AGROCIENCIA URUGUAY

Agrociencia Uruguay 2026 | Volume 30 | Number NE2 | Article e1726
DOI: 10.31285/AGRO.30.1726
ISSN 2730-5066

2nd Olive Oil Conference

Reuse of Olive Mill Wastewater in Olive Trees Grown in Uruguayan Clayey Soils

Conde-Innamorato, P.[1]; Villamil, J. J.[1]; Bianchi, D.[1]; Trujillo, M.[2]; Fasiolo, C.[2]; García-Inza, G. P.[1]

[1]*Instituto Nacional de Investigación Agropecuaria (INIA), Sistema Vegetal intensivo, Canelones, Uruguay*

[2]*Instituto Nacional de Investigación Agropecuaria (INIA), Dirección de Comunicación y Gestión del Conocimiento, Canelones, Uruguay*

Editor

Ana Claudia Ellis
Universidad de la República, Facultad de Química, Montevideo, Uruguay

Received *25 Mar 2025*
Accepted *4 Mar 2026*
Published *5 Jun 2026*

Correspondence

Paula Conde-Innamorato
pconde@inia.org.uy

Abstract

Olive cultivation in Uruguay has grown exponentially over the past 20 years, leading to an increase in the volume of waste generated by olive mills. This waste, composed of vegetation water (*alpechín*), pulp, and ground olive pit (orujo), could be phytotoxic due to its high organic load. This study aimed to evaluate vegetative growth and nutrient changes in plants in response to the application of alpechín, aged for six months, through fertigation in Arbequina olive trees. An experiment was conducted using a completely randomized design, with two treatments: application of alpechín in the olive grove rows versus a control with water. Physicochemical analyses of the alpechín and foliar analyses of the olive trees before and after application were performed, and vegetative growth was measured in four branches per tree. Under field conditions, no significant differences in annual shoot growth were observed between treatments, indicating that the application of aged alpechín did not cause phytotoxicity in the plants, mainly due to the reduction in organic load and the high fertility of the soil where it was applied. Similarly, foliar analysis showed no differences relative to the control, suggesting that it can be used as an irrigation input in olive groves. This study provides scientific evidence, generated under national conditions, supporting the valorization of olive mill wastewater as a coproduct with potential for use within the same farm where it is produced.

Keywords: *Olea europaea* L., sustainability, olive oil extraction, wastewater, olive orchard irrigation

CC BY

Conde-Innamorato, P., Villamil, J. J., Bianchi, D., Trujillo, M., Fasiolo, C., & García-Inza, GP. (2026). Reuse of olive mill wastewater in olive trees grown in Uruguayan clayey soils. *Agrociencia Uruguay, 30*(NE2), Article e1726. https://doi.org/10.31285/AGRO.30.1726

Aprovechamiento de aguas residuales de la extracción de aceite de oliva para el cultivo de olivos en suelos arcillosos de Uruguay

Resumen

La olivicultura en Uruguay creció exponencialmente en los últimos 20 años, lo que provocó un aumento del volumen del residuo generado en almazaras. Este residuo, compuesto por agua de vegetación (alpechín), pulpa y carozo molido (orujo), puede ser fitotóxico debido a su elevada carga orgánica. El objetivo fue evaluar el crecimiento vegetativo y los cambios en nutrientes de las plantas en respuesta a la aplicación de alpechín, estacionado durante seis meses, mediante fertirriego en Arbequina. Se realizó un experimento completo al azar, aplicando en la fila de los olivares el alpechín vs. el control con agua. Se realizaron análisis fisicoquímicos del alpechín y análisis foliares de los olivos pre y posaplicación, y se midió el crecimiento vegetativo por árbol. A campo no se observaron diferencias significativas en el crecimiento de brindillas entre tratamientos, lo que indica que la aplicación de alpechín estacionado no provocó fitotoxicidad en las plantas, explicado principalmente por la disminución de la carga orgánica y la alta fertilidad del suelo donde fue aplicado. Asimismo, el análisis foliar no mostró diferencias respecto al control, lo que sugiere que es posible aplicarlo como riego en los olivares. Este trabajo aporta evidencia científica, generada en condiciones nacionales, que respalda la valorización del alpechín como un coproducto con potencial de uso dentro del propio establecimiento donde se genera.

Palabras clave: *Olea europaea* L., sostenibilidad, extracción de aceite de oliva, aguas residuales, riego de olivares

Reutilização das águas residuais da extração de azeite em oliveiras cultivadas em solo argiloso do Uruguai

Resumo

A olivicultura no Uruguai cresceu exponencialmente nos últimos 20 anos, causando um aumento no volume de resíduos gerados nos lagares. Esse resíduo, composto por água de vegetação (alpechín), polpa e caroço moído (bagaço), pode ser fitotóxico devido à sua elevada carga orgânica. O lagar onde o estudo foi realizado é de duas fases e, no campo, procedeu-se à separação da fase sólida da líquida, chamado alpechín. O objetivo foi avaliar o crescimento vegetativo e as mudanças nos nutrientes das plantas em resposta à aplicação de alpechín, armazenado por seis meses, por meio de fertirrigação em oliveiras da variedade Arbequina. Foi realizado um experimento com um delineamento inteiramente casualizado, com dois tratamentos: aplicação de alpechín na linha dos olivais versus o controle com água. Foram feitas análises físico-químicas do alpechín e análises foliares das oliveiras antes e depois da aplicação, além da medição do crescimento vegetativo em quatro ramos por árvore. No campo, não foram observadas diferenças significativas no crescimento dos brotos entre os tratamentos, indicando que a aplicação de alpechín armazenado não causou fitotoxicidade nas plantas, explicada principalmente pela redução da carga orgânica e devido à alta fertilidade do solo onde foi aplicado. Da mesma forma, a análise foliar não mostrou diferenças em relação ao controle, sugerindo que é possível utilizá-lo como irrigação nos olivais. Este trabalho fornece evidências científicas, geradas em condições nacionais, que respaldam a valorização do alpechín como um coproduto com potencial de uso dentro do próprio estabelecimento onde é gerado.

Palavras-chave: *Olea europaea* L., sustentabilidade, extração de azeite de oliva, águas residuais, irrigação de olivais

1. Introduction

Olive cultivation in Uruguay has grown exponentially over the past 20 years and currently covers 5927 ha, with 30 olive mills distributed throughout the country (Oficina de Estadísticas Agropecuarias, 2023). The country's productive objective is to produce extra-virgin olive oil, with technologies and production processes aligned with this goal. Most olive mills in Uruguay operate with a two-phase oil extraction system, in which a liquid phase is obtained, corresponding to olive oil, and another formed by the combined output of vegetation water (*alpechín*) pulp and and ground olive pit (*orujo*), known as *alperujo*. The volume of alperujo represents 80% of the volume of processed fruit (De La Casa et al., 2012). However, in Uruguay there are no established

protocols for the environmentally safe disposal of this waste. Both alpechín (vegetation water) and orujo (pulp and ground pits) can be phytotoxic if applied to the soil without prior treatment (Sierra et al., 2007).

The alpechín represents one of the main environmental challenges associated with the olive industry for several reasons: it is produced in large volumes at a time of the year when evaporation is low (autumn); it contains high levels of phenolic compounds, high acidity, salinity, high biochemical oxygen demand (BOD), and chemical oxygen demand (COD), which contribute to its persistence and environmental impact (Dermeche et al., 2013). These characteristics make alpechín a potential risk to ecosystems if not properly managed (Chatzistathis & Koutsos, 2017). Its composition also includes organic matter and nutrients (Lozano-García et al., 2011; Magdich et al., 2013), which has generated interest in its use as an organic amendment to improve soil properties and promote crop growth, following the recommended guidelines for reuse (Environmental Protection Agency, 2004). Its application has even been proposed for the restoration of degraded soils (Hanifi & El-Hadrami, 2009) or as fertigation in olive trees at low doses (Pierantozzi et al., 2013).

There is evidence of phytotoxicity of alpechín and raw alperujo before ageing. Numerous studies from the Mediterranean region have documented phytotoxic effects on seed germination and root growth, mainly associated with its high organic load, phenolic compounds, and electrical conductivity. These effects have been reported in crops such as wheat, barley, tomato, lettuce, and various forage species, especially when untreated or low-dilution volumes are applied (Mekki et al., 2013; Muscolo et al., 2010; Rusan et al., 2015, 2016). Various treatments have been proposed to reduce the toxicity and pollutant load of alpechín before field application (del Águila Pérez, 1996). These processes vary in complexity; for example, biological treatments such as biodigesters, stabilization ponds, biofilters, and wetlands, as well as dilution and controlled reuse (de Heredia Alonso et al., 2000). Among the simplest and most cost-effective approaches in terms of field operation, materials, and infrastructure are stabilization ponds, dilution, and controlled reuse (Comisión Nacional del Agua, 2007; del Águila Pérez, 1996). Stabilization ponds are pools with a waterproofed bottom where the alpechín is stored, and the microorganisms, together with sunlight, contribute to the degradation of contaminants. In contrast, dilution and controlled reuse involve the addition of water to reduce concentration, thereby minimizing localized contamination and phytotoxic effects.

Due to the high content of organic matter and macronutrients (especially potassium), alpechín could be considered a useful and low-cost fertilizer (Chartzoulakis et al., 2010; Mekersi et al., 2023; Paredes et al., 1999). The use of alpechín as a fertilizer in olive groves poses an opportunity to close nutrient cycles and reduce agronomic management costs, contributing to the sustainability of the sector. However, it is necessary to take into account the physical, chemical, and biological processes involved in transforming it into an environmentally safe substance, with a positive impact on the vegetative growth of olive trees. Plant response will depend on the dose of amendment applied (Abril et al., 2014), the soil characteristics, and the climatic conditions (Cuevas et al., 2006). In addition, the presence of phenolic compounds can produce beneficial or phytotoxic effects, depending on their concentration and management. Given this complexity, it is necessary to develop appropriate management strategies that include environmental monitoring and assessment of plant physiological responses.

This study aims to evaluate the impact of irrigation with aged alpechín on vegetative growth and nutrient concentration at foliar and soil levels in olive trees of the Arbequina cultivar. The results obtained will contribute to establishing technical guidelines for the efficient and sustainable use of this agricultural waste, promoting the valorization of coproducts and environmentally responsible management within the olive sector.

2. Materials and Methods

2.1 Site and Alpechín Collection

The experiment was conducted at the Olivos de las Ánimas farm, located in Maldonado, Uruguay, over two consecutive seasons (2023 and 2024). The predominant soil type is Luvic Subeutric Brunosol. The predominant climate is humid temperate with an average annual rainfall of 1200 mm and an average temperature of 17 °C (Castaño et al., 2011). Figure 1 presents the monthly accumulated precipitation (mm) (A), monthly average relative humidity (%) (B), and mean air temperature (°C) (C) recorded for the area from January 2023 to February 2025 ("INUMET", n.d.).

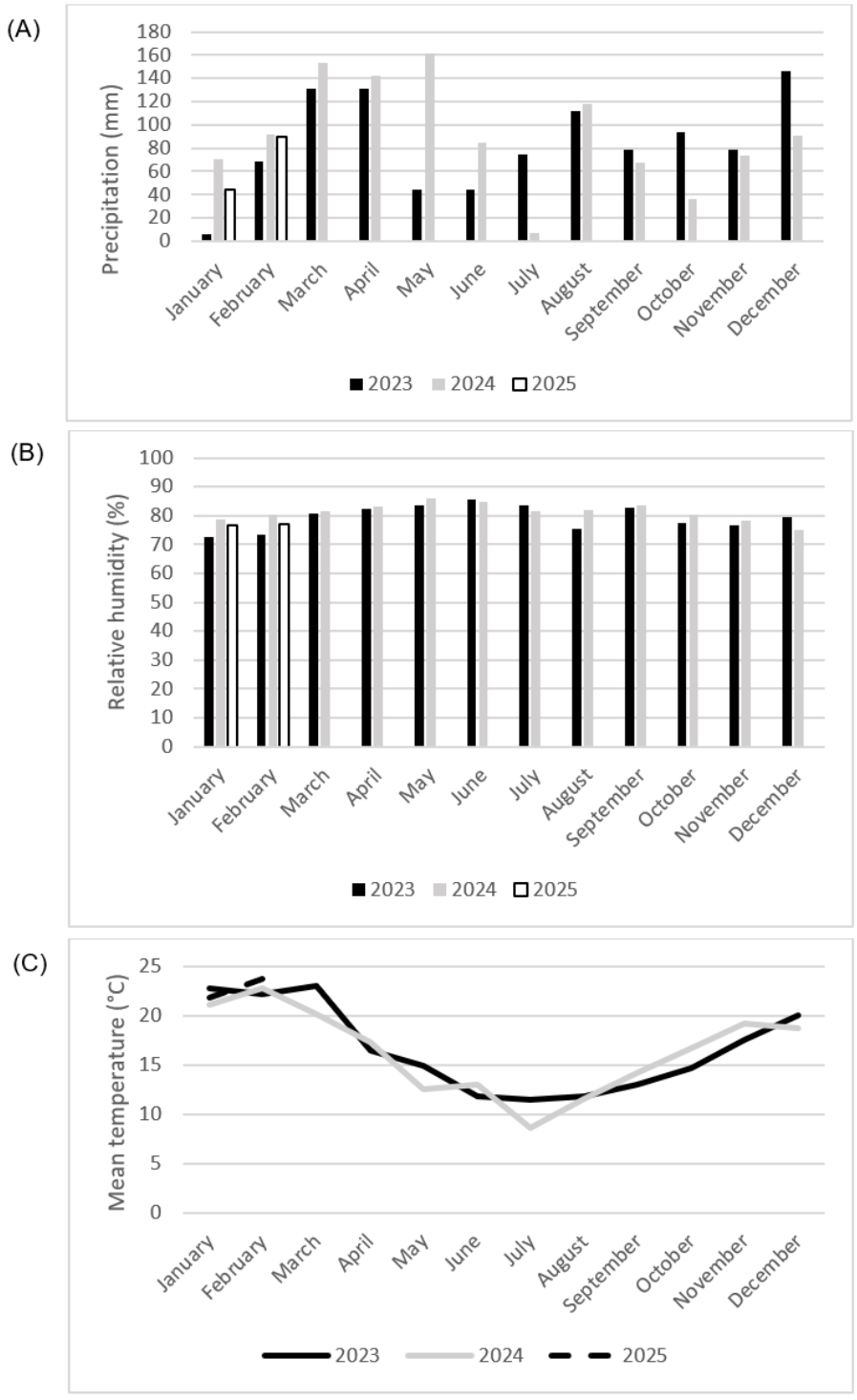

Figure 1. Monthly accumulated precipitation (mm) (A), monthly average relative humidity (%) (B), and mean air temperature (°C) (C), recorded from January 2023 to February 2025

Data recorded by "INUMET" (n.d.).

The farm has an olive mill with a capacity of 500 kg/hour, processing 500 t of olives per season of the Arbequina, Coratina, and Picual cultivars. The olive mill operates under a two-phase system, where a liquid phase is obtained, corresponding to olive oil, and another phase consisting of the combination of vegetation water (alpechín) and pulp and ground olive pit (orujo), known as alperujo. In three-phase olive mills, the vegetation water is separated from the orujo and the oil. In the present study, a field filtration was carried out to obtain the alpechín separately from the orujo. The alperujo, a by-product generated during the milling, was deposited in a waterproofed-bottom outdoor storage pond. To verify the adequate waterproofing, a study of soil infiltration in the storage pond was carried out using the double ring method (Reynolds et al., 2002). The measured infiltration rate was below 1×10^{-7} cm s^{-1}, which complies with the limit established by Ministerio de Vivienda, Ordenamiento Territorial y Medio Ambiente (2014), within the regulatory framework of the Environmental Impact Assessment Law 16,466 and the Water Code Law 14,859, aimed at preventing leachate infiltration.

Through a field filtration system and the use of a pump, the liquid phase, corresponding to the alpechín, was separated and transferred to an adjacent pond, previously waterproofed by soil compaction. The pond was located in the open field, at a high altitude, receiving only direct precipitation inputs, with a water surface area of 600 m^2. The alpechín was left in the pond for a period of six months, hereafter referred to as "aged alpechín". In addition, water from a nearby stream was monitored in the vicinity of the storage pond to verify that the system did not cause contamination. No alterations in the quality of the water were detected, showing that the waterproofing of the pond was adequate. The monitored values of stream water variables in March (before the disposal of the alperujo in the pond) and in August (after five months of storage of the alperujo and alpechín in the pond) were: BOD_5 of 3 to 5 mg/L O2; pH 6.7 to 7.1; electrical conductivity from 0.095 to 0.120 dS/m; total nitrogen from 2 to 3 mg/L of N; total phosphorus 0.1 mg/L of P, and total potassium 6.1 to 8.9 mg/L of K.

After a six-month storage period, the alpechín was used to establish the present experiment in a 12-year-old Arbequina olive grove in December 2023. This procedure was repeated in December 2024, using the alpechín generated during the autumn of the same year.

Physicochemical parameters of the alpechín and the water used as a control were analyzed. The analytical techniques used to analyze the alpechín were based on the A.P.H.A. standard methods and included: 4500-H B (pH), 2510 B (electrical conductivity), 5210 B (BOD_5), 5220 D (COD), 4500-N C (total nitrogen), 4500-P E (total phosphorus), 3111 B (potassium), 2540 B (total solids), 5520 D (fats and oils), and 5530 C (phenolic compounds) (American Public Health Association, 1992).

2.2 Experimental Design and Statistical Analysis

The experiment was conducted under a completely randomized design, with five replications and two treatments. The first treatment consisted of the application of 50 liters of alpechín per tree, divided into two applications with an interval of 15 days. The second treatment, used as a control, consisted of the application of 50 liters of water per tree under the same conditions. The first application was made at the end of December and the second at the beginning of January, on the same trees in both seasons. The experimental unit consisted of five trees per plot, evaluating the three central trees.

Before the installation of the experiment and after two months of the application of the treatments, soil and foliar analyses were conducted for both years of the study. Soil samples were collected along the tree row, within the root zone, at a depth of 10 cm. The following were determined: N, P, K, Ca, Mg, organic carbon, Ph, and electrical conductivity. After the initial analysis was carried out in September 2023, the producer applied a uniform soil management practice across the entire plot, consisting of compost at a rate of 10 t/ha and phosphorite at 120 kg/ha; therefore, soil phosphorus was not considered in the analysis. Foliar analysis was conducted by

collecting 200 healthy leaves from the current season's growth, taken from the middle section of the shoots. The following elements were determined: N, P, K, Ca, Mg, Cu, Fe, Zn, and B.

To determine vegetative growth, four shoots per tree were marked in the four cardinal directions before the application of the treatments, in the three central trees of each experimental unit. The length was measured, and the number of nodes on each shoot was counted; these measurements were repeated two months after the treatments were applied.

An analysis of variance (ANOVA) was performed on the variables vegetative growth (cm) and number of nodes, considering the alpechín application treatment in each season. ANOVA was also applied to foliar and soil data by treatment, analyzing each season separately and comparing only the initial sampling with the final sampling. For the comparison of means, Tukey's test was applied at a significance level of $p \leq 0.05$. In all cases, the statistical software used was InfoStat version 2020.

3. Results

Table 1 presents the physicochemical composition of alperujo (initial material), according to the range found in the 2023 and 2024 seasons, where the mineral content of the macronutrients is observed, highlighting the contribution of K and N; while P, Ca, and Mg are present at low levels. The material exhibits high content of organic carbon, over 50%. The pH is acidic, with values ranging between 4.6 and 5.4, while the electrical conductivity is between 1.4 and 2.2 dS/m, remaining below the threshold value of 3 dS/m established by the national regulations for the use of waste as soil improvers (Dirección Nacional de Medio Ambiente, 2018). The results also indicate high levels of phenolic compounds and oil content, which confirms its classification as a product that can cause a negative impact if it is applied directly into the environment.

Table 1. Physical and chemical composition of the alperujo corresponding to the 2023 and 2024 harvests, obtained from the Olivos de las Ánimas olive mill, Uruguay

Parameter evaluated	Range
Total nitrogen (% N)	0.8 - 1.7
Total phosphorus (% P_2O_5)	0.1 - 0.2
Total potassium (% K_2O)	0.8 - 1.4
Organic carbon (%)	51.7 - 56.8
Calcium (%)	0.1 - 0.2
Magnesium (%)	0.03 - 0.06
Electrical conductivity (dS/m)	1.4 - 2.2
pH	4.6 - 5.4
Phenols on a dry basis (g/kg)	1.4 - 2.9
Oils and fats (%)	1.4 - 4.6

The physicochemical composition of fresh alpechín, that is, immediately after olive oil production, was also analyzed. That alpechín remained in the stabilization pond for six months. The values of fresh and aged alpechín in the 2023 and 2024 seasons are presented in Table 2. It can be observed that the levels of chemical and biochemical oxygen demand decrease markedly during the stabilization period. BOD decreased by 7 to 29 times, and COD decreased by 5 to 21 times. In turn, electrical conductivity also decreased between 4.4 and 5.7 times after storage. The pH, initially around 5.2, increased after storage, reaching values between 5.9 and 6.8. The total solids content was high at first and then decreased over time, probably due to sedimentation. A notably

high K content was observed in fresh alpechín of 1130 mg/l. The values of N, P, and K decreased after the storage period.

Table 2. Physical and chemical characteristics of fresh alpechín (at the time of production) and aged alpechín (after 6 months in stabilization ponds) from the 2023 and 2024 harvest seasons, obtained from the Olivos de las Ánimas olive mill, Uruguay

Parameters evaluated	Fresh alpechín	Aged alpechín range 2023-2024
BOD_5 (mg/L O2)	16300	550 - 2200
COD (mg/L O2)	32700	1500 - 6650
Electrical conductivity (dS/m)	9.7	1.7 - 2.2
pH	5.2	5.9 - 6.8
Total solids (mg/L)	26000	2150 - 5200
Total nitrogen (mg/L N)	160	22 - 98
Total phosphorus (mg/L P)	176	17 - 38
Potassium (mg/L K)	1130	413 - 630

The physicochemical composition of the soil before the installation of the experiment (initial) and after two months of applying both the control treatment with water and the alpechín irrigation, for the 2023 and 2024 seasons, is presented in Table 3. The soil exhibited a high cation exchange capacity and a high percentage of base saturation, with similar values in both treatments and seasons. The pH showed low values of around 5.1. It also presented high levels of organic carbon and medium levels of nitrogen, with similar values across treatments and seasons. Only K levels were significantly higher in the alpechín treatment compared to the water control at the end of the 2024 season. The rest of the analyzed parameters did not show significant differences between treatments in either of the seasons.

Table 3. Physicochemical composition of the soil before and after the application of irrigation treatments with alpechín and water control in two seasons (2023 and 2024)

		Ca	Mg	K	Na	Tit. Ac.	CICpH7	T. Bases	% Sat	pH	Org. C	N
Season	Treatment*	Meq/100g	Meq/100g	Meq/100g	Meq/ 100g	Meq/100g	Meq/100g	Meq/100g	Bases	(H2O)	%	%
2023	Initial	6.8	2.7	0.6	0.18	3.7	14.0	10.3	73.5	5.52	2.28	0.18
	Final water	9.9	2.9	2.0	0.28	5.4	20.5	15.2	74.0	5.11	4.06	0.24
	Final alpechín	10.2	3.0	2.4	0.24	5.5	21.3	15.9	74.4	5.08	3.53	0.22
2024	Initial water	9.2	2.7	1.0	0.12	4.7	17.4	13.0	75.0	5.36	2.80	0.24
	Initial alpechín	9.7	2.7	0.9	0.12	4.5	17.9	13.4	75.0	5.39	2.89	0.24
	Final water	9.2	2.1	1.0b	0.14	5.2	17.6	12.4	70.4	5.44	3.16	0.29
	Final alpechín	9.5	2.2	1.3a	0.13	4.9	18.0	13.1	72.7	5.49	3.37	0.29

The values represent the average of five replicates. * No significant differences were found between treatments, considering each season separately and the initial and final sampling, according to Tukey's test, with a significance level of $p \leq 0.05$. Only K values were significantly different at the final sampling of 2024.

Shoot growth two months after the installation of the experiment did not present significant differences between the control treatment with water and the irrigation with alpechín, in either of the seasons (Figure 2 A and B). In 2023, shoot length ranged from 6.2 to 7.9 cm, and the number of nodes ranged from 4.3 to 5.2, while in the 2024 season, values were lower, since the trees had a high fruit load (on year), whereas in 2023 they had a low fruit load (off year). Shoot growth values in the second season were between 2.3 and 3.4, and the number of nodes was between 2.3 and 3.1.

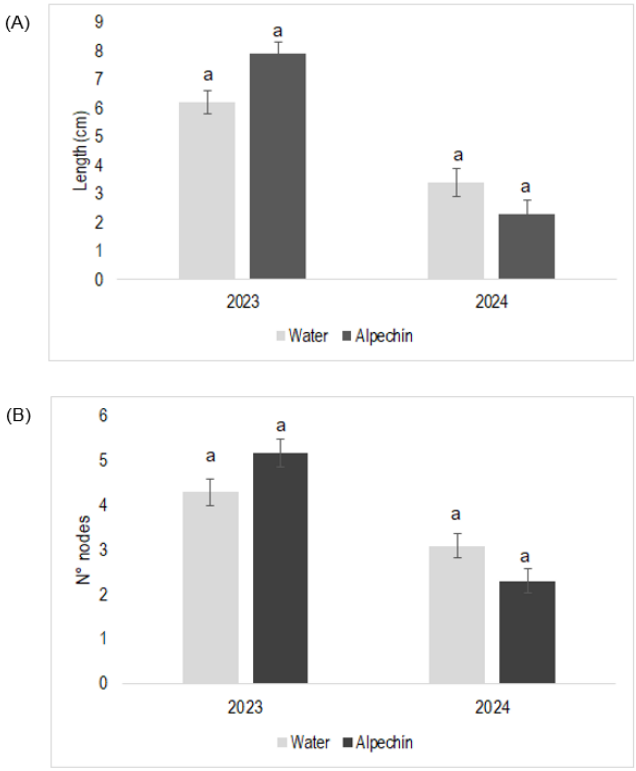

Figure 2. Shoot growth of Arbequina olive groves (A) and number of nodes (B) two months after the application of irrigation treatments with aged alpechín and water control, over two consecutive seasons (2023-2024)

Bars with the same letters are not significantly different according to Tukey's test ($p \leq 0.05$) for each variable and each year separately.

When analyzing the initial foliar composition of the olive trees in the 2023 season (Table 4), it was observed that the N level was within the optimal range according to the reference interpretation tables (Freeman et al., 1994). The content of K and P was close to the upper limit, while the Ca and Mg contents were below the lower limit. Regarding micronutrients, Cu, Fe, and Zn were close to the optimum, and B was at the lower limit. After the treatments were applied, there were no differences between the water control and the treatment irrigated with aged alpechín. Values remained similar to the initial levels before treatment applications. Some small variations were observed, but these were not attributed to treatment effects and may instead be related to changes in the phenological stage of the olive trees. In the 2024 season, after the treatments were applied, the levels of N and K were close to optimal, while P content was at the upper limit, presenting similar values in both treatments. The Ca content was within the optimal range, while the Mg content was close to the lower limit. Regarding micronutrients, Cu and Fe were close to the optimum, and Zn and B were below the lower limit.

Table 4. Foliar mineral composition in olive trees before irrigation with alpechín and after applying irrigation treatments, aged alpechín, and control (water) over two seasons (2023 and 2024)

Season	Treatment*	Ca %	Mg %	K %	P %	N %	B mg/kg	Cu mg/Kg	Fe mg/kg	Zn mg/kg
2023	Initial water and alpechín	0.82	0.08	1.42	0.18	1.85	18.5	12.4	80.3	26.0
	Final water	0.89	0.08	1.35	0.18	1.50	18.6	10.1	57.6	18.0
	Final alpechín	0.80	0.08	1.30	0.19	1.52	17.2	10.0	53.0	16.8
2024	Initial water	0.94	0.09	1.00	0.17	1.61	23.3	7.8	47.5	10.9
	Initial alpechín	0.92	0.09	1.00	0.17	1.56	20.8	8.2	41.5	10.3
	Final water	1.36	0.11	1.13	0.23	1.76	18.2	6.3	35.6	9.0
	Final alpechín	1.46	0.12	1.09	0.23	1.73	18.2	6.3	49.4	9.5

The values represent the mean of three replicates. * No significant differences were found between treatments, considering each season and the initial and final sampling separately, according to Tukey's test, with a significance level of $p \leq 0.05$.

4. Discussion

The present study evaluated the effects of applying alpechín aged for six months on vegetative growth, the nutritional status of Arbequina olive trees, and changes in soil nutrients in Uruguay. The results indicate that the application of alpechín did not produce phytotoxic effects in the plants under the experimental conditions, which is attributed to the reduction of the organic load of the material during the six-month stabilization period. During that time, the storage pond served as a stabilization pond, facilitating sedimentation and degrading contaminants, possibly due to microbial activity and exposure to sunlight. In addition, the natural addition of rainwater contributed to its dilution, reducing its potential environmental impact. This sustainable waste management strategy represents a cost-effective and easily implementable solution for producers.

The alpechín is produced seasonally, in a short period after the olive harvest, during winter, when evapotranspiration is low and rainfall is frequent (Castaño et al., 2011). If applied directly to the field, the alpechín may lead to surface runoff, particularly when soils are saturated. The application of fresh alpechín can generate phytotoxicity due to phenolic compounds, salinity, or groundwater contamination (Chatzistathis & Koutsos, 2017; Dermeche et al., 2013). In other semi-arid production areas, successive winter applications of alperujo (residue obtained from two-phase centrifuges) have shown positive effects on olive yield and on the physical, chemical, and biochemical properties of the soil, with doses of up to 30 m³/ha (López-Piñeiro et al., 2011). However, the potential for contamination through leaching under humid climatic conditions such as those in Uruguay remains unclear.

The strategy evaluated in this study consisted of storing the alpechín in a pond, allowing its stabilization before its application in spring and summer, when the atmospheric demand of the crop is higher. In Uruguay, rainfall is highly variable both within and between years, with periods of water deficit (Conde-Innamorato et al., 2022). In this context, the alpechín may serve as a complementary source of water, partially contributing to the water requirements of olive trees. A preliminary evaluation in vitro on lettuce seeds determined the phytotoxic effect of alpechín at high BOD concentrations. The control treatment with water and the 1:10 dilution showed a germination of 83% of the seeds at 24 h. While the treatments with higher concentrations resulted in 55% germination or no germination (1:4 dilution and pure alpechín) for the same period of time (data not shown).

Research has shown that the effect of alpechín irrigation on plant growth varies according to the dose applied (Magdich & Ammar, 2022; Mechri et al., 2011; Ouzounidou et al., 2008), soil type (Ouzounidou et al., 2008), and plant species involved (Belaqziz et al., 2008; Kapellakis et al., 2015; Ouzounidou et al., 2008). The dose applied in this study did not generate significant differences in shoot growth between treatments (Figure 2). These results suggest that the aged alpechín did not stimulate or inhibit the vegetative growth of the olive trees under the evaluated conditions. This lack of response could be associated with the low dose applied (two applications of 50 L/plant = 30 m³/ha), which, although it provides potentially beneficial organic and mineral compounds that may enhance the biological activity of the soil (Sierra et al., 2007), would not have been sufficient to produce a measurable effect on vegetative growth during the evaluation period. Likewise, given that the largest proportion of olive tree vegetative growth occurs in spring (Iglesias et al., 2024; Pierantozzi et al., 2020), the timing of application could have limited the expression of responses. Finally, the adequate nutritional status of the plants, with nutrient concentrations within optimal ranges, indicates that nutrition was not a limiting factor, explaining the lack of response in the evaluated growth parameters.

One of the risks of using alpechín as a fertilizer is the potential contamination of the soil and infiltration waters (Sierra Llopart et al., 2000). Therefore, it is essential to consider soil type and to evaluate appropriate application strategies. In this study, the experiment was conducted on a clayey Brunosol soil, a physical characteristic that represents an advantage for the construction of waterproof storage ponds for the alpechín. The results confirmed that the storage system was adequate, without causing contamination of the nearby water stream.

Soil analysis indicated a fertile soil with a high percentage of base saturation and high organic carbon content. It is possible that in soils with a lower buffer capacity, responses to the application of alpechín may differ from those found in this type of soil. The application of alpechín in a sandy loam soil in Córdoba, Argentina, increased the content of organic matter, organic carbon, total nitrogen, and extractable phosphorus, recommending doses of 80 m³/ha for this semi-arid region (Pierantozzi et al., 2013). Similarly, it has been reported that doses of 100 m³/ha of alpechín applied annually for 10 years improved soil fertility (Rouina et al., 2006). In contrast, in Catalonia, Spain, a maximum limit of 30 m³/ha per year has been established for the use of alpechín as fertilizer in agricultural soils (Sierra Llopart et al., 2000), while in Uruguay, there is no legislation on the application rates of alpechín. Under the doses used in this study, no significant changes were found in the main soil nutrients, except for K in the second season. Consistently, other studies have reported significant increases in potassium availability, which improved soil fertility (Magdich et al., 2013).

A relevant aspect of the study is its contribution to the environmental management of alpechín, a waste that represents a significant challenge for the olive industry. Given the scale and seasonal volumes of alpechín generated in Uruguay, its integral use within the olive production system, through its use as fertigation, would be sufficient. In this way, it would be valorized, shifting from being a problematic waste to a resource with agronomic value, since it can be reused as an input. Nevertheless, it is essential to continue exploring the long-term effects of its application on both soil and plants to ensure the sustainability of this practice. In this context, this study represents an important contribution to the Uruguayan olive sector by proposing a viable solution for the management of alpechín based on experimental data. However, the lack of significant effects on the evaluated parameters highlights the need to optimize application frequency and dosage, to maximize the potential benefits of this coproduct in olive cultivation.

5. Conclusions

The alpechín coproduct, under the conditions evaluated, is presented as an environmentally viable alternative, since its use does not generate negative effects on soil or crop development, and it is also feasible for its application in olive cultivation. However, the two applications conducted in the summer with aged alpechín were not sufficient to show significant differences in either vegetative growth or foliar nutritional analysis, indicating the absence of phytotoxicity. Likewise, no significant changes were observed in the main soil nutrients as a result of the applications. Further studies are needed, increasing the frequency of applications to assess long-term effects. This study provides scientific evidence, generated under local conditions, that supports the valorization of alpechín as a coproduct with potential for on-farm use within the system where it is generated.

Acknowledgements

This research was funded by the Instituto Nacional de Investigación Agropecuaria (National Institute of Agricultural Research, INIA, Uruguay) (DRT Project: Alperujo Management System). The authors gratefully acknowledge the Olivos de las Ánimas establishment for their collaboration and continuous support of this research.

Transparency of Data

Available data: The entire data set that supports the results of this study was published in the article itself.

Author Contribution Statement

	P Conde-Innamorato	JJ Villamil	D Bianchi	M Trujillo	C Fasiolo	GP García-Inza
Conceptualization	■	■				■
Data curation	■	■	■			
Funding acquisition	■			■	■	■
Investigation	■	■	■			■
Methodology	■	■	■			■
Project administration	■					
Writing – original draft	■					■
Writing – review and editing	■	■	■	■	■	■

References

Abril, A., Noe, L., & Filippini, M. F. (2014). Manejo de enmiendas para restaurar la materia orgánica del suelo en oasis de regadío de Mendoza, Argentina. *Revista de Investigaciones Agropecuarias*, *40*(1), 83-91. https://www.scielo.org.ar/scielo.php?script=sci_arttext&pid=S1669-23142014000100013&lng=es&tlng=es

American Public Health Association. (1992). *Standard methods for the examination of water and wastewater* (18th ed.).

Belaqziz, M., Lakhal, E. K., Mbouobda, H. D., & El Hadrami, I. (2008). Land spreading of olive mill wastewater: Effect on maize (*Zea mays*) crop. *Journal of Agronomy, 7*(4), 297-305. https://doi.org/10.3923/ja.2008.297.305

Castaño, J. P., Giménez, A., Ceroni, M., Furest, J., & Aunchayna, R. (2011). *Caracterización agroclimática del Uruguay 1980–2009*. INIA. https://ainfo.inia.uy/digital/bitstream/item/2538/1/18429021211104157.pdf

Chartzoulakis, K., Psarras, G., Moutsopoulou, M., & Stefanoudaki, E. (2010). Application of olive mill wastewater to a Cretan olive orchard: Effects on soil properties, plant performance and the environment. *Agriculture, Ecosystems & Environment, 138*(3-4), 293-298. https://doi.org/10.1016/j.agee.2010.05.014

Chatzistathis, T., & Koutsos, T. (2017). Olive mill wastewater as a source of organic matter, water and nutrients for restoration of degraded soils and for crops managed with sustainable systems. *Agricultural Water Management, 190*, 55-64. https://doi.org/10.1016/j.agwat.2017.05.008

Comisión Nacional del Agua. (2007). *Manual de agua potable, alcantarillado y saneamiento: Diseño de lagunas de estabilización*. http://www.conagua.gob.mx/CONAGUA07/Publicaciones/Publicaciones/Libros/10DisenoDeLagunasDeEstabilizacion.pdf

Conde-Innamorato, P., García, C., Villamil, J. J., Ibáñez, F., Zoppolo, R., Arias-Sibillotte, M., Ponce De León, I., Borsani, O., & García-Inza, G. P. (2022). The impact of irrigation on olive fruit yield and oil quality in a humid climate. *Agronomy*, *12*(2), Article 313. https://doi.org/10.3390/agronomy12020313

Cuevas, B. J., Seguel, S. O., Ellies, S. A., & Dörner, F. J. (2006). Efectos de las enmiendas orgánicas sobre las propiedades físicas del suelo con especial referencias a la adición de lodos urbanos. *Revista de la Ciencia del Suelo y Nutrición Vegetal*, *6*(2), 1-12. https://dx.doi.org/10.4067/S0718-27912006000200001

de Heredia Alonso, J. B., Torregrosa Antón, J., García Rodríguez, J., Ramos Viseas, M. del P., & Domínguez Vargas, J. R. (2000). Tratamiento biológico aerobio de alpechín depurado previamente con ozono. *Grasas y Aceites*, *51*(5), 332-339. https://doi.org/10.3989/gya.2000.v51.i5.434

De La Casa, J. A., Romero, I., Jiménez, J., & Castro, E. (2012). Fired clay masonry units production incorporating two-phase olive mill waste (*alperujo*). *Ceramics International, 38*(6), 5027-5037. https://doi.org/10.1016/j.ceramint.2012.03.003

del Águila Pérez, F. J. (1996). Tratamientos de alpechines: Comparación de los distintos métodos. *Agricultura: Revista Agropecuaria*, (767), 516-519. https://www.mapa.gob.es/ministerio/pags/biblioteca/revistas/pdf_Agri%2FAgri_1996_767_516_519.pdf

Dermeche, S., Nadour, M., Larroche, C., Moulti-Mati, F., & Michaud, P. (2013). Olive mill wastes: Biochemical characterizations and valorization strategies. *Process Biochemistry, 48*(10), 1532-1552. https://doi.org/10.1016/j.procbio.2013.07.010

Dirección Nacional de Medio Ambiente. (2018). *Decreto No. 182/013: Pauta técnica para el uso de residuos como mejoradores de suelo* (versión borrador). https://www.gub.uy/ministerio-ambiente/comunicacion/publicaciones/pauta-tecnica-para-uso-residuos-mejoradores-suelo

Environmental Protection Agency. (2004). *Guidelines for Water Reuse*. https://www.epa.gov/sites/default/files/2019-08/documents/2004-guidelines-water-reuse.pdf

Freeman, M., Uriu, K., & Hartmann, H. T. (1994). Diagnosing and correcting nutrient problems. In *Olive production manual* (pp. 77-86). University of California.

Hanifi, S., & El-Hadrami, I. (2009). Olive mill wastewaters: Diversity of the fatal product in olive oil industry and its valorisation as agronomical amendment of poor soils: A review. *Journal of Agronomy, 8*(1), 1-13. https://doi.org/10.3923/ja.2009.1.13

Iglesias, M. A., Rousseaux, M. C., & Searles, P. S. (2024). Deficit irrigation and warming during the late winter and spring affect vegetative growth and reproductive development in young olive trees. *Irrigation Science, 42*, 815-828. https://doi.org/10.1007/s00271-024-00935-5

INUMET. (n.d.). In *Catálogo de datos abiertos*. https://catalogodatos.gub.uy/organization/inumet?page=2

Kapellakis, I., Tzanakakis, V. A., & Angelakis, A. N. (2015). Land application-based olive mill wastewater management. *Water*, *7*(2), 362-376. https://doi.org/10.3390/w7020362

López-Piñeiro, A., Albarrán, A., Nunes, J. M. R., Peña, D., & Cabrera, D. (2011). Cumulative and residual effects of two-phase olive mill waste on olive grove production and soil properties. *Soil Science Society of America Journal*, *75*, 1061-1069. https://doi.org/10.2136/sssaj2010.0230

Lozano-García, B., Parras-Alcántara, L., & del Toro Carrillo de Albornoz, M. (2011). Effects of oil mill wastes on surface soil properties, runoff and soil losses in traditional olive groves in southern Spain. *Catena, 85*(3), 187-193. https://doi.org/10.1016/j.catena.2011.01.017

Magdich, S., & Ammar, E. (2022). Agronomic olive bio-waste management: Combination of olive mill wastewater spreading and compost amendment—Effects on soil properties and olive tree performance. In M. F. Ramadan & M. A. Farag (Eds.), *Mediterranean fruits bio-wastes* (pp. 91-114). Springer. https://doi.org/10.1007/978-3-030-84436-3_5

Magdich, S., Ben Ahmed, C., Jarboui, R., Ben Rouina, B., Boukhris, M., & Ammar, E. (2013). Dose and frequency dependent effects of olive mill wastewater treatment on the chemical and microbial properties of soil. *Chemosphere*, *93*(9), 1896-1903. https://doi.org/10.1016/j.chemosphere.2013.06.066

Mechri, B., Cheheb, H., Boussadia, O., Attia, F., Ben Mariem, F., & Braham, M. (2011). Effects of agronomic application of olive mill wastewater in a field of olive trees on carbohydrate profiles, chlorophyll a fluorescence and mineral nutrient content. *Environmental and Experimental Botany, 71*(2), 184-191. https://doi.org/10.1016/j.envexpbot.2010.12.004

Mekersi, N., Addad, D., & Kadi, K. (2023). Effects of olive mill wastewater and olive mill pomace on soil physicochemical properties and soil polyphenols. *Journal of Material Cycles and Waste Management, 25*, 1404-1416. https://doi.org/10.1007/s10163-023-01618-7

Mekki, A., Dhouib, A., & Sayadi, S. (2013). Effects of olive mill wastewater application on soil properties and plant growth: A review. *International Journal of Recycling of Organic Waste in Agriculture, 2*(1), Article 15. https://doi.org/10.1186/2251-7715-2-15

Ministerio de Vivienda, Ordenamiento Territorial y Medio Ambiente. (2014). *Decreto N° 162/014: Fijación de las condiciones ambientales aplicables a establecimientos de engorde de bovinos a corral con destino a faena: Modificacion del reglamento de evaluación de impacto ambiental y autorizaciones ambientales.* IMPO. https://www.impo.com.uy/bases/decretos/162-2014

Muscolo, A., Sidari, M., Mallamaci, C., & Attinà, E. (2010). Effects of olive mill wastewater on seed germination and seedling growth. *Terrestrial and Aquatic Environmental Toxicology, 4*(1), 75-83.

Oficina de Estadísticas Agropecuarias. (2023). *Resultados del censo nacional de olivos 2023*. MGAP. https://www.gub.uy/ministerio-ganaderia-agricultura-pesca/comunicacion/noticias/diea-presenta-resultados-del-censo-nacional-olivos-2023

Ouzounidou, G., Asfi, M., Sotirakis, N., Papadopoulou, P., & Gaitis, F. (2008). Olive mill wastewater triggered changes in physiology and nutritional quality of tomato (Lycopersicon esculentum mill) depending on growth substrate. *Journal of Hazardous Materials*, *158*(2-3), 523-530. https://doi.org/10.1016/j.jhazmat.2008.01.100

Paredes, C., Cegarra, J., Roig, A., Sánchez-Monedero, M. A., & Bernal, M. P. (1999). Characterization of olive mill wastewater (alpechin) and its sludge for agricultural purposes. *Bioresource Technology, 67*(2), 111-115. https://doi.org/10.1016/S0960-8524(98)00106-0

Pierantozzi, P., Torres, M., Tivani, M., Contreras, C., Gentili, L., Parera, C., & Maestri, D. (2020). Spring deficit irrigation in olive (cv. Genovesa) growing under arid continental climate: Effects on vegetative growth and productive parameters. *Agricultural Water Management, 238,* Article 106212. https://doi.org/10.1016/j.agwat.2020.106212

Pierantozzi, P., Torres, M., Verdenelli, R., Basanta, M., Maestri, D. M., & Meriles, J. M. (2013). Short-term impact of olive mill wastewater (OMWW) applications on the physico-chemical and microbiological soil properties of an olive grove in Argentina. *Journal of Environmental Science and Health B, 48*(5), 393-401. https://doi.org/10.1080/03601234.2013.742398

Reynolds, W. D., Elrick, D. E., Youngs, E. G., Amoozegar, A., & Booltink, H. W. G. (2002). Saturated and field-saturated water flow parameters. In J. H. Dane & G. C. Topp (Eds.), *Methods of soil analysis: Part 4: Physical methods* (pp. 797-878). Soil Science Society of America.

Rouina, B., Gargouri, K., Abichou, M., & Taamallah, H. (2006). Mill wastewater as an ecological fertilizer for olive tree orchards. In *Olivebioteq 2006: Second International Seminar: Biotechnology and Quality of Olive Tree Products Around the Mediterranean Basin: Proceedings* (pp. 139-142).

Rusan, M. J. M., Albalasmeh, A. A., & Malkawi, H. I. (2016). Treated olive mill wastewater effects on soil properties and plant growth. *Water, Air, and Soil Pollution, 227*, Article 135. https://doi.org/10.1007/s11270-016-2837-8

Rusan, M. J., Albalasmeh, A. A., Zuraiqi, S., & Bashabsheh, M. (2015). Evaluation of phytotoxicity effect of olive mill wastewater treated by different technologies on seed germination of barley (Hordeum vulgare L.). *Environmental Science and Pollution Research International*, *22*(12), 9127-9135. https://doi.org/10.1007/s11356-014-4004-3

Sierra, J., Martí, E., Garau, M. A., & Cruañas, R. (2007). Effects of the agronomic use of olive oil mill wastewater: Field experiment. *The Science of the Total Environment*, *378*(1-2), 90-94. https://doi.org/10.1016/j.scitotenv.2007.01.009

Sierra Llopart, J., Martí Vergé, E., Montserrat Bueno, G., & Gili Gaya, M. (2000). Aprovechamiento del alpechín a través del suelo: Estimación del posible impacto sobre las aguas de infiltración. *Edafología, 7*(2), 91-102.