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Energy Audits from Farm to Factory in Oilseeds and Cereals

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ABSTRACT: Oilseeds and cereals consume considerable energy and power from the farm to the factory, where it is employed for formulations, namely heat and drying, cold storage, and prior to many applications that might be taken, the steps in the farm such as pumping for irrigation and other works applied. This research is concerned with energy consumption from the farm to the factory with particular reference to oilseeds and cereals. A narrative review was made in depth and important sources were cited. Many factors and steps concerned were taken into account. It was concluded that energy consumptions work at best when they are continuous and tied to basic planning and control. The reviewed study indicates that steady flow, better water and input choices, smarter utilities, and real use of by-products can put energy and emissions without harming output or quality. Clear system lines, meters with time stamps, and before-and-after tracking make gains easy to compare and repeat across sites. This gives farms and plants a practical way to save energy now while building more resilient supply chain.

Keywords: Beeswax, Biodiesel Purification, Energy Audits, Energy Efficiency, Oilseeds and Cereals, Olive oil Extraction.

Introduction

Oilseeds and cereals are central to food and bio‑based products, but their energy footprints remain high from field to factory. Broad reviews list repeating hotspots: heat for cooking and evaporation, refrigeration, water pumping for irrigation, diesel for traction, and the embodied energy of fertilizers and chemicals (Corigliano & Algieri, 2024).

A growing set of case studies ties process choices and control to measurable audit gains. In olive mills, moving from batch to continuous management reduces idle power and raises efficiency (Perone *et al*., 2022). Assisted extraction such as pulsed‑electric‑fields (PEF) can increase first‑pass yield, which lets plants finish runs sooner and use less electricity and hot water (Navarro *et al*., 2022; Puértolas & Martínez, 2015; Dias *et al*., 2024;

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Tamborrino *et al*., 2019; Martínez‑Beamonte *et al*., 2022). On farms, exergy analysis helps focus on where useful‑work quality is lost, improving sustainability indices while protecting yield (Esmaeilpour‑Troujeni *et al*., 2021; Kaab *et al*., 2024; Yıldızhan, 2019; Rafiee *et al*., 2022). In palm mills, mechanization lowers specific energy and residues can fuel steam and power (Akolgo *et al*., 2023). Factory audits that pair meters with forecasting improve dispatch decisions and cut carbon intensity (Mirasçı *et al*., 2025). In biodiesel, most energy and water penalties sit in washing and polishing; dry‑wash and ion‑exchange routes can shrink that burden (Osman *et al*., 2024; Ma & Hanna, 1999; Van, 2005; Meher *et al*., 2006; Atadashi *et al*., 2011; Quispe *et al*., 2013; Kusdiana & Saka, 2004).

Three gaps recur. First, studies mix different boundaries—energy, exergy and cradle‑to‑gate LCA—so results are hard to compare (Corigliano & Algieri, 2024; Esmaeilpour‑Troujeni *et al*., 2021; Kaab *et al*., 2024; Yousefi *et al*., 2014; Yıldızhan, 2019; Rafiee *et al*., 2022; Lozano‑Castellón *et al*., 2024). Second, many audits are static snapshots and do not pair measurement with scheduling and control to lock savings in (Perone *et al*., 2022; Wang, 2008; Mirasçı *et al*., 2025). Third, valorization options are often listed but not quantified in audit terms, therefore the real effect on utilities and cost stays unclear (Akolgo *et al*., 2023; Ningsih *et al*., 2024; Osman *et al*., 2024; Quispe *et al*., 2013).

Our aim is practical. We read nine core studies closely and combine them with supporting work to extract actions that plants and farms can take now. We focus on scheduling and continuous flow in olive mills (Perone *et al*., 2022; Navarro *et al*., 2022; Puértolas & Martínez, 2015; Dias *et al*., 2024; Tamborrino *et al*., 2019; Martínez‑Beamonte *et al*., 2022); exergy‑guided irrigation and nutrient choices in rapeseed and cereals (Esmaeilpour‑Troujeni *et al*., 2021; Kaab *et al*., 2024; Yıldızhan, 2019; Rafiee *et al*., 2022); mechanization and residue‑to‑energy in palm mills and tofu plants (Akolgo *et al*., 2023; Ningsih *et al*., 2024); and energy‑lean purification and coproduct use in biodiesel (Osman *et al*., 2024; Ma & Hanna, 1999; Van, 2005; Meher *et al*., 2006; Atadashi *et al*., 2011; Quispe *et al*., 2013; Kusdiana & Saka, 2004). We propose a staged audit pathway that is easy to apply and easy to verify.

Materials and Methods

This narrative review covers nine core investigations with plant‑ or farm‑level measurements: a sector‑wide assessment of food‑industry energy (Corigliano & Algieri, 2024); a review of sustainable extraction options and their energy implications (Gaikwad *et al*., 2025); olive‑mill scheduling with measured equipment effectiveness and energy use (Perone *et al*., 2022); exergy‑based optimization of rapeseed production (Esmaeilpour‑Troujeni *et al*., 2021); energy analysis of palm oil mills with residue valorization (Akolgo *et al*., 2023); a practical guide to utilities and heat recovery in food plants (Wang, 2008); a life‑cycle energy and emissions audit of barley under three irrigation systems (Kaab *et al*., 2024); machine‑learning forecasts for a food factory with cogeneration (Mirasçı *et al*., 2025); a tofu‑industry audit with wastewater biogas potential (Ningsih *et al*., 2024); and a comparative review of biodiesel production and purification (Osman *et al*., 2024; Ma & Hanna, 1999; Van, 2005; Meher *et al*., 2006; Atadashi *et* *al*., 2011; Quispe *et al*., 2013; Kusdiana & Saka, 2004). We read each paper closely and extracted the main levers for saving energy and for valorization.

Results and Discussion

- *Olive oil extraction: scheduling and assisted extraction*

Scheduling strongly shapes energy use in olive mills. Comparing batch lines (malaxers in parallel) as shown in figure 1, with continuous lines (malaxers in series) as shown in figure 2, shows that continuous management cuts dead time on malaxers and decanters. In the study, Overall Equipment Effectiveness rose from 51.2% to 93.1%, and Energy Use Efficiency improved from 32.86 to 62.65 in the continuous setup (Perone *et al*., 2022) (Table 1). These gains reflect fewer start–stop losses, fewer idle minutes at high power draw, and better matching of paste flow to decanter capacity.

Two practical steps help to lock in those gains. First, stabilize fruit reception so that paste feeds malaxers at a steady rate. Rapid screening of fruit moisture and oil content can support small-lot pooling. Second, coordinate cleaning-in-place and decanter bleed-off with low-tariff hours to avoid spikes. When intake peaks seasonally, simple queuing rules keep equipment near design load (Perone *et al*., 2022).

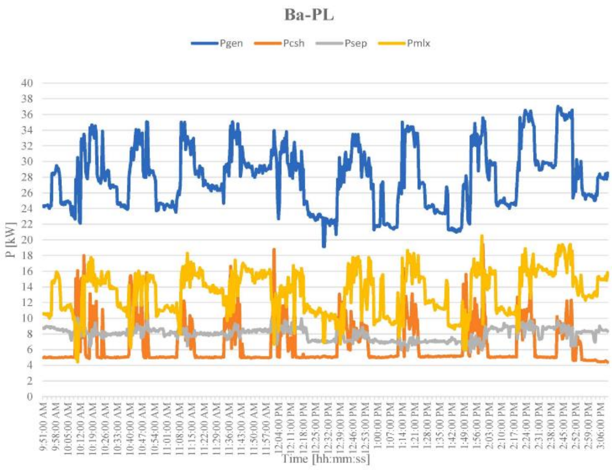

Fig. 1. Ba-PL power trend over 5 operating hours.

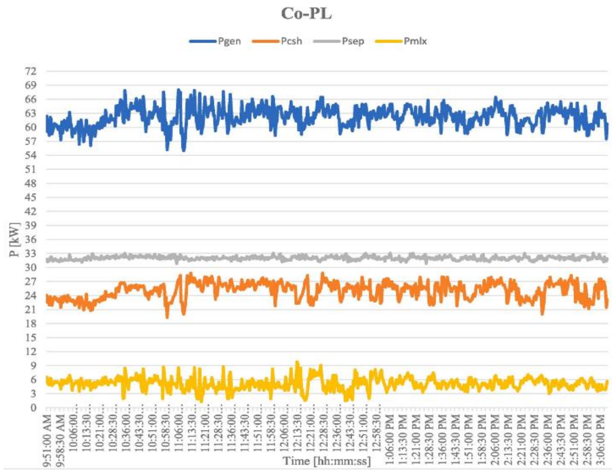

Fig. 2. Co-PL power trend over 5 operating hours.

Assisted extraction can add a second layer of savings. PEF treatment weakens cell walls and speeds oil release, which lets mills shorten malaxation at the same yield or reach a higher first-pass yield at the same time. Pilot and industrial work report higher extraction yield while maintaining legal and sensory quality markers (Navarro *et al*., 2022; Puértolas & Martínez, 2015; Dias *et al*., 2024; Tamborrino *et al*., 2019; Martínez-Beamonte *et al*., 2022). In energy terms, the same daily throughput can be reached in shorter runs, so electricity and hot-water demand fall. The benefit is largest when the line already runs close to continuous conditions so the added yield translates into time saved rather than extra rework.

- *Sustainable extraction routes: where energy savings come from*

Different assisted methods share the same two energy mechanisms. By improving mass transfer and disrupting cell structures, they raise first-pass yield and cut time at temperature; and by lowering solvent circulation or enabling solvent-free operation, they reduce downstream separation loads. Ultrasound and microwaves provide fast, targeted energy input that limits heat losses. Enzyme pretreatments break down pectin and cell walls under mild conditions. Supercritical CO_2 avoids hexane and can achieve high recoveries with careful heat integration (Gaikwad *et al*., 2025) (Table 2).

Real savings depend on how the new step fits into the line. If upstream preparation is variable or if downstream polishing is a bottleneck, the energy benefit will not be realized even if lab yield is higher. This is why audits should pair any technology change with a short trial that tracks residence time, rework, and utilities over several days, not just yield in a single batch (Gaikwad *et al*., 2025).

- *Rapeseed production: exergy-guided changes*

Exergy accounting highlights where useful-work quality is lost in the field. In the rapeseed study, irrigation electricity and chemical inputs dominated the losses. The optimized plan reduced irrigation water and electricity and adjusted fertilizer and manure to lift yield by 24.55%, raising the cumulative degree of perfection from 2.19 to 2.75 and the renewability index from 0.72 to 0.81 (Esmaeilpour-Troujeni *et al*., 2021) (Table 3). The findings suggest that audit recommendations should cover irrigation schedules, pump efficiency, and the choice of nitrogen sources, not only diesel and tractor time (Figure 3).

Table 1. Key performance outcomes reported for two olive-oil plant management models (Perone *et al*. 2022)

Configuration	Overall Equipment Effectiveness (%)	Energy Use Efficiency (-)
Batch	51.2	32.86
Continuons	93.1	63.65

Table 2. Mechanisms and integration notes for assisted extraction options (Gaikwad *et al*., 2025)

Modality	Energy-saving mechanism	Integration considerations
Pulsed electric fields	Faster oil release at lower/shorter malaxation	Requires stable paste flow and control of treatment dose
Ultrasound/Microwave	Enhanced mass transfer; lower time at temperature	Uniformity, scaling and equipment duty management
Enzyme-assisted	Cell wall breakdown at mild temperatures	Enzyme cost, contact time, downstream filtration
Supercritical CO_2	Solvent-free or low-solvent extraction	High-pressure duty; demands strong heat integration

Because electricity emissions factors vary by region and time of day, the same irrigation kilowatt‑hour can have very different carbon impacts. Where time‑of‑use tariffs are available, shifting pumping away from peak hours can save both costs and emissions. Exergy analysis helps to compare these scenarios fairly by focusing on the quality of energy supplied versus useful work delivered (Esmaeilpour‑Troujeni *et al*., 2021).

- ***Palm oil mills: mechanization and residues***

Field audits across manual, semi‑mechanized, and mechanized mills showed specific energy falling from 122.5 to 112.9 to 82.4 kJ per kilogram as mechanization rose (Figure 4). On the supply side of utilities, residues carry real value: shells, fiber and empty fruit bunches can provide about 299 kJ per kilogram as on‑site power when dried and burned properly (Akolgo *et al*., 2023) (Table.4). That is enough to support sterilization and part of pressing if the boiler and turbine are right‑sized.

Two cautions recur. Empty fruit bunches are wet; drying or co‑firing is usually needed. Because crop flow is seasonal, a boiler sized for peak may run far from its best point for the rest of the year. Audits should therefore match cogeneration equipment to average seasonal loads and confirm residue logistics before recommending large investments (Akolgo *et al*., 2023).

- ***Barley and irrigation choice***

Life‑cycle and energy auditing across flood, sprinkler and drip irrigation showed strong differences in total energy inputs: approximately 62.67, 49.81 and 75.59 GJ per hectare, respectively. In flood and sprinkler systems, diesel use took roughly one‑third of inputs; in drip, polyethylene pipelines accounted for about one‑third due to embodied energy (Kaab *et al*., 2024). The right choice is context‑specific: drip can still raise energy productivity when it improves water‑use efficiency and yields, while well‑tuned sprinkler may lower diesel consumption on windy sites (Table 5).

Pump efficiency, pipe friction losses, and the emissions factor of grid electricity versus diesel drive results. Audits should measure pumping energy per hectare, review pump curves, and assess pipe layouts. Because yields and water‑use efficiencies are plot‑specific, testing a small block before full roll‑out avoids costly mis‑steps (Kaab *et al*., 2024).

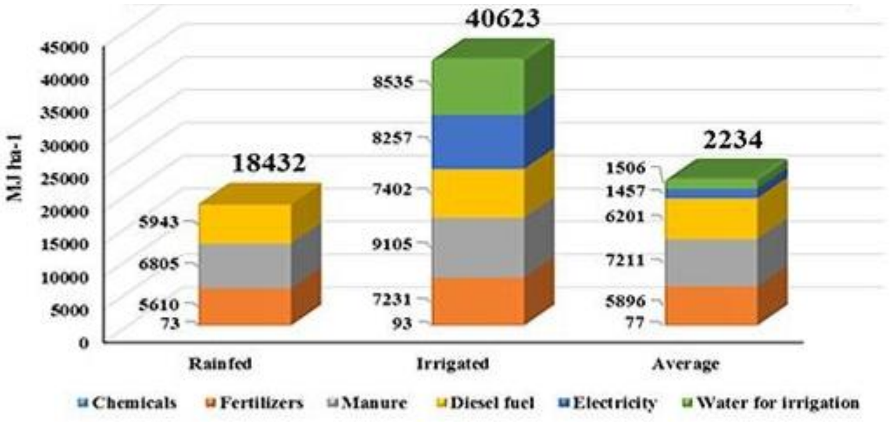

Fig. 3. Total CExC in the RPS and IPS of rapeseed in Mazandaran province, Iran.

Table.3. Exergy‑based optimization outcomes for rapeseed production (Esmaeilpour‑Troujeni *et al.*, 2021)

Scenario	Yield change (%)	Cumulative degree of perfection (–)	Renewability index (–)
Baseline	—	2.19	0.72
Optimized	+24.55	2.75	0.81

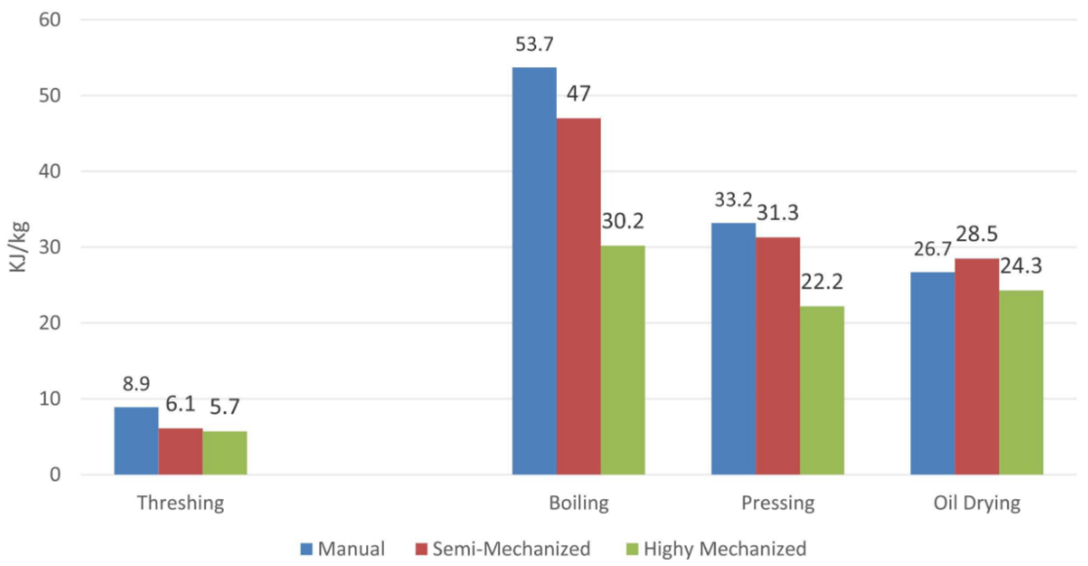

Fig. 4. The energy consumption of various processes in the extraction of palm oil.

Table 4. Reported specific energy and residue‑derived electricity potential in palm oil mills (Akolgo *et al.*, 2023)

Mechanization level	Specific energy (kJ/kg product)	Residue electricity potential (kJ/kg)
Manual	122.5	—
Semi‑mechanized	112.9	—
Highly mechanized	82.4	299

Table 5. .Energy inputs and dominant contributors by irrigation method for barley (Kaab *et al.* 2024)

Irrigation system	Total energy input (GJ/ha)	Dominant contributor
Flood	62.67	Diesel (~one‑third)
Sprinkler	49.81	Diesel (~one‑third)
Drip	75.59	Polyethylene pipelines(~one‑third)

- ***Forecasting to stabilize operations and cut carbon (Machine Learning and Digital Optimization)***

In mixed food factories, refrigeration and steam dominate utility bills. A case study combined short‑term electricity forecasts with on‑site cogeneration and changed dispatch rules (Figure 5). The new planning reduced forecast error and was associated with a 52.42% drop in carbon intensity compared with routine planning (Mirasçı *et al.*, 2025) (Table. 6).

The mechanism is simple: production runs were grouped in windows when the combined heat‑and‑power unit delivered stable heat and power, which reduced grid imports and avoided inefficient cycling.

In order to make these savings stick, the audit should deliver a basic forecast model and a playbook that the plant can follow. Benefits depend on tariff structure, the flexibility of production schedules, and the ability of the CHP to modulate output. Plants with fixed schedules or single‑

product lines may still gain by shifting cleaning‑in‑place and defrost cycles to low‑tariff hours (Wang, 2008; Mirasçı *et al*., 2025).

In the context of oilseed processing, Machine learning (ML) tools are increasingly applied to optimize extraction scheduling, detect energy anomalies, and guide maintenance decisions. Exergy-informed ML models further allow prediction of inefficiencies and provide corrective strategies for system optimization. These applications highlight the role of digital tools in complementing physical efficiency improvements, moving energy management in agro-industries toward predictive, adaptive, and intelligent paradigms (Mirasçı *et al*., 2025).

- *Tofu industry energy audits and valorization*

Audits across tofu factories found that cooking is the main thermal sink and varies by fuel: around 71.1 MJ per kilogram of soybeans with firewood, 16.9 MJ/kg with LPG and 6.0 MJ/kg with wood pellets (Figure 6) Water use averaged about 25.2 L/kg with wastewater near 14.5 L/kg (Figure 7).Wastewater has a methane potential of around 0.056 m³ per kilogram of soybeans, enough to replace roughly 2.8% of firewood, 11.9% of LPG or 33.4% of pellets under the study's assumptions (Ningsih *et al*., 2024) (Table 7).

Small steps matter and should be taken into consideration. Fixing insulation and seals cuts heat loss. Simple heat recovery can preheat soak water. A small digester shared by nearby shops can turn wastewater into biogas for preheating or even for low‑pressure steam. Because digesters need steady feed and temperature, pilots should run for several weeks before scaling (Ningsih *et al*., 2024).

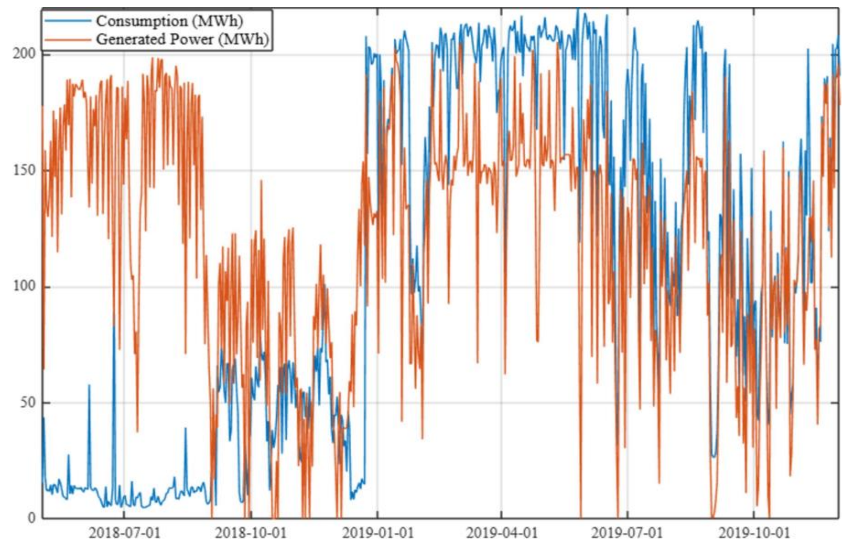

Fig. 5. Time series plot for the amount of generated power and consumed energy.

Table 6. Reported change in carbon intensity after adopting forecast‑driven utilities scheduling (Mirasçı *et al*. 2025)

Operating mode	CO_2 change (%)
Baseline planning	—
Forecast‑driven dispatch	−52.42

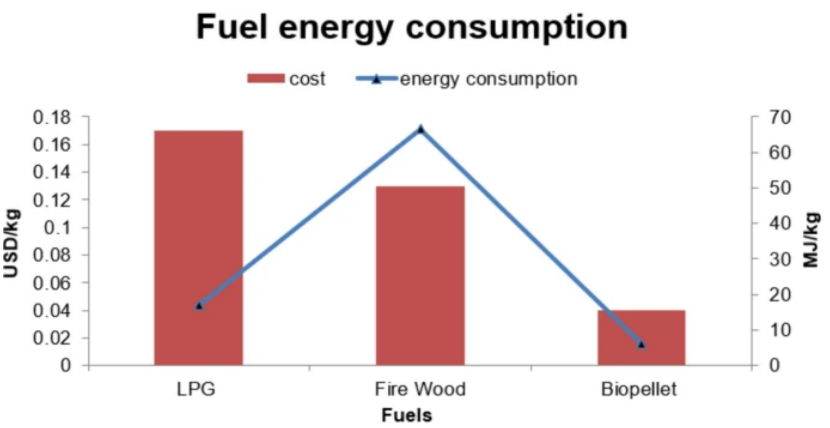

Fig. 6. Fuel consumption for cooking.

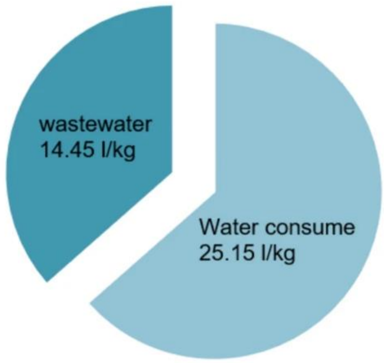

Fig. 7. Water consumption for processing production in the tofu industry.

Table 7. Thermal and valorization metrics from a multi‑site tofu audit (Ningsih *et al*. 2024)

Metric	Value
Cooking specific energy (firewood)	71.1 MJ/kg soybean
Cooking specific energy (LPG)	16.9 MJ/kg
Cooking specific energy (pellets)	6.0 MJ/kg
Water use	25.2 L/kg
Wastewater	14.5 L/kg
Methane potential	0.056 m^3/kg soybeans
Fuel offset potential	≈2.8% firewood; 11.9% LPG; 33.4% pellets

- ***Biodiesel: where the penalties sit and how to cut them***

Reaction sections in biodiesel plants are well understood (Figure 8). The heavy penalties often arrive later in washing and polishing. Traditional aqueous washing uses a lot of water and heat and creates large wastewater streams. Dry‑wash media, ion‑exchange resins and membranes reduce those loads when sized and operated correctly (Table 8). Alcohol recovery loops further lower both utility use and cost. Cleaner glycerol improves the site energy balance and opens up sales into chemical markets. Supercritical methanol removes the need for catalysts and simplifies purification, but it demands strong heat integration to be net‑efficient (Osman *et al*., 2024; Ma & Hanna, 1999; Van, 2005; Meher *et al*., 2006; Atadashi *et al*., 2011; Quispe *et al*., 2013; Kusdiana & Saka, 2004).

Because feedstock free‑fatty‑acid content can vary, plants often need flexible pretreatment to avoid soap formation. Audits should therefore cover feed quality tracking, the ratio of alcohol to oil, mixing and temperature control, and the pressure drop and fouling behaviour in polishing steps. A short campaign comparing aqueous and dry‑wash routes, with real utility meters, gives the clearest basis for decisions (Osman *et al.*, 2024; Ma & Hanna, 1999; Van, 2005; Meher *et al.*, 2006; Atadashi *et al.*, 2011; Quispe *et al.*, 2013; Kusdiana & Saka, 2004).

- *Cross‑cutting patterns from the food industry audit literature*

At sector scale, thermal processing and cold chains dominate plant utilities, while logistics and retail add non‑trivial shares (Figure 9). Across cases, savings persist when metering is paired with controls and when residues are treated as resources rather than waste (Corigliano & Algieri, 2024).

Sensitivity often traces back to load profiles and control discipline. Plants with stable schedules and verified metering capture larger, more durable savings (Corigliano & Algieri, 2024) (Table 9).

Audit checklist at portfolio level: confirm meters and intervals; tie key performance indicators (KPIs) to production units; review controls against measured profiles; and include residue valorization in the scope from the outset (Corigliano & Algieri, 2024).

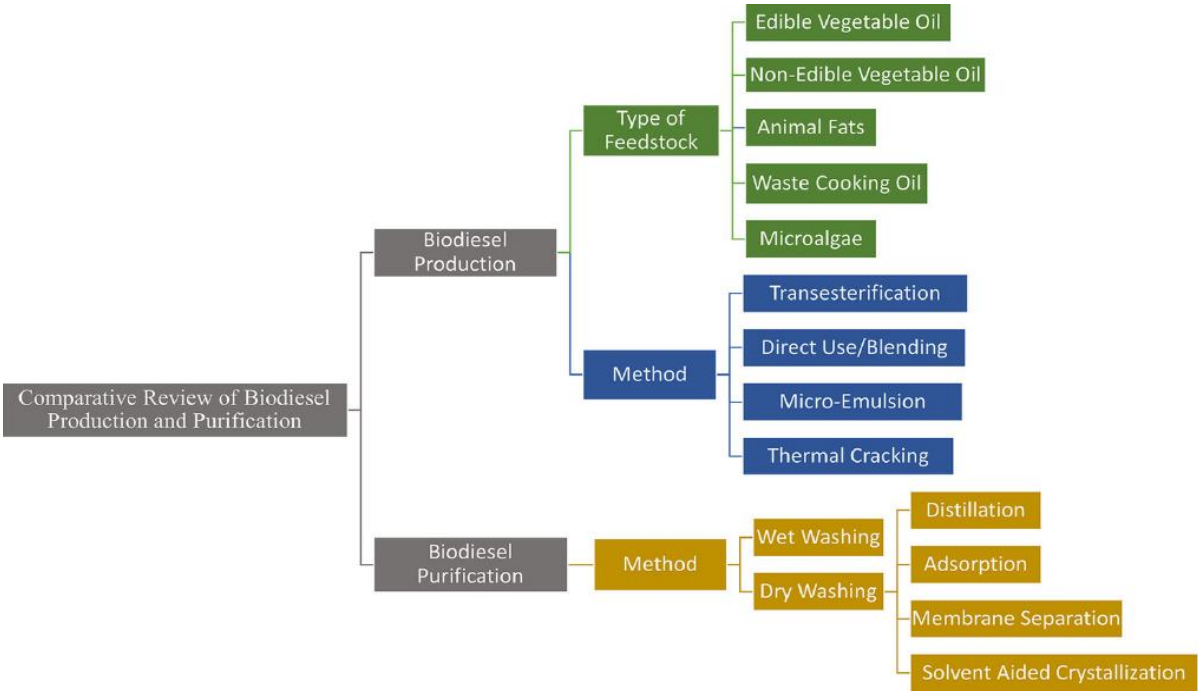

Fig. 8. Biodiesel production.

Table 8. Utility implications of biodiesel purification options and audit notes (Osman *et al*. 2024)

Purification route	Utility implication	Notes for audits
Aqueous washing	High water and heat duty	Requires wastewater treatment capacity
Dry‑wash media	Lower heat/water	Track media life and disposal
Ion exchange	Lower heat/water	Monitor resin fouling/pressure drop
Membranes	Lower heat/water	Needs pre-filtration; monitor fouling

- *Putting it together: a staged audit pathway*

Across these settings the pattern is clear. First measure the right things—electricity and fuels with time stamps, and production in comparable units. Next stabilise flows with better reception, scheduling and basic controls. Then intensify the steps that set throughput—malaxation in olive milling, irrigation and pumping on farms, utilities dispatch in factories—so first‑pass yield is higher and time at temperature is shorter. Finally, treat residues as resources: shells, fibre and bunches for steam and power in palm mills, tofu wastewater for biogas, and glycerol as a fuel or chemical in biodiesel (Perone *et al.*, 2022; Esmaeilpour‑Troujeni *et al.*, 2021; Akolgo *et al.*, 2023; Kaab *et al.*, 2024; Mirasçı *et al.*, 2025; Ningsih *et al.*, 2024; Osman *et al.*, 2024; Ma & Hanna, 1999; Van, 2005; Meher *et al.*, 2006; Atadashi *et al.*, 2011; Quispe *et al.*, 2013; Kusdiana & Saka, 2004).

To make results comparable, reports should specify boundaries and use a small set of shared indices. Alongside standard energy per unit of product, include exergy‑based indices in field studies and note grid emissions factors and tariff windows in factory audits. This helps other sites reuse the findings without repeating the full study (Corigliano & Algieri, 2024; Perone *et al.*, 2022; Esmaeilpour‑Troujeni *et al.*, 2021; Kaab *et al.*, 2024; Lozano‑Castellón *et al.*, 2024) (Table 10).

Conclusion

The evidence synthesized in this review demonstrates that oilseed and cereal production systems present both significant energy challenges and vast opportunities for efficiency improvements. At the process level, the transition from batch to continuous operations in olive oil mills, the mechanization of palm oil extraction, and the adoption of advanced extraction technologies such as ultrasound-

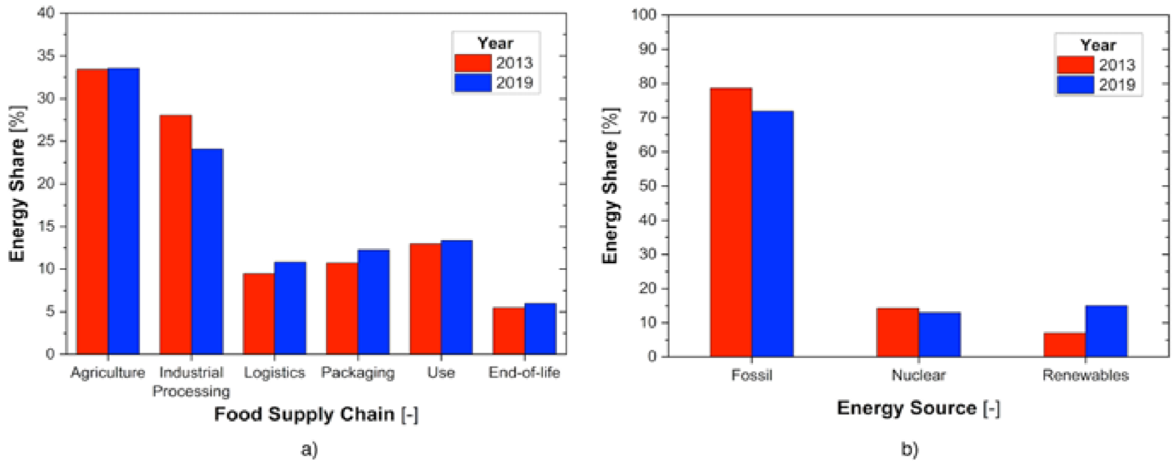

Fig. 9. Energy flows per FSC phase (a) and energy source (b). European Union.

Table 9. Common hotspots and levers identified across food‑industry audits (Corigliano & Algieri 2024)

Hotspot	Typical levers noted in audits
Thermal loops	Heat recovery, insulation, lower time at temperature
Cold chains	Set‑point discipline, defrost control, efficient compressors
Irrigation pumping	Pump efficiency, pipe design, scheduling
Embodied inputs	Fertilizer and pipeline choices, logistics

Table 10. Pooled comparison of levers and observed shifts across oilseed and cereal contexts

Context	Primary lever/action	Observed metric shift (from study)	Implied energy/CO_2 effect	Notes
Olive mill	Continuous scheduling	OEE 51.2→93.1; EUE 32.86→62.65 (Gaikwad *et al.*, 2025)	Lower idle kWh and shorter runs	Bank savings by holding throughput constant
Extraction tech	PEF/UAE/MAE/SFE	Higher first‑pass yield; shorter residence (Ningsih *et al.*, 2024)	Lower heat and solvent duty	Benefits require stable loading and controls
Rapeseed farm	Exergy‑tuned inputs	Yield +24.55%; CDP 2.19→2.75; RI 0.72→0.81 (Perone *et al.*, 2022)	Lower pump and input energy per ton	Leverage varies with water and grid factors
Palm mill	Mechanization + residues	SE 122.5→82.4 kJ/kg; residue power ≈299 kJ/kg (Esmaeilpour‑Troujeni *et al.*, 2021)	Lower specific energy; on‑site steam/power	Size boilers/turbines for average loads
Barley farm	Irrigation redesign	Flood 62.67; Sprinkler 49.81; Drip 75.59 GJ/ha (Akolgo *et al.*, 2023)	Shift among diesel/embodied energy shares	Model yield and water efficiency together
Factory utilities	Forecast‑driven dispatch	CO_2 down 52.42% (Wang, 2008)	Less grid import, better CHP use	Value depends on tariff and schedule flexibility
Tofu plants	Heat recovery + AD	Cooking 71.1/16.9/6.0 MJ/kg; CH_4 0.056 m³/kg (Kaab *et al.*, 2024)	Replace LPG/pellets; preheat water	Stability of digester is key
Biodiesel plant	Dry‑wash/membrane/IX	Lower water/heat vs. aqueous (Mirasçı *et al.*, 2025)	Lower utilities; improved waste handling	Alcohol recovery and glycerol quality matter

assisted, microwave-assisted, and supercritical fluid methods contribute to substantial reductions in energy consumption and emissions. At the system level, the application of exergy analysis in rapeseed production and life cycle assessments of soybean oil have provided valuable insights into inefficiencies, highlighting critical intervention points in cultivation, irrigation, fertilizer use, and industrial processing(Corigliano & Algieri, 2024; Gaikwad *et al.*, 2025; Perone *et al.*, 2022; Esmaeilpour‑Troujeni *et al.*, 2021; Akolgo *et al.*, 2023; Wang, 2008; Kaab *et al.*, 2024; Mirasçı *et al.*, 2025; Ningsih *et al.*, 2024; Osman *et al.*, 2024; Navarro *et al.*, 2022; Puértolas & Martínez, 2015; Dias *et al.*, 2024; Ma & Hanna, 1999; Van, 2005; Meher *et al.*, 2006; Atadashi *et al.*, 2011; Quispe *et al.*, 2013; Yousefi *et al.*, 2014; Yıldızhan, 2019; Rafiee *et al.*, 2022; Tamborrino *et al.*, 2019; Martínez‑Beamonte *et al.*, 2022; Lozano‑Castellón *et al.*, 2024; Kusdiana & Saka, 2004).

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