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Circular Valorization and Biochar Based Treatment of Agro-Industrial Effluents: Insights from the VALCARB Project

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Abstract: In response to growing environmental challenges linked to agro-industrial wastewater management, the VALCARB project aims to develop a real-world circular economy model through the valorization of agricultural residues for the production of eco-friendly biosorbents dedicated to wastewater treatment.

We carried out comprehensive analyses to characterize the organic, saline, and microbiological pollution of effluents collected from the Société des Boissons de Tunisie (SBT) and its discharge site. The results revealed high electrical conductivity (9,420 µS/cm), chloride levels (2,455 mg/L), and chemical oxygen demand (COD ≈ 820 mg O_2/L), indicating severe salinization and organic loading, with potential risks of soil degradation. Microbiological analyses confirmed fecal and fungal contamination, including Trichoderma, Penicillium, Alternaria, and Aspergillus species.

Conversely, treated wastewater samples showed a marked improvement in quality, with COD reduced to 90 mg O_2/L and conductivity below 2,400 µS/cm, demonstrating partial effectiveness of the biological treatment system. Simultaneously, biochars produced from olive residues showed high specific surface areas (200–300 m²/g) and a porous structure suitable for pollutant adsorption, suggesting strong potential for effluent purification.

These preliminary results highlight the synergy between biomass valorization and wastewater remediation, supporting the development of sustainable agroecological solutions for arid and semi-arid regions of Tunisia.

1 Introduction

The management of agro-industrial effluents represents a major environmental challenge, particularly in arid and semi-arid regions where water scarcity, soil salinization, and organic pollution converge to threaten agricultural sustainability [1,2]. In Mediterranean countries,

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the increasing reuse of treated and untreated wastewater has intensified concerns regarding soil degradation, salinity accumulation, and microbiological risks [4,5]. These challenges call for innovative, low-cost, and environmentally friendly solutions that combine wastewater treatment with resource recovery within a circular economy framework.

Circular economy approaches emphasize the valorization of agricultural and agro-industrial residues as secondary raw materials, transforming waste streams into value-added products while minimizing environmental impacts [6]. Among emerging technologies, biochar produced through the pyrolysis of biomass under limited oxygen—has attracted growing attention due to its high porosity, large specific surface area, and strong adsorption capacity for organic pollutants, salts, and heavy metals [7,8]. Numerous studies have demonstrated the effectiveness of biochar derived from agricultural residues in improving wastewater quality and mitigating soil salinity when reused for irrigation [9–10]. Recent research highlights that biochar application can significantly improve soil physicochemical properties, enhance nutrient retention, and reduce sodium toxicity in salt-affected soils [11,12]. In addition, biochar-based systems have shown promising results in reducing chemical oxygen demand (COD), electrical conductivity (EC), and microbial contamination in treated effluents, thereby supporting their safe agricultural reuse [13,14]. Despite these advances, field-based studies integrating wastewater characterization, soil impact assessment, and locally produced biochar remain limited in North African and arid Mediterranean contexts.

In this framework, the VALCARB project aims to develop a practical circular valorization model based on the conversion of local agricultural residues into carbonized materials for the treatment and reuse of agro-industrial effluents. The present study reports the first-year outcomes of VALCARB, focusing on (i) the physicochemical and microbiological characterization of agro-industrial effluents, (ii) the assessment of soil quality at the discharge site, and (iii) the production and preliminary characterization of biochars derived from olive and date palm residues. These results provide a scientific basis for evaluating biochar-based remediation strategies adapted to arid and semi-arid environments [15].

2. Materials and Methods

2.1 Study site and sampling

Wastewater samples were collected from the Société des Boissons de Tunisie (SBT) at two locations: (i) directly at the industrial outlet and (ii) at the receiving wadi downstream. Soil samples were collected from the effluent discharge site for saturated paste analysis. Treated wastewater samples were obtained from the biological treatment unit of the SBT plant on April 17, 2025.

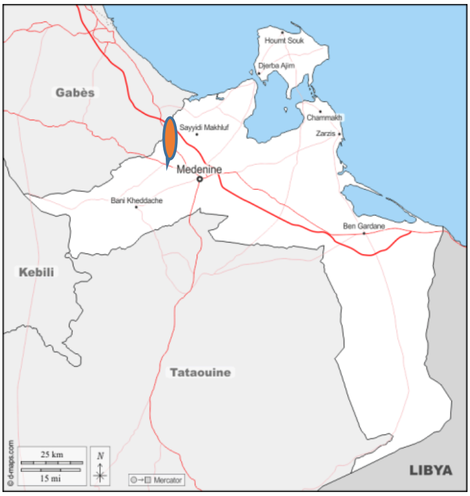

Fig. 1. Study site of SBT Medenine

2.2 Physicochemical analysis of effluents and soils

Water and soil saturated paste analyses included temperature, pH, electrical conductivity (EC), salinity, chloride concentration, sodium content, chemical oxygen demand (COD), and biochemical oxygen demand (BOD_5), following standard methods [8]. Results were compared with national and international regulatory thresholds for wastewater discharge and irrigation reuse.

2.3 Microbiological analyses

Microbiological quality was assessed through enumeration of fecal coliforms and fecal enterococci using standard culture-based techniques. Fungal strains were isolated and identified based on morphological characteristics, with particular attention to dominant genera.

2.4 Biochar production and preliminary characterization

Olive pruning residues were collected from local agricultural operations in southern Tunisia. The biomass was air-dried under ambient laboratory conditions for 72 h to reduce moisture content below 10% (w/w). Dried materials were mechanically milled and sieved to obtain a uniform particle size of 2–5 mm in order to ensure homogeneous heat transfer during pyrolysis. The prepared feedstocks were stored in sealed polyethylene containers prior to carbonization.

Biochars were produced via slow pyrolysis under oxygen-limited conditions using a programmable muffle furnace. Approximately 50 g of dried biomass were placed in covered ceramic crucibles to minimize oxygen exposure. The pyrolysis temperature was selected based on established thermochemical optimization studies demonstrating the critical influence of temperature on carbon structure, aromaticity, yield, and surface functionality [3].

Biochar yield was calculated gravimetrically. pH determination, Electrical conductivity (EC) and surface characteristics and porosity were evaluated using specific surface area measurements using the Brunauer–Emmett–Teller (BET) method.

Previous work has demonstrated that optimization of pyrolysis temperature significantly affects the physicochemical properties and functional performance of biochar materials [3].

3 Results and Discussion

3.1 Physicochemical characterization of agro-industrial effluents

In table1, the untreated effluents collected from the Société des Boissons de Tunisie (SBT) showed high salinity and organic pollution, as reflected by elevated electrical conductivity (9,420 µS/cm), chloride concentration (2,455 mg/L), and chemical oxygen demand (COD is arround 820 mg O_2/L). These values exceed commonly accepted thresholds for agricultural reuse and indicate a strong risk of soil salinization and organic overload [4,7]. Similar ranges have been reported for agro-industrial effluents in arid regions, where insufficient treatment leads to cumulative environmental stress on receiving soils [9,12].

Table1. Characterization of SBT Effluents

Parameters	**Measured values**	**Tunisian standard (NT 106.03)**	**Status**
pH	6.5	6.5–8.5	Limit
EC	9,420 µS/cm	≤ 7,000 µS/cm	Non-compliant
Salinity	6 g/L	—	High
Chlorides (Cl^-)	2,455 mg/L	≤ 2,000 mg/L	Non-compliant
Sodium (Na^+)	820 mg/L	—	High
COD	820 mg O_2/L	≤ 90 mg O_2/L	Very high
BOD_5	200–300 mg O_2/L	≤ 30 mg O_2/L	Very high

High sodium concentrations (820 mg/L) further suggest a potential long-term deterioration of soil structure through clay dispersion and reduced permeability, a phenomenon widely documented in saline-sodic environments [13]. The combination of high EC, chlorides, and organic load confirms the necessity of complementary treatment solutions prior to reuse or discharge.

3.2 Soil saturated paste characterization

Soil analyses from the effluent discharge site revealed physicochemical characteristics closely mirroring those of the wastewater, with elevated EC, chloride, and sodium levels. This strong correspondence indicates a direct impact of effluent infiltration on soil quality. Such salinity accumulation is known to impair water infiltration, induce osmotic stress in plants, and disrupt soil microbial activity [5,12].

Comparable observations have been reported in studies assessing long-term wastewater irrigation, where continuous exposure to saline effluents resulted in progressive soil degradation and reduced agricultural productivity [11,14]. These findings highlight the urgency of integrating remediation strategies capable of reducing salt and organic loads before reuse.

Table 2. Soil Status at Effluent Receiving Area

Soil parameters	**Observation**	**Implication**

Electrical conductivity	High	Progressive salinization
Sodium accumulation	Elevated	Structural degradation risk
Organic matter	Increased (degraded)	Anaerobic processes
Heavy metals	Below thresholds	No immediate risk
Overall soil quality	Altered	Long-term degradation risk

3.3 Microbiological contamination

Microbiological analyses revealed significant fecal contamination (figure2), with coliforms exceeding 2,000 CFU/100 mL, alongside the presence of enterococci and filamentous fungi (*Trichoderma*, *Penicillium*, *Alternaria*, *Aspergillus*). These results confirm that untreated effluents pose a serious sanitary risk, particularly if reused for irrigation of food crops [2,15]. The detection of fungal genera commonly associated with organic-rich environments further supports the classification of these effluents as biologically active and potentially hazardous. Similar microbial profiles have been reported in agro-industrial wastewater streams lacking advanced disinfection steps [7].

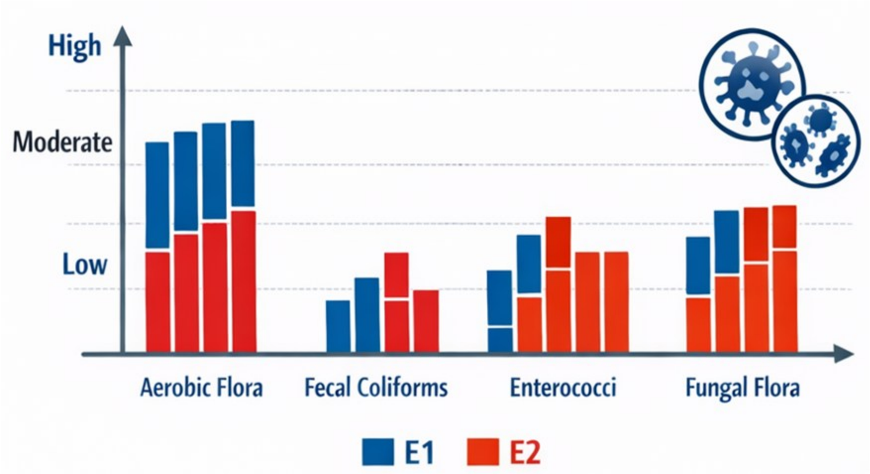

Fig. 2. Microbiological indicators. E1: industrial outlet, E2: downstream site.

3.4 Quality of treated wastewater

In contrast, treated wastewater samples displayed a marked improvement in quality, with COD reduced to 90 mg O_2/L and EC below 2,400 µS/cm, values approaching regulatory thresholds for controlled reuse. These results demonstrate the partial effectiveness of the biological treatment process implemented at SBT, in agreement with previous studies on secondary wastewater treatment systems [1,10].

However, organic parameters remained close to critical limits, indicating that further optimization or complementary treatment, such as adsorption using biochar, could enhance effluent quality and reduce environmental risks [8,16].

3.5 Biochar production and preliminary properties

Biochars produced from olive and date palm residues displayed variable yields depending on biomass type and pyrolysis temperature, with specific surface areas reaching 200–300 m^2/g. Such values are consistent with those reported for agricultural-residue-derived biochars used in wastewater treatment [8,11].

The developed micro- and mesoporous structure provides extensive surface accessibility, enhancing the physical adsorption of dissolved organic matter and contributing to chemical oxygen demand (COD) reduction [9].

Beyond porosity, the biochars displayed key physicochemical characteristics governing ion retention: near-neutral pH (7.6), moderate electrical conductivity (1.3 dS m^{-1}), and a relatively high cation exchange capacity (CEC is around 54 cmol(+)/kg) which are widely recognized as key determinants of cation retention efficiency in saline environments [4,5]. Mineral analysis revealed Ca^{2+} dominance (1192 mg kg^{-1}), compared with K^+ (58.7 mg kg^{-1}) and Na^+ (27.9 mg kg^{-1}), alongside measurable concentrations of Fe (16.5 mg kg^{-1}) and P (325 mg kg^{-1}). This Ca-rich composition strongly supports Na^+ immobilization through Ca^{2+}/Na^+ exchange reactions occurring at negatively charged functional groups ($–COO^-$, phenolic $–O^-$) on the biochar surface. Similar ion-exchange-driven salinity mitigation mechanisms have been demonstrated in salt-affected soils treated with biochar [4,6]. These properties indicate that salinity mitigation is primarily controlled by surface chemistry and ion-exchange mechanisms, rather than porosity alone.

The relatively low intrinsic Na^+ content of the biochar further minimizes the risk of secondary sodium release, enhancing its suitability for saline effluent treatment. Studies on biochar–wastewater interactions confirm that ion exchange and surface functional groups play a dominant role in sodium retention under slightly alkaline conditions [8,11].

In contrast, chloride (Cl^-) retention is not governed by strong electrostatic attraction, as biochar surfaces are predominantly negatively charged at neutral pH. Therefore, any observed decrease in chloride concentration likely results from indirect mechanisms, including ion pairing with immobilized Na^+, physical entrapment within microporous structures, or dilution effects, rather than specific chemical adsorption.

The presence of Fe and P introduces additional functional benefits. Iron may contribute to redox buffering and potential sorption of organic compounds, whereas phosphorus enrichment enhances the agronomic value of the spent biochar when reused as a soil amendment. Similar multifunctional behavior has been reported for agricultural biochars that simultaneously reduce EC, COD, and microbial loads in contaminated effluents while improving soil fertility upon reuse [12,13,14].

Overall, the remediation efficiency of the studied biochars arises from a synergistic interaction between developed porosity (supporting organic adsorption), high cation exchange capacity, and Ca-dominated mineral composition (driving Na^+ immobilization). This integrated structural–chemical functionality explains the observed reductions in salinity and organic load more convincingly than surface area considerations alone and aligns with recent advances in sustainable biochar technologies for saline wastewater treatment and agricultural reuse [8,9].

4 Synthesis and Perspectives

Overall, the first-year results of the VALCARB project confirm the strong potential of integrating biochar production with wastewater treatment within a circular economy framework. The simultaneous management of agro-industrial residues and effluents offers a sustainable pathway to mitigate environmental risks while enhancing resource efficiency in arid and semi-arid regions [6,10].

The integrated bio-physico-chemical functionality explains the observed improvement in irrigation water quality and supports the sustainability of wastewater reuse in arid agroecosystems.

These findings provide a solid scientific foundation for second-year experimental trials focusing on biochar-based adsorption performance and field-scale validation of treated effluent reuse for irrigation, contributing to resilient and sustainable agroecosystems [1,15].

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References

1. Paliaga, S., Muscarella, S. M., Alduina, R., Badalucco, L., Bulacio Fischer, P. T., Di Leto, Y., et al., Effects of enriched biochar and zeolite and treated wastewater irrigation on soil fertility and tomato growth, *J. Environ. Manage.*, **380**, 124990 (2025).
2. Mdpi Sustainability, Biochar Derived from Agricultural Residues for Wastewater Contaminant Removal, *Sustainability*, **18**, 435 (2026).
3. Boutaieb, M., Guiza, M., Román, S., Noglas, S., Ledesma, B., & Ouederni, A. Pine cone pyrolysis: Optimization of temperature for energy recovery. Environmental Progress & Sustainable Energy, **39**(1), 1–12. https://doi.org/10.1002/ep.13272. (2020).
4. Wu, B., Yang, H., Li, S., The effect of biochar on crop productivity and soil salinity in salt-affected soils: a meta-analysis, *Carbon Res.*, **3**, 56 (2024).
5. Yang Chen, Xuyu Feng, Xiao Zhao, Xinmei Hao, Ling Tong, Sufen Wang, Risheng Ding , Shaozhong Kang. Biochar application enhances soil quality by improving soil physical structure under particular water and salt conditions in arid region of Northwest China, J. Integr. Agric., **24**, 3242–3263 (2025).
6. Shahzadi, A., Noreen, Z., Alamery, S., Effects of biochar on growth and yield of Wheat (Triticum aestivum L.) under salt stress, *Sci. Rep.*, **14**, 20024 (2024).
7. Abonyi, M. N., Obi, C. C., Nwabanne, J. T., Emerging and eco-friendly biological methods for agricultural wastewater treatment, *Environ. Syst. Res.*, **13**, 45 (2024).
8. Tadesse, A. W., Biochar for Wastewater Treatment: Preparation, Properties and Environmental Applications, *Molecules*, **30**, 4288 (2025).
9. Lima, M. A., Advancements in sustainable biochar technology for aquatic pollution remediation, *Environ. Sustain.*, (2025).
10. Poonia, P., Gaur, R., Biochar from invasive weeds for enhanced removal of organic pollutants and pathogens from municipal wastewater, *Sci. Rep.*, (2025).
11. Liu, P., Boffa, L., Cravotto, G., Review on the adsorption removal of contaminants from wastewater using biochar derived from agricultural waste, Preprint (2025).
12. Abdelaziz, W. M., Abed El-Gany M., Arafa Y.E., Aboukila A., Improving water resource management and treated wastewater reuse for irrigation, *Water Pract. Technol.*, 39-1, (2025).
13. Muscarella, S. M., Alduina, R., Laudicina, V. A., Water reuse of treated domestic wastewater in agriculture: impacts on soil nutrient availability and microbial community, *Sci. Total Environ.*, **928**, 172259 (2024).

14. Journal news (Biochar & Zeolite mitigates salinity increase under wastewater irrigation for tomato growth), *J. Environ. Manage.* (2025).