ISSN INTERNATIONAL STANDARD SERIAL NUMBER
ISSN 2782-4365
Проверить номер:

Научно-образовательный электронный журнал

ОБРАЗОВАНИЕ И НАУКА В XXI ВЕКЕ

Выпуск №74-3 (том 3)
(май, 2026)

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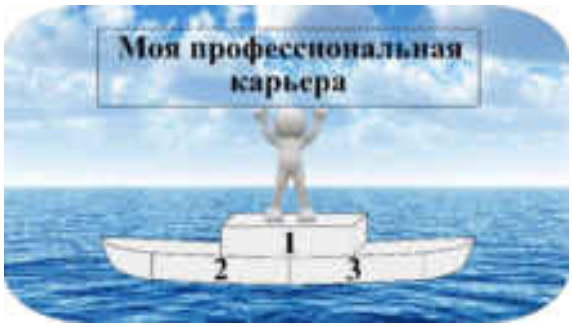

Международный научно-образовательный электронный журнал «ОБРАЗОВАНИЕ И НАУКА В XXI ВЕКЕ»

ISSN 2782-4365
УДК 37
ББК 94

Международный научно-образовательный электронный журнал «ОБРАЗОВАНИЕ И НАУКА В XXI ВЕКЕ». Выпуск №74-3 (том 3) (май, 2026). Дата выхода в свет: 18.05.2026.

Журнал объединяет авторов на территории стран СНГ и помогает обмениваться передовыми научно-образовательными исследованиями.

Содержит научные работы отечественных и зарубежных авторов по экономическим, техническим, философским, юридическим и другим наукам.

Миссия научно-образовательного электронного журнала «ОБРАЗОВАНИЕ И НАУКА В XXI ВЕКЕ» состоит в поддержке интереса читателей к оригинальным исследованиям и инновационным подходам в различных тематических направлениях, которые способствуют распространению лучшей отечественной и зарубежной практики в интернет пространстве.

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Название публикации: «TECHNOLOGY OF SOAP PRODUCTION FROM VEGETABLE OIL WASTE»

Abstract

The global production and processing of vegetable oils generates enormous volumes of waste streams — including spent frying oils, soap stocks, fatty acid distillates, and sludge — that pose significant environmental challenges if improperly managed. Simultaneously, these waste streams represent valuable lipid-rich feedstocks for the manufacture of soaps and surfactants, offering a sustainable pathway for waste valorization within the circular bioeconomy. This review comprehensively examines the technology of soap production from vegetable oil waste, covering feedstock characterization and pre-treatment, saponification chemistry, cold and hot process methods, continuous and semi-continuous production technologies, additives and formulation, quality control, and environmental considerations. The transformation of low-value oil waste into marketable soap products can simultaneously reduce industrial pollution, lower production costs, and contribute to cleaner manufacturing practices, making it a compelling topic at the intersection of green chemistry, waste management, and industrial biotechnology.

1. Introduction

Soap is one of humanity's oldest manufactured products, with evidence of its production dating back over 4,500 years to ancient Mesopotamia. At its most fundamental level, soap is the product of the saponification reaction between a fatty acid-containing substrate and an alkali, yielding a mixture of fatty acid salts (soaps) and glycerol. Despite thousands of years of history, soap manufacturing remains a major global industry: world soap production exceeds 15 million metric tons annually,

serving markets ranging from personal hygiene and household cleaning to industrial and institutional applications.

The vegetable oil industry — encompassing the production and processing of palm, soybean, sunflower, canola, olive, coconut, and cottonseed oils — generates waste streams at every stage of the value chain. During oil refining, the degumming, neutralization, bleaching, and deodorization steps produce by-products such as gums (phosphatides), soap stocks, spent bleaching earth, and fatty acid distillates. During food preparation and frying, large volumes of spent or waste frying oil (WFO) accumulate in food service establishments, restaurants, and households. Collectively, these waste streams amount to tens of millions of metric tons per year globally, with problematic disposal pathways including wastewater discharge, landfill, and illegal dumping that cause soil and water pollution.

Converting vegetable oil waste into soap offers an elegant solution to this waste management problem while creating economic value. The high free fatty acid (FFA) content of many oil waste streams, which renders them unsuitable for food-grade applications or requires costly processing for biodiesel production, is actually favorable for soap making, since FFAs can be directly saponified without prior transesterification. This review provides a detailed account of the technical processes, chemical principles, and practical considerations involved in soap production from vegetable oil waste, from feedstock handling to finished product quality assessment.

2. Feedstock Characterization and Pre-treatment

2.1 Types of Vegetable Oil Waste

Vegetable oil waste suitable for soap production can be categorized into several major types, each with distinct chemical compositions and pre-treatment requirements. Spent frying oil (SFO) is the most abundant type, collected from restaurants, food processing plants, and households after use in high-temperature frying operations. SFO is characterized by elevated FFA content (2–15%), increased viscosity, dark color, off-odors from thermal oxidation and polymerization products, and the presence of water and food particulates. Soap stock is an alkaline by-product of the oil neutralization step

in refining, containing sodium salts of fatty acids (soaps), neutral oil, phosphatides, and water; it can be acidulated with sulfuric acid to recover the fatty acids.

Fatty acid distillates (FAD) are obtained during the steam deodorization step of oil refining and contain a mixture of fatty acids, tocopherols, sterols, and squalene; they are highly concentrated sources of FFAs (60–90%). Trap grease and brown grease, collected from grease traps in food service wastewater systems, represent a lower-quality but widely available waste stream. Spent bleaching earth (SBE), recovered from the bleaching step of oil refining, contains 20–35% residual oil that can be extracted by solvent extraction or pressing for use in soap production. Each of these feedstocks presents distinct challenges for pre-treatment and process integration.

2.2 Key Quality Parameters and Analytical Methods

Before processing, vegetable oil waste must be characterized for the parameters most relevant to soap making. The free fatty acid (FFA) value, expressed as the percentage of oleic acid equivalent or as the acid value (mg KOH/g oil), is the primary indicator of the alkali requirement for saponification. The saponification value (SV) indicates the total amount of alkali (mg KOH) required to saponify one gram of fat, including both free and esterified fatty acids. The iodine value (IV) measures the degree of unsaturation of the fatty acid profile, which influences the hardness, lathering, and oxidative stability of the resulting soap. Moisture content, color (AOCS Lovibond method), peroxide value, and the presence of unsaponifiable matter (sterols, hydrocarbons, waxes) are also routinely determined.

2.3 Pre-treatment Operations

Pre-treatment of vegetable oil waste prior to saponification is essential to ensure consistent soap quality and process efficiency. Filtration through stainless steel screens (mesh 100–200 microns) removes coarse food particles and suspended solids from spent frying oil. Centrifugation (3,000–5,000 g) or gravity settling in heated tanks (60–70°C) separates water, sediment, and denser impurities. Dehydration by vacuum evaporation or heating to 105–110°C under atmospheric pressure reduces moisture content below 0.5%, which is critical because water inhibits saponification efficiency and promotes hydrolysis of the formed soap. Activated bleaching earth (1–3% w/w) or

activated carbon treatment followed by filtration reduces color bodies and oxidation products. For soap stock feedstocks, acidulation with 15–20% H_2SO_4 at 80–90°C splits the soap into FFAs and releases the glycerol phase, yielding an acid oil with FFA content above 90% suitable for direct saponification.

3. Chemistry of Saponification

3.1 Reaction Mechanisms

Saponification is the alkaline hydrolysis of ester bonds in triglycerides, diglycerides, monoglycerides, and free fatty acids to produce fatty acid salts (soaps) and glycerol. The reaction proceeds via nucleophilic acyl substitution: the hydroxide ion (OH^-) attacks the electrophilic carbonyl carbon of the ester bond, forming a tetrahedral intermediate that collapses with the expulsion of the alkoxide anion (glycerol), yielding the carboxylate (soap) and glycerol as products. The overall reaction for a triglyceride with sodium hydroxide (NaOH) is: Triglyceride + 3 NaOH → 3 Sodium Fatty Acid Salts (Soap) + Glycerol.

The saponification of free fatty acids is faster and simpler than that of triglycerides, proceeding by a direct acid-base neutralization: $RCOOH + NaOH \rightarrow RCOONa + H_2O$. This reaction is essentially instantaneous at room temperature and explains why high-FFA feedstocks from oil waste can be particularly suitable for soap making. Potassium hydroxide (KOH) can be used in place of NaOH to produce soft or liquid soaps, since potassium soaps are more water-soluble and have higher solubility at ambient temperature. Mixed alkali systems (NaOH + KOH) are used to produce soaps with intermediate consistency. The alkali requirement must be precisely calculated based on the FFA and saponification values of the feedstock to avoid excess unreacted alkali (which causes skin irritation) or unsaponified fat (which reduces lathering performance).

3.2 Role of Fatty Acid Composition in Soap Properties

The physical and functional properties of the resulting soap are intimately linked to the fatty acid profile of the starting oil. Short- and medium-chain saturated fatty acids (lauric C12:0, myristic C14:0) produce soaps with excellent lathering and rapid solubility, characteristic of coconut and palm kernel oil-based soaps. Long-chain

saturated fatty acids (palmitic C16:0, stearic C18:0) contribute to soap hardness, bar firmness, and longevity. Oleic acid (C18:1) produces a mild, conditioning soap with moderate lathering, while linoleic (C18:2) and linolenic (C18:3) acids increase soap softness and susceptibility to oxidative rancidity (dreaded orange spots, or DOS). Consequently, the formulation of soap from oil waste requires blending of feedstocks with complementary fatty acid profiles to achieve the desired balance of hardness, lather, conditioning, and oxidative stability.

4. Soap Production Methods and Technologies

4.1 Cold Process (CP) Method

The cold process (CP) method is the simplest and most energy-efficient approach to soap making, widely used by artisan producers and small-scale manufacturers. In the CP method, the oil or fat feedstock is gently warmed to 40–50°C, and a concentrated NaOH solution (typically 28–35% w/w in water) is prepared separately and cooled to approximately 35–40°C. The two phases are combined and mixed vigorously — by hand stirring, mechanical agitation, or immersion blending — until emulsification occurs and the mixture reaches a thick, pudding-like consistency known as "trace." At trace, additional components such as essential oils, colorants, antioxidants, and botanical extracts can be incorporated. The soap mass is poured into molds and allowed to cure at ambient temperature for 24–72 hours, during which saponification completes (the reaction is exothermic and the soap mass heats internally, often reaching 60–80°C in a process called "gel phase"). After demolding, bars are air-cured for 4–6 weeks to allow moisture evaporation, hardening, and completion of any residual saponification.

The principal advantage of the CP method is its simplicity and low energy consumption. However, it has several limitations when applied to oil waste feedstocks: the high FFA content of waste oils can cause acceleration (premature trace) and difficulty in achieving smooth, homogeneous mixing; the presence of colorants and impurities in the waste oil is incorporated directly into the final soap; and the long curing time reduces production throughput. These challenges can be partly mitigated

by pre-treatment of the waste oil to reduce FFA content (e.g., by esterification with glycerol) and color (activated carbon treatment) prior to CP saponification.

4.2 Hot Process (HP) Method

In the hot process (HP) method, saponification is driven to completion by the application of external heat, typically 80–100°C, for 1–3 hours in a jacketed reactor or slow cooker. The elevated temperature significantly accelerates the saponification reaction, eliminates the need for extended curing, and produces a fully saponified soap that can be used immediately after cooling and molding. The HP method is better suited to high-FFA feedstocks because the elevated temperature and prolonged reaction time ensure complete conversion of both triglycerides and free fatty acids. However, the high temperatures restrict the incorporation of heat-sensitive additives (essential oils, botanical extracts) until the cooking phase is complete and the soap mass has cooled to below 50°C.

4.3 Industrial Continuous and Semi-Continuous Processes

At industrial scale, soap is produced by continuous or semi-continuous processes that offer high throughput, precise process control, and efficient energy utilization. The Sharples continuous saponification process and the Mazzoni continuous saponification systems are among the most widely deployed industrial platforms. In the continuous fat-splitting/saponification approach, triglycerides are first hydrolyzed to fatty acids and glycerol using high-pressure steam (20–60 bar, 200–260°C) in a counter-current hydrolysis column, followed by neutralization of the fatty acids with aqueous NaOH in a continuous mixer-reactor. This two-stage approach allows glycerol recovery as a high-purity by-product, which significantly improves process economics.

For waste oil feedstocks, a modified continuous process is employed where the pretreated waste oil is metered via positive displacement pumps to a series of continuous stirred-tank reactors (CSTRs) or tubular plug-flow reactors operating at 80–100°C, with controlled NaOH solution addition and inline mixing. The saponification degree is monitored continuously by inline pH measurement and near-infrared (NIR) spectroscopy, allowing automatic adjustment of alkali dosing. The crude soap mass exits the reactor train and is sent to a finishing section comprising vacuum evaporation

(to adjust moisture content to 10–15%), amalgamation (mixing with additives), plodding (extrusion through a die to form billets), cutting, and stamping to produce finished soap bars.

4.4 Glycerol Recovery and By-product Management

Glycerol (glycerin) is produced in equimolar amounts alongside soap during saponification, representing approximately 10% by weight of the fat input. Recovery and purification of glycerol significantly improves the overall economics of the soap production process. In industrial soap manufacture, the crude glycerol-water phase (sweet water, 10–20% glycerol) is separated from the soap phase by gravity settling or centrifugation, then concentrated by multi-effect evaporation to 80–88% glycerol (crude glycerol) and further purified by distillation under vacuum to pharmaceutical-grade (99.5%+) glycerol. In waste oil soap production, glycerol quality may be lower due to impurities in the feedstock, requiring additional purification steps such as ion exchange chromatography or activated carbon treatment.

5. Soap Formulation, Additives, and Product Types

Soap formulation from waste vegetable oil involves blending multiple feedstocks to achieve target fatty acid profiles, complemented by the incorporation of functional additives. Since spent frying oils are predominantly derived from sunflower, canola, or palm oil — rich in oleic and linoleic acids but relatively poor in lauric acid — they produce soft, conditioning soaps with moderate lathering. Blending with coconut oil (or coconut oil-based waste streams) at 20–30% of the total fat phase introduces lauric and myristic acids, significantly improving lather quality and bar hardness. Palm oil or palm stearin (rich in palmitic acid) can be incorporated to increase firmness and extend bar life.

Commonly used additives in waste oil soap formulation include:

- Antioxidants: rosemary oleoresin extract (ROE), vitamin E (tocopherol), and BHT (butylated hydroxytoluene) at 0.05–0.5% to retard oxidative rancidity
- Chelating agents: EDTA (ethylenediaminetetraacetic acid) or citric acid (0.1–0.5%) to sequester metal ions that catalyze oxidation

- Fragrances and essential oils: lavender, eucalyptus, tea tree, or synthetic fragrance blends at 1–3% for scent masking of residual off-odors from waste oil
- Colorants: iron oxide pigments, ultramarine pigments, or skin-safe cosmetic colorants at 0.1–1.0% for aesthetic appeal
- Exfoliants: ground apricot kernels, oatmeal, pumice, or sea salt for mechanical cleansing action
- Superfatting agents: shea butter, castor oil, or cocoa butter added at 3–8% above the calculated saponification requirement to provide free moisturizing oils in the final bar
- Preservatives: germaben, optiphen, or phenoxyethanol for liquid soap formulations to prevent microbial growth

Product types manufactured from waste vegetable oil include: solid bar soap (toilet, laundry, and industrial grades), liquid soap (hand wash, dish wash, and shampoo formulations), soft soap paste (for traditional market applications), transparent soap (produced by dissolving the base soap in ethanol-water mixtures and controlled crystallization), and noodle soap (intermediate product for further compounding by soap finishers). The quality tier — toilet soap versus laundry or industrial soap — is largely determined by the degree of feedstock pre-treatment, the purity of the alkali used, and the extent of the finishing operations.

6. Quality Control and Analytical Testing

Soap quality is assessed by a range of physical, chemical, and functional tests standardized by bodies including the American Oil Chemists' Society (AOCS), the International Organization for Standardization (ISO), and national standards authorities. Total fatty matter (TFM), expressed as a percentage of the dry soap weight, is the primary commercial quality indicator; toilet soap typically requires TFM above 76%, while laundry soap may have TFM of 60–70%. The free caustic alkali content must not exceed 0.1–0.3% (depending on grade) to ensure skin safety. Total alkali, free fatty acid content, moisture, unsaponifiable matter, chloride content, and pH (1% solution) are also routinely determined.

Functional performance testing includes lather volume and stability assessment (using standardized foam generation apparatus), hardness measurement (penetrometer or Shore durometer), rancidity testing (peroxide value of extracted fat, olfactory assessment), and skin irritation testing for consumer-grade products (dermatological patch testing on human volunteers). For soaps destined for export markets, heavy metal analysis (lead, arsenic, mercury, cadmium) by ICP-OES and microbiological testing for Staphylococcus aureus, Pseudomonas aeruginosa, and total viable count are additionally required. Soaps produced from waste oils require particular attention to the removal of polycyclic aromatic hydrocarbons (PAHs) and other thermal degradation products that may accumulate in spent frying oils.

7. Environmental Impact and Economic Considerations

The environmental case for soap production from vegetable oil waste is compelling. Spent frying oil discharged into sewage systems causes severe blockages (fatbergs) and aquatic ecosystem damage, with a chemical oxygen demand (COD) of 1.7–2.0 million mg/L — approximately 200 times more polluting than domestic wastewater. Diverting this waste stream into soap production eliminates these discharge impacts while avoiding the environmental costs of virgin oil cultivation and processing. Life cycle assessment (LCA) studies comparing waste oil soap against petroleum-based synthetic detergents consistently demonstrate lower global warming potential, reduced fossil resource depletion, and lower land use for the bio-based soap option.

Economically, the use of waste oil as feedstock can reduce raw material costs by 40–70% compared to virgin refined oils. In developing countries and emerging markets, community-scale soap production from locally collected waste cooking oil provides a viable microenterprise model, requiring modest capital investment (mixing vessels, molds, curing racks) and offering attractive profit margins on finished soap sold in local markets. At industrial scale, the integration of waste oil soap production with biodiesel production — using the glycerol by-product stream and the fatty acid-rich soap stock as co-products — creates a multi-product biorefinery with significantly improved overall economics and waste minimization.

8. Emerging Technologies and Innovations

Enzymatic saponification using lipase enzymes (EC 3.1.1.3) represents one of the most promising emerging technologies for soap production from waste oils. Unlike conventional alkaline saponification, enzymatic processes operate at mild temperatures (30–55°C) and neutral pH, producing fatty acid soaps (as their ammonium or potassium salts when combined with mild alkali) without the harsh conditions that degrade heat-sensitive bioactive compounds. Immobilized lipases — particularly Candida antarctica lipase B (CALB) on mesoporous silica or polymeric supports — have demonstrated excellent stability and reusability over hundreds of reaction cycles. Although enzyme costs remain a barrier to widespread industrial adoption, the continuous reduction in enzyme production costs through improved fermentation technology and immobilization strategies is making enzymatic soap production increasingly competitive.

Ultrasound-assisted saponification has been demonstrated to significantly accelerate the saponification reaction of waste oils, reducing reaction times from hours (conventional) to minutes. The intense micro-mixing and cavitation effects generated by ultrasonic irradiation (20–40 kHz) dramatically improve mass transfer between the oil and aqueous alkali phases, overcoming the interfacial limitation that is the primary rate-limiting step in conventional saponification. Microwave-assisted saponification similarly reduces reaction times while improving energy efficiency, with saponification of waste frying oil achievable in under 10 minutes at 600 W microwave power. Both technologies are readily scalable using continuous flow reactors equipped with ultrasonic transducers or microwave applicators.

Supercritical fluid technology offers another innovative route for both the extraction of residual oil from spent bleaching earth and the saponification of waste oils. Supercritical carbon dioxide (scCO2) at 31.1°C and 73.8 bar is an excellent selective solvent for lipids, enabling the extraction of residual oil from SBE without thermal degradation or solvent residues. When combined with supercritical methanol or ethanol-based alkali solutions, saponification of the extracted oil can be performed in situ under supercritical conditions, offering a clean, continuous, and highly efficient

process. Digital twin modeling and AI-assisted process optimization are increasingly applied to waste oil soap production lines to maximize yield, minimize by-product formation, and ensure consistent product quality across variable feedstock compositions.

9. Conclusion

The production of soap from vegetable oil waste represents a well-established yet continuously evolving field that sits at the intersection of waste management, sustainable chemistry, and industrial manufacturing. The technical foundations of saponification are robust and well-understood, and established production methods — from artisan cold-process soap making to large-scale continuous industrial processes — can be adapted for the diverse range of waste oil feedstocks available globally. The principal technical challenges are associated with the variable and often compromised quality of waste oil feedstocks, necessitating effective pre-treatment, precise alkali calculation, and careful formulation to achieve soap products that meet commercial quality standards.

The environmental and economic arguments for waste oil soap production are strong and growing stronger as regulatory pressure on waste oil disposal tightens and demand for bio-based personal care products increases. Emerging technologies — enzymatic saponification, ultrasound and microwave assistance, supercritical fluid processing, and AI-driven process control — offer promising pathways to further improve the efficiency, product quality, and sustainability of waste oil soap production. Integration into circular bioeconomy frameworks, where waste oil soap production is combined with biodiesel production, glycerol recovery, and other valorization activities, will maximize the economic and environmental benefits of this important industrial process.

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