performed based on the total energy consumption of the building. Even if energy consumption could be captured by space usage or building service, there are no industry standards for these classifications, and similar information is not collected for other properties used in benchmarking [43].

Energy use assessment is a crucial tool for estimating energy requirements in processes before conservation, which enables the use of renewable energy technologies. This method helps alleviate energy constraints and reduce costs by identifying energy use patterns, energy loss sources, and excess energy use points. Variations in energy use may depend on machine parameters, material properties, plant layout, capacity, and processing methods. The main purpose of energy use assessment is to judge energy use patterns, energy loss sources, and excess energy use points [37,38,40,43].

The energy consumption patterns in small cashew nut processing industries in Panruti taluk, Cuddalore district, Tamil Nadu, India. It compares energy utilization, specific energy consumption, and intensity of processing raw cashew nuts. The energy input for drying, steaming, cooling, tempering, cutting, separation, drying, kernel cooling, peeling, and grading and packing were quantified using standard equations. The total energy consumption for processing 1000 kg of raw cashew nuts was 5866.2 MJ, 5911.69 MJ, and 6897.36 MJ for electrical drying, steam drying, and biomass drying industries, respectively. Cashew kernel drying, raw cashew nut drying, and steaming consume 95% of the energy. Cashew processing's energy intensity varied from 1.5 MJ/kg to 3 MJ/kg [19].

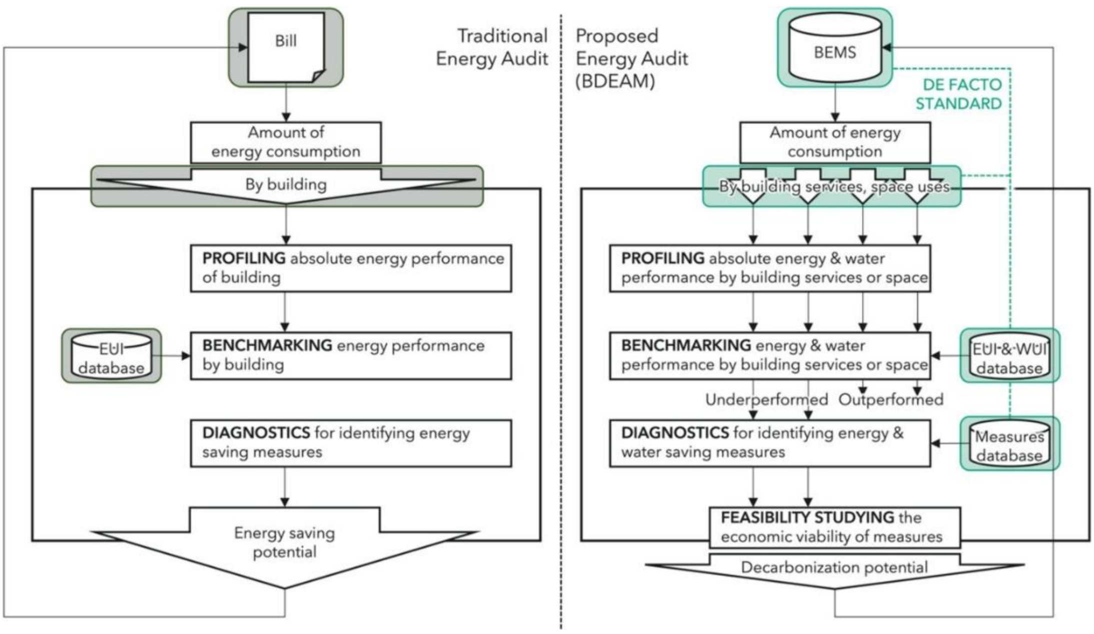


Fig. 4. Conventional (left) and proposed (right) energy audit frameworks

“The study estimates energy consumption in eight small-scale cashew nut processing operations in India, with drying, steaming, and kernel drying being the most energy-intensive processes. These operations consume 90% of the total energy. The study suggests the use of renewable energy technologies like solar tunnel dryers and forced convection solar cabinet dryers for energy conservation. The fuel analysis of cashew nut shells suggests gasification technology for heat generation” [38].

“The energy analysis of the baby boiler for steaming of cashew nut seeds. Solar energy, electricity, and fuel are the major sources of energy consumed for cashew nut processing. Finally, the results showed that while using electricity in the baby boiler for the steaming operation, for 60, 30 and 15 kg batch capacity industries, their corresponding total energy was estimated at 5321.43, 5540.14, and 6061.34 MJ” [37].

The energy audit of cashew nut processing industries in Karnataka revealed significant disparities in energy consumption for producing similar products. 60% of units had a percentage production capacity utilization below 50%, with higher specific energy consumption and energy intensity. The energy intensity varied from 4.43 to 8.66 kg per kernel, suggesting a potential energy conservation of 30 to 48%. The relationship between specific energy consumption and production showed an improvement with increased production, indicating optimal utilization of installed capacity [52].

The bakery and pastry sector's energy consumption and technologies are crucial for global competitiveness. The agri-food sector must ensure a strong, innovative industrial base at all stages of the value chain, capable of international competition and product and service quality differentiation [40]. The characteristics of confectionery plants are influenced by raw material type, production technology, equipment structure, and automation. These factors influence energy consumption. This article provides technical and technological factors for analyzing energy efficiency in the confectionery industry, aiding in selecting optimal techniques and creating a database tracking these characteristics. [70].

The energy audit in a tea manufacturing industry in North Bengal, India, reveals concerns about rising energy bills and environmental impacts. The audit helps identify opportunities to reduce energy bills while maintaining production quality and conserving the environment. The focus is on a medium-scale tea manufacturing industry with a garden in Jalpaiguri, North Bengal. The audit determines energy usage by machines and production processes and suggests recommendations to reduce overall energy use. [40].

The study surveyed 25 tea estates in Assam to assess the energy consumption for processing green tea leaves. Data was collected through questionnaires and personal interviews. The data pertaining to energy input per tone of made tea for various operations were converted into equivalent energy units: human labor = 1.96 MJ h^{-1}, coal = 32.8 MJ kg^{-1}, electricity = 11.93 MJ kWh-1, and oil = 41.3 MJ l^{-1}. The total energy input for processing tea leaves on small, medium, and large estates was 53600, 40718, and 38026 MJ per tone, respectively [71].

A study on a vegetable oil refinery in Nigeria evaluated its energy and energy efficiency. The plant's four main operations were neutralizer, bleacher, filter, and deodorizer. The energy intensity for processing 100 tons of palm kennel oil into edible oil was 487.04 MJ/tonne, with electrical energy accounting for 4.65%, thermal energy at 95.23%, and manual energy at 0.12%. The deodorizer was the most energy-intensive operation, accounting for 56.26% of the net energy input, [62].

The dairy industry faces a significant energy crisis due to depleting conventional sources and growing industrial and domestic loads. To address this, it is crucial to explore energy-generating and conservation methods. The dairy industry uses electrical and thermal energy, and identifying potential energy savings is crucial for a competitive advantage. Energy consumption and savings are assessed based on equipment and functional purpose. [68].

The pulp and paper manufacturing process requires steam for pulping and papermaking, while electricity is used for pumping and rollers. To reduce energy bills, several energy-saving measures can be implemented, including steam optimization, replacing inefficient pumps, and installing high-tensile motors. The proposed energy conservation measures can reduce the total annual cumulative bill by 18%, resulting in an annual savings of around Rs. 446.53 lakhs. [25].

The energy audit of condiment industries found that electric motors and boilers consume the most energy. Despite the absence of variable-speed drives, motors run under loaded conditions. Variable speed drives can save up to 60% of electrical energy by reducing motor speed by 20%, 40%, and 60%, respectively. This could save about 276 MWh, 551 MWh, and 827 MWh of electrical energy. [67].

A Nigerian wheat processing plant conducted an energy study to determine the energy consumption pattern for flour production. The study used a process analysis method to evaluate energy requirements for eight-unit operations. The energy used was electrical and manual, with an average intensity of 0.101 MJ/kg. The milling unit was the most energy-intensive, with an intensity of 0.073 MJ/kg (72.20%). Optimizing the milling process is suggested to make the system more energy-efficient [44].

“The energy audit in the flour mill plant was studied and revealed that an energy audit of the 2015 production year of Crown Flour Mill Plants reported that the energy requirement of the process machines and consumption capacities for Mills A and B was a total of 14.1 GWh/year, which is far less than the energy generated from the diesel fuel used. Hence, a lot of energy is being wasted in the flour production plants”. [1].

Inefficient sugar processing in Gur and Khandsari units in northern India results in significant sugar loss and excess commercial energy consumption. The loss exceeds 1.5 million tons per year, and the commercial energy required to produce raw sugar is higher than refined sugar production. [47].

5. OPPORTUNITIES FOR RENEWABLE ENERGY TECHNOLOGIES FOR PHF SYSTEM

There are several opportunities and renewable energy technologies that the post-harvest food system (PHF) can consider incorporating. These options can provide numerous benefits in terms of sustainability, cost savings, and environmental impact. Here are some opportunities in technologies worth exploring: Solar PV power on PHF buildings can reduce energy costs and traditional power reliance. Wind turbines can generate electricity from wind energy, reducing dependence on fossil fuels and carbon emissions. Solar drying reduces moisture content and increases the shelf life of fruits, vegetables, and grains. Biogas production from organic waste serves as a fuel source for cooking and other food industry energy needs. Biomass energy, derived from organic matter, can be used for heating, cooking, and other food industry needs.

Renewable energy resources are being utilized as a replacement for conventional fuel in the post-harvest food system. Solar and biomass technologies are widely adopted as suitable energy replacements, as energy accounting units are energy-intensive operations.

5.1 Solar Energy Technologies

The study explores post-harvest operations for turmeric processing, including conventional boiling and drying. A new technology for boiling and drying agricultural produce, specifically turmeric rhizomes, was developed. Results show solar drying is superior to direct sun drying, achieving desired moisture content and essential quality in 42 hours. [54].

The techno-economic analysis of typical dryers found that plastic collectors with a 5–10-year lifespan are the cheapest, while conventional collectors have a useful lifetime of over 20 years but are more economical [60].

The economics were assessed of drying timber in the title kiln along with the conventional drying techniques. Compared to air drying, solar drying was cheaper and cost less than half of the steam kiln [61].

The study evaluated the efficiency of a forced convection solar dryer for drying groundnut, ginger, and garlic compared to an electrically operated tray-type mechanical dryer. Results showed the solar dryer was more cost-effective and efficient, with a benefit-cost ratio of 1.56 and 1.18, respectively. [31].

“The study evaluated a solar tunnel dryer's techno-economic analysis using net present worth, benefit cost ratio, and payback period. The commercial solar tunnel dryer had a net present worth of Rs 78,74,500, compared to Rs 36,52,500 for a diesel-fired dryer. The benefit cost ratio was 7.08 for the solar tunnel dryer and 2.56 for the diesel-fired dryer”. [57].

“A solar dryer was developed for drying vegetables and fruit, with a separate collector and drying chamber and two axial flow fans. The drying cost was Rs 17.52 and 41.35 kg-1, respectively. The cumulative present worth of annual savings over 20 years was Rs 31659.00, much higher than the capital cost of Rs 6500.00. The payback period was 3.26 years" [61].

The study examined the energy requirements of a solar-assisted dryer for drying onion slices. The energy required per unit mass of water removed without air recirculation ranged from 23.548 to 62.117 MJ kg-1, while the energy required per unit mass of water removed was between 12.040 and 38.777 MJ kg-1 [48].

"A comparative study on solar cabinets, vacuum-assisted solar dryers, and open-sun drying for drying of tomato slices (4-, 6-, and 8-mm thicknesses) was reported. The overall study concluded that good-quality dehydrated tomato slices could be produced by using a vacuum-assisted solar dryer compared to solar cabinet and open-sun drying methods" [48].

5.2 Biomass Energy Technologies

"The study evaluated the techno-economic aspects of biomass briquetting in India, analyzing its financial performance using simple cost functions for briquetting machines. It calculated unit costs for different raw materials and units and analyzed factors affecting briquette production costs" [64].

"The study evaluated the financial aspects of biomass gasifier-based institutional cooking, comparing its thermal energy unit cost to LPG and coal-based options. It works out to Rs 0.37 MJ-1 for a 29 kW_{th} (25000 kcal/h) biomass gasifier system, while for a 291 kW_{th} (250 000 kcal/h) system it was Rs 0.23 MJ^{-1}. Biomass gasifier-based institutional cooking systems were always financially more attractive than corresponding coal-based systems and are even better than LPG-based systems for capacities over 58 kW_{th}" [65].

Table 3. Matrix of solar energy technologies for post-harvest operations [36]

SN	Solar Energy Technologies	Application Media	Temp. range	Applications/use
1.	Solar water heater	Hot water	(<80°C)	Blanching, washing, cleaning, Boiler feed water etc.
2.	Solar box cooker	Cooking	80-100°C	Cooking, Boiling, brewing, baking, mashing, extraction etc
3.	Parabolic solar cooker	Process heat	100-250°C	Cooking, frying, roasting, baking, etc
4.	Solar concentrating collector	-Process heat -Steam	>200°C	Sterilization, pasteurization, bleaching, hydrogenation.
5.	Solar air heater	Hot air	50-80 °C	Heating, drying, dehydration
6.	Direct solar dryer	Hot air	50-80 °C	Drying of grain, agricultural commodity which are not thermal sensitive
7.	Indirect solar dryer	Hot air	50-80 °C	Drying of food commodity which are thermal sensitive

Table 4. Matrix of biomass energy technologies in post-harvest operations [36]

SN	Biomass Technologies	Biomass Feedstock	Product	Uses in Industries
1	Direct Combustion	Wood, agro residue Process waste, MS W Shells, Briquetted fuel	--	Heat and power
2	Gasification		Producer gas	Heat and Electricity
3.	Carbonization		Charcoal	Heat Electricity
4	Pyrolysis		Crude oil	Lubrication, Transport
5	Anaerobic digestion	Animal manure, Agro-waste, Landfills, Waste Water, effluent, DE- Oiled cake	Biogas	Cooking, power generation, heat, boiling, lighting etc
6	Aerobic digestion	Sugar or starch crops, Wood waste, Pulp sludge, Gras straw	Ethanol	Transport fuel

"The performance of an energy-efficient biomass cook stove suitable for different fuels (wood and briquetted fuel) was reported. It was tested with babul wood *(Prosopis julliflora)*, groundnut *(Arachis hypogaea)* shell briquettes, sawdust briquettes, and cashew nut *(Anacardium occidentale)* shell. The stove was insulated by refractory cement (Insulyte-11U) to minimize heat losses. The stove has exhibited about 35% thermal efficiency" [45].

The reliability of power systems is crucial for achieving decarbonization targets, but challenges and failures often hinder this. The literature rarely discusses these challenges and technological solutions. Future research should focus on developing a solution matrix for renewable technologies to address these challenges. The potential of these solutions, particularly cost-effective energy, can help prioritize and reduce specific challenges. The study's categories can help determine specific needs and increase transparency in the renewable energy integration process. [5].

5.3 Other Emerging Technologies

The implementation of these opportunities and renewable energy technologies can provide PHF with a more sustainable, cost-effective, and environmentally friendly approach to processing operations. It is essential to conduct feasibility studies, evaluate potential returns on investment, and engage relevant stakeholders to ensure successful integration and long-term benefits.

The costs and performance of renewable energy technologies have reached the stage where the number of economical applications in developing countries is increasing, particularly in the grid and off-grid markets for electricity [www.fao.org].

The conclusions are as follows. (a) Competition and regulatory reform in the energy industry, particularly in the electricity sector, can boost investments in renewable energy by reducing subsidies for fossil and hydro resource electricity production.

(b) Key technologies offer potential for further cost reductions, with each generation acting to lower future costs. These benefits should be acknowledged in tax and regulatory policies, as well as in budgetary allocations for R&D and education.

(c) The environmental advantages of renewable energy will become more apparent as developing countries begin to introduce their environmental policies on fossil fuels.

(d) Accelerating the development of renewable energy options would be a more effective and focused policy, reducing uncertainties and costs associated with climate change response.

6. CONCLUSION

The energy auditing in the post-harvest food (PHF) system, as well as exploring opportunities for using renewable energy sources is the key tool to assess and analyze the energy usage within the PHF system and identify potential areas for implementing renewable energy solutions. It is necessary to standardise reported consumption data across the sector and policy efforts must be devoted to this task urgently to develop efficient strategies to optimise the whole food system, allocate resources more effectively and reduce both waste and fossil fuel dependency.

The systematic approach for estimation of energy in industry helps to identify the energy intensive operation and type of energy used. The wide utilization of commercially available renewable energy technologies for post – harvest operations can provide the profitable solution for energy security and clean environment. Solar drying, biogas production, hydroelectric power, wind power, and biomass energy are just a few examples of the various renewable energy options that can be harnessed in this sector.

7. FUTURE DIRECTIONS

This manuscript is scientifically robust and technically sound because it provides a detailed and systematic methodology for assessing energy consumption in post-harvest food systems, which is a critical aspect of modern food processing. The inclusion of both renewable and non-renewable energy sources, along with real-world case studies, ensures that the findings are grounded in practical applications. The equations and parameters for energy audits are well-referenced, drawing from reliable sources, which adds credibility to the analysis. Additionally, the exploration of renewable energy opportunities, such as solar and biomass, aligns with current global sustainability goals, making the manuscript both timely and relevant to the scientific community.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

The authors hereby declare that no generative AI technologies, including Large Language Models (such as ChatGPT, COPILOT, etc.) and text-to-image generators, have been utilized in the writing or editing of this manuscript titled "Energy Assessment Methodology and Analysis in Post Harvest Food System and Opportunities for Use of Renewable Energy Sources: A Review."

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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