DWSIM simulation and thermal analysis of orange peel ashes as an ict tool in biodiesel production

Simulación en DWSIM y análisis térmico de cenizas de cáscara de naranja como herramienta tic en la producción de biodiesel

Simulação em DWSIM e análise térmica de cinzas de casca de laranja como ferramenta tic na produção de biodiesel

Astrid del Socorro Altamar Consuegra[1]
Wilson Alexander Pinzón Rueda[2]
Jaime Aguilar-Arias[3]

Received: December 10th, 2025
Accepted: March 20th, 2026
Available: May 5th, 2026

How to cite this article:
A. del S. Altamar Consuegra, W. A. Pinzón Rueda, and J. Aguilar-Arias, "DWSIM Simulation and Thermal Analysis of Orange Peel Ashes as an ICT Tool in Biodiesel Production," *Revista Ingeniería Solidaria,* vol. 22, no. 2, 2026.
doi: https://doi.org/10.16925/2357-6014.2026.02.06

Research article. https://doi.org/10.16925/2357-6014.2026.02.06

1 Faculty of Technology, Universidad Distrital Francisco José de Caldas, Bogotá, Colombia.
Email: asaltamarc@udistrital.edu.co
ORCID: https://orcid.org/0000-0001-6965-7076

2 Faculty of Technology, Universidad Distrital Francisco José de Caldas, Bogotá, Colombia.
Email: wapinzon@udistrital.edu.co
ORCID: https://orcid.org/0000-0003-4847-2085

3 Department of Chemical and Environmental Engineering, Faculty of Engineering, Universidad Nacional de Colombia, Bogotá Campus, Bogotá, Colombia.
Email: jlaguilara@unal.edu.co
ORCID: https://orcid.org/0000-0002-9241-1960

Abstract

Introduction: This article is derived from the research project entitled "Characterization and valorization of orange peel waste through circular economy approaches: preliminary foundations for the design of sustainable solutions," code PNFF-2025-2076, funded and supported by the Universidad Distrital Francisco José de Caldas and the Office of Research (ODI).

Problem: Process simulation has become a fundamental tool within information and communication technologies (ICT) for systematic analysis and the improvement of sustainable technological frameworks.

Objective: This research aims to evaluate agro-industrial by-products, specifically orange peel, as a precursor of catalytic ash in biodiesel synthesis.

Methodology: The methodology included the extraction of essential oils from orange peel through steam distillation, conditioning of the residual material after extraction, and its thermal characterization using thermogravimetric analysis (TGA) and derivative thermogravimetry (DTG). The biodiesel production process was simulated using the open-source simulator DWSIM v9.0.4.

Results: The thermal characterization of orange peel ash enabled the identification of decomposition phases associated with hemicellulose, cellulose, and lignin, as well as a mineral residue enriched with potassium and calcium. A simplified schematic representation of the transesterification process with palm oil and methanol (molar ratio 6:1) was developed in DWSIM software, using the alkaline catalyst $K_2CO_3 \cdot 2H_2O$.

Conclusion: The simulation reinforces the viability of orange peel as a catalyst in biodiesel production, contributing to waste valorization within the circular economy framework.

Originality: This research highlights the importance of synergistically combining thermal characterization of ashes with computational modeling for the optimization of processes such as biodiesel production.

Limitations: Further development is required for the validation of the proposed model.

Keywords: orange peel ash; heterogeneous catalysis; process simulation.

Resumen

Introducción: El presente artículo se deriva del proyecto de investigación "Caracterización y valorización de residuos de cáscara de naranja mediante enfoques de economía circular: bases preliminares para el diseño de soluciones sostenibles", código PNFF-2025-2076, financiado y apoyado por la Universidad Distrital Francisco José de Caldas y la Oficina de Investigación (ODI).

Problema: La simulación de procesos se ha convertido en un instrumento fundamental de las tecnologías de la información y la comunicación (TIC) para el análisis sistemático y la mejora de los marcos tecnológicos sostenibles.

Objetivo: La investigación tiene como objetivo evaluar subproductos agroindustriales, específicamente la cáscara de naranja, como precursor de ceniza catalítica en la síntesis de biodiésel.

Metodología: La metodología incluyó la extracción de aceites esenciales de la cáscara de naranja mediante destilación con arrastre de vapor, el acondicionamiento del material residual posterior a la extracción y su caracterización térmica mediante análisis termogravimétrico (TGA) y termogravimetría diferencial (DTG). La simulación del proceso de producción de biodiésel se realizó en el simulador de código abierto DWSIM v9.0.4.

Resultados: La caracterización térmica de la ceniza de cáscara de naranja permitió identificar las fases de descomposición asociadas a la hemicelulosa, la celulosa y la lignina, así como un residuo mineral enriquecido con potasio y calcio. Se desarrolló una representación esquemática simplificada del proceso de transesterificación con aceite de palma y metanol (relación molar 6:1) en el software DWSIM, utilizando el catalizador alcalino $K_2CO_3 \cdot 2H_2O$.

Conclusión: La simulación realizada refuerza la viabilidad de la cáscara de naranja como catalizador en la producción de biodiésel, contribuyendo a la valorización de residuos dentro del paradigma de la economía circular.

Originalidad: Esta investigación resalta la importancia de combinar de manera sinérgica la caracterización térmica de las cenizas con el modelado computacional para la optimización de procesos como la producción de biodiésel.

Limitaciones: Se requiere un mayor desarrollo en la validación del modelo propuesto.

Palabras clave: ceniza de cáscara de naranja; catálisis heterogénea; simulación de procesos; economía circular.

Resumo

Introdução: Este artigo é derivado do projeto de pesquisa "Caracterização e valorização de resíduos de casca de laranja por meio de abordagens de economia circular: bases preliminares para o desenho de soluções sustentáveis", código PNFF-2025-2076, financiado e apoiado pela Universidad Distrital Francisco José de Caldas e pelo Escritório de Pesquisa (ODI).

Desafio: A simulação de processos tornou-se uma ferramenta fundamental das tecnologias da informação e comunicação (TIC) para a análise sistemática e melhoria de estruturas tecnológicas sustentáveis.

Objetivo: A pesquisa visa avaliar subprodutos agroindustriais, especificamente a casca de laranja, como precursor de cinzas catalíticas na síntese de biodiesel.

Metodologia: A metodologia incluiu a extração de óleos essenciais da casca de laranja por destilação a vapor, o condicionamento do material residual após a extração e sua caracterização térmica por análise termogravimétrica (TGA) e termogravimetria diferencial (DTG). A simulação do processo de produção de biodiesel foi realizada no simulador de código aberto DWSIM v9.0.4.

Resultados: A caracterização térmica da cinza de casca de laranja permitiu identificar as fases de decomposição relacionadas à hemicelulose, celulose e lignina, além de um resíduo mineral enriquecido com potássio e cálcio. Foi desenvolvida uma representação esquemática simplificada do processo de transesterificação com óleo de palma e metanol (razão molar 6:1) no software DWSIM, utilizando o catalisador alcalino $K_2CO_3 \cdot 2H_2O$.

Conclusão: A simulação realizada reforça a viabilidade da casca de laranja como catalisador na produção de biodiesel, contribuindo para a valorização de resíduos dentro do paradigma da economia circular.

Originalidade: Esta pesquisa evidencia a importância de combinar, de forma sinérgica, a caracterização térmica das cinzas com a modelagem computacional para a otimização de processos como a produção de biodiesel.

Limitações: É necessário maior desenvolvimento na validação do modelo proposto.

Palavras-chave: cinzas de casca de laranja; catálise heterogênea; simulação de processos; economia circular.

1. INTRODUCTION

Due to the increasing demand for energy and the environmental impacts associated with the use of non-renewable fuels, the search for sustainable energy sources has intensified. In this context, biodiesel represents a viable alternative due to its biodegradability, lower carbon footprint in terms of greenhouse gas emissions, and its compatibility with existing infrastructures. However, traditional biodiesel production relies on homogeneous alkaline catalysts, which generate waste streams and increase operating costs, thereby limiting the sustainability of the process [1].

Similarly, the use and valorization of agro-industrial waste have gained importance within the framework of the circular economy. Citrus peels, particularly orange peels, represent a relevant example, as they constitute an abundant residue in producing countries such as Colombia. Through the calcination of these biomasses, ashes rich in compounds such as potassium are obtained [1]–[3], which have significant potential as basic catalysts in transesterification reactions. Thus, the use of orange peels not only contributes to waste reduction but also provides sustainable inputs for biofuel production.

1.1. Literature Review or Research Background

Globally, citrus production exceeds 150 million tons per year, of which approximately 50% corresponds to oranges [4]. In Colombia, production reached approximately 1,614,912 tons in 2023, with 46.8% corresponding to oranges, mainly in departments such as Santander, Tolima, and Meta [5]. In previous years, the Price and Market Information System reported production values between 1.12 and 1.33 million tons of citrus fruits for the period 2016–2020 [6]. Of this production, between 40% and 50% of the total weight corresponds to peels, generating a considerable volume of underutilized agro-industrial waste [7].

In the Colombian biodiesel sector, the installed capacity exceeds 700,000 tons per year, largely relying on conventional catalysts such as NaOH or KOH. This results in increased costs and the generation of liquid effluents that are difficult to manage [8].

Various studies have demonstrated that biomass ash is a reliable source of heterogeneous catalysts for biodiesel production due to its high content of alkaline compounds, such as calcium and potassium [2], [9]–[11]. In particular, research on agricultural residues, such as citrus peels, has reported transesterification yields above 90% when using calcined ash as a basic catalyst [3], [12], [13]. The main advantage of these catalysts lies in their reusability and the reduction of liquid effluents compared to conventional homogeneous catalysts such as NaOH or KOH [14], [15].

Recently, process simulation software such as DWSIM® has emerged as a relevant open-source ICT tool for modeling biodiesel production, as it integrates thermodynamic models, reaction kinetics, and mass and energy balances [14]. Current research has demonstrated that DWSIM® simulations can reproduce, with high fidelity, experimentally reported conversions in systems catalyzed by oxides derived from agro-industrial waste, consolidating its role as both a pedagogical and research tool in the transition toward sustainable biofuels [16].

Despite advances in biodiesel production, many industrial-scale processes still rely on conventional homogeneous catalysts, such as hydroxides and alkali carbonates, resulting in high separation costs and environmentally impactful waste streams [17]. In Colombia, where agro-industrial residues such as orange peel are widely available, there remains a gap in applied research aimed at utilizing these residues as a source of low-cost, high-performance heterogeneous catalysts. Although successful experiences with biomass ash have been documented [13], few studies have specifically linked citrus ash with ICT-based simulation tools such as DWSIM® to validate its potential in local scenarios of sustainable biofuel production.

In this context, it is necessary to consolidate an approach that integrates the valorization of citrus waste, heterogeneous catalysis based on potassium compounds, and computational modeling, in order to provide scientific and technical evidence supporting the transition toward more sustainable processes aligned with the circular economy in Colombia.

This study aims to simulate biodiesel production from palm oil and methanol using DWSIM®, including methanol recovery and recycling. A catalyst derived from orange peel ash, rich in potassium compounds, is employed, and the conversion of triglycerides, as well as the formation of biodiesel and glycerol, are determined. In addition, the thermal characterization of orange peel and its ash is included as a complement to the simulation.

2. MATERIALS AND METHODS

Simulation of Palm Oil Biodiesel Production

The simulation of the biodiesel production process was carried out using the open-source simulator DWSIM® v9.0.4 [18], employing the ChemSep® [19] and Electrolytes databases for the calculation of physicochemical properties. All chemical components used were obtained from the DWSIM database. Palm oil was used as the raw material and, for simulation purposes, was represented in a simplified manner using only the triglyceride tripalmitin (PPP) as a model compound. This approach was adopted to reduce the compositional complexity of real oil, which consists of a mixture of triglycerides with different fatty acids (mainly palmitic, oleic, and linoleic). In the simulation, methanol was used at a molar ratio of 6:1 relative to the triglyceride (tripalmitin), following commonly reported conditions that favor the transesterification reaction. A potassium compound was used as a catalyst, modeled in DWSIM as $K_2CO_3 \cdot 2H_2O$ (potassium carbonate dihydrate), considered representative of the alkaline compounds present in orange peel ash. This selection enabled the approximation of the basic catalytic effect within the simulation environment, ensuring consistency between the computational model and experimental characterizations reported in the literature.

The NRTL (Non-Random Two-Liquid) thermodynamic package [20] was used to model non-ideal liquid systems. This model is appropriate for biodiesel production, as the mixture of triglycerides, methanol, methyl esters, and glycerol exhibits complex molecular interactions and deviations from ideal behavior. The use of NRTL allows for an accurate description of liquid–liquid and vapor–liquid phase equilibria, which are critical in transesterification and subsequent separation stages, ensuring a more realistic representation of system behavior within the simulator.

The oil was assumed to have a low content of free fatty acids in order to avoid saponification. Additionally, a reactor conversion of 95% was defined.

Extraction of Essential Oils from Orange Peel by Steam Distillation

To obtain orange peel ash, fresh oranges from a marketplace in Fontibón (Bogotá, Colombia) were used. For processing, the peel (zest) was separated manually, and pieces of approximately 1 cm were used for subsequent treatments.

Essential oil extraction was performed by steam distillation using a Clevenger-type laboratory glass apparatus [21]. The water was maintained at boiling conditions to ensure mild extraction.

The post-extraction residue was first washed with tap water to remove soluble sugars, then with 0.5% (m/v) acetic acid to eliminate soluble mineral compounds and metallic contaminants, and finally with distilled water until neutral pH was reached.

The washed sample was then dried in an oven at 105 °C for 24 h [22], ground using an adapted domestic knife mill, and sieved to obtain a particle size of less than 500 µm.

Thermal Characterization of the Post-Extraction Residue (TGA/DTG)

The solid material obtained after extraction was washed with distilled water, dried in an oven at 105 °C for 24 h, ground, and sieved to particles smaller than 500 µm.

Thermogravimetric (TGA) and derivative thermogravimetric (DTG) analyses were performed under a nitrogen atmosphere (50 mL/min), in the temperature range of 25 to 800 °C, with a heating rate of 10 °C/min and sample masses of approximately 10 mg in alumina crucibles, using a Mettler Toledo thermogravimetric analyzer.

Ash Production from Post-Extraction Waste

A fraction of the post-extraction residue was calcined in a Vulcan analog muffle furnace at 550 °C for 2 h [23]. The resulting ash was homogenized in an agate mortar and stored in a desiccator with silica gel for subsequent analysis. To evaluate thermal stability and the presence of residual carbonates, thermogravimetric analysis (TGA) was performed using Mettler Toledo equipment under a nitrogen atmosphere (N_2, flow rate 60 mL/min), with a heating rate of 10 °C/min from 25 to 900 °C.

3. RESULTS

Simulation of Palm Oil Biodiesel Production

Figure 1 presents the flow diagram of the transesterification process simulated in DWSIM, using palm oil as feedstock, methanol at a 6:1 molar ratio, and orange peel ash as a heterogeneous catalyst represented by potassium compounds.

The scheme integrates the main unit operations: premixing of methanol and catalyst, combined feeding with the oil into an adiabatic RCSTR (Continuous Stirred Tank Reactor), and subsequent phase separation using a decanter, which allows differentiation between the biodiesel stream and the glycerol–methanol phase.

This representation enables visualization of the sequence of unit operations, as well as input and output streams, facilitating interpretation and optimization of the results obtained in subsequent stages of the simulation.

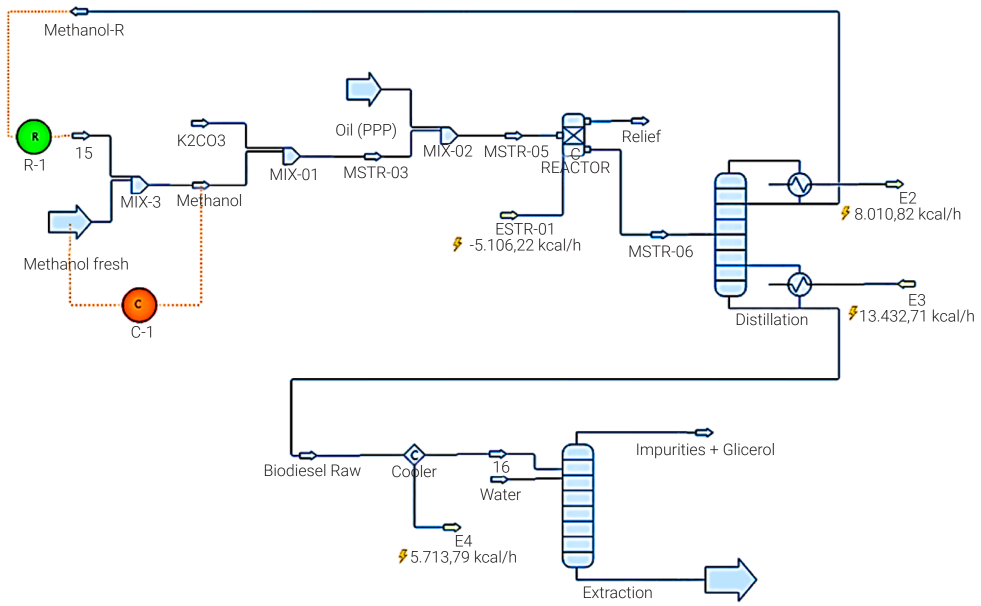

Figure 1. Flow Chart of Biodiesel Production Process Simulated in DWSIM.
Source: own work

It is highlighted that the simulation effectively recycles the excess ethanol recovered in the distillation column, and the control of the fresh methanol that is fed to the process.

Table 1 presents the main results of the simulation carried out in DWSIM for the production process of biodiesel from triglycerides and methanol, using orange peel ash as a catalytic source. The information includes the most relevant streams of the system, along with their predominant composition, mass flow, operating conditions (temperature and pressure) and observations associated with triglyceride conversion and the formation of biodiesel and glycerol. This data allows to show the overall behavior of the process under the chosen conditions and are a key input for the subsequent analysis of efficiency and sustainability.

Table 1. Main results of the simulation in DWSIM, mass fractions of the components are reported.

Variable	Methanol-Rec	Methanol	K_2CO_3	Impurities + Glycerol	Biodiesel	Water	Oil (PPP)	Units
Temperature	65,0	25,0	60,0	36,0	25,0	25,0	60,0	C
Mass flow	10,9	20,2	1,0	138,0	79,1	126,1	80,7	kg/h

(continúa)

(viene)

Variable	Methanol-Rec	Methanol	K_2CO_3	Impurities + Glycerol	Biodiesel	Water	Oil (PPP)	Units
Molar flow	0,316	0,605	0,006	7,108	0,286	7,000	0,100	kmol/h
TriPalmitine (PPP)	$2,28E^{-04}$	0	0	0,011	0,031	0	1	
Glycerol	0,011	0,006	0	0,063	$3,70E^{-61}$	0	0	
Potassium Carbonate	$6,53E^{-19}$	0	1	0,007	$3,00E^{-19}$	0	0	
Water	0	0	0	0,914	$3,57E^{-08}$	1	0	
Methanol	0,911	0,952	0	0,001	$2,49E^{-32}$	0	0	
Methyl Palmitate	0,078	0,042	0	0,003	0,969	0	0	

Source: own work

Thermal characterization of the post-extraction residue (TGA/DTG)

Four stages are observed in the analysis of the curve TGA/DTG of the orange peel after extraction of the essential oils (Figure 2). The first stage is below 150 °C and is attributed to the loss of surface moisture and adsorbed water. The second stage occurs between 200–380 °C and shows the degradation of structural carbohydrates. The depolymerization of cellulose between 200–280 °C and between 300–350 °C the degradation of cellulose. Subsequently, between 380–600 °C, a loss of mass corresponding to lignin is observed. Finally, above 600 °C, the sample reaches a state of stability, with minor losses related to the decomposition of mineral carbonates ($CaCO_3$, K_2CO_3) and the formation of basic oxides. The final residue (approximately 15–20% by weight) corresponds to the carbonaceous fraction and the mineral content, which is the basis for the formation of ash with catalytic potential.

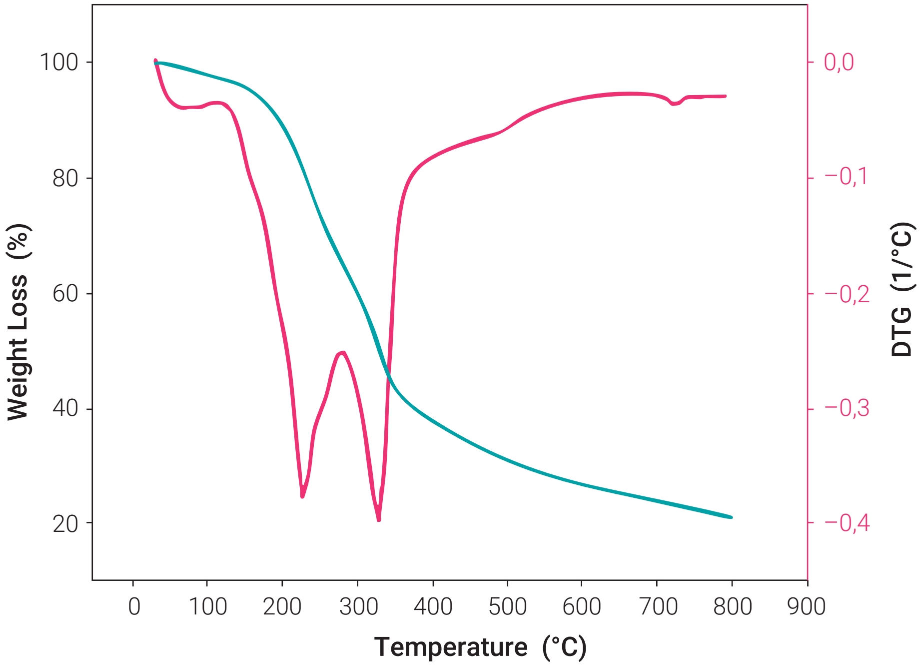

Figure 2. Orange peel TGA/DTG (post-extraction residue).
Source: own work

Obtaining ash from post-extraction waste.

Figure 3 presents the results of the thermogravimetric analysis (TGA) and the mass loss derivative (DTG) obtained for the ash of calcined orange peel at 550°C. The TGA profile shows that the material remains stable up to approximately 600 °C, with minor weight losses attributable to residual moisture and trace organic matter. From 650 °C a more pronounced decrease in mass is observed, reaching a cumulative loss of about 15–20 % at 850 °C.

This behavior is related to the thermal decomposition of carbonates present in the mineral matrix, mainly $CaCO_3$ y K_2CO_3, that release CO_2 during the process. The DTG curve confirms this event by a well-defined peak between 750 and 800 °C, which supports the transformation of carbonates into metal oxides, among them CaO y K_2O, responsible for catalytic activity in transesterification reactions. These results show that the ash, initially obtained at 550 °C, preserves carbonate species that require additional calcination treatment to fully activate their basic sites. In this way, thermal analysis not only allows quantifying the stability of the waste but also identifying the critical thermal conditions to maximize its potential as a heterogeneous catalyst in biodiesel production.

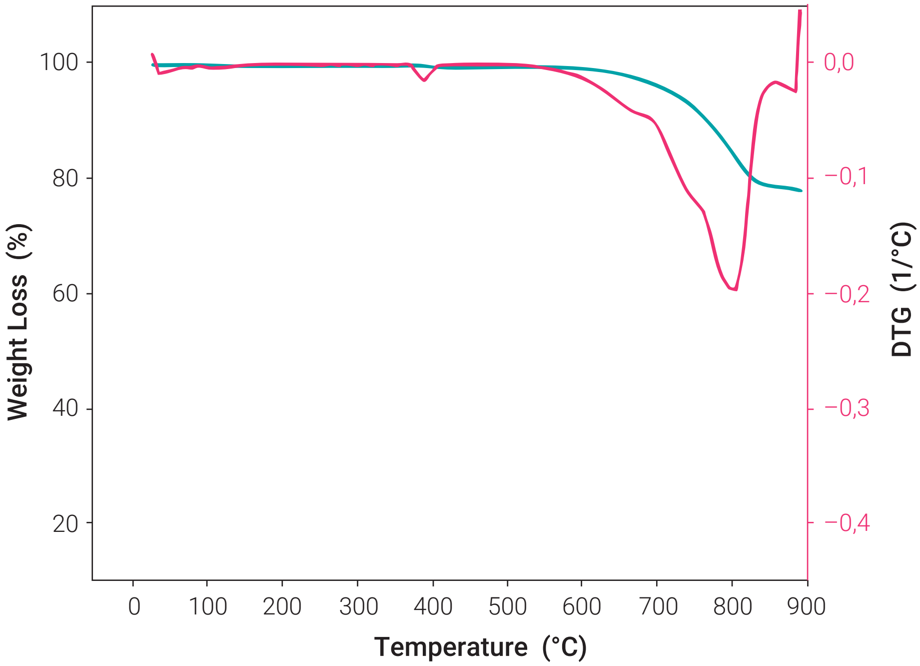

Figure 3. TGA/DTG from calcined orange peel ash at 550°C.
Source: own work

However, when comparing with the literature, it is important to note that the observed catalytic activity is not mainly due to CaO, but to the presence of potassium-derived alkaline compounds (K_2CO_3/K_2O), that remain stable under calcination conditions and are recognized as the most active species in the basic catalysis of transesterification [12], [13], [24], [25][26].

4. DISCUSSION AND CONCLUSIONS

The results obtained from the DWSIM simulation, complemented by the thermal analysis of orange peel, demonstrate that this agro-industrial waste has significant potential as a heterogeneous catalyst in biodiesel production. The presence of alkaline potassium compounds in the ash favors the conversion of triglycerides, while at higher temperatures, CaO fractions are generated that also contribute to catalytic activity. These findings reinforce the relevance of integrating ICT-based simulation tools with experimental characterization, not only to optimize sustainable processes but also to promote waste valorization within a circular economy framework.

The thermal behavior of the post-extraction residues is consistent with that reported in the literature for citrus lignocellulosic residues. Several authors [13], [27],

[28] report that hemicellulose decomposes within the range of 200–280 °C and cellulose between 300–350 °C, while lignin undergoes prolonged degradation up to 600 °C, providing thermal stability to the material. In specific studies on orange peel, [12], [29] report similar TGA profiles, with major weight losses associated with polysaccharides [30] and a mineral residue enriched with potassium and calcium [31]. These minerals, after calcination, are transformed into compounds such as K_2CO_3, K_2O, and CaO, which have demonstrated catalytic activity in transesterification processes for biodiesel [10], [32], [33].

Therefore, the results confirm that orange peel not only contains an organic fraction with thermal behavior typical of lignocellulosic biomass but also a relevant mineral content that, when thermally activated, can be utilized as a heterogeneous catalyst. The synergy between potassium compounds (active at moderate temperatures) and CaO (formed at temperatures above 700 °C) reinforces the relevance of recovering this waste within a circular economy framework.

The TGA/DTG results obtained for orange peel ash confirm that this material exhibits thermal stability up to approximately 600 °C, followed by a decomposition process mainly associated with CO_2 release between 700 and 800 °C. This behavior is consistent with the findings reported by [13], who identified that carbonate-rich biomass ash undergoes a catalytic activation stage through conversion into metal oxides, particularly CaO and K_2O. Similarly, [12] indicate that ash derived from citrus peels shows decomposition peaks within the same thermal range, favoring its subsequent use as a heterogeneous catalyst in transesterification processes.

When compared with studies on non-citrus biomasses, such as those reported by [17], the magnitude of weight loss in orange peel ash is lower, reflecting a higher content of stable mineral compounds and, consequently, a greater potential for reuse as a source of active basic sites. This suggests that, under controlled calcination at temperatures between 750 and 800 °C, orange peel ash can reach activation levels comparable to those of commercial catalysts, with the additional advantages of low cost and renewable origin. These findings confirm that the catalytic behavior of orange peel ash calcined at 550 °C is dominated by potassium species, while CaO plays a significant role in ashes calcined at temperatures around 800 °C.

In conclusion, ash obtained at 550 °C retains carbonate fractions; however, at this temperature, alkaline compounds derived from potassium remain active and are primarily responsible for catalytic activity. At higher temperatures (≥ 750 °C), $CaCO_3$ decarbonation and CaO formation are promoted, contributing to basic catalysis, although with an increased risk of sintering and recarbonation. Overall, these results demonstrate that orange peel ash is a sustainable heterogeneous catalyst, offering a dual contribution: immediate catalytic activity associated with potassium at 550 °C and the formation of CaO active sites at higher temperatures, reinforcing its potential within agro-industrial waste valorization and the circular economy.

REFERENCES

[1] C. H. Tsai and W. T. Tsai, “Sustainable processes reusing potassium-rich biomass ash as a green catalyst for biodiesel production: A mini-review,” *Processes*, vol. 12, no. 12, p. 2736, Dec. 2024, doi: https://doi.org/10.3390/pr12122736.

[2] P. Prajapati *et al.*, “Karanja seed shell ash: A sustainable green heterogeneous catalyst for biodiesel production,” *Results in Engineering*, vol. 18, Jun. 2023, doi: https://doi.org/10.1016/j.rineng.2023.101063.

[3] A. K. Rajak *et al.*, “Exploring the peel ash of *Musa acuminata* as a heterogeneous green catalyst for producing biodiesel from Niger oil: A sustainable and circular bioeconomic approach,” *Sustainable Chemistry and Pharmacy*, vol. 39, Jun. 2024, doi: https://doi.org/10.1016/j.scp.2024.101622.

[4] United States Department of Agriculture, Foreign Agricultural Service, “Turkey’s mandarin production and exports to rebound,” 2024. Accessed: Jan. 24, 2026. [Online]. Available: https://www.fas.usda.gov/sites/default/files/2024-07/citrus.pdf

[5] Asohofrucol, “Producción nacional de cítricos en Colombia 2023,” in *Proc. III Seminario Internacional Citrícola*, 2024. Accessed: Jan. 24, 2026. [Online]. Available: https://www.asohofrucol.com.co/img/archivosGeneralesFiles/3295Pcitricola2024.pdf

[6] Ministerio de Agricultura y Desarrollo Rural, “Cifras sectoriales de cítricos 2016–2020,” 2020. Accessed: Jan. 24, 2026. [Online]. Available: https://sioc.minagricultura.gov.co/Citricos/Documentos/2020-03-30%20Cifras%20Sectoriales.pdf

[7] A. D. S. Altamar Consuegra, “Cinética da gaseificação do bagaço de laranja e serragem de madeira com CO_2,” B.S. thesis, Universidade Federal de Santa Catarina, Florianópolis, 2013. Accessed: May 07, 2025. [Online]. Available: http://repositorio.ufsc.br/handle/123456789/103529

[8] Fedebiocombustibles, “Informe 2024–2025,” 2025. Accessed: Jan. 24, 2026. [Online]. Available: https://fedebiocombustibles.com/wp-content/uploads/2025/04/Informe-2024-2025-PW.pdf

[9] A. K. Rajak *et al.*, "Valorising orange and banana peels: Green catalysts for transesterification and biodiesel production in a circular bioeconomy," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 177, Dec. 2025, doi: https://doi.org/10.1016/j.jtice.2024.105804.

[10] B. Changmai, P. Sudarsanam, and S. L. Rokhum, "Biodiesel production using a renewable mesoporous solid catalyst," *Industrial Crops and Products*, vol. 145, Mar. 2020, doi: https://doi.org/10.1016/j.indcrop.2019.111911.

[11] B. Basumatary, B. Nath, B. Das, A. Dhar, and S. Basumatary, "Biomass (*Amritsagar*) derived efficient solid base catalyst for eco-friendly biodiesel synthesis: A study on synthesis, reaction kinetics, and thermodynamic properties," *Next Sustainability*, vol. 6, p. 100127, 2025, doi: https://doi.org/10.1016/j.nxsust.2025.100127.

[12] C. H. Tsai and W. T. Tsai, "Sustainable processes reusing potassium-rich biomass ash as a green catalyst for biodiesel production: A mini-review," *Processes*, vol. 12, no. 12, p. 2736, 2024, doi: https://doi.org/10.3390/pr12122736.

[13] B. Changmai, C. Vanlalveni, A. P. Ingle, R. Bhagat, and L. Rokhum, "Widely used catalysts in biodiesel production: A review," *RSC Advances*, vol. 10, no. 68, pp. 41625–41679, Nov. 2020, doi: https://doi.org/10.1039/d0ra07931f.

[14] J. A. Herrera Guailla, "Simulación de un proceso de producción de biodiesel a partir de aceite de palma mediante el software DWSIM," B.S. thesis, 2021. Accessed: Jan. 24, 2026. [Online]. Available: https://dspace.espoch.edu.ec:8080/server/api/core/bitstreams/64ce-15bb-a44c-44c0 -8438-5b0745fb955d/content

[15] B. T. Asfaw, M. T. Gari, and M. Jayakumar, "Transesterification of biodiesel from non-edible oils using heterogeneous base catalysts: A comprehensive review of potential renewable biomass feedstocks," *Chemical Engineering Journal*, vol. 511, May 2025, doi: https://doi.org/10.1016/j.cej.2025.162028.

[16] L. E. Barroso, I. Tobío-Pérez, A. A. Cardero, and R. Piloto-Rodríguez, "DWSim simulation of biodiesel production and gasification from *Jatropha curcas* biomass," *Afinidad*, vol. 80, no. 598, pp. 67–78, 2023, doi: https://doi.org/10.55815/413410.

[17] M. Hamza *et al.*, "A review on waste biomass-derived catalysts for biodiesel production," *Environmental Technology & Innovation*, vol. 21, p. 101200, 2021, doi: https://doi.org/10.1016/j.eti.2020.101200.

[18] "DWSIM – Open-source chemical process simulator," Accessed: Feb. 12, 2026. [Online]. Available: https://dwsim.org/

[19] "ChemSep – Modeling separation processes," Accessed: Feb. 12, 2026. [Online]. Available: http://www.chemsep.org/

[20] H. Renon and J. M. Prausnitz, "Local compositions in thermodynamic excess functions for liquid mixtures," *AIChE Journal*, vol. 14, no. 1, pp. 135–144, Jan. 1968, doi: https://doi.org/10.1002/aic.690140124.

[21] J. F. Clevenger, "Apparatus for the determination of volatile oil," *Journal of the American Pharmaceutical Association*, vol. 17, no. 4, pp. 345–349, 1928, doi: https://doi.org/10.1002/jps.3080170407.

[22] ASTM, "ASTM E1756-08: Standard test method for determination of total solids in biomass," 2008, doi: https://doi.org/10.1520/E1756-08.

[23] ASTM, "ASTM D1102-84 (2013): Standard test method for ash in wood," 2013, doi: https://doi.org/10.1520/D1102-84R13.

[24] A. B. Fadhil, H. M. Al-Khayat, and M. H. Altamer, "Valorization of *Vicia faba* L. peel ash as a novel heterogeneous green catalyst for biodiesel production from waste cooking oil," *Biomass and Bioenergy*, vol. 208, May 2026, doi: https://doi.org/10.1016/j.biombioe.2025.108817.

[25] J. Suresh, N. B. Talib, N. I. W. Azelee, S. J. M. Rosid, and S. Toemen, "Exploring the acidic character of carbon derived from biomass waste along with potassium oxide as bifunctional catalyst for biodiesel synthesis," *Journal of Environmental Chemical Engineering*, vol. 13, no. 6, Dec. 2025, doi: https://doi.org/10.1016/j.jece.2025.119568.

[26] M. R. Miladinović *et al.*, "Transesterification of used cooking sunflower oil catalyzed by hazelnut shell ash," *Renewable Energy*, vol. 183, pp. 103–113, Jan. 2022, doi: https://doi.org/10.1016/j.renene.2021.10.071.

[27] P. Wang *et al.*, "Composition, structural, and thermal analysis of cellulose, hemicellulose, and lignin of reconstituted cut stems in tobacco," *Industrial Crops and Products*, vol. 222, Dec. 2024, doi: https://doi.org/10.1016/j.indcrop.2024.119614.

[28] M. Rojas, D. Ruano, E. Orrego-Restrepo, and F. Chejne, "Non-isothermal kinetics of cellulose, hemicellulose, and lignin degradation during cocoa bean shell pyrolysis," *Biomass and Bioenergy*, vol. 177, Oct. 2023, doi: https://doi.org/10.1016/j.biombioe.2023.106932.

[29] V. Chilla and S. Suranani, "Thermogravimetric and kinetic analysis of orange peel using iso-conversional methods," in *Materials Today: Proceedings*, Elsevier, 2023, pp. 104–109, doi: https://doi.org/10.1016/j.matpr.2022.06.196.

[30] S. Sohni *et al.*, "Physicochemical characterization of microcrystalline cellulose derived from underutilized orange peel waste as a sustainable resource under the biorefinery concept," *Bioresource Technology Reports*, vol. 25, 2024, doi: https://doi.org/10.1016/j.biteb.2023.101731.

[31] A. Tanveer *et al.*, "Valorization of orange peel via slow pyrolysis: Effect of particle size on biochar characteristics for wastewater remediation," *Results in Engineering*, vol. 27, Sep. 2025, doi: https://doi.org/10.1016/j.rineng.2025.106612.

[32] S. Lalhmangaihzuala *et al.*, "Orange peel ash coated Fe_3O_4 nanoparticles as a magnetically retrievable catalyst for glycolysis and methanolysis of PET waste," *Advanced Powder Technology*, vol. 34, no. 7, Jul. 2023, doi: https://doi.org/10.1016/j.apt.2023.104076.

[33] B. Changmai, R. Rano, C. Vanlalveni, and S. L. Rokhum, "A novel *Citrus sinensis* peel ash coated magnetic nanoparticles as an easily recoverable solid catalyst for biodiesel production," *Fuel*, vol. 286, Feb. 2021, doi: https://doi.org/10.1016/j.fuel.2020.119447