Baku State University Journal of Life Sciences & Biology 2026, v.3 (2), p. 7-16

journal homepage: http://bsuj.bsu.edu.az/en
https://doi.org/10.30546/300045.2026.3.01.10

ASSESSMENT OF THE FEASIBILITY OF BIOFLUEL PRODUCTION FROM *PINUS ELDARICA* MEDW. SEED OIL VIA GREEN NANOCATALYSIS

Tural Djabbarov[1], Afat Mammadova[1], Muhammad Zafar[2]
[1]*Baku State University, Baku State University, 23 Z. Khalilov St, AZ-1073, Baku, Azerbaijan*
[2]*Department of Plant Sciences, Quaid-i-Azam University Islamabad, Pakistan***

Received: 08 June 2026
Accepted: 28 June 2026
Published: 30 June 2026

The escalating demand for renewable energy necessitates the exploration of novel, non-edible feedstocks for biodiesel production that do not compete with food security. This study investigates the potential of *Pinus eldarica* Medw., a Near Threatened endemic conifer of the Caucasus Biodiversity Hotspot, as a sustainable feedstock for fatty acid methyl ester (FAME) production. Seeds collected from naturally occurring populations on the Eilyar-Oyugu range in Azerbaijan were processed by Soxhlet extraction to recover the seed oil, the yield of which compares favourably with that of several conventional non-edible feedstocks such as *Acacia senegal, Jatropha curcas, and Calophyllum inophyllum* (the last of which, however, carries a high free fatty acid content). A green magnesium oxide (MgO) nanocatalyst was biosynthesized from *P. eldarica* bark extract via an environmentally benign route, eliminating the need for hazardous reducing agents. Transesterification of the seed oil using the green MgO nanocatalyst achieved up to 96% FAME conversion efficiency. The physicochemical properties of *P. eldarica* biodiesel were evaluated against the ASTM D6751 and EN 14214 international standards. Furthermore, life cycle assessment perspectives and blending strategies (e.g., B20) were discussed as pathways to improve economic viability and engine compatibility. This research contributes a dual-purpose framework that simultaneously advances biofuel science through green catalysis innovation and supports the conservation of a critically important endemic species within a recognized global biodiversity hotspot.

Keywords: Biofuel, *Pinus eldarica* Medw., green nanocatalyst, MgO nanoparticles, Caucasus Biodiversity Hotspot

INTRODUCTION

Energy systems worldwide are being reshaped by two converging pressures: the need to curb climate change and the need to secure reliable energy supplies. Fossil fuel extraction is one of the most environmentally destructive practices as in an instance at Azerbaijan more than 12.000 hectares of soil is directly contaminated by oil [26]. Because fossil sources still supply roughly 80% of primary energy and transport alone generates about 25% of global CO_2 emissions [19], developing renewable, carbon-neutral fuels has moved to the top of the scientific and policy agenda. Within this search, biodiesel—a mono-alkyl ester obtained from renewable lipids—stands out as one of the most practical near-term replacements for petroleum diesel, since its combustion

---

E-mail address: Turaldjabarov@gmail.com

markedly lowers greenhouse gases, particulates, carbon monoxide, and unburnt hydrocarbons relative to conventional diesel [4, 18].

The selection of appropriate feedstocks remains the most critical determinant of biodiesel economic viability, environmental sustainability, and social acceptability. First-generation biodiesel feedstocks, including soybean, rapeseed, palm, and sunflower oils, have raised substantial concerns regarding the food-versus-fuel debate, indirect land use change, and deforestation-driven biodiversity loss [33, 12]. Consequently, the scientific community has increasingly focused on non-edible oilseeds and waste lipids as second-generation feedstocks that circumvent these ethical and ecological constraints. Notable examples include *Jatropha curcas*, *Pongamia pinnata*, *Calophyllum inophyllum*, *Ricinus communis*, and various species of *Moringa* [3, 29].

Pinus eldarica Medw. (Eldar Pine, syn. *Pinus brutia* var. *eldarica*) is a Near Threatened conifer endemic to the Caucasus Biodiversity Hotspot, with its sole natural population confined to the north- and northeast-facing slopes of the Eilyar-Oyugu range in the Samukh district of Azerbaijan, at elevations of 400–650 m a.s.l. [13, 14]. This species has evolved remarkable adaptations to arid and semi-arid conditions, including exceptional drought tolerance, wind resistance, salt tolerance, and the ability to thrive on nutrient-poor, rocky substrates [38]. These properties have led to its extensive cultivation across Central Asia, Iran, Afghanistan, and Pakistan as a reforestation and urban greening species [9]. The Eldar Pine State Reserve, originally established in 1910 as the first protected area in the Caucasus and expanded to 16.86 km² in 2004, attests to the ecological significance of this species [25].

Despite its cultural and ecological importance, the potential of *P. eldarica* as a bioenergy feedstock has received minimal scientific attention. Pine seeds are known to contain substantial lipid reserves with favorable fatty acid profiles for transesterification [6], and the genus *Pinus* encompasses over 120 species with diverse phytochemical portfolios. The present study represents the first comprehensive investigation of *P. eldarica* seed oil as a biodiesel feedstock, employing a fully green production pathway through the biosynthesis of MgO nanocatalyst from the species' own bark extract.

Solid (heterogeneous) nanocatalysts have increasingly been favoured over the conventional homogeneous bases (NaOH, KOH) used in transesterification, chiefly because they are easy to recover and reuse, generate less wastewater, and tolerate free fatty acids [15, 17]. Among the metal-oxide options, MgO nanoparticles are especially attractive, combining strong basicity with thermal stability, low toxicity, and modest cost [22, 36]. Preparing these nanoparticles by green routes—using plant extracts as the reducing and capping agents—adds a further environmental benefit by removing toxic reagents from the synthesis [11].

The objectives of this study are: (i) to characterize the physicochemical properties of *P. eldarica* seed oil and evaluate its suitability as a biodiesel feedstock; (ii) to synthesize and characterize a green MgO nanocatalyst using *P. eldarica* bark extract; (iii) to optimize the transesterification process and characterize the resultant FAME product; and (iv) to contextualize these findings within the broader frameworks of sustainable bioenergy development and endemic species conservation.

MATERIALS AND METHODS

Study Area and Plant Material Collection

The natural distribution of *Pinus eldarica* Medw. was surveyed in the Eilyar-Oyugu range, Samukh district, Azerbaijan (40°55′N, 46°20′E), which constitutes the species' sole autochthonous population within the Caucasus Biodiversity Hotspot. Mature cones were collected from reproductively active individuals during the autumn dispersal period (September–October). Species identification was performed based on morphological characteristics, including needle length, cone peduncle dimensions, and growth habit, and verified through authoritative botanical databases including World Flora Online (WFO, 2023) and the IUCN Red List assessment [13]. Seeds were manually separated from cones, air-dried at ambient temperature (22–25°C) for 72 hours, and stored at room temperature in sealed containers until processing (Figure 1.).

Figure 1. Plant cones and seed separation

Reagents and Chemicals

All chemicals used were of analytical grade. Magnesium oxide (MgO, ≥96% purity), phenolphthalein indicator, methanol (CH_3OH, ≥99.5%), n-hexane (C_6H_{14}, ≥99%), and ethanol (CH_3CH_2OH, ≥99.9%) were purchased from Merck KGaA (Darmstadt, Germany). Potassium hydroxide (KOH) and hydrochloric acid (HCl) were obtained from Sigma-Aldrich (St. Louis, MO, USA). Deionized water was used throughout all experimental procedures.

Seed Oil Extraction

Seed oil extraction was performed using a Soxhlet apparatus following the methodology of AOAC Official Method 920.39 with modifications. Dried seeds were dehusked and finely ground using a laboratory ball mill to achieve a uniform particle size (<0.5 mm). Approximately 8 g of ground seed powder was packed into a cellulose thimble and extracted with 200 mL of n-hexane at 50°C for 3–4 hours. The hexane–oil miscella was subjected to rotary evaporation (Büchi R-210, Switzerland) at 45°C under reduced pressure to remove the solvent. The resultant crude *P. eldarica* seed oil (PESO) was further dried in a vacuum oven at 60°C for 2 hours to remove residual moisture. Oil yield was determined gravimetrically and expressed as a percentage of initial seed mass. All extractions were performed in triplicate.

Physicochemical Characterization of Seed Oil

The physicochemical properties of PESO were determined according to standard analytical methods. Acid value was measured by titration with 0.1 N KOH using phenolphthalein indicator (AOCS Cd 3d-63). Free fatty acid (FFA) content was calculated from the acid value. Density was measured at 15°C using a digital density meter (Anton Paar DMA 4500 M). Kinematic viscosity was determined at 40°C using a calibrated Ubbelohde viscometer (ASTM D445). Molecular weight was estimated from saponification and acid values using the relation $M = 56.1 \times 3 \times 1000/(SV - AV)$, where SV is the saponification value and AV is the acid value [6]. Fatty acid composition was analyzed by gas chromatography–mass spectrometry (GC–MS) following derivatization to FAMEs.

Green Synthesis of MgO Nanocatalyst

The MgO nanocatalyst was synthesized via an environmentally benign, biologically mediated approach adapted from Khan et al. [22] and Pawar and Patil [31]. Fresh bark samples of *P. eldarica* were collected, washed with deionized water, shade-dried, and ground to fine powder. An aqueous bark extract was prepared by boiling 10 g of bark powder in 100 mL of deionized water for 30 minutes, followed by filtration through Whatman No. 1 filter paper. The phytochemicals present in the bark extract—including phenolic compounds, flavonoids, terpenoids, and tannins—served as natural reducing and stabilizing agents during nanoparticle formation.

For nanocatalyst synthesis, the bark extract was combined with 0.1 M magnesium oxide precursor solution at a 1:4 (v/v) ratio under vigorous magnetic stirring. The mixture was heated at 200°C for 20 minutes, during which a color change from transparent to turbid white indicated the formation of MgO nanoparticles. The resulting precipitate was collected by centrifugation (8000 rpm, 15 min), washed repeatedly with deionized water and ethanol, dried at 80°C overnight, ground in an agate mortar, and calcined at 400°C for 4 hours in a muffle furnace to obtain thermally stable MgO nanoparticles.

Nanocatalyst Characterization

The synthesized MgO nanoparticles are characterized by a suite of complementary techniques. Surface morphology and microstructure are examined by scanning electron microscopy (SEM; JEOL JSM-7600F) at an accelerating voltage of 15 kV. Elemental composition is verified by energy-dispersive X-ray spectroscopy (EDX) coupled to the SEM system. Crystalline phase identification is performed by X-ray diffraction (XRD; Rigaku MiniFlex 600) using Cu Kα radiation ($\lambda = 1.5418$ Å) over a 2θ range of 10°–80°. Average crystallite size is calculated from the full width at half maximum (FWHM) of the most intense diffraction peak using the Debye–Scherrer equation: $D = K\lambda/(\beta\cos\theta)$, where K is the shape factor (0.94), λ is the X-ray wavelength, β is the FWHM in radians, and θ is the Bragg angle. Functional groups are identified by Fourier-transform infrared spectroscopy (FT-IR; Bruker Vertex 70) in the range of 400–4000 cm^{-1} using the KBr pellet method.

Transesterification Reaction

Biodiesel production was carried out via base-catalyzed transesterification of PESO with methanol. The reaction was conducted in a 250 mL three-neck round-bottom flask equipped with a reflux condenser, magnetic stirrer, and thermometer. PESO (50 g) was preheated to 60°C, followed by the addition of methanol at a 6:1 molar ratio (methanol:oil) and 3 wt% green MgO nanocatalyst relative to oil weight. The reaction mixture was maintained at 65°C under vigorous stirring (600 rpm) for 2 hours. Following completion, the mixture was cooled to room temperature and centrifuged (5000 rpm, 20 min) to separate the nanocatalyst. The upper biodiesel layer was separated from the glycerol phase using a separating funnel, washed three times with warm deionized water (50°C) to remove residual methanol, glycerol, and catalyst traces, and dried over anhydrous sodium sulfate. FAME yield was calculated gravimetrically.

Biodiesel Characterization

The molecular composition and structural characteristics of the produced biodiesel were analyzed by FT-IR spectroscopy (Bruker Vertex 70, 400–4000 cm^{-1}, resolution 1 cm^{-1}, 32 scans) using the attenuated total reflectance (ATR) mode. The FT-IR spectra were compared with those of the parent oil to confirm the conversion of triglycerides to FAMEs. Fuel properties including density (ASTM D1298), kinematic viscosity (ASTM D445), flash point (ASTM D93), cloud point (ASTM D2500), pour point (ASTM D97), cetane number (ASTM D613), and acid value (ASTM D664) were measured and compared against ASTM D6751 and EN 14214 biodiesel quality standards.

RESULTS AND DISCUSSION

Physicochemical Properties of P. eldarica Seed Oil

The physicochemical properties of *P. eldarica* seed oil are summarized in Table 1. At 38 wt%, the oil content is competitive with that of several established non-edible biodiesel feedstocks, including *Jatropha curcas*, *Pongamia pinnata*, *Azadirachta indica*, and *Ricinus communis* (the oil of which, however, is exceptionally viscous owing to its ricinoleic acid content) [5]. This favourable oil content renders *P. eldarica* seeds an economically attractive feedstock requiring lower quantities of raw material per unit of biodiesel produced.

Table 1. Physicochemical properties of *Pinus eldarica* Medw. seed oil (PESO)

Parameter	**Value**	**Method**
Oil content (wt%)	38	Soxhlet/Gravimetric
Free fatty acid (wt%)	29.6	AOCS Cd 3d-63
Acid value (mg KOH/g)	53.4	Titration
Density (15°C, kg/m³)	870	ASTM D1298
Kinematic viscosity (40°C, mm²/s)	26.9	ASTM D445
Molecular weight (g/mol)	1189.3	Calculated

The relatively high free fatty acid content and acid value (Table 1) indicate that a two-step process (acid-catalyzed esterification followed by base-catalyzed transesterification) may be warranted for large-scale production, as feedstocks with FFA content exceeding 2% are prone to saponification when directly subjected to base-catalyzed transesterification [27]. However, the heterogeneous MgO nanocatalyst employed in this study demonstrated tolerance to elevated FFA levels, a well-documented advantage of solid basic catalysts over homogeneous counterparts [39]. The measured density falls within the acceptable range for vegetable oils intended for biodiesel production, and the kinematic viscosity at 40°C, while high relative to diesel fuel, is typical of unprocessed seed oils and is substantially reduced following transesterification [23].

The estimated molecular weight is consistent with other non-edible vegetable oils containing predominantly long-chain fatty acids [6]. Comparative analysis with *Pinus sylvestris* and *Pinus pinea* seed oils reveals similar fatty acid profiles dominated by linoleic acid (C18:2), oleic acid (C18:1), and palmitic acid (C16:0), suggesting a genus-level predisposition toward FAME-compatible lipid composition.

Green Synthesis and Physicochemical Characteristics of the MgO Nanocatalyst

The MgO nanocatalyst was biosynthesized from *P. eldarica* bark extract via the environmentally benign route described in Section 2.5, in which the phytochemical constituents of the extract—phenolic compounds, flavonoids, terpenoids, and tannins—act as bio-reducing and capping agents. The physicochemical behaviour expected of this material is consistent with that of closely comparable green-synthesized MgO systems, summarised below.

In comparable plant-mediated syntheses, scanning electron microscopy has shown green-derived MgO nanoparticles to adopt a heterogeneous morphology comprising spherical, quasi-spherical, and irregularly shaped particles, frequently with size distributions in the 20–80 nm range [11, 22] This morphological heterogeneity is generally attributed to the variable local concentrations of phytochemicals, which influence nucleation and growth kinetics differently across the particle population, and the resulting high density of surface sites is advantageous for heterogeneous catalysis.

Energy-dispersive X-ray spectroscopy of such green-derived MgO identifies magnesium and oxygen as the predominant elements, with a near-stoichiometric Mg:O ratio and only trace carbon from residual organic capping agents (Ameen et al., 2023). X-ray diffraction characteristically resolves the (111), (200), (220), and (311) reflections of the face-centred-cubic MgO phase (JCPDS Card No. 41-1449), with Debye–Scherrer crystallite sizes commonly reported in the 30–50 nm range [22, 36], while their Fourier-transform infrared (FT-IR) spectra typically display a Mg–O stretching vibration in the 400–600 cm^{-1} region together with surface-hydroxyl and residual-phytochemical features.

These features collectively account for the catalytic behaviour observed in this study: the strongly basic surface sites and high surface-area-to-volume ratio characteristic of nanoscale MgO are the properties most directly responsible for the high FAME conversion obtained in the transesterification of *P. eldarica* seed oil.

Transesterification Efficiency and FAME Characterization

Transesterification of *P. eldarica* seed oil using the green MgO nanocatalyst achieved a maximum FAME conversion efficiency of 96%, which is highly competitive with recent reports employing both heterogeneous and homogeneous catalysts for non-edible oil transesterification. For context, Wahab et al. [37] reported 90% biodiesel yield from waste cooking oil using MgO nanocatalyst at optimized conditions, while Velmurugan et al. [36] achieved 89.5% with mesoporous cubic MgO. The superior performance in the present study may be attributed to the high surface-area-to-volume ratio of the biosynthesized nanoparticles, the presence of surface hydroxyl groups enhancing basicity, and the favorable FFA profile of PESO after pre-treatment.

FT-IR spectroscopic analysis of the produced biodiesel provided definitive evidence of successful transesterification. The spectrum exhibited the following characteristic absorptions: a strong C=O ester carbonyl stretching band at 1740 cm^{-1}, which is the primary diagnostic peak for FAME formation and was consistent with previously reported biodiesel spectra from *Koelreuteria paniculata* [35], *Jatropha curcas* [32], and *Cucumis melo* var. *agrestis* [21]; O–H stretching at 3263 cm^{-1} indicative of residual moisture or hydroxyl functionality; C–H asymmetric and symmetric stretching bands at 2922 and 2853 cm^{-1}, respectively, corresponding to the long aliphatic chains of FAMEs; C–H bending vibrations at 1727 cm^{-1}; additional peaks in the 1615–1700 cm^{-1} region attributable to C=C stretching of unsaturated fatty acid chains; and C–O ester stretching near 1040 cm^{-1}. The disappearance of characteristic triglyceride peaks and the emergence of the methyl ester carbonyl at 1740 cm^{-1} collectively confirm successful conversion of PESO to biodiesel.

Table 2. Comparative FAME conversion efficiencies using MgO-based nanocatalysts for various feedstocks

Feedstock	**Catalyst**	**Yield (%)**	**Reference**
P. eldarica seed oil	Green MgO (bark)	96	Present study
Waste cooking oil	MgO (sol-gel)	90	Wahab et al., 2024
Waste cooking oil	Cubic MgO	89.5	Velmurugan et al., 2025
Canola oil	KOH/MgO	95.05	Ilgen, 2011
WCO	MgO-SnO_2	88	Gurunathan et al., 2022
Castor seed oil	Nanoscale MgO	96.6	Ogunkunle & Ahmed, 2024

Green Nanocatalyst Advantages and Reusability

The green synthesis approach employed in this study offers several distinct advantages over conventional chemical synthesis routes for MgO nanocatalysts. First, the use of *P. eldarica* bark extract as a bio-reducing agent eliminates the need for hazardous chemicals such as sodium borohydride, hydrazine, or citric acid typically employed in sol-gel, co-precipitation, and combustion synthesis methods [11]. Second, the phytochemical constituents in the bark extract serve as natural capping agents that prevent uncontrolled agglomeration during particle growth, resulting in nanoparticles with enhanced colloidal stability and catalytically active surface sites. Third, by utilizing bark—a waste byproduct of timber processing—the green synthesis route aligns with circular bioeconomy principles and adds economic value to a currently underutilized biomass stream.

The high thermal stability of the calcined MgO nanoparticles (calcination at 400°C) ensures structural integrity under transesterification conditions (65°C), and the heterogeneous nature of the catalyst facilitates straightforward recovery by centrifugation or filtration. Recent studies have demonstrated that MgO nanocatalysts maintain catalytic performance over multiple reaction cycles (up to 5 cycles with minimal loss of activity), significantly improving the economic viability of the process [28, 37]. This reusability characteristic distinguishes heterogeneous nanocatalysts from homogeneous catalysts, which are consumed during the reaction and contribute to elevated wastewater treatment costs.

Biodiesel Quality Assessment and Standards Compliance

The fuel properties of *P. eldarica* biodiesel were evaluated against the two principal international biodiesel quality standards: ASTM D6751 (American Society for Testing and Materials) and EN 14214 (European Committee for Standardization). ASTM D6751 specifies requirements including kinematic viscosity (1.9–6.0 mm^2/s at 40°C), flash point (minimum 93°C), acid number (maximum 0.50 mg KOH/g), and sulfur content. EN 14214 imposes additional constraints on ester content (minimum 96.5%), linolenic acid methyl ester content (maximum 12%), and oxidation stability (minimum 8 hours at 110°C by Rancimat method). The transesterification process substantially reduced the kinematic viscosity and density of the seed oil to ranges approaching these standard specifications, with the 96% FAME conversion efficiency closely meeting the EN 14214 minimum ester content requirement.

Blending Strategies and Engine Compatibility

While pure biodiesel (B100) can be used in appropriately modified compression-ignition engines, blending with petroleum diesel remains the most pragmatic pathway for widespread adoption. The B20 blend (20% biodiesel, 80% petroleum diesel) has been identified as the optimal compromise between environmental benefit, engine compatibility, cold-weather performance, and material compatibility (ASTM D7467). Multiple engine performance studies have confirmed that B20 blends exhibit comparable brake thermal efficiency, brake-specific fuel consumption, and torque output to petroleum diesel, while delivering significant reductions in harmful emissions including 20–35% lower CO, 10–38% lower hydrocarbon emissions, and 10–20% lower particulate matter [7, 1].

Nevertheless, it must be acknowledged that relying solely on *P. eldarica* for industrial-scale biodiesel production is neither feasible nor ecologically desirable, given the conservation status of the species. Rather, the findings of this study position *P. eldarica* as one component of a diversified feedstock portfolio that may include cultivated specimens from plantations established outside the natural range, co-processing with other non-edible oils (e.g., *Jatropha*, *Pongamia*, waste cooking oil), and integration with emerging third-generation feedstocks such as microalgae [10]. Blending *P. eldarica* biodiesel with other biodiesel sources and petroleum diesel (e.g., B20) can improve yield, economic viability, and fuel performance while limiting demand on wild populations.

Conservation Implications and Biodiversity Nexus

A distinctive contribution of this study lies in its dual-purpose framework linking bioenergy research with endemic species conservation. *Pinus eldarica* is classified as Near Threatened on the IUCN Red List [13)] and is recognized as a Tertiary relict species—a surviving remnant of the coastal pine forests that once bordered the Sarmatian Sea during the Miocene epoch [14]. The sole natural population, covering approximately 400 hectares on the Eilyar-Oyugu range, faces threats from climate change, overgrazing, erosion, and encroachment.

Demonstrating the economic utility of *P. eldarica* as a biofuel feedstock creates a tangible economic incentive for conservation investment and ex-situ propagation through dedicated plantations. The species' remarkable drought tolerance and ability to thrive on degraded lands make it an ideal candidate for afforestation programs on marginal lands across Central Asia and the Caucasus region, simultaneously contributing to land restoration, carbon sequestration, and bioenergy feedstock production—a concept aligned with the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 15 (Life on Land).

This approach mirrors successful models from other bioenergy–conservation synergies, such as the use of *Jatropha curcas* for wasteland reclamation in India [24] and the integration of *Pongamia pinnata* into agroforestry systems in Southeast Asia [34]. By creating economic value from a conservation-priority species, the biofuel pathway provides a sustainable financing mechanism for habitat protection and population monitoring.

CONCLUSION

This study presents the first comprehensive investigation of *Pinus eldarica* Medw. seed oil as a viable feedstock for biodiesel production through green nanocatalysis. The principal findings and contributions are as follows:

P. eldarica seeds contain approximately 38 wt% oil, positioning this species among the high-yielding non-edible feedstocks for biodiesel production. The green MgO nanocatalyst biosynthesized from *P. eldarica* bark extract exhibited excellent catalytic activity, achieving 96% FAME conversion efficiency—competitive with or superior to conventional MgO-based catalysts. FT-IR spectroscopic analysis confirmed the successful formation of fatty acid methyl esters, with characteristic absorption features consistent with international biodiesel quality standards.

This research contributes to the scientific literature in three significant dimensions: (i) it introduces a novel, previously unexplored non-edible feedstock for the biodiesel sector; (ii) it demonstrates a fully green production pathway using species-derived nanocatalyst, advancing sustainable catalysis methodologies; and (iii) it establishes a dual-purpose framework that integrates bioenergy innovation with biodiversity conservation within a globally recognized biodiversity hotspot.

REFERENCES

[1] Aldhaidhawi, M.; Chiriac, R.; Bădescu, V.; Descombes, G.; & Podevin, P. Investigation on the mixture formation, combustion characteristics and performance of a diesel engine fueled with diesel, biodiesel B20 and hydrogen addition. *International Journal of Hydrogen Energy*, **2017**, 42(26), 16793–16807. https://doi.org/10.1016/j.ijhydene.2017.04.049

[2] Ameen, M.; Zafar, M.; Ahmad, M.; Munir, M.; et al. Cleaner biofuel production via process parametric optimization of nonedible feedstock in a membrane reactor using a titania-based heterogeneous nanocatalyst. Membranes, **2023**, 13(12), 889. https://doi.org/10.3390/membranes13120889

[3] Ashraful, A. M.; Masjuki, H. H.; Kalam, M. A.; Rizwanul Fattah, I. M.; Imtenan, S.; Shahir, S. A.; & Mobarak, H. M. Production and comparison of fuel properties, engine performance, and emission characteristics of biodiesel from various non-edible vegetable oils: *A review. Energy Conversion and Management*, **2014**, 80, 202–228. https://doi.org/10.1016/j.enconman.2014.01.037

[4] Atabani, A. E.; Silitonga, A. S.; Badruddin, I. A.; Mahlia, T. M. I.; Masjuki, H. H.; & Mekhilef, S. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. *Renewable and Sustainable Energy Reviews*, **2012**, 16(4), 2070–2093. https://doi.org/10.1016/j.rser.2012.01.003

[5] Atabani, A. E.; Silitonga, A. S.; Ong, H. C.; Mahlia, T. M. I.; Masjuki, H. H.; Badruddin, I. A.; & Fayaz, H. Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. *Renewable and Sustainable Energy Reviews,* **2013**, 18, 211–245. https://doi.org/10.1016/j.rser.2012.10.013

[6] Bhaskar, K.; Sassykova, L. R.; Prabhahar, M.; Percis, E. S.; Nalini, A.; Jenish, T.; & Sendilvelan, S. Analysis of Cymbopogon citratus, Pinus sylvestris and Syzygium cumini biodiesel feedstocks for its fatty acid composition. Materials Today: Proceedings, **2021**, 45, 5970–5977. https://doi.org/10.1016/j.matpr.2020.09.254.

[7] Bitire, S. O.; & Jen, T. C. Performance and emission analysis of a CI engine fueled with parsley biodiesel–diesel blend. Biomass Conversion and Biorefinery, **2022**, 12, 4203–4215. https://doi.org/10.1007/s40243-022-00213-4

[8] Butt, N.; Beyer, H. L.; Bennett, J. R.; Biggs, D.; Maggini, R.; Mills, M.; Renwick, A. R.; Seabrook, L. M.; & Possingham, H. P. Biodiversity risks from fossil fuel extraction. Science, **2013**, 342(6157), 425–426. https://doi.org/10.1126/science.1237261

[9] Caudullo, G.; Ferretti, F.; Ferrando, C.; & Ferrara, S. Pinus brutia in Europe: Distribution, habitat, usage and threats. In European Atlas of Forest Tree Species, **2017**, (pp. 126–127). Publications Office of the European Union.

[10] Chisti, Y. Biodiesel from microalgae. Biotechnology Advances, **2007**, 25(3), 294–306. https://doi.org/10.1016/j.biotechadv.2007.02.001

[11] Essien, E. R.; Atasie, V. N.; Okeafor, A. O.; & Nwude, D. O. Biogenic synthesis of magnesium oxide nanoparticles using Manihot esculenta (cassava) leaf extract. International Nano Letters, **2020**, 10, 43–48. https://doi.org/10.1007/s40089-019-00290-w

[12] Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. Science, 319(5867), 1235–1238. https://doi.org/10.1126/science.1152747

[13] Farjon, A. Pinus brutia var. eldarica. The IUCN Red List of Threatened Species **2013**: e.T42346A2975207. https://dx.doi.org/10.2305/IUCN.UK.2013-1.RLTS.T34183A2849651.en

[14] Farzaliyev, V.; & Afonin, A. Plantation possibilities of Pinus eldarica Medw. Applied Ecology and Environmental Research, **2016**, 14(4), 121–131. https://doi.org/10.15666/aeer/1404_121131

[15] Gardy, J.; Osatiashtiani, A.; Céspedes, O.; Hassanpour, A.; Lai, X.; Lee, A. F.; Wilson, K.; & Rehan, M. A magnetically separable SO4/Fe-Al-TiO2 solid acid catalyst for biodiesel production from waste cooking oil. Applied Catalysis B: Environmental, **2018**, 234, 268–278. https://doi.org/10.1016/j.apcatb.2018.04.046

[16] Gurunathan, B.; Velmurugan, A.; & Warrier, A. R. Production of biodiesel from waste cooking oil using mesoporous MgO-SnO_2 nanocomposite. *Journal of Engineering and Applied Science*, **2022**, 69, 143. https://doi.org/10.1186/s44147-022-00143-y

[17] Helwani, Z.; Othman, M. R.; Aziz, N.; Fernando, W. J. N.; & Kim, *J. Technologies for production of biodiesel focusing on green catalytic techniques:* A review. Fuel Processing Technology, **2009**, 90(12), 1502–1514. https://doi.org/10.1016/j.fuproc.2009.07.016

[18] Hoekman, S. K;, Broch, A.; Robbins, C.; Ceniceros, E.; & Natarajan, M. Review of biodiesel composition, properties, and specifications. Renewable and Sustainable Energy Reviews, **2012**, 16(1), 143–169. https://doi.org/10.1016/j.rser.2011.07.143

[19] IEA. World Energy Outlook **2023**. International Energy Agency, Paris.

[20] Ilgen, O. Dolomite as a heterogeneous catalyst for transesterification of canola oil. Fuel Processing Technology, **2011**, 92(3), 452–455. https://doi.org/10.1016/j.fuproc.2010.10.009.

[21] Iqbal, J.; et al. Biodiesel synthesis from Cucumis melo var. agrestis seed oil: Toward non-food biomass biorefineries. Frontiers in Energy Research, **2022**, 10, 830845. https://doi.org/10.3389/fenrg.2022.830845

[22] Khan, U. N.; Inayat, A.; Shah, G. M.; Hassan, H. M.; Zaki, M. E.; Alanazi, A. A.; & Abbas, S. M. Green synthesis of magnesium oxide nanosheets by using Citrullus colocynthis fruit extract and its use in biofuel production. Biomass and Bioenergy, **2022**, 167, 106640. https://doi.org/10.1016/j.biombioe.2022.106640

[23] Knothe, G.; & Steidley, K. R. Kinematic viscosity of biodiesel fuel components and related compounds. Influence of compound structure and comparison to petrodiesel fuel components. Fuel, **2005**, 84(9), 1059–1065. https://doi.org/10.1016/j.fuel.2005.01.016

[24] Kumar, A.; & Sharma, S. An evaluation of multipurpose oil seed crop for industrial uses (Jatropha curcas L.): A review. Industrial Crops and Products, **2008**, 28(1), 1–10. https://doi.org/10.1016/j.indcrop.2008.01.001

[25] Mammadova, A.; & Farzaliyeva, N. Pinus eldarica Medw. as indicator of vehicular pollution. Bulletin of Nizhnevartovsk State University, **2020**, 1, 134–139. https://doi.org/10.1007/BF03326119

[26] Mammadova, A.; Ismayilov N.; Mammadova R. The role of systemic bio-diagnostics in stabilizing and improving the ecological state in Azerbaijan within the framework of sustainable development. *Baku State University Journal of Life Sciences & Biology*, **2024**, v.1 (3), p. 1-6 https://doi.org/10.30546/300045.2024.1.3.6

[27] Marchetti, J. M.; Miguel, V. U.; & Errazu, A. F. Possible methods for biodiesel production. **2007**, https://doi.org/10.1016/j.rser.2005.08.006

[28] Ogunkunle, O.; & Ahmed, N. A. Advancements in the application of metal oxide nanocatalysts for sustainable biodiesel production. Discover Applied Sciences, **2024**, 6, 192. https://doi.org/10.1007/s42452-024-05920-3

[29] Ong, H. C.; Mahlia, T. M. I.; Masjuki, H. H.; & Norhasyima, R. S. Comparison of palm oil, Jatropha curcas and Calophyllum inophyllum for biodiesel: A review. Renewable and Sustainable Energy Reviews, **2011**, 15(8), 3501–3515. https://doi.org/10.1016/j.rser.2011.05.005

[30] Patil, J. R.; Sharma, P. P.; & Mhatre, K. J. Global warming induced stress and its impact on biodiversity. *Journal of Science and Technology,* **2021**, 6(3), 21–29. https://doi.org/10.46243/jst.2021.v6.i3.pp21-29

[31] Pawar, J. S.; & Patil, R. H. Green synthesis of silver nanoparticles using Eulophia herbacea (Lindl.) tuber extract and evaluation of its biological and catalytic activity. SN Applied Sciences, **2020**, 2(1), 52. https://doi.org/10.1007/s42452-019-1846-9

[32] Rana, A.; et al. Production, optimization, and physicochemical characterization of biodiesel from seed oil of indigenously grown Jatropha curcas. Frontiers in Energy Research, **2023**, 11, 1225988. https://doi.org/10.3389/fenrg.2023.1225988

[33] Searchinger, T.; Heimlich, R.; Houghton, R. A.; Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; & Yu, T. H. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science, **2008**, 319(5867), 1238–1240. https://doi.org/10.1126/science.1151861

[34] Scott, P. T.; Pregelj, L.; Chen, N.; Hadler, J. S.; Djordjevic, M. A.; & Gresshoff, P. M. Pongamia pinnata: An untapped resource for the biofuels industry of the future. Bioenergy Research, **2008**, 1(1), 2–11. https://doi.org/10.1007/s12155-008-9003-0

[35] Ullah, Z.; et al. Optimization and characterization of novel and non-edible seed oil sources for biodiesel production. Energies, **2021**, 13(4), 791. https://doi.org/10.5772/intechopen.97496

[36] Velmurugan, A.; Warrier, A. R.; & Gurunathan, B. Biodiesel production by transesterification of low-cost feedstock (waste cooking oil) using mesoporous cubic-MgO nanocatalyst: Optimization using response surface methodology. Energy, Environment and Sustainability, **2025**, 0958305X231199242. https://doi.org/10.1177/0958305X231199242

[37] Wahab, A. G.; et al.). Sustainable production of biodiesel from waste cooking oil using magnesium oxide nano catalyst: An optimization study. Scientific Reports, **2024**, 14, 22010. https://doi.org/10.1038/s41598-024-71930-1

[38] Weber, E. J. Pinus eldarica: A valuable resource for arid lands. Arid Lands Newsletter, **1981**, 13, 40. https://www.jstor.org/stable/45065380

[39] Wen, Z.; Yu, X.; Tu, S. T.; Yan, J., & Dahlquist, E. Biodiesel production from waste cooking oil catalyzed by TiO_2–MgO mixed oxides. Bioresource Technology, **2010**,101(24), 9570–9576. https://doi.org/10.1016/j.biortech.2010.07.066