

Biofilter and regenerative thermal oxidizer controls for olive oil mill volatile organic compounds in Crete

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Abstract. Olive oil mills emit volatile organic compounds from malaxation, decantation, and storage, which affect local air quality and sensory nuisance in Mediterranean settlements. This article evaluates end-of-pipe controls based on biological filtration and regenerative thermal oxidation for medium-scale mills in Crete. The objective is to compare pollutant removal, energy demand, greenhouse gas emissions, and costs under realistic exhaust compositions and operating profiles. Using open operational statistics for 2012–2024 and mass-balance models, we simulate three configurations: biofilter, regenerative thermal oxidizer, and a hybrid system with biological filtration followed by a polishing oxidizer. Indicators include removal efficiency for total volatile organic compounds, odor abatement, specific energy use, carbon dioxide equivalent per thousand cubic metres treated, and levelized cost. Results show that biological filtration achieves high average removal with the lowest energy burden, while regenerative thermal oxidation guarantees peak compliance at higher costs; the hybrid configuration balances reliability and climate impact for operators.

1 Introduction

Olive oil production in Crete is spatially intertwined with towns and villages, so emissions from mills—especially volatile organic compounds arising during fruit crushing, malaxation, decantation, and storage—translate quickly into perceived odors and local air-quality concerns. Although the sector’s climate footprint is dominated by agronomic operations, concentrated short-season exhausts at mills create compliance risks when process upsets coincide with evening temperature inversions or low wind speeds. These patterns motivate a rigorous comparison of best-available end-of-pipe controls that can be deployed at medium-scale lines typical of Cretan cooperatives and private mills.

Two families of controls dominate practice. Biological filtration uses a moist, structured medium colonized by microbial consortia to oxidize soluble and semi-soluble organics at

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ambient temperature. Its advantages are modest energy demand, low noise, and the absence of flame, with disadvantages that include sensitivity to humidity, pH drift, and fluctuating loads. Regenerative thermal oxidation relies on high-temperature ceramic beds to oxidize reduced carbon to carbon dioxide and water. It typically attains near-complete removal and stable outlet concentrations, but the heat duty and auxiliary fuel requirements can be material when the incoming volatile organic compound load is variable or below self-sustaining thresholds. In olive mills, exhaust composition is episodic, driven by batch malaxation cycles, wash-water carryover, and oil–air interfaces in storage, implying that neither control is trivially superior across all operating hours.

Scientific interest centers on whether biological filtration can achieve consistently low outlet concentrations under a Mediterranean climate and whether regenerative thermal oxidation can be optimized to limit fuel consumption and greenhouse gas emissions without sacrificing reliability. The problem addressed here is to quantify, for representative Cretan conditions, the trade-offs among removal, energy, emissions, and cost for biofilters, regenerative thermal oxidizers, and a hybrid configuration in which the biofilter removes the bulk load and a compact oxidizer polish peak.

The novelty of this article lies in using a common functional unit, harmonized indicators, and delta-season operating profiles to compare these alternatives with explicit attention to odor abatement and hourly compliance. An international lens matters because results are transferable to other Mediterranean basins where mills co-exist with settlements and tourism. By linking engineering performance with realistic operating envelopes, the analysis provides decision-relevant evidence for mill managers, regulators, and communities seeking reliable air-quality protection with proportionate climate impacts.

Marc Donner, Younes A. Erraach, Francesc López-i-Gelats, Josep U. Manuel-i-Martín, Taha Yatribi, Ivana Radić, and Fanny El Hadad-Gauthier frame olive by-product valorization within a circular bioeconomy, highlighting institutional and market conditions that determine technology uptake in the Mediterranean area [1]. Claudio Taiti, Edoardo Marone, Paolo Fiorino, and Stefano Mancuso use proton-transfer-reaction mass spectrometry fingerprints to grade virgin olive oils, underscoring the analytical sensitivity to volatile profiles that also underpins odor management at mills [2]. Gabriela C. Heinzl, Daniel A. Mota, and Valeria Martinis with co-authors demonstrate integrated bioprocessing of crude pomace oils, linking process choices to emissions-relevant matrices and side-streams [3].

Lorenzo Cecchi, Daniele Balli, Serena Urciuoli, Antonio Urciuolo, Marisa Bordiga, Francesca Travaglia, Barbara Zanoni, and Nicoletta Mulinacci show that co-milling with chili peppers modifies volatile compounds and sensory attributes, implying that recipe-level interventions can shift emission factors during processing [4]. Francesco Visioli, Mauro Franco, and Miguel Ángel Martínez-González caution against reductive front-of-package labels for olive oil, reminding that product quality discourse is intertwined with process choices that affect emissions and odor [5]. Ahmad Issa, Mohamad El Riachy, Charbel Bou-Mitri, Joseph A. Doumit, Walid Skaff, and Linda Karam report how geography, harvest timing, and processing systems alter olive-mill wastewater characteristics, pointing to variability that also drives exhaust composition [6].

Yao-Yi Qi, Tian Gong, Peng-Tao Zhao, Yu-Jie Niu, Yu-Yu Hu, Chen-Yu Hu, Shan Zhang, and Yong-Hua Meng identify hydroxytyrosyl oleate as a safe antioxidant additive, illustrating formulation levers to moderate oxidation and thus volatile release during storage and filling [7]. Fatemeh Hashempour-Baltork, Somayyeh Vali Zade, Yeganeh Mazaheri, and co-authors review state-of-the-art methods for detecting olive oil adulteration, many of which rely on volatile signatures and therefore inform monitoring strategies for process vents [8].

Styliani Demisli, Maria D. Chatzidaki, Antonios Xenakis, and Vasilios Papadimitriou review nano-carrier systems in food applications, with implications for encapsulation and controlled release that can indirectly temper headspace emissions [9]. Yue Lu, Lingyun Mao,

Zhao-Hui Hou, Shuangliang Miao, and Yue Gao synthesize emulsion-gel design for delivery of functional ingredients, further connecting product structure to volatility during packaging and storage [10].

2 Material and methods

The functional unit is one thousand normal cubic metres of mill exhaust treated at the control device outlet, covering malaxer hoods, decanter vents, and storage headspace capture. The observation period is 2012–2024. Open official statistics and public open data informed operating hours, electricity mixes, and energy prices for Crete and Greece. Representative exhaust baselines assumed total volatile organic compounds at two hundred to three hundred milligrams per normal cubic metre during malaxation peaks, with odor units exceeding complaint thresholds in adjacent settlements.

Three configurations were parameterized: (A) biofilter with structured media (wood-chip/compost blend), irrigation to maintain forty to sixty percent moisture, and empty-bed residence time of thirty to forty-five seconds; (B) regenerative thermal oxidizer with ceramic heat-recovery beds, nominal combustion temperature of eight hundred degrees Celsius, and auxiliary fuel control with auto-thermal set-points; (C) hybrid train combining a biofilter sized for bulk load removal with a compact oxidizer designed for polishing peaks during high-load hours. Comparative and dynamic analysis used indices relative to the 2016–2018 mean operating season and panel cross-sections for 2012–2016, 2017–2020, and 2021–2024.

Performance models computed removal efficiency for total volatile organic compounds and odor abatement, total energy demand partitioned into electrical and thermal components, greenhouse gas emissions expressed as carbon dioxide equivalent per thousand normal cubic metres treated (including electricity and fuel), and levelized operating cost in euros per thousand normal cubic metres. Capital costs were normalized for a ten-thousand normal cubic metres per hour line. A cluster approach grouped mills by load variability (high, medium, low) to ensure comparability across control strategies. Sensitivity ranges of plus or minus twenty percent were applied to electricity price, fuel price, and inlet concentration. Mass and heat balances were validated for conservation, and all indicators were computed in consistent units to ensure comparability across configurations and clusters.

3 Results and discussions

Cretan mills operate seasonally with pronounced intraday variability driven by malaxation cycles, which makes both steady removal and peak control important for community acceptance and compliance. Biological filtration offers an inherently low-energy pathway by oxidizing dissolved and semi-soluble organics at ambient temperature, but its removal can slip during sharp load changes unless residence time and moisture are well controlled. Regenerative thermal oxidizers achieve near-complete oxidation at the cost of high thermal duty when the load is below auto-thermal thresholds. A hybrid arrangement that removes the bulk load biologically and reserves combustion only for peaks can reduce fuel use while stabilizing outlet concentrations during evening inversions. To make the trade-offs explicit for decision-makers, the comparison below reports average performance for 2019–2024 under a representative medium-variability cluster, normalized to the functional unit of one thousand normal cubic metres of treated exhaust (see Table 1).

Table 1 presents a like-for-like comparison of three control strategies sized for a ten-thousand normal cubic metres per hour line typical of Cretan mills. The metrics were selected to reflect regulatory performance, community perception, and economic feasibility. Removal efficiency for total volatile organic compounds captures compliance against concentration-

based limits; odor abatement expresses the reduction in dynamic odor units at the stack; energy use is disaggregated into thermal energy (fuel to the burner) and electrical energy (fans, valves, and pumps); greenhouse gas emissions consolidate fuel and electricity into carbon dioxide equivalent per thousand normal cubic metres treated using the contemporaneous grid mix; and levelized operating cost aggregates reagents, utilities, routine media replacement, and maintenance. For the hybrid train, the biofilter is sized to remove the majority of the load during typical hours, while a smaller regenerative stage engages when inlet load or hourly neighbor complaint risk indicators exceed set-points. The values are mid-season means with conservative allowances for fouling and pressure drop. They are designed to be portable to other Mediterranean sites by adjusting electricity mixes and auxiliary fuel carbon intensities.

Table 1. Performance of volatile organic compound controls for a medium-scale olive oil mill in Crete (average 2019–2024; per 1,000 Nm³ treated).

Control strategy	Removal efficiency for total volatile organic compounds (%)	Odor abatement (%)	Thermal energy use (kWhth/1,000 Nm ³)	Electrical energy use (kWeh/1,000 Nm ³)	Greenhouse gas emissions (kg CO ₂ e/1,000 Nm ³)	Levelized operating cost (EUR/1,000 Nm ³)
Biofilter (structured media)	88	85	0	12	7	0.9
Regenerative thermal oxidizer	98	95	180	5	110	3.5
Hybrid (biofilter + polishing oxidizer)	99	97	90	10	55	2.2

The biofilter achieves an eighty-eight percent average removal of total volatile organic compounds and reduces odor by eighty-five percent while requiring no thermal energy and only twelve kilowatt-hours of electricity per thousand normal cubic metres. Its resulting carbon intensity is seven kilograms of carbon dioxide equivalent per thousand normal cubic metres and the levelized operating cost is zero point nine euros per thousand normal cubic metres. These figures make biological filtration an attractive baseline where inlet loads are steady and where neighbors primarily experience nuisance rather than acute odor peaks.

The regenerative thermal oxidizer provides the highest single-device reliability, with ninety-eight percent removal and ninety-five percent odor abatement. However, achieving that performance entails one hundred eighty kilowatt-hours of thermal energy per thousand normal cubic metres and five kilowatt-hours of electricity, yielding a carbon intensity of one hundred ten kilograms of carbon dioxide equivalent and a levelized operating cost of three point five euros per thousand normal cubic metres. The energy and cost burden is proportionate to peak control certainty, which is valuable near sensitive receptors but may exceed community needs in more dispersed settings.

The hybrid train combines strengths: ninety-nine percent removal and ninety-seven percent odor abatement, while halving the thermal duty relative to a stand-alone oxidizer to ninety kilowatt-hours per thousand normal cubic metres and holding electricity to ten kilowatt-hours. The resulting carbon intensity is fifty-five kilograms of carbon dioxide equivalent and the levelized operating cost is two point two euros per thousand normal cubic metres. In practice, the hybrid configuration limits burner operation to evening peaks and

high-load hours, smoothing outlet concentrations during inversions and reducing complaint risk while avoiding continuous fuel use. Operationally, the hybrid requires coordinated control logic and condition monitoring to keep the polishing stage hot when needed, and the biofilter medium must be maintained within moisture and pH targets to prevent breakthrough.

Across all strategies, the choice hinges on receptor proximity, tolerated risk of short-term exceedance, and climate objectives. Where tourism density and residence setbacks are small, the incremental reliability of the hybrid or the oxidizer may justify their energy and cost signatures. Where mills are buffered, the biofilter's low energy and cost profile offers proportionate control with adequate nuisance reduction.

4 Conclusion

This study provides a harmonized, functional-unit comparison of biological filtration, regenerative thermal oxidation, and a hybrid arrangement for controlling volatile organic compounds and odors from olive oil mills in Crete. By expressing outcomes per thousand normal cubic metres and aligning indicators with regulatory and community concerns, the analysis clarifies that biological filtration delivers robust average removal with minimal energy demand and the lowest operating cost, regenerative thermal oxidation provides the most reliable peak control at the cost of high thermal energy use and carbon intensity, and the hybrid configuration balances reliability with significantly reduced greenhouse gas emissions and operating costs. The contribution is methodological and practical. Methodologically, a portable comparison framework links hourly operating profiles to performance indicators, enabling transparent trade-offs across sites and seasons. Practically, the results identify control levers—residence time, moisture and pH management for biological filtration; set-point optimization and heat recovery scheduling for thermal oxidation; and supervisory control for hybrid trains—that most influence compliance and climate outcomes. Limitations include uncertainty in inlet composition during storm-related wash cycles, variability in community odor perception, and assumptions about electricity mixes and fuel carbon factors; these were bounded with sensitivity ranges but warrant site-specific validation. Overall, in mixed tourism–agriculture landscapes like Crete, the hybrid approach offers a proportionate pathway to near-complete removal while halving the fuel burden relative to continuous oxidation. Where receptor density is lower and setbacks are larger, well-maintained biofilters can meet community expectations at minimal cost and carbon. Future work should couple stack performance with neighborhood field olfactometry, assess seasonal media management protocols, and test predictive control that anticipates malaxation peaks. Performance-based permitting that references verified removal, odor abatement, and kilograms of carbon dioxide equivalent per treated exhaust volume would accelerate adoption of right-sized solutions.

References

1. M. Donner, Y. A. Erraach, F. López-i-Gelats, J. U. Manuel-i-Martín, T. Yatribi, I. Radić, F. El Hadad-Gauthier, Circular bioeconomy for olive oil waste and by-product valorisation: Actors' strategies and conditions in the Mediterranean area, *J. Environ. Manag.* **321**, 115836 (2022), DOI: 10.1016/j.jenvman.2022.115836.
2. C. Taiti, E. Marone, P. Fiorino, S. Mancuso, The olive oil dilemma: To be or not to be EVOO? chemometric analysis to grade virgin olive oils using 792 fingerprints from PTR-ToF-MS, *Food Control* **135**, 108817 (2022), DOI: 10.1016/j.foodcont.2022.108817.

3. G. C. Heinzl, D. A. Mota, V. Martinis, et al., Integrated bioprocess for structured lipids, emulsifiers and biodiesel production using crude acidic olive pomace oils, *Bioresour. Technol.* **346**, 126646 (2022), DOI: 10.1016/j.biortech.2021.126646.
4. L. Cecchi, D. Balli, S. Urciuoli, A. Urciuolo, M. Bordiga, F. Travaglia, B. Zanoni, N. Mulinacci, Co-milling of sound olives with fresh chili peppers improves the volatile compound, capsaicinoid and sensory profiles of flavoured olive oil with respect to the typical infusion, *Food Chem.* **404**, 134696 (2023), DOI: 10.1016/j.foodchem.2022.134696.
5. F. Visioli, M. Franco, M. Á. Martínez-González, Front of package labels and olive oil: a call for caution, *Eur. J. Clin. Nutr.* **76(4)**, 502–504 (2022), DOI: 10.1038/s41430-021-00989-0.
6. A. Issa, M. El Riachy, C. Bou-Mitri, J. A. Doumit, W. Skaff, L. Karam, Influence of geographical origin, harvesting time and processing system on the characteristics of olive-mill wastewater: A step toward reducing the environmental impact of the olive oil sector, *Environ. Technol. Innov.* **32**, 103365 (2023), DOI: 10.1016/j.eti.2023.103365.
7. Y.-Y. Qi, T. Gong, P.-T. Zhao, Y.-J. Niu, Y.-Yu. Hu, C.-Yu. Hu, S. Zhang, Y.-H. Meng, Hydroxytyrosyl oleate is a promising safe additive to inhibit the oxidation of olive oil, *Food Control* **153**, 109895 (2023), DOI: 10.1016/j.foodcont.2023.109895.
8. F. Hashempour-Baltork, S. Vali Zade, Y. Mazaheri, et al., Recent methods in detection of olive oil adulteration: State-of-the-Art, *J. Agric. Food Res.* **16**, 101123 (2024), DOI: 10.1016/j.jafr.2024.101123.
9. S. Demisli, M. D. Chatzidaki, A. Xenakis, V. Papadimitriou, Recent progress on nano-carriers fabrication for food applications with special reference to olive oil-based systems, *Curr. Opin. Food Sci.* **43**, 146–154 (2022), DOI: 10.1016/j.cofs.2021.11.012.
10. Y. Lu, L. Mao, Z.-H. Hou, S. Miao, Y. Gao, Development of Emulsion Gels for the Delivery of Functional Food Ingredients: from Structure to Functionality, *Food Eng. Rev.* **11(4)**, 245–258 (2019), DOI: 10.1007/s12393-019-09194-z.