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Effluent from Winery Waste Biorefinery: A Strategic Input for Biomass Generation with Different Objectives to Add Value in Arid Regions

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Abstract: Agro-industrial activities generate significant amounts of organic waste and a variety of effluents thus posing environmental challenges. Viticulture in Argentina, which covered 204,847 ha in 2023, faces water scarcity as a limiting factor conditioning its production. This industry produces large volumes of grape marc, sediments, and stalks, which can be valorised into products like alcohol, tartaric acid, and compost. However, these valorisation processes generate effluents with high organic load and salinity, further stressing water resources. This study explores the potential of utilising these effluents to cultivate plant biomass in arid regions (sorghum or perennial pasture), which could serve as bioenergy, animal feed, or composting co-substrates, contributing to circular bioeconomy principles. The combined use of effluent as a water resource and the sowing of sorghum and pasture increased soil organic matter content and led to a slight reduction in pH (depth: 0.30–0.60 m) compared to the control treatment. The sorghum plots showed better establishment and higher dry biomass yield (32.6 Tn/ha) compared to the pasture plots (6.5 Tn/ha). Sorghum demonstrated better tolerance to saline soils and high salinity effluents, aligning with previous studies. Although pasture had a lower biomass yield, it was more efficient in nutrient uptake, concentrating more NPK, ash, and soluble salts. Sorghum's higher yield compensated for its lower nutrient concentration. For biomass production, sorghum is preferable, but if nutrient capture from effluents is prioritised, summer polyphytic pastures are more suitable. These results suggest that the final selection between plant biomass alternatives highly depends on whether the goal is biomass generation or nutrient capture.

Keywords: distillery effluents; biomass; bioenergy; animal feedstock; composting co-substrate; circular bioeconomy

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1. Introduction

Agro-industrial activity generates large quantities of effluents and organic waste that can negatively impact the environment [1,2]. In particular, the wine industry is an attractive productive activity that allows for the valorization of arid ecoregions with some existing production limitations. In Argentina, viticulture is an important economic activity, with 204,847 ha. cultivated in 2023 [3]. In this sense, one of the main factors limiting production is the scarcity of water resources [3]. Viticulture generates large quantities of grape marc, wine production sediments, and stalks, among others. However, in clear alignment with the principles of a circular bioeconomy, these organic residues have the potential to be valorised by other industries that produce other value-added products, such as food-grade alcohol, tartaric acid, grape seed oil, and compost [4–6]. Although this approach contributes to achieving these principles, it is evident that such production also generates high volumes of effluents with high organic load and salt content, with water resources being the most limiting factor for their production in arid regions [7].

In the province of Mendoza, the discharge and agricultural reuse of industrial liquid effluents is regulated by the General Department of Irrigation (DGI). The regulations define the maximum allowable parameters for use on crops (Resolution 778/96 HTA DGI) [8]. At present, treated effluents from wine distilleries generally have conductivity values higher than those defined and a pH below the specified range, so one of the common practices is to dilute the treated effluent with low salinity, neutral pH well water. Water salinity affects plant biomass productivity by reducing plant growth and development. This is because salinity causes salt stress in plants, which forces them to use more energy to extract water from the soil. Water absorption is altered, photosynthetic yield is reduced, and chlorosis and leaf necrosis, toxicity, and nutritional imbalance can occur.

In the current regional context of water shortage for several consecutive seasons, as well as projections that foresee a worsening of the restriction situation for the future, the DGI seeks, together with the industries, to evaluate tolerant crop alternatives for the use of less diluted effluents, avoiding the use of too much water of good suitability for irrigation, which is somehow degraded to improve effluents. The information from these pilot experiences can serve as a basis for adapting the reuse regulations for these effluents in the future.

Although there are antecedents for the use of viticultural biomass in value adding strategies, there is a lack of studies that evaluate the possible use of these effluents to valorise them thus reducing their impact on the environment. The use of agro-industrial effluents could be a strategy to cultivate plant biomass in arid areas to be valorised as bioenergy sources, animal feed, or as a co-substrate in the composting process. In this sense, the aim of this study was to evaluate alternatives for the use of these industrial effluents with high electrical conductivity in productive agro-ecosystems for the generation of vegetal biomass for energy, animal feed, or raw materials for composting and further applications. It is also important to verify how irrigation with this type of effluent affects the agricultural suitability of the soil. All the experiments presented in this study used real effluents and full-scale reproducible tests.

2. Materials and Methods

2.1. Study Site and Starting Materials

DERVINSA company is located at Palmira, San Martin Department (Mendoza Province, Argentina). DERVINSA is a company that receives 80% of the vinification organic waste generated in Argentina such as grape marc (120,000–140,000 Tn/year), vinification sediment (40,000 Tn/year), and 20,000 Tn/year of other tartaric raw materials. From these wine production waste, this company produces tartaric acid (4000 Tn/year), grape oil (3000 Tn/year), food-grade alcohol (3000 Tn/year), and compost (12,000 Tn/year).

This production process generates the following two types of effluents: (i) effluent from the processing of grape marc (EGM, generation: 25 m^3/h) and (ii) vinasse from the processing of wine lees (V, generation: 25 m^3/h). Both effluent streams are characterised by high electrical conductivity (EC) and slightly acidic pH (Table 1).

Table 1. Characterization of effluents from the distillery industry in terms of pH and electrical conductivity (EC).

Parameter	EGM [2]	V [3]
pH	4.32	5.99
EC [1] (dS/m)	13.57	17.88

[1] EC: electrical conductivity; [2] EGM: effluent from the processing of grape marc, [3] V: vinasse.

2.2. Exploratory Preliminary Study

A plant growth exploratory assay of the three selected forage species was conducted to evaluate the effect of dilutions of the different effluent streams on small-scale experiments.

First, an initial mixture of EGM and V effluents was made in a 1:1 (*v:v*) ratio. The following four dilutions (%, in volume) were used from this mixture: (i) Control (water, 0% mixture), (ii) Dilution 1 (9% mixture), (iii) Dilution 2 (15% mixture), and (iv) Dilution 3 (24% mixture).

The following different forage species were planted: (i) sorghum (*Sorghum × drummondii*) and (ii) mixed perennial pasture composed of sweet clover (*Melilotus officinalis*) and wheatgrass (*Thinopyrum ponticum*). This resulted in 8 treatments that were evaluated in triplicate as follows: (i) Pasture-control, (ii) Pasture-dilution 1, (iii) Pasture-dilution 2, (iv) Pasture-dilution 3, (v) Sorghum-control, (vi) Sorghum-dilution 1, (vii) Sorghum-dilution 2, and (viii) Sorghum-dilution 3.

The seeds were sown in 20 L containers with a seeding density equivalent to 16, 30, and 60 Kg/ha for sweet clover, wheatgrass and sorghum, respectively. The substrate used was the topsoil (typical torrifluent entisol) from the demonstration/experimental site of the company's property [9]. It was manually homogenised prior to filling the cultivation containers.

Irrigation was carried out with the previously described solutions at a frequency of 5 days, applying a total volume of 23 L per container during the crop cycle for mixed pastures and 32 L for sorghum.

This exploratory study was carried out under greenhouse conditions and lasted 43 days (temperature range: 11–28 °C, humidity range: 40–60%). At the end of the assay, the plants were harvested, and the fresh and dry weight of each pot was quantified.

2.3. Experimental Design of Field Assay

A plot assay with the previously selected dilution 1 (9%) was carried out in a plot located at the Dervinsa company (−33.040623, −68.563479). The study site is characterised by a semi-arid climate, typical of the Cuyo region (Argentina). Summer is hot and dry, with maximum temperatures that can exceed 35 °C, while winter is cold and more humid, with minimum temperatures that sometimes fall below 0 °C. Rainfall is low throughout the year, and it is mainly concentrated in the summer months, with an annual average of around 200–300 mm. This climate favours agricultural activities, especially viticulture and fruit production, which are characteristic of the area [3].

The soil where the plot assay was carried out belongs to the typical torrifluent entisol class [9]. The organoleptic texture of the first horizon (0–0.40 m) was sandy, followed by a very compacted sandy layer (0.40–1.00 m) and a sandy layer with black specks (1–1.5 m). The apparent density in the upper layer was less than 1 (0.91 g/cm^3) and that of the subsurface layer was higher (1.40 g/cm^3).

According to the elemental textural analysis, a very low clay content was detected, with less than 1% in the first 0.40 m, silt content (2 to 50 μm) at 26 g%g, and sand at 73 g%g, specifying the observed texture (Table 2).

Table 2. Soil physicochemical properties for the plot assay.

Deep (m)	EC [1] (dS/m)	pH	SV [2] (g/100 g Soil)	Textural Qualification
0–0.30	3.65	7.58	102	loam
0.30–0.60	3.08	7.76	92	sandy loam
0.60–0.90	3.23	7.81	94	loam

[1] EC: electrical conductivity, [2] SV: sedimentable volume.

Experimental plots were set up to evaluate the productivity of crops irrigated with the effluent mixture. Each experimental unit had an area of 1000 m^2. Prior to sowing, the soil was tilled into 35 cm wide and 15 cm high ridges. A completely randomised experimental design with three replications was used, where the treatments were as follows: (i) Control (irrigated soil without crop); (ii) perennial pasture (sweet clover and wheatgrass); and (iii) Sorghum. According to the exploratory assay, a 9% dilution of the effluent mixture with irrigation water was selected. Sowing density was equivalent to 16, 30, and 60 kg/ha for sweet clover, wheatgrass, and sorghum, respectively.

To calculate the water demand of the designed plots, the available effluent flow was analysed, the soil characteristics were evaluated, the replacement lamina was calculated to obtain the water demand of the area and the demand of the crops. Subsequently, an irrigation schedule was designed using the Winsrfr Software 4.1 [10], and the irrigation schedule was adjusted. During the plot experiments, it was necessary to arrange a new in situ adjustment of the schedule (especially in the initial stage of the crop after sowing), as the actual demand of the plants was different from the theoretical one at the beginning of the experience, due to the depth explored by the roots of the crops (sown and/or transplanted). Thus, a total of 15 irrigations were finally used during the entire crop cycle, with an overall surface irrigation flow of 48.47 L/s for 3 h each.

2.4. Analisys Methodology

2.4.1. Effluent Analysis

Composite samples were taken from the 9% diluted effluent. The parameters analysed to characterise the effluent were pH, EC (dS/m), carbonates (CO_3^{2-}), bicarbonates (HCO_3^-), chloride (Cl^-), sulphate (SO_4^{2-}), sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg), and sodium adsorption ratio (SAR) was determined as an indicator of risk of sodification or salinisation. All parameters were analysed by standardised methods described by APHA (2001) and INTA (2021) [11,12].

2.4.2. Soil Analysis

Soil samples were taken in triplicate in the exploratory and plot trials, at the beginning and at the end of the trials. The parameters analysed in the soil samples were pH, EC (dS/m), carbonates (meq/L), bicarbonates (meq/L), chloride (meq/L), sulphate (meq/L), sodium (Na), exchangeable potassium (Ext-K), calcium (Ca), magnesium (Mg), total nitrogen (TN), available phosphoruos (Available-P), and organic matter (OM). All parameters were analysed by standardised methods described by SAMLA (2004) [13]. The soil texture was determined using the sedimentable volume (SV) method proposed by Nijenshon and Maffei (1996) [14].

2.4.3. Vegetal Biomass Analysis

The aerial plant biomass generated in the exploratory study (duration: 43 days) and in the plot assay (duration: 99 days) was harvested at the end of the trials and its fresh and dry weights were determined.

A descriptive characterization of the nutrient content in plant biomass was performed. Subsamples were taken from each plot (1 kg dry matter) and, subsequently, the material was homogenized, and a composite sample was prepared for subsequent analysis (1 kg dry matter). The parameters analysed in the harvested aerial plant biomass from the plot assay were EC (1:10, *v*:*v*), biomass weight, dry matter (DM), ashes (%), total nitrogen (TN), total phosphorus (PT), total potassium (TK), organic matter (OM), and total organic carbon and C:N ratio. All parameters were analysed by standardised methods [13].

2.5. Statistical Analysis

ANOVA test coupled to LSD Fisher mean comparison test ($p < 0.05$) was used to compare the different cultures. In order to corroborate the ANOVA assumptions, the Shapiro–Wilk normality tests and the residue regression text were also carried out. InfoStat software (version 2015) was used to perform all statistical analyses (InfoStat Group, FCA, National University of Córdoba, Córdoba City, Argentina). All data are expressed as mean ± standard deviation.

3. Results

3.1. Preliminary Results

The harvested biomass results are shown in Figure 1. These preliminary results allowed us to identify that the most appropriate dilution of the effluent mixture was dilution 1 (9%) for both treatments. Therefore, the effluent mixture dilution of 9% was selected for the plot trial. It should be noted that in the sorghum treatments, 51% of the plant biomass belonged to other opportunistic plant species from to the local soil seed bank.

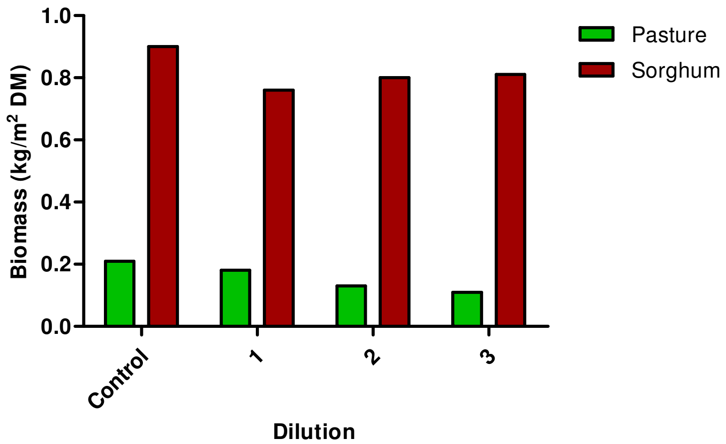

Figure 1. Biomass harvested (pasture and sorghum) in the exploratory assay under greenhouse conditions.

3.2. Characteristics of Effluent Used in the Demonstration Plot for Biomass Generation

The diluted effluent used as irrigation water showed a low suitability for agricultural use, according to the normal parameters of irrigation water characterization [15]. However, the electrical conductivity of the effluent is lower than the soil conductivity. The electrical conductivity is above 0.75 dS/m, presenting a risk of chloride and potassium toxicity. Despite this fact, the value corresponds to high K and Ca contents (Table 3). Regarding the pH, the values were found to be close to the optimal range for wastewater use, according to the published main guidelines [15].

Table 3. Effluent physicochemical variables used in the plot assay.

Parameter [1]	Effluent
pH	6.35
EC (dS/m)	2.82
CO_3^{2-} (meq/L)	0.00
HCO_3^- (meq/L)	31.68
Cl^- (meq/L)	5.22
SO_4^{2-} (meq/L)	13.55
Na (meq/L)	3.98
K (meq/L)	20.97
Ca (meq/L)	22.10
Mg (meq/L)	3.40
SAR	1.11

[1] EC: electrical conductivity, CO_3^{2-}: carbonates, HCO_3^-: bicarbonates, Cl^-: chloride, SO_4^{2-}: sulphate, Na: sodium, K: potassium, Ca: calcium, Mg: magnesium, SAR: sodium adsorption ratio.

3.3. Effects of Cultivation and Effluent Use on Soil Properties

It was verified that the soil texture presented a higher sedimentable volume, which could be influenced by the high organic matter content compared to the initial levels (Tables 4–6). This value was mainly observed in the sites where sorghum and pasture were cultivated, compared to the control soil (Table 5).

Table 4. Initial soil properties at different depths (0–0.30, 0.30–0.60, and 0.60–0.90 m).

Parameter [1]	Soil Depth (0–0.30 m)	Soil Depth (0.30–0.60 m)	Soil Depth (0.60–0.90 m)
pH	7.58	7.76	7.81
EC (dS/m)	3.65	3.08	3.23
SV (g/100 g soil)	102	92	94
CO_3^{2-} (meq/L)	0.00	1.00	2.00
HCO_3^- (meq/L)	2.94	3.65	3.57
Cl^- (meq/L)	5.54	3.02	3.02
SO_4^{2-} (meq/L)	31.81	28.28	29.56
Na (meq/L)	8.63	5.24	6.00
Ext-K (mg/kg)	1874	1286	2510
Ca (meq/L)	25.30	25.05	24.35
Mg (meq/L)	6.35	4.65	5.80
TN (mg/kg)	2490	838	468
P available (mg/kg)	21	5	1
OM (%)	2.74	0.89	0.74

[1] EC: electrical conductivity, SV: sedimentable volume, CO_3^{2-}: carbonates, HCO_3^-: bicarbonates, Cl^-: chloride, SO_4^{2-}: sulphate, Na: sodium, Ext-K: exchangeable potassium, Ca: calcium, Mg: magnesium, TN: total nitrogen, P available: phosphorous available, OM: organic matter.

In the case of the physico–chemical variables, the pH did not show differences between the cultivated soil and the control, with no differentiation at the depth of 0.00–0.30 m. However, the pH value at the depth of 0.30–0.60 m was significantly lower in the cultivated soil than in the control treatment. The electrical conductivity in the saturation extract was high, maintaining the classification of saline soil. Although there were no significant differences between the sowing treatments, the mean EC values obtained indicated that in the plots cultivated with pasture, the value was lower, representing almost half that of the plots with sorghum and the control in the 0–30 cm layer ($p > 0.05$). The deeper layer showed lower values but was still a saline soil. The soluble chloride content showed the same behaviour, which requires special attention as it is a highly toxic element for crops. In the surface layer, 0–30 cm, the plot cultivated with pasture showed an average value close to 10 meq/L, while it was 2.5 times higher in the sorghum plot and 5 times higher than in the pasture plot in the control plot. This indicates that sorghum did not decrease the EC but decreased the soluble chloride content in the saturated extract instead. Soluble potassium remains high, with higher contents than sodium. The rest of the physico-chemical parameters were similar between treatments ($p > 0.05$) and slightly higher at the beginning (Table 4). The use of the effluent resulted in an increase in soil salinity and the crops planted allowed a partial reduction in soluble salt content, thus being the pasture more efficient in nutrient absorption than sorghum.

Table 5. Final soil properties at surface depth (0.00–0.30 m).

Parameter [1]	Control (0–0.30 m)	Pasture (0–0.30 m)	Sorghum (0–0.30 m)
pH	7.57 ± 0.16	7.28 ± 0.07	7.37 ± 0.19
EC (dS/m)	9.11 ± 5.16	5.67 ± 0.90	10.21 ± 6.00
SV (g/100 g soil)	92.0 ± 2.0	116.00 ± 14.42	115.00 ± 17.01
CO_3^{2-} (meq/L)	0.26 ± 0.45	0.00 ± 0.00	0.00 ± 0.00
HCO_3^- (meq/L)	3.53 ± 0.68	3.01 ± 0.30	3.72 ± 1.02
Cl^- (meq/L)	50.63 ± 77.57	9.80 ± 0.98	27.05 ± 13.29
SO_4^{2-} (meq/L)	59.74 ± 20.96	65.49 ± 10.68	88.97 ± 52.79
Na (meq/L)	36.70 ± 35.52	16.96 ± 4.54	38.79 ± 30.58
Ext-K (mg/kg)	2447 ± 960	1647 ± 564	2781 ± 1054
Ca (meq/L)	25.59 ± 2.10 ^{a}	30.64 ± 0.58 ^{ab}	34.34 ± 7.07 ^{b}
Mg (meq/L)	14.48 ± 8.82	6.73 ± 1.17	9.43 ± 4.55
TN (mg/kg)	1132 ± 208	5427 ± 3012	5311 ± 2787
P available (mg/kg)	6.00 ± 2.80	6.40 ± 1.30	6.80 ± 1.00
OM (%)	1.30 ± 0.20	5.90 ± 3.30	4.60 ± 3.50

[1] EC: electrical conductivity, SV: sedimentable volume, CO_3^{2-}: carbonates, HCO_3^-: bicarbonates, Cl^-: chloride, SO_4^{2-}: sulphate, Na: sodium, Ext-K: exchangeable potassium, Ca: calcium, Mg: magnesium, TN: total nitrogen, P available: phosphorous available, OM: organic matter. Different letters indicate significant differences ($p < 0.05$).

Table 6. Final soil properties at sub-surface (0.30–0.60 m).

Parameter [1]	Control (0.30–0.60 m)	Pasture (0.30–0.60 m)	Sorghum (0.30–0.60 m)
pH	7.62 ± 0.19 ^{b}	7.35 ± 0.16 ^{ab}	7.31 ± 0.07 ^{a}
EC (dS/m)	7.83 ± 1.68	4.67 ± 0.08	6.94 ± 2.40
SV (g/100 g soil)	88.00 ± 4.00 ^{a}	95.00 ± 1.15 ^{ab}	109.00 ± 12.22 ^{b}
CO_3^{2-} (meq/L)	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
HCO_3^- (meq/L)	3.20 ± 0.11	3.53 ± 0.34	2.74 ± 1.04
Cl^- (meq/L)	23.39 ± 29.21	6.86 ± 0.00	36.26 ± 32.09
SO_4^{2-} (meq/L)	74.34 ± 20.00	57.73 ± 5.59	50.21 ± 19.34
Na (meq/L)	24.22 ± 9.23	12.13 ± 1.02	21.21 ± 10.17
Ext-K (mg/kg)	38.67 ± 5.05 ^{b}	17.28 ± 1.39 ^{a}	29.62 ± 11.14 ^{ab}
Ca (meq/L)	24.91 ± 2.54 ^{a}	29.29 ± 1.75 ^{ab}	29.96 ± 2.54 ^{b}
Mg (meq/L)	13.13 ± 3.03	9.43 ± 4.98	8.42 ± 3.09

[1] EC: electrical conductivity, SV: sedimentable volume, CO_3^{2-}: carbonates, HCO_3^-: bicarbonates, Cl^-: chloride, SO_4^{2-}: sulphate, Na: sodium, Ext-K: exchangeable potassium, Ca: calcium, Mg: magnesium. Different letters indicate significant differences ($p < 0.05$).

3.4. Biomass Generation from Mixed Grassland and Sorghum

The sorghum plots showed better homogeneity in settlement (Figure 2), while pasture showed more variability in this parameter, reaching an average dry biomass yield equivalent to 32.6 and 6.5 Tn/ha, respectively (Table 7). On the other hand, these results suggest that sorghum has better established abilities in saline soils irrigated with high salinity effluents. These results are in agreement with the exploratory study.

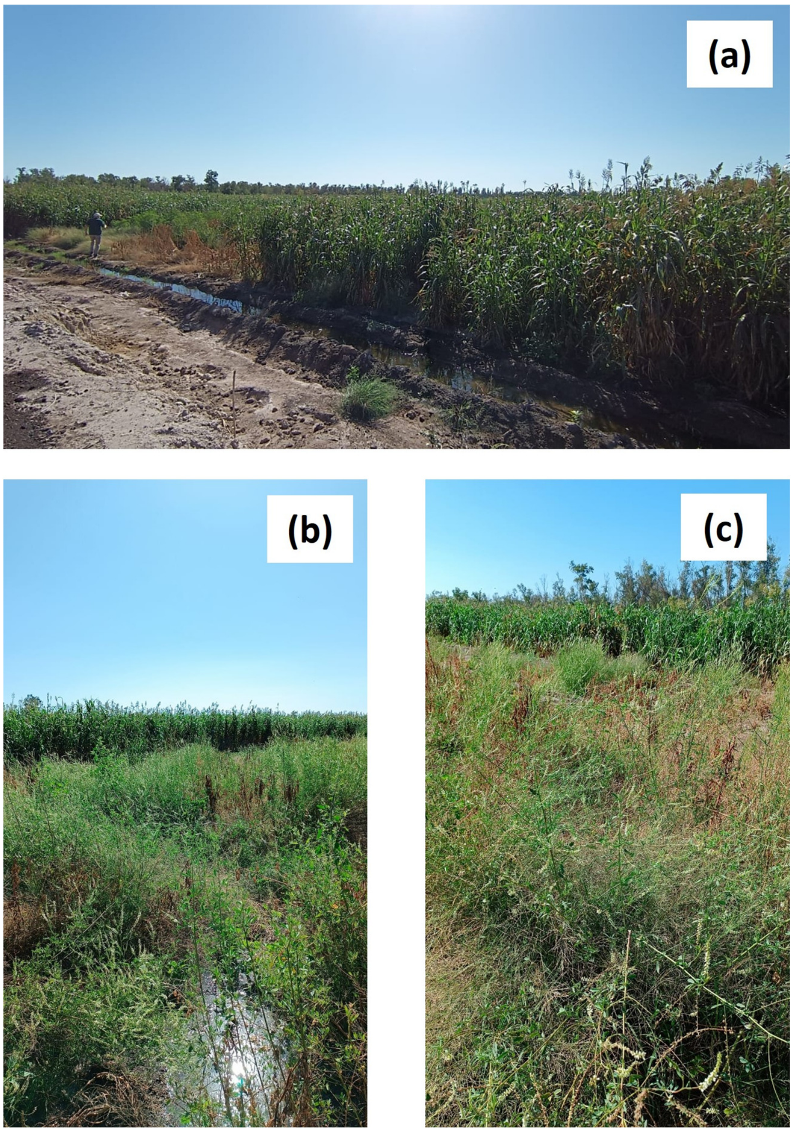

Figure 2. (**a**) General view of the plots cultivated in the field assay (in the front: sorghum; in the background: perennial pasture); (**b**) North view of the plots cultivated in the field assay (in the front: perennial pasture; in the background: sorghum); (**c**) South view of the plots cultivated in the field assay (in the front: perennial pasture; in the background: sorghum).

Table 7. Final biomass in each treatment.

Treatments	Fresh Biomass (kg/m^2)	Dry Biomass (kg/m^2)	Dry Matter (%)	Height (cm)
Pasture	1.96 ± 0.60	0.70 ± 0.20	33.9 ± 5.10 ^{a}	97.7 ± 40.1 ^{a}
Sorghum	6.30 ± 3.3	3.30 ± 1.80	51.5 ± 1.50 ^{b}	273.00 ± 26.70 ^{b}

Different letters indicate significant differences ($p < 0.05$).

Although sorghum had a higher biomass yield than pasture (Figure 3), pasture was more efficient in nutrient uptake in different soil extracts (Tables 5 and 6). This is closely related to the nutrient analysis found in the plant biomass (Figure 3). Most of the analysed macronutrients (NPKs), ash content, and soluble salts (EC) are more concentrated in the pasture biomass.

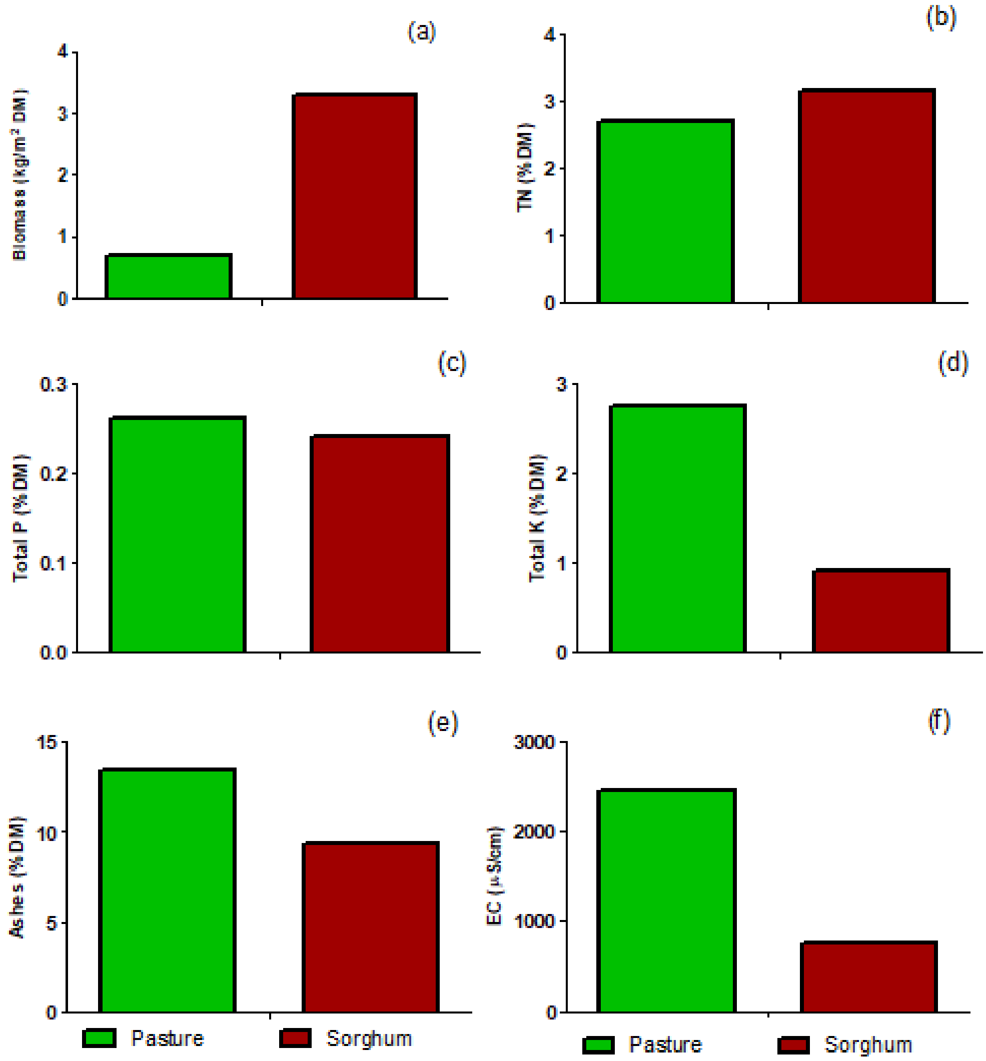

Figure 3. (**a**) Biomass harvested (pasture and sorghum) in the plot assay under (kg/m^2 dry weight); (**b**) Total nitrogen contend in biomass; (**c**) Total phosphorus content in biomass; (**d**) Total potassium content in biomass; (**e**) Ash content in biomass; (**f**) Electrical conductivity in biomass.

This fact presents different alternatives according to the production objectives. If the main strategy has the objective of maximising biomass production (e.g., for bioenergy, animal feed, or composting), the most appropriate approach would be to plant a summer annual crop such as sorghum. On the contrary, if the strategy is to capture as much of the nutrients provided by the effluent, the most appropriate approach would be to plant a summer polyphytic pasture (e.g., sweet clover and wheatgrass).

4. Discussion

From the results obtained in this study, it is evident that the use of distillery effluents from the processing of viticulture by-products represents a valuable strategy in the sustainable management of water resources and waste in arid regions. Regarding this, recent research has shown that these nutrient-rich effluents can be effectively used in crop irrigation, contributing to agricultural production and reducing pollution load in arid regions. For instance, Buelow et al. (2015) analysed the reuse of viticultural wastewater in a drought context in California [16]. The authors noted that the treatment of this wastewater reduces the levels of biological oxygen demand (BOD_5) and dissolved organic carbon, which minimises the negative effects on soil and plants. However, dissolved salts, especially sodium and potassium, persist after treatment, presenting a challenge for irrigation use. Despite this, overall salinity was moderate, and the treated water is, in most cases, suitable for salinity-tolerant crops such as grapes [16]. In this sense, the effluents treated in our study also presented high levels of salts, mainly Ca > K > Na > Mg (EC of EGM: 13.57 dS/cm; EC of V: 17.88 dS/cm). Therefore, it is recommended to dilute the effluent (9%). This dilution made it possible to reduce water consumption by 9% and to provide nutrients for the crops.

On the other hand, Livia et al. (2020) analysed wastewater treatment alternatives while considering the technical, economic, social and environmental aspects. The results showed that wastewater could be complemented but does not fully replace conventional water sources in the agriculture region. Among the options evaluated, the septic tank combined with a constructed wetland was the most sustainable according to local preferences. This study underlines the importance of integrating environmental and social criteria in decision-making on wastewater reuse [17]. This aspect should be considered to avoid the salinity risks associated with water balance and nutrient uptake by crops. In the case of this study, the challenge is to have an adequate effluent containment system, diluted effluent channelling, and sufficient arable land to avoid salinization problems. In addition, the water demand of the crops and the atmospheric demand must be considered in order to design a correct irrigation programme, avoiding temporary waterlogging and salt accumulation.

Recent studies have evaluated the use of vinasse, a liquid residue generated in the production of alcohol from sugar cane, sugar beet, mezcal, and tequila, as a soil amendment. Although they provide nutrients and organic matter, they can also alter soil properties, increase salinity and negatively affect microbiota. The application of vinasse increases greenhouse gas emissions (CO_2, CH_4, and N_2O), which contributes to global warming. The authors conclude that its agricultural use requires regulations and controlled doses to minimise environmental impact, especially in soils with high salinity and in areas close to water sources [18]. The effluent in our study presented different characteristics to those evaluated by these authors, presenting less risk of salinity and organic load. However, the recommendations by Moran-Salazar et al. (2016) [18] should be considered to avoid environmental problems due to a cumulative effect of the application of effluents derived from the distillation of wine by-products.

Khaskhoussy et al. (2020) evaluated the use of distillery effluent in maize (*Zea mays*) irrigation and found that this wastewater not only promoted vegetative growth but also improved soil properties, increasing the availability of essential nutrients [19]. This finding is consistent with our research that reported an increase in the biomass of crops irrigated with wine effluent, evidencing the possibility of reusing these by-products in agricultural systems in arid regions with high environmental constraints. The authors highlighted that treated wastewater can be used for irrigation in different soil types and that factors such as pH, clay content, carbonates, and organic matter affect the accumulation of toxic metals in plants and soil. However, high levels of certain metals in crops vary between species, suggesting that the risk may depend on the type of crop. The authors highlighted the importance of more field studies and advanced analytical techniques to better assess contamination and health risks, especially in the prolonged use of treated wastewater in the face of stricter environmental regulations [19]. These recommendations are applicable to our study because, although the application of the diluted effluent promoted crop establishment and growth, the salt content in the soil increased.

The high content of nutrients, such as nitrogen, calcium, and potassium, detected in both the soil and effluent of the experimental site seem to favour high biomass production in Sudan sorghum. In this sense, the results obtained correspond with those of Cavalcante et al. (2018), who concluded that the order of extraction and accumulation of macro- and micronutrients in Sorghum bicolor was K > N > Ca > Mg > S > P > Fe > Zn > Mn > Cu, with the first three coinciding with those determined in the soil and effluent of our study [20]. A long-term study suggests that the inorganic material present in effluents accumulates with successive applications over time, which is of concern as most wastewater treatment processes fail to significantly reduce salt concentrations in wastewater flows. However, it was highlighted that the application of effluents generated in the industrialization of viticultural by-products is an alternative that can provide greater competitiveness of the sector in arid environments, generating vegetal biomass for various uses in a circular economy framework [21]. In this sense, the authors highlighted that the incorporation of distillery effluent from viticultural waste into irrigation systems not only allows for sustainable waste management but also optimises the use of water resources and improves agricultural productivity. The combination of these approaches may be the key to promoting more sustainable agricultural practices in viticulture, improving productivity in arid areas, and generating biomass for various commercial purposes. The present study confirms the conclusion provided by Mosse et al. (2012) [21] that the diluted effluent allowed the water resource to be reduced by 9% and provided nutrients and water for the optimal development of pasture and sorghum. However, precautions should be taken to avoid problems associated with soil salinity. If the biomass produced by the perennial pasture is destined for animal fodder, the potential risk of high potassium content, which could affect the uptake of other nutrients such as calcium, must be evaluated. In any case, the effluent also contains high levels of this nutrient.

5. Conclusions

Agro-industrial waste and effluents pose challenges in arid areas due to water scarcity and high organic loads. This study explores using effluents to grow plant biomass, showing sorghum as highly efficient in dry biomass yield (32.6 Tn/ha) compared to pasture (6.5 Tn/ha). Sorghum's tolerance to salinity makes it suitable for bioenergy, animal feed, or as a compost co-substrate, while pastures, although lower in biomass, excel in nutrient capture and are ideal for nutrient recovery goals. Both crops help moderate soil salinity, with pasture reducing electrical conductivity more effectively. This flexibility enables tailored crop choices based on biomass or nutrient recovery objectives, warranting further research on the economic and long-term impacts. The experience confirmed the feasibility of the efficient use of the effluents from the wine waste distillation plant and their valorisation through the generation of biomass for various purposes.

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