

INTEGRATED EVALUATION OF SOIL PROPERTIES AND CROP RESPONSE TO TREATED DAIRY WASTEWATER IRRIGATION

ÉVALUATION INTÉGRÉE DES PROPRIÉTÉS DU SOL ET DE LA RÉACTION DES CULTURES À L'IRRIGATION AVEC DES EAUX USÉES LAITIÈRES TRAITÉES

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ABSTRACT

Morocco, like many Mediterranean countries, faces increasing water scarcity due to recurrent droughts, creating significant challenges for agricultural production and food security. In this context, the reuse of treated wastewater offers a sustainable alternative for irrigation. This study evaluated the short-term effects of treated dairy industry wastewater "whitewater" on soil chemical properties, crop performance, and ecophysiological responses of oat (*Avena sativa* L.) and triticale ($\times$ Triticosecale) under field conditions. A field experiment was conducted in November 2024 using a randomized complete block design with four replicates. Three irrigation treatments were applied: T₁ (100% treated whitewater), T_{1/2} (50% treated whitewater + 50% conventional water), and T₀ (100% conventional water). Soil pH, electrical conductivity (EC), nitrogen content, plant growth, biomass yield, and physiological parameters were assessed. In both crops, whitewater irrigation significantly increased soil pH and EC compared with the control, reflecting the higher ionic content of the effluent. In oat, these changes did not affect plant growth, chlorophyll content, leaf water potential, or biomass yield, which remained comparable across treatments. Similarly, triticale showed no significant differences in morphological traits or biomass production. However, triticale exhibited higher sodium accumulation under T₁ and significant changes in chlorophyll content and stomatal conductance, indicating greater physiological sensitivity to the effluent's salinity. Despite these responses, treated whitewater did not reduce biomass productivity in either species during the experimental period, demonstrating its short-term agronomic potential. Nevertheless, the observed sodium accumulation and species-specific physiological responses highlight the need for long-term monitoring to prevent salinity buildup and ionic imbalance. Overall, the results support the reuse of treated dairy wastewater as a sustainable irrigation resource, contributing to water conservation, resource efficiency, and circular water management in drought-prone agricultural systems.

Keywords: Whitewater, Wastewater, Reuse, *Avena sativa* L., Triticosecale.

RÉSUMÉ

Le Maroc, à l'instar de nombreux pays méditerranéens, est confronté à une pénurie d'eau croissante due à des sécheresses récurrentes, ce qui pose des défis importants pour la production agricole et la sécurité alimentaire. Dans ce contexte, la réutilisation des eaux usées traitées offre une alternative durable pour l'irrigation. Cette étude a évalué les effets à court terme des eaux usées traitées issues de l'industrie laitière (« eaux blanches ») sur les propriétés chimiques du sol, le rendement des cultures et les réponses écophysologiques de l'avoine (*Avena sativa* L.) et du triticale ($\times$ Triticosecale) en conditions de plein champ. Une expérience en plein champ a été menée en novembre 2024 selon un plan en blocs complets randomisés avec quatre répétitions. Trois traitements d'irrigation ont été

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appliqués : T1 (100 % d'eaux blanches traitées), T1/2 (50 % d'eaux blanches traitées + 50 % d'eau conventionnelle) et T0 (100 % d'eau conventionnelle).

Le pH du sol, la conductivité électrique (CE), la teneur en azote, la croissance des plantes, le rendement en biomasse et les paramètres physiologiques ont été évalués. Pour les deux cultures, l'irrigation à l'eau blanche a augmenté de manière significative le pH et la CE du sol par rapport au témoin, ce qui reflète la teneur ionique plus élevée de l'effluent. Pour l'avoine, ces modifications n'ont pas affecté la croissance des plantes, la teneur en chlorophylle, le potentiel hydrique foliaire, ni le rendement en biomasse, qui sont restés comparables entre les traitements. De même, le triticale n'a présenté aucune différence significative au niveau des caractères morphologiques ou de la production de biomasse. Cependant, le triticale a présenté une accumulation de sodium plus élevée sous le traitement T1 ainsi que des changements significatifs de la teneur en chlorophylle et de la conductance stomatique, indiquant une plus grande sensibilité physiologique à la salinité de l'effluent.

Malgré ces réponses, l'eau blanche traitée n'a pas réduit la productivité en biomasse chez l'une ou l'autre des espèces au cours de la période expérimentale, démontrant ainsi son potentiel agronomique à court terme. Néanmoins, l'accumulation de sodium observée et les réponses physiologiques spécifiques à chaque espèce soulignent la nécessité d'un suivi à long terme afin de prévenir l'accumulation de salinité et le déséquilibre ionique. Dans l'ensemble, les résultats plaident en faveur de la réutilisation des eaux usées laitières traitées comme ressource d'irrigation durable, contribuant ainsi à la conservation de l'eau, à l'efficacité des ressources et à la gestion circulaire de l'eau dans les systèmes agricoles sujets à la sécheresse.

Mots-clés. Eaux blanches, Eaux usées, Réutilisation, *Avena sativa* L., *Triticosecale*.

1. INTRODUCTION

Agricultural systems in Mediterranean regions, particularly in Morocco, are increasingly challenged by recurrent and prolonged drought events driven by climate change. Morocco is currently among the most water-stressed countries worldwide, with a persistent decline in precipitation and a growing frequency of drought episodes (Khomsi *et al.*, 2016). These climatic constraints exert considerable pressure on agricultural productivity and represent a major threat to national food security. In water-limited environments, agricultural development is occurring under conditions of increasing scarcity of both surface and groundwater resources, leading to the progressive overexploitation of aquifers (Cramer, 2018). Although irrigation has significantly contributed to enhancing crop yields and agricultural production over recent decades, its expansion has intensified groundwater abstraction, resulting in a substantial decline in water table levels and raising concerns regarding the long-term sustainability of water resources (Abdelmajid *et al.*, 2021).

In response to these challenges, the agricultural reuse of treated wastewater (TWW) has emerged as a strategic component of integrated water resource management (Farouk *et al.*, 2021). As a non-conventional water resource, treated wastewater offers a viable alternative to groundwater extraction and contributes to reducing pressure on increasingly depleted aquifers (Njomou Chimi *et al.*, 2023). Beyond augmenting water availability, treated wastewater can provide valuable nutrients for crop production, thereby enhancing resource-use efficiency. Consequently, its reuse for irrigation has gained considerable attention due to its potential to simultaneously address water scarcity, support agricultural sustainability, and promote the conservation of freshwater resources. When properly treated and managed, treated wastewater can meet the quality standards required for sustainable agricultural irrigation while contributing to the development of circular water management practices in water-scarce regions (Christou *et al.*, 2021).

2. MATERIAL AND METHODS

2.1 Soil Characterizations

The experiment was conducted under open-field conditions from November 2024 to April 2025 at the experimental farm of the National School of Agriculture (ENA) in Meknes, Morocco (33°84'51" N,

5°48'11" W). The soil at the study site is classified as clayey and is characterized by an alkaline pH, satisfactory nitrogen availability, and elevated levels of potassium and organic matter. These soil properties are typical of many Mediterranean agroecosystems and constitute a relevant pedoclimatic context for evaluating the agronomic performance and environmental implications of treated wastewater reuse in agriculture. The initial physicochemical characteristics of the soil are reported in **Table 1**.

Table 1. Physicochemical characterization of the soil

Parameters (unit)	Soil
Clay %	53
Fine silt %	10.5
Coarse silt %	13.8
Fine sand %	15.3
Coarse sand %	6.5
pHeau	8.1
pHkcl	7.3
Electrical conductivity (ms cm ⁻¹)	0.21
OM (%)	3.14
NT (%)	0.17
N-NH ₄	0.15
N-NO ₃	3.09
C/N ratio	10.71
CEC (méq/100g)	28
Cl (mg kg ⁻¹)	6.44
Na ₂ O (mg kg ⁻¹)	156
P ₂ O ₅ (mg kg ⁻¹)	30
K ₂ O (mg kg ⁻¹)	609

2.2 Treated wastewater Characterizations

The treated wastewater used in this study, commonly referred to as whitewater, originated from dairy processing activities and was subjected to a biological treatment process based on the activated sludge system. This process relies on the development of a heterotrophic microbial community specifically adapted to degrade biodegradable organic matter present in the effluent (Koivuranta et al., 2014). Treatment is conducted under aerobic conditions maintained through continuous mechanical aeration and mixing, ensuring adequate oxygen transfer and homogeneous distribution of microbial biomass throughout the reactor. These conditions promote the efficient biodegradation of organic pollutants and enhance microbial metabolic activity. Through the combined action of biological oxidation and aeration, organic carbon is mineralized, while essential nutrients, particularly nitrogen and phosphorus, undergo biogeochemical transformations that contribute to the reduction of the effluent's pollution load (Oliveira et al., 2017). Consequently, the activated sludge process represents an effective and sustainable approach for the treatment and valorization of dairy industry wastewater. The temporal evolution of the physicochemical characteristics of the treated effluent during the experimental period is presented in the following figure.

During the experimental period, the physicochemical quality of the irrigation water varied according to the water source and sampling date. Treated wastewater (TWW) exhibited marked temporal fluctuations in its ionic composition, whereas conventional water (CW) remained relatively stable throughout the study period (Table 2). The most pronounced variations were observed for sodium (Na⁺) and chloride (Cl⁻) concentrations. Sodium levels in CW remained nearly constant at approximately 130 mg L⁻¹, while those in TWW showed substantial variability, ranging from 186 to 646 mg L⁻¹. A similar pattern was recorded for chloride concentrations. In CW, chloride levels were relatively stable, averaging 214 mg

L⁻¹, whereas TWW displayed considerably higher concentrations and greater temporal variability, with values ranging from 3,572 to 14,000 mg L⁻¹. These results indicate a higher and more variable salt load in treated wastewater compared with conventional irrigation water, reflecting fluctuations in the composition of the dairy effluent and its treatment process.

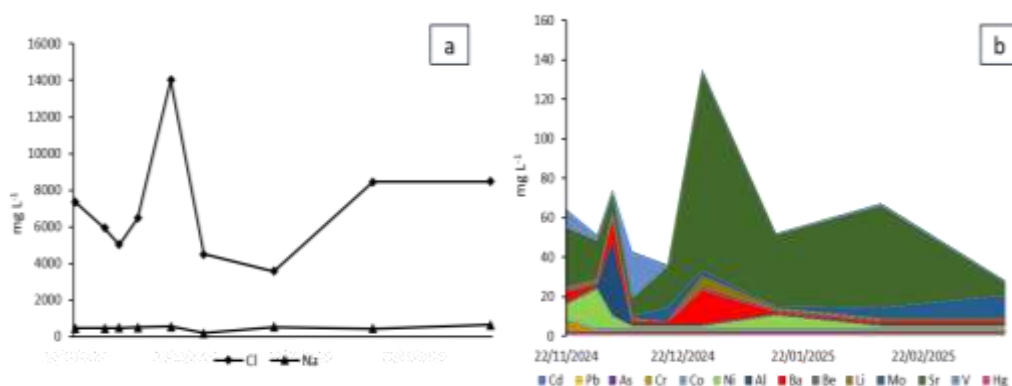


Figure 1. Temporal dynamics of physicochemical parameters and elemental composition of treated dairy effluent during the irrigation period, including (a) salinity indicators and (b) toxic elements.

2.3 Plant Material, Experimental Design, and Growth Conditions

The experiment was conducted under open-field conditions at the experimental farm of the National School of Agriculture (ENA) in Meknes, Morocco, under natural photoperiodic conditions. Throughout the study period, air temperature and relative humidity varied according to the prevailing meteorological conditions characteristic of the semi-arid Mediterranean climate of the region. Irrigation management was based on crop evapotranspiration (ET_c) to ensure an accurate estimation of crop water requirements throughout the growing season. Daily reference evapotranspiration (ET₀) was calculated using the FAO Penman–Monteith method following the guidelines established by the Food and Agriculture Organization (FAO) (Matsui *et al.*, 2023). The calculation was performed using meteorological data, including air temperature, relative humidity, wind speed, and solar radiation, obtained from a nearby weather station. Crop evapotranspiration was then estimated according to the relationship $ET_c = ET_0 \times K_c$, where K_c represents the crop coefficient corresponding to each phenological growth stage (Wang *et al.*, 2024). Irrigation water was applied daily to replenish 100% of ET_c losses, thereby maintaining optimal soil moisture conditions and preventing water deficit throughout the experimental period. The irrigation volume supplied was identical across all treatments and was determined exclusively based on ET_c requirements.

The plant material consisted of certified oat (*Avena sativa* L.) seeds of the forage variety 'ALLAL', provided by the National Seed and Plant Office (SONACOS, Morocco) (Saidi *et al.*, 2020), and triticale ($\times$ Triticosecale Wittmack), represented by a locally cultivated variety commonly grown in the region. The experiment was established using a randomized complete block design comprising three irrigation treatments and four replicates per treatment. The irrigation treatments were defined as follows:

- T₁, consisting of irrigation with 100% treated dairy wastewater (whitewater);
- T_{1/2}, consisting of irrigation with a mixture of 50% treated whitewater and 50% conventional water;
- T₀, serving as the control treatment and receiving 100% conventional water.

Each experimental unit measured 5 m × 7 m, resulting in a total of twelve plots distributed across four blocks to minimize the influence of spatial variability within the experimental field by every culture. The allocation of treatments within each block was randomized to ensure the statistical validity of treatment comparisons. A schematic representation of the experimental design and plot arrangement is provided

in **Figure 2**. Throughout the growing season, plant growth was monitored at 15-day intervals through the measurement of key agronomic parameters, including plant height and leaf number. In addition, regular field inspections were conducted to detect the occurrence of pests and diseases, ensuring that crop performance was not influenced by biotic stress factors that could interfere with the assessment of irrigation treatment effects.

Stomatal conductance was measured at a critical phenological stage, namely the heading stage, using an AP4 porometer (Delta-T Devices, UK). Measurements were performed on one fully expanded leaf randomly selected from each plant at a standardized canopy position to ensure consistency among observations and accurately characterize plant transpiration dynamics. At the same developmental stages, leaf physiological status was evaluated using a DUALEX Scientific sensor (FORCE-A, France). This non-destructive device was employed to determine chlorophyll content ($\mu\text{g cm}^{-2}$). To monitor the effects of irrigation water quality on soil properties, soil electrical conductivity (EC) was measured weekly at depth of 20 cm using a FieldScout Direct Soil EC Meter (Spectrum Technologies Inc., USA). Measurements were conducted in situ within each experimental plot to evaluate temporal changes in soil salinity throughout the cropping cycle. Soil pH was simultaneously monitored on a weekly basis using a calibrated portable pH meter (ExStik, Extech Instruments, USA) to assess potential treatment-induced modifications in soil chemical conditions.

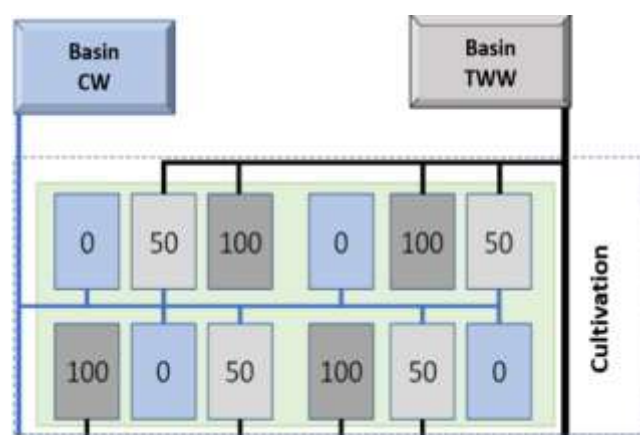


Figure 2. Schematic representation of the experimental design

2.4. Sampling

At the end of the growing season, aboveground plant biomass was assessed by harvesting vegetation within a randomly placed 0.25 m² quadrat in each experimental plot. All plants contained within the quadrat were cut at soil surface level and weighed immediately to determine fresh biomass yield. Subsequently, plant samples were oven-dried at 65 °C to constant mass (approximately 36 h) for the determination of dry biomass. Simultaneously, composite soil samples were collected from the 0–20 cm depth layer within the harvested area of each plot. Soil samples were air-dried under laboratory conditions, gently crushed, and sieved through a 2-mm mesh to obtain a homogeneous fraction suitable for subsequent physicochemical characterization. This sampling strategy enabled the evaluation of treatment effects on both crop productivity and soil quality parameters.

2.5. Statistical Analysis

Data are expressed as mean $\pm$ standard deviation (SD) with a sample size of $n = 4$. Data processing and graphical display were conducted utilizing Microsoft Excel 2023. Statistical analyses were performed utilizing SPSS software. Variations among treatments were evaluated using analysis of variance (ANOVA). Upon detecting significant effects ($p < 0.05$), mean comparisons were conducted with the Student–Newman–Keuls (SNK) post hoc test at a 5% significance threshold.

3. Results

3.1. Impact of Treated Wastewater Irrigation on Soil

Changes in soil parameters following treated wastewater irrigation harvest are presented in **Table 2**.

Table 2. Post-harvest assessment of soil nutrient dynamics and physicochemical attributes under treated wastewater irrigation after oat (*Avena sativa* L.) and triticale ($\times$ Triticosecale) cultivation. The data represent mean $\pm$ SD (n = 4); different letters indicate significant differences according to the SNK test at $p < 0.05$.

	Oat			Triticale		
	T ₀	T _{1/2}	T ₁	T ₀	T _{1/2}	T ₁
OM (%)	3,36 ^a $\pm$ 0,14	3,14 ^a $\pm$ 0,18	2,28 ^b $\pm$ 0,12	3,26 ^a $\pm$ 0,13	3,34 ^a $\pm$ 0,19	3,28 ^a $\pm$ 0,18
Cl (mg kg ⁻¹)	40,11 ^a $\pm$ 1,21	45,61 ^b $\pm$ 2,32	45,83 ^b $\pm$ 1,89	38,11 ^a $\pm$ 1,81	39,61 ^a $\pm$ 2,69	45,93 ^b $\pm$ 2,87
Na ₂ O (mg kg ⁻¹)	444 ^a $\pm$ 12	472 ^b $\pm$ 10	474 ^b $\pm$ 17	399 ^a $\pm$ 22	456 ^b $\pm$ 18	489 ^c $\pm$ 13
CaO (mg kg ⁻¹)	14830 ^a $\pm$ 218	14570 ^a $\pm$ 173	15215 ^b $\pm$ 371	14840 ^a $\pm$ 218	14950 ^a $\pm$ 173	15341 ^b $\pm$ 371
P ₂ O ₅ (mg kg ⁻¹)	33,5 ^a $\pm$ 2,1	43,8 ^a $\pm$ 1,3	44,8 ^b $\pm$ 3,2	43,7 ^a $\pm$ 4,3	42,6 ^a $\pm$ 8,7	47,9 ^b $\pm$ 5,4
K ₂ O (mg kg ⁻¹)	602 ^a $\pm$ 30	608 ^a $\pm$ 45	612 ^a $\pm$ 52	613 ^a $\pm$ 27	615 ^a $\pm$ 47	620 ^a $\pm$ 54
MgO (mg kg ⁻¹)	618 ^a $\pm$ 48	644 ^a $\pm$ 45	765 ^b $\pm$ 52	599 ^a $\pm$ 38	624 ^a $\pm$ 35	729 ^b $\pm$ 42
Cu (mg kg ⁻¹)	1,24 ^a $\pm$ 0,04	1,11 ^a $\pm$ 0,07	1,19 ^a $\pm$ 0,06	1,17 ^a $\pm$ 0,05	1,10 ^b $\pm$ 0,07	1,09 ^b $\pm$ 0,08
Mn (mg kg ⁻¹)	19,9 ^a $\pm$ 1,2	20,2 ^a $\pm$ 1,5	18,2 ^a $\pm$ 2,4	18,7 ^a $\pm$ 1,2	19,2 ^a $\pm$ 1,5	21,2 ^a $\pm$ 2,4
Fe (mg kg ⁻¹)	5,48 ^a $\pm$ 0,75	4,92 ^a $\pm$ 0,54	5,26 ^a $\pm$ 0,83	5,48 ^a $\pm$ 0,85	4,82 ^a $\pm$ 1,04	5,37 ^a $\pm$ 0,93
Zn (mg kg ⁻¹)	1,45 ^a $\pm$ 0,12	1,43 ^a $\pm$ 0,23	1,51 ^a $\pm$ 0,41	1,47 ^a $\pm$ 0,45	1,49 ^a $\pm$ 0,33	1,52 ^a $\pm$ 0,31
Bore (mg kg ⁻¹)	0,29 ^a $\pm$ 0,05	0,25 ^a $\pm$ 0,03	0,31 ^a $\pm$ 0,07	0,23 ^a $\pm$ 0,05	0,24 ^a $\pm$ 0,03	0,27 ^a $\pm$ 0,07

3.1.1 Nutrient dynamic

In oat-cultivated soils, chloride content increased significantly from 40.11 mg kg⁻¹ under the control treatment (T₀) to 45.61 mg kg⁻¹ in T_{1/2} and 45.83 mg kg⁻¹ in T₁, corresponding to an overall increase of approximately 14.3%. A similar trend was observed for sodium, with Na₂O concentrations rising from 444 mg kg⁻¹ in T₀ to 472 mg kg⁻¹ in T_{1/2} and 474 mg kg⁻¹ in T₁. These results indicate a progressive accumulation of soluble salts associated with treated wastewater application. In contrast, soil organic matter decreased markedly from 3.36% in T₀ to 2.28% in T₁. Calcium (CaO), phosphorus (P₂O₅), and magnesium (MgO) increased under treated wastewater irrigation, whereas potassium (K₂O) remained relatively stable. Micronutrients exhibited only minor variations among treatments.

A comparable pattern was observed in triticale cultivated soils. Chloride concentrations increased from 38.11 mg kg⁻¹ in T₀ to 39.61 mg kg⁻¹ in T_{1/2} and reached 45.93 mg kg⁻¹ in T₁, representing an increase of approximately 20.5% relative to the control. Sodium accumulation was even more pronounced, with Na₂O concentrations increasing from 399 mg kg⁻¹ in T₀ to 456 mg kg⁻¹ in T_{1/2} and 489 mg kg⁻¹ in T₁, corresponding to a 22.6% increase under full-strength treated wastewater irrigation. Similar to oat, CaO and MgO contents increased with increasing proportions of treated wastewater, while K₂O remained largely unaffected. Phosphorus concentrations were slightly higher in T₁ than in the other treatments. Micronutrient concentrations (Cu, Mn, Fe, Zn, and B) showed only limited fluctuations and remained within a relatively narrow range across treatments.

3.1.2 EC

Soil electrical conductivity (EC) measured at a depth of 20 cm (**Figure 3**) showed a clear response to irrigation water quality, with significant differences observed among treatments throughout the experimental period. Statistical analysis revealed that treatment effects became significant as early as 7 days after emergence. Compared with the control treatment (T₀), EC values increased by approximately 10% and 26% under T_{1/2} (50% treated wastewater + 50% conventional water) and T₁ (100% treated wastewater), respectively. Thereafter, EC remained consistently higher in plots irrigated

with treated wastewater, particularly under T_1 , while the control treatment maintained the lowest and most stable values throughout the monitoring period. Temporal variations in EC were observed across all treatments, likely reflecting the combined influence of irrigation applications, rainfall events, and soil water dynamics.

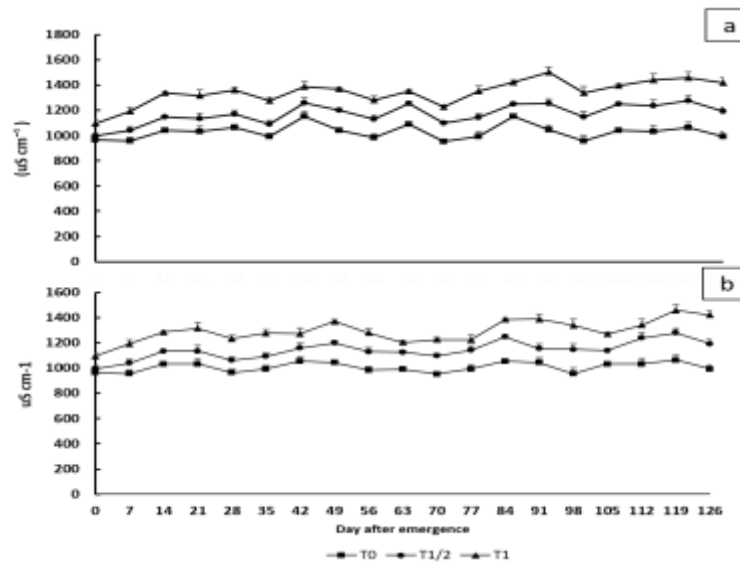


Figure 3. Temporal evolution of soil electrical conductivity at 20 cm depths under three irrigation regimes during oat (*Avena sativa* L.) (a) and triticale ($\times$ *Triticosecale*) (b) cultivation; T_0 : control, irrigated with conventional water ($\blacksquare$), $T_{1/2}$ irrigated with 50% conventional water + 50% whitewater ($\bullet$), and T_1 irrigated with 100% whitewater ($\blacktriangle$). The data represent the mean of four replicates; the vertical bars indicate standard deviations.

3.1.3 Soil pH

Soil pH increased significantly with increasing proportions of treated wastewater irrigation. Significant differences among treatments were observed from 14 days after emergence. At the end of the experiment, pH values reached 7.28 and 7.90 under $T_{1/2}$ and T_1 , respectively, compared with 6.92 in the control (T_0) for oat cultivation and 6.65, 7.21 and 8.22 under T_0 ; $T_{1/2}$ and T_1 respectively. A strong positive correlation was found between soil pH and electrical conductivity ($R^2 = 0.91$).

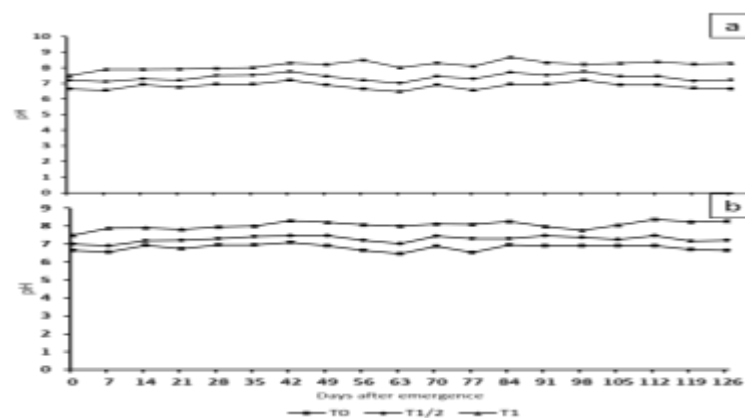


Figure 4. Temporal evolution of soil pH under three irrigation regimes during oat (*Avena sativa* L.) (a) and triticale ($\times$ *Triticosecale*) (b) cultivation; T_0 : control, irrigated with conventional water ($\blacksquare$), $T_{1/2}$ irrigated with 50% conventional water + 50% whitewater ($\bullet$), and T_1 irrigated with 100% whitewater ($\blacktriangle$). The data represent the mean of four replicates; the vertical bars indicate standard deviations.

3.2 Impact of Treated Wastewater Irrigation on Oat

3.2.1 Growth Parameters

Plant height and leaf development of oat and triticale were not significantly affected by irrigation with treated wastewater. Statistical analysis revealed no significant differences among treatments from 7 days after emergence onward. Similarly, the temporal dynamics of leaf number remained comparable across treatments throughout the growing period, indicating that treated wastewater irrigation did not alter the vegetative growth of either crop (**Figure 5**).

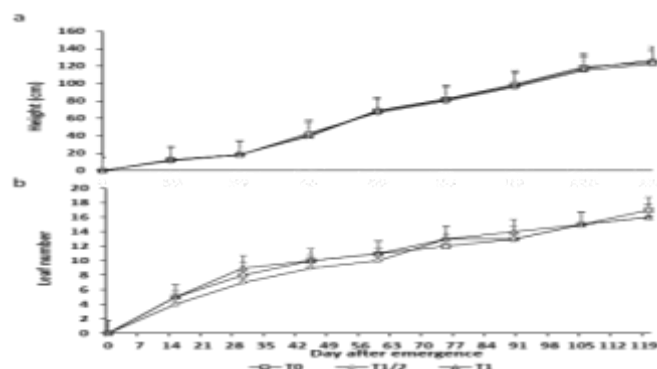


Figure 5. Height (a), leaf number (c), and the evolution of *Avena sativa* L. irrigated with conventional water (T_0 : ■), with 50% conventional water + 50% whitewater ($T_{1/2}$: ●), and with 100% whitewater (T_1 : ▲). The data represent the mean of four replicates; the vertical bars indicate standard deviations.



Figure 6. Comparative agronomic performance of *Avena sativa* L. at 60 days after emergence as influenced by different irrigation regimes: (a) conventional water (control), (b) 50% conventional water combined with 50% whitewater, and (c) 100% whitewater irrigation.

3.2.3. Ecophysiological Parameters

3.2.3.1. Stomatal conductance

Stomatal conductance was significantly affected by irrigation treatment, particularly in triticale (**Figure 7**). In oat, stomatal conductance decreased slightly from approximately $120 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$ under the control treatment (T_0) to 112 and 116 $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$ under $T_{1/2}$ and T_1 , respectively. Although both treated wastewater treatments differed significantly from the control, no significant difference was observed between $T_{1/2}$ and T_1 . In contrast, triticale exhibited a more pronounced response, with stomatal conductance declining progressively from 111 $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$ in T_0 to 100 $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$ in $T_{1/2}$ and 95 $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$ in T_1 . The significant reduction observed under full-strength treated wastewater irrigation suggests a greater physiological sensitivity of triticale to the increased salt load associated with wastewater application.

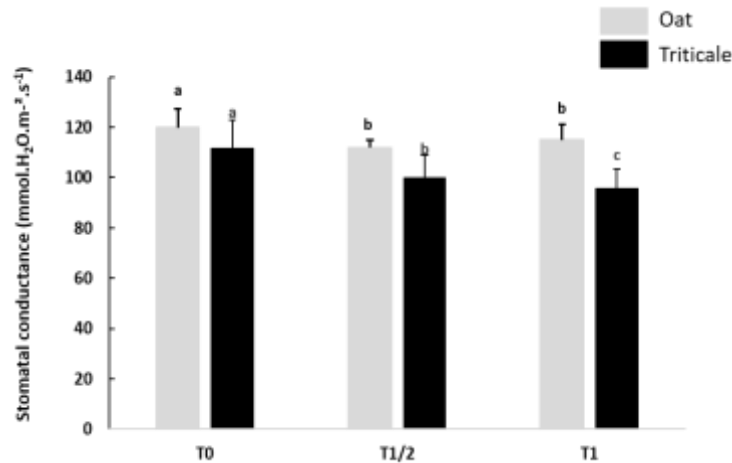


Figure 7. Stomatal conductance and its variation at 100 days after emergence in oat (*Avena sativa* L.) (a) and triticale (*× Triticosecale*) (b) under three irrigation regimes: T₀, irrigated with conventional water; T_{1/2}, irrigated with 50% conventional water and 50% treated wastewater (TWW); and T₁, irrigated with 100% treated wastewater. Data are presented as mean ± standard deviation (n = 4). Different letters (a–e) indicate significant differences among treatments according to the Student–Newman–Keuls (SNK) test at $p < 0.05$.

3.2.3.2 Chlorophyll

Chlorophyll content decreased significantly with increasing proportions of treated wastewater irrigation (**Figure 8**). The highest chlorophyll concentration was recorded in the control treatment (T₀), while progressively lower values were observed under T_{1/2} and T₁. Statistical analysis revealed significant differences among all treatments ($p < 0.05$), as indicated by the distinct letter groupings.

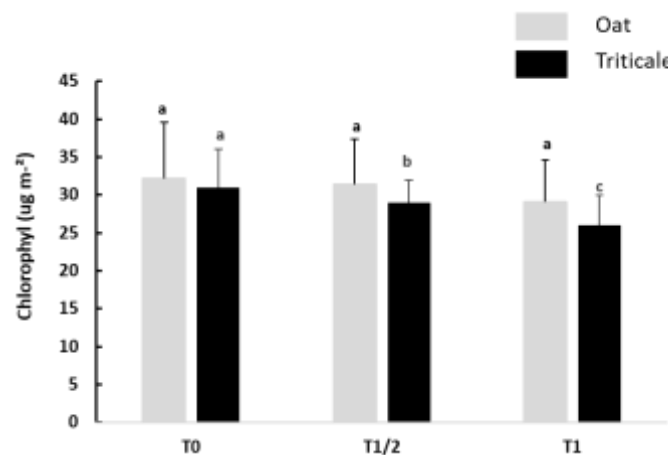


Figure 8. Chlorophyll content and its variation at 100 days after emergence in oat (*Avena sativa* L.) (a) and triticale (*× Triticosecale*) (b) under three irrigation regimes: T₀, irrigated with conventional water; T_{1/2}, irrigated with 50% conventional water and 50% treated wastewater (TWW); and T₁, irrigated with 100% treated wastewater. Data are presented as mean ± standard deviation (n = 4). Different letters (a–e) indicate significant differences among treatments according to the Student–Newman–Keuls (SNK) test at $p < 0.05$.

Discussion

The results demonstrated that irrigation with treated dairy wastewater significantly modified soil chemical properties, particularly salinity-related parameters, while exerting limited effects on crop growth and biomass production (Chen *et al.*, 2018). The increase in soil chloride and sodium concentrations observed in both oat and triticale plots is consistent with the elevated ionic content of the treated effluent.

Similar findings have been reported in previous studies evaluating wastewater reuse in agriculture, where repeated applications of treated effluents led to the accumulation of soluble salts in the root zone (Porghahreman *et al.*, 2024). The greater increase in sodium and chloride observed under T₁ indicates that soil salinity responses were directly proportional to the proportion of treated wastewater applied.

The observed increase in soil pH is likely related to the alkaline nature of the treated wastewater and the accumulation of basic cations in the soil (Louati *et al.*, 2018). The strong positive correlation between pH and EC suggests that both parameters were driven by similar processes associated with salt enrichment. Comparable increases in soil alkalinity following wastewater irrigation have been reported in Mediterranean environments, where effluents rich in bicarbonates and alkaline ions contribute to gradual shifts in soil chemical equilibrium (Alawneh *et al.*, 2025). Although the increase in pH was significant, the values recorded remained within a range generally considered suitable for cereal cultivation.

Despite the significant modifications observed in soil properties, neither oat nor triticale exhibited significant changes in plant height or leaf development. These findings indicate that the levels of salinity and alkalinity reached during the study were insufficient to affect vegetative growth (Gimeno *et al.*, 2009). In contrast, ecophysiological parameters proved more sensitive than morphological traits. The reduction in stomatal conductance observed under treated wastewater irrigation, particularly in triticale, suggests the onset of physiological adjustments to increasing soil salinity (Jouini *et al.*, 2026). Reduced stomatal aperture is a common adaptive response that limits water loss and maintains plant water status under osmotic stress conditions (Guzeev *et al.*, 2025).

The progressive decline in chlorophyll content further supports the occurrence of moderate physiological stress under treated wastewater irrigation (Belasri *et al.*, 2026). Elevated concentrations of sodium and chloride can interfere with chlorophyll biosynthesis, accelerate pigment degradation, and impair photosynthetic processes (De Vrieze *et al.*, 2016). Nevertheless, the decrease remained relatively limited and was not accompanied by reductions in plant growth, suggesting that photosynthetic capacity was only moderately affected. The maintenance of satisfactory agronomic performance despite lower chlorophyll concentrations indicates that both species were able to compensate for these physiological adjustments and sustain biomass production.

Conclusion

Treated dairy wastewater can be considered a promising alternative irrigation resource under water-scarce conditions. The effluent provided nutrients that may contribute to crop nutrition while maintaining satisfactory crop growth and productivity during the short-term experimental period. However, the observed accumulation of sodium and chloride, together with the increases in soil EC and pH, highlights the importance of long-term monitoring. Repeated applications over multiple growing seasons could lead to progressive salinity buildup, nutrient imbalances, or soil structural degradation. Consequently, sustainable implementation of treated wastewater irrigation should be accompanied by regular soil quality assessments and appropriate management practices to prevent adverse long-term effects. These results support the integration of treated agro-industrial effluents into circular water management strategies aimed at enhancing water-use efficiency and improving the resilience of agricultural systems in drought-prone Mediterranean regions.

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