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Original article

Utilization of Brandy Industry Waste for Soil Amelioration and Plant Nutrient Enhancement

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The accumulation and disposal of waste present significant environmental challenges, particularly in the wine and brandy industry, where distillery dregs, a by-product of ethanol distillation, contribute to pollution when discharged into waterways. This study explores the potential of distillery dregs as an agricultural ameliorant and fertiliser, focusing on their effects on soil quality and water conservation. Field experiments were conducted between 2017 and 2018, involving the application of 1,500 m³ of distillery dregs per hectare to semi-desert brown soils. Cultivated with alfalfa to assess the impact on plant growth, soil properties were analysed before and after the application. The results demonstrated that distillery dregs improved soil quality by reducing carbonate content and enhancing soil structure, with a 2.6% increase in sand-sized aggregates. Electrical conductivity decreased by up to 55% in certain sections, indicating a significant reduction in salinity. Nutrient levels, specifically nitrogen and phosphorus, showed marked increases of 55% and 49% on average, respectively, while humus content also rose significantly by 45%. Alfalfa yield increased by 22%, with improvements in plant height, green mass, and dry weight. Furthermore, concentrating distillery dregs reduced transportation costs, thereby enhancing the cost-effectiveness of the application. The findings suggest using the distillery dregs, particularly when concentrated, as an environmentally sustainable solution for improving soil health, mitigating pollution, and promoting sustainable agricultural practices.

Key words: soil improvement, waste management, distillery by-products, sustainable agriculture, resource recycling, agricultural productivity

Waste production and accumulation pose significant environmental challenges that threaten global sustainability. The increasing demand for strategies prioritising waste reduction and promoting a circular economy has garnered substantial attention within environmental policies and resource management frameworks (Duque-Acevedo *et al.* 2020; Khodkam *et al.* 2024). Since 1998, research into agricultural waste has become increasingly important, driven by shifts in global energy and environmental policies (Maina*et al.* 2017; Saleem 2022). Over recent decades, industrial innovations have led to the development of advanced waste processing technologies, improving resource efficiency and promoting sustainable agricultural production while reducing environmental impact (España-Gamboa *et al.* 2011;

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Sherwood 2020; Clauser *et al.* 2021; Coulibaly *et al.* 2021).

A key focus of these innovations is the application of biofertilisers, which provide a sustainable alternative to chemical fertilisers, pesticides and herbicides, thereby mitigating their adverse effects on human and environmental health (Sharma *et al.* 2017; Xu & Geelen 2018; El-Mogy *et al.* 2020; Puglia *et al.* 2021). Biofertilisers enhance nutrient uptake and plant resilience, positioning them as a critical component of sustainable agricultural practices (Bhardwaj *et al.* 2014; Singh *et al.* 2016; Daniel *et al.* 2022).

Among various agricultural by-products, the management of wine waste, particularly distillery dregs (DD), has emerged as a pressing concern, driven by the global expansion of wine and brandy production (Maicas & Mateo 2020). DD, a by-product rich in organic acids and nutrients, poses environmental risks such as depleting oxygen levels in water bodies and threatening aquatic ecosystems when improperly disposed of (Ahmed *et al.* 2017; Ranta *et al.* 2021).

In response to these risks, DD has been explored as a valuable resource for soil enhancement and fertilization, owing to its organic acids and nutrient content, which can improve soil fertility and agricultural productivity (Mikucka *et al.* 2022). Various physicochemical, biological, and combined treatment methods have been employed to process and repurpose DD. However, challenges persist in mitigating its environmental impact and optimising its reuse, particularly regarding the waste generated during treatment processes (Fitz-Gibbon *et al.* 1998; Bezuneh *et al.* 2015; Sahakyan *et al.* 2021; Asaithambi *et al.* 2023). These methods facilitate the biological decomposition of DD, yielding methane gas that can be used as an energy source (Gurreri *et al.* 2020). Despite these advancements, challenges remain in managing the environmental impact of DD and optimising its reuse, especially concerning the by-products produced during treatment (Larramendy & Solonesky 2021). Furthermore, the extraction of valuable materials from DD using electrodialysis technology has been proven to be both energy-intensive and economically inefficient, complicating efforts to process this waste sustainably (Kuznetsov *et al.* 2010; Patel *et al.* 2024). Consequently, alternative, more cost-effective, and environmentally friendly solutions are required to address the challenges associated with DD treatment and reuse.

As global brandy production rises, the volume of DD waste also increases, creating escalating urgency for effective waste management strategies. In European countries, where brandy production is one of the key industries, the environmental challenges associated with DD waste are being systematically addressed through a combination of regulatory frameworks, technological innovations and best practices. France, as the leading producer, plays a central role in driving these initiatives, setting a precedent for countries confronting similar issues (Lončarić 2022).

In countries like Armenia, where brandy production is integral to the economy, DD disposal has become a significant environmental concern, with substantial quantities entering surface waters and intensifying environmental degradation. Innovative solutions, such as DD condensation, have been proposed to reduce transportation costs and maintain the quality of DD for agricultural use (Sahakyan *et al.* 2023).

This research aimed to explore the potential of DD as an environmentally sustainable and economically feasible solution for improving semi-desert brown (SDB) soils in Armenia, which cover approximately 140,000 ha. These soils are characterised by low humus content, poor fertility, high carbonate levels, and a tendency to form surface crusts. The use of DD as a soil amendment offers a dual solution for waste management and soil fertility improvement, with the potential to increase agricultural productivity. This study hypothesises that the application of DD will enhance soil fertility and boost agricultural productivity in SDB soils, offering a sustainable solution to waste management and soil reclamation. By exploring this approach, the study sought to contribute to sustainable agricultural practices and environmental protection, providing practical solutions that can be implemented globally to mitigate the impacts of agricultural and industrial waste.

MATERIAL AND METHODS

This study was conducted between 2017 and

2018 in the Armavir community, located within the Armavir region of Armenia, on SDB soil, classified as Calcisol according to the World Reference Base (WRB) for Soil Resources classification system (Figure 1). The field experiment covered an area of 2.1 ha, subdivided into two distinct sites: Site I (1.5 ha), where DD was applied, and Site II (0.6 ha), which served as the control (Figure 2). The study area is at 44.0358° E longitude | 40.1008° N latitude, referenced in the WGS84 coordinate system.

Soil samples were collected in mid-May 2017 from five sections at Site I and three at Site II, each at a depth of 0 – 0.3 m. These samples were subsequently analysed for physical, chemical, and agrochemical properties to assess the initial soil conditions and monitor the effects of the applied DD.

Soil Characterisation and Experimental Setup

The soil analysis was conducted to evaluate key parameters critical for assessing soil quality and fertility. The key parameters measured included:

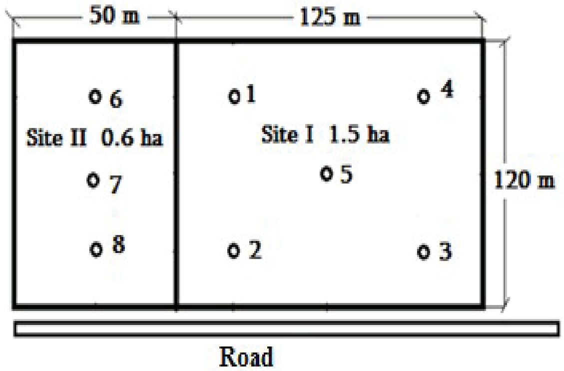

Figure 2. The scheme of the experimental field.

Electrical Conductivity (EC): EC was determined using saturated paste extracts (soil : water ratio 1 : 0.5), providing an estimate of the total concentration of soluble salts in the soil, which is a critical indicator of salinity levels and their potential impact on plant growth.

Water-soluble salts and pH: Water extracts (soil : water ratio is 1 : 5) were used to measure total soluble salts, pH, and specific ions including carbon-

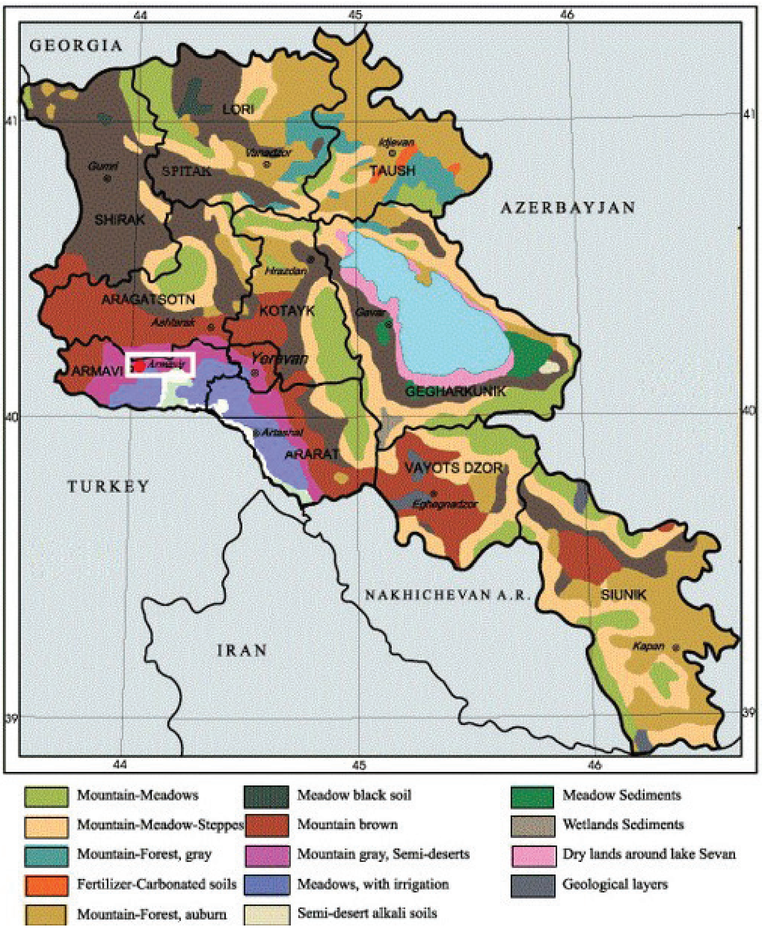

Figure 1. The location of the experiments (Montanarella *et al.* 2013).

ate (CO_3^{2-}), bicarbonate chloride (HCO_3^-), sulphate (SO_4^{2-}), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and exchangeable sodium percentage (ESP). The total water-soluble salt content in the 0 − 0.3 m soil layer ranged from 0.114% to 0.384%, with pH values between 7.3 and 7.8, indicating slightly alkaline conditions. Notably, no sodium carbonate was detected in any of the sections (Table 1).

ESP − Exchangeable Sodium Percentage

Cation Exchange Capacity (CEC): CEC was determined using a compulsive exchange procedure with barium chloride ($BaCl_2$) as outlined by Gillman and Sumpter (1986). The total exchangeable cation content in the soil was relatively high, ranging from 30.6 to 32.3 $mmol_c$/kg. Exchangeable calcium varied between 61.6% and 79.5%, while magnesium content ranged from 7.7% to 28.1%. The exchangeable potassium and sodium contents ranged from 4.6% to 8.2% and 4.5% to 7.1%, respectively, all of which fall within the acceptable limits for soil fertility.

Mechanical Composition: Granulometric analysis revealed that the soil was classified as light loam, with silt content ranging from 8% to 12% and physical clay content between 21.03% and 28.08%. The-

T a b l e 1

Water soluble salts of 0 − 0.3 m layer of semi-desert soils of the experimental field

№ of sections	Total salts [%]	pH	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	ESP [%]
			[mmol/kg]							
1	0.159	7.4	0	0.08	1.41	1.11	1.50	0.32	0.78	4.53
2	0.144	7.6	0	0.03	1.21	1.13	1.10	0.56	0.71	4.93
3	0.154	7.7	0	0.52	1.04	0.84	0.90	0.24	1.26	6.81
4	0.114	7.5	0	0.20	0.59	1.01	0.70	0.56	0.54	7.43
5	0.384	7.8	0	0.11	2.09	3.87	2.35	1.44	2.28	5.60
6	0.181	7.5	0	0.84	1.21	0.84	0.50	0.08	2.31	6.28
7	0.169	7.3	0	0.20	1.89	0.65	1.35	0.05	1.34	7.37
8	0.282	7.6	0	0.20	2.48	1.83	2.60	0.08	1.83	3.33

ESP − exchangeable sodium percentage.

T a b l e 2

Mechanical composition [%] of 0 − 0.3m layer of semi-desert soils of the experimental field

№ of sections	Fractions [mm]						
	1 − 0.25	0.25 − 0.05	0.05 − 0.01	0.01 − 0.005	0.005 − 0.001	<0.001	Physical clay
1	35.00	31.00	9.03	4.73	9.97	10.27	24.97
2	40.00	17.32	14.60	7.56	8.52	12.00	28.08
3	34.27	24.18	11.27	5.87	9.63	14.78	30.28
4	37.00	30.00	6.24	6.26	8.93	11.57	26.76
5	30.08	27.17	15.15	6.30	12.05	9.25	27.60
6	36.15	30.24	8.53	8.27	9.67	7.14	25.08
7	31.07	33.48	7.53	7.84	11.28	8.80	27.92
8	38.10	34.35	6.52	8.28	4.75	8.00	21.03

Table 3

Composition of wine distillery dregs

Colour	Dark brown liquid
pH	3.30
Suspended solids [g/L]	2.40
Ethanol [g/L]	0.13
Total acids [g/L]	5.65
Tartaric acid [g/L]	3.89
Malic acid [g/L]	1.45
Acetic acid [g/L]	0.31
Total titratable acidity of [mmol/L]	75 – 104
Nitrogen [g/L]	0.224
Phosphorus [g/L]	0.592
Potassium [g/L)	1.193
Sulphate (SO_4) [g/L]	0.264
Dry substances [%]	6.00

se results indicate a relatively homogenous texture across the experimental field (Table 2).

Experimental Design and Treatment

The experiment incorporated two treatments:

DD Application (Treatment): To evaluate its impact on soil reclamation and fertility, 1,500 m³ of DD per hectare was applied to Site I between June 1 and 20, 2017. The DD, supplied by the Yerevan Cognac Factory, was distributed through furrows that were prepared in advance. The chemical composition of the DD is presented in Table 3.

For the 1.5 ha area, a total of 2,250 m³ (equivalent to 90 tanker trucks) of DD was used. The application dosage was determined based on the nutrient content of the DD and its potential to improve the physical and chemical properties of the soil.

Control: Site II, which remained untreated, served as a control to compare the alfalfa yields between the reclamation and untreated areas. To assess the impact of DD on the physical and chemical properties of the soil, soil samples were collected from five sections of Site I prior to the reclamation process (Figure 2). Following the application of DD, additional soil samples were collected from the same sections. These samples were analysed to monitor changes in soil quality. For comparison, data from the pre-DD soil samples taken from Site I were used as a control.

Crop Planting and Growth Monitoring

Following the application of DD, the experimental field was tilled, and alfalfa seeds were sown in mid-September 2017. Irrigation was performed as required to maintain optimal growing conditions. Throughout the growing season, phenological observations were conducted to monitor plant development. Alfalfa growth was periodically assessed by recording the green mass weight and plant height. Measurements were performed after the second cut in the end-May, 2018, on five randomly selected plots (distributed in an envelope form) for each treatment (I and II) using the metric method and recorded before each harvest to assess the impact of DD application on alfalfa yield.

Statistical Analysis

A Student‘s *t*-test was employed to assess the statistical significance of the difference in alfalfa yields between the control and experimental groups. This analysis aimed to determine whether the observed differences in alfalfa yield and available nutrients could be attributed to the experimental treatment.

RESULTS

Carbonate Composition

Table 4 illustrates the changes in the carbonate composition of SDB soil during the chemical remediation process. The total carbon content in the experimental area ranged from 14.92% to 20%. Specifically, the $CaCO_3$ content varied between 10% and 12.4%, while the $MgCO_3$ content fluctuated between 2.59% and 10%.

Chemical amelioration led to a modest reduction in the total carbonate content within the 0 − 0.3 m soil layer, with decreases ranging from 0.6% to 2.0%. The average reduction in total carbonates was 1.03% (a 13.2% decrease relative to the control). Similarly, the concentrations of calcium and magnesium carbonates decreased by an average of 0.50% and 0.53%, respectively.

Soil Aggregate Composition

Following chemical amelioration, a marked change in the soil's aggregate composition was observed (Figure 3), with a 2.6% increase in sand-sized aggregates a 15.3% increase relative to the control), while clay-sized particles decreased by the same rate. This shift suggests an improvement in soil structure, which may enhance aeration and water retention.

Exchangeable Cations

The changes in exchangeable cation composition revealed a slight increase in exchangeable magnesium levels following amelioration, ranging from 1.5% to 2.6%, while the ESP decreased by 1.7% (28.8% decrease compared to the control). Although the calcium ion content decreased to 3.0 $mmol_c$/kg, the average calcium content remained largely unaffected (Table 5).

T a b l e 4

Carbonate composition in the 0 − 0.3 m layer of soils in the experimental field

№ of sections	Total carbonates [%]		$CaCO_3$ [%]		$MgCO_3$ [%]	
	I	II	I	II	I	II
1	14.92	13.93	11.50	11.30	3.42	2.66
2	14.99	14.33	12.40	12.10	2.59	2.23
3	17.60	16.70	10.70	10.20	6.90	6.50
4	20.00	18.40	10.00	9.40	10.00	9.00
5	15.00	14.00	10.50	9.60	4.50	4.40
Average	16.50	15.47	11.02	10.52	5.49	4.96

I – before amelioration, II – after amelioration.

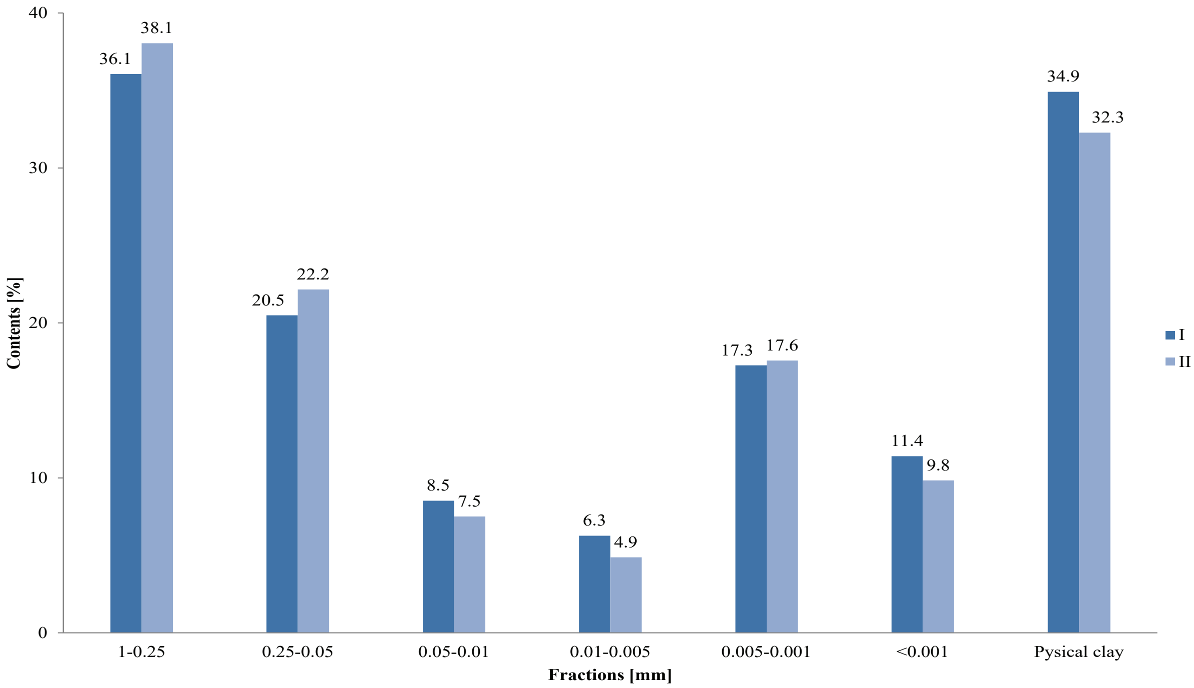

Figure 3. Changes in soil aggregate composition before and after chemical reclamation in the experimental field.
I– before amelioration, II– after amelioration.

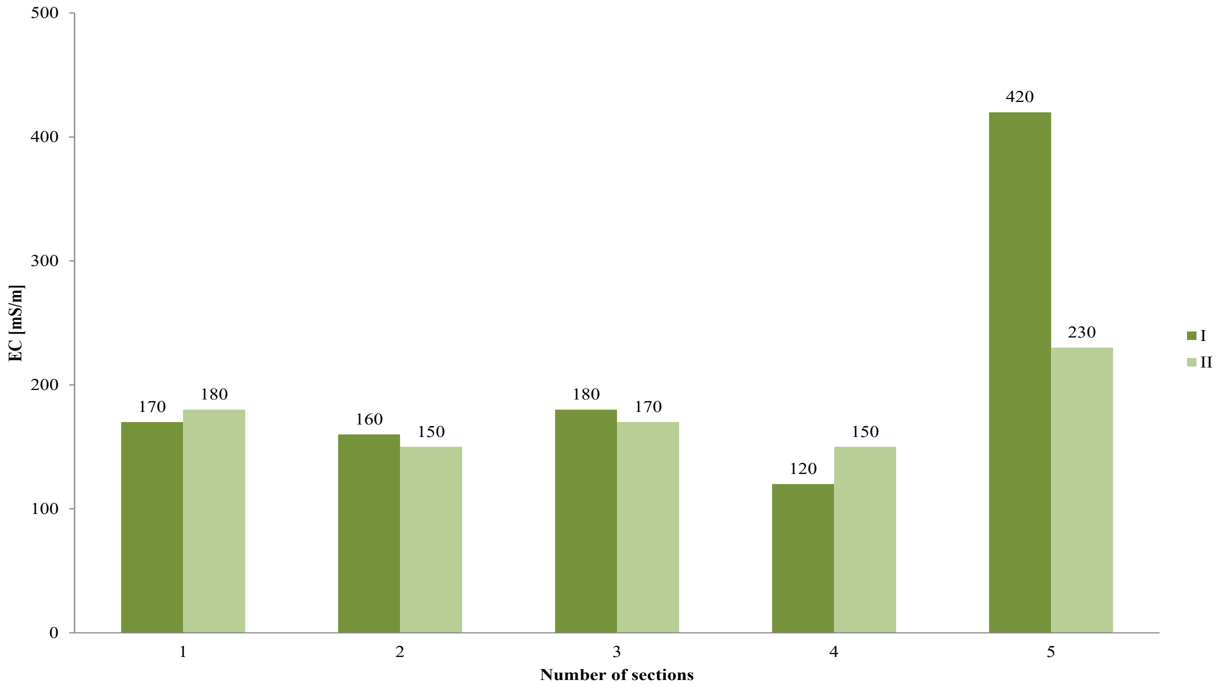

Figure 4. Changes in EC during the amelioration process in the experimental field.
I – before amelioration; II – after amelioration; EC – electrical conductivity.

T a b l e 5

Change in exchangeable cations content at the 0 – 0.3 m soil depth

№ of sections from the Site I		[mmol$_c$/kg]					[%]			
		Ca	Mg	K	Na	Total	Ca	Mg	K	Na
1	I	23.0	3.7	2.5	1.4	30.6	75.1	12.1	8.2	4.5
	II	23.0	4.2	2.5	1.2	30.9	74.4	13.6	8.1	3.9
2	I	25.4	3.9	1.5	1.5	32.3	78.6	12.1	4.6	4.6
	II	24.5	3.7	1.3	1.3	30.8	79.5	12.0	4.2	4.2
3	I	25.2	3.6	1.9	1.5	32.2	78.3	11.2	5.9	4.6
	II	24.7	4.4	1.8	1.2	32.1	76.9	13.7	5.6	3.8
4	I	24.8	2.4	1.8	2.2	31.2	79.5	7.7	5.8	7.1
	II	27.1	3.2	1.8	0.7	32.8	82.6	9.8	5.5	2.1
5	I	19.7	9.0	1.6	1.7	32.0	61.6	28.1	5.0	5.3
	II	18.7	10.1	1.6	1.4	31.8	58.8	31.7	5.0	4.4
Average	I	23.2	4.8	1.9	1.7	31.5	73.7	15.0	5.9	5.4
	II	23.3	5.3	1.8	1.2	31.6	73.8	16.8	5.7	3.7

I – before amelioration, II – after amelioration.

Electrical Conductivity (EC)

The EC values exhibited considerable variation prior to amelioration, ranging from 120 to 420 mS/m. Following the application of DD, a significant reduction in EC was observed in section 5, where it decreased from 420 mS/m to 230 mS/m (a reduction of 55%). On average, EC decreased by 16.2%. This decrease indicates a reduction in soil salinity, which is likely to be beneficial for plant growth (Figure 4).

Soil Fertility and Nutrient Content

Following the application of DD, a notable improvement in soil fertility was observed. The humus content increased by an average of 0.42%, nitrogen levels rose by 2.3 mg/100 g, and phosphorus content also experienced a rise of 1.7 mg/100 g (or 45%, 55%, and 49%, respectively, compared to the control on average). These findings signify a notable enhancement in the availability of key soil fertility. However, potassium levels remained unaffected (Table 6).

Alfalfa Yield Improvements

Table 7 presents the alfalfa yield data before and after the application of DD. The average plant height increased from 50 cm in the untreated control to 80 cm in the treated variant.

DD – Distillery Dreg

Additionally, fresh weight (FW) and dry weight (DW) showed significant improvements in the treated plants. Specifically, FW production increased from 1,250 g/m² in the control plot to 1,450 g/m² in the treated plot, while DW rose from 240 g/m² to 292 g/m². Overall, the treated plants demonstrated a yield increase ranging from 15.4% to 36.4%, with

T a b l e 6

Changes in humus content [%] and available nutrients [mg/100g] in semi-desert grey soils during chemical amelioration (based on data from 5 sections)

Parameters	I	II	I	II	I	II	I	II
	Hummus		N		P_2O_5		K_2O	
Minimum	0.70	0.72	2.1	5.3	3.2	3.2	37	40
Maximum	1.50	1.85	5.2	7.5	3.9	6.3	61	60
Average	0.95	1.38	4.2	6.5	3.5	5.2	50	51

I – before amelioration; II – after amelioration.

T a b l e 7

Alfalfa yield indicators in the experimental fields

Number of measurements	Plant height [cm]		Green grass [g/m^2]		Dry grass [g/m^2]		Yield addition to the control [%]
	I	II	I	II	I	II	
1	50	80	1,250	1,450	250	290	16.0
2	48	80	1,300	1,500	260	300	15.4
3	52	83	1,200	1,400	240	290	20.8
4	46	79	1,150	1,400	230	280	21.7
5	53	81	1,100	1,500	220	300	36.4
Average	50	81	1,200	1,450	240	292	22.0

I – before amelioration(control, site II); II – after amelioration with DD (site I).

T a b l e 8

Statistical analysis of alfalfa DW [g/m²], nitrogen (N), and phosphorus (P_2O_5) [mg/100g] data

Site	n	Results					Mean	Variance	Standard error	t	p
Alfalfa DW											
I	5	250	260	240	230	220	240	8.36	3.74	6.5	$1.9\ 10^{-4}$
II	5	290	300	290	280	300	292	15.80	7.07		
Nitrogen (N)											
I	5	2.1	3.2	1.8	1.8	1.4	2.06	0.468	0.21	4.3	$2.5\ 10^{-4}$
II	5	5.3	7.5	5.5	6.2	3.0	5.50	2.695	1.21		
Phosphorus (P_2O_5)											
I	5	3.0	3.9	2.3	3.0	2.6	2.96	0.363	0.16	2.7	$2.6\ 10^{-4}$
I I	5	3.2	6.3	5.8	4.6	3.7	4.72	1.757	0.78		

n – number of observations in each group; t – t-value from Student's *t*-test, indicating the degree of difference between means; p – probability that the observed difference occurred by chance. A *p*-value of < 0.05 denotes statistical significance; DW – dry weight; I-control; II-experimental.

an average improvement of 22% compared to the control.

Figure 5 displays images of the alfalfa fields following the second cutting. Panel I shows the untreated control (without amelioration), while Panel II illustrates the fields after amelioration with DD.

Statistical Analysis of Alfalfa Harvest Data and Available Nutrients

A comprehensive statistical analysis of the alfalfa DW, nitrogen and phosphorus data is presented in Table 8. The statistical examination of DW revealed t-values ranging from 2.7 to 6.5, which quantify the difference between the means of the two groups in relation to the variability within the groups.

The corresponding *p*-value, representing the probability of obtaining results at least as extreme as those observed under the null hypothesis, ranged from 0.26×10^{-4} to 1.9×10^{-4}. The corresponding *p*-value, representing the probability of obtaining results at least as extreme as those observed assuming the null hypothesis is true, was 1.9×10^{-4}. Since the *p*-value is significantly lower than the conventional threshold of 0.05, this indicates that the means of the two groups differ significantly.

I II

Figure 5. Alfalfa fields after the second cutting.
I – without amelioration (control), II – after amelioration with DD

DISCUSSION

Utilization of Brandy Production Waste in Agriculture

This study underscores the significant potential of brandy production waste, specifically DD, as a highly effective soil ameliorant and fertiliser. Rich in nitrogen, phosphorus, and organic acids, DD has been shown to confer substantial benefits to soil health in various countries (Fillaudeau *et al.* 2008; Terefe & Eyob 2015). Our findings corroborate these results, indicating that DD can enhance soil fertility and contribute to the advancement of sustainable agricultural practices. This study demonstrates that the use of DD effectively addresses the challenges related to waste management, while simultaneously reducing reliance on synthetic fertilisers. By integrating DD into agricultural practices, the research contributes to the promotion of more sustainable farming systems, offering an alternative to conventional fertilisation methods and supporting environmental sustainability (Toop *et al.* 2020). Despite the environmental benefits of distillery dregs (DD), its economic feasibility is limited by substantial transportation costs, primarily due to its high water content, which accounts for approximately 95% of its total weight. These elevated transportation expenses present a significant challenge to the widespread adoption of DD as a soil amendment, thereby hindering its potential for broader implementation in sustainable agricultural practices

Reducing Transportation Costs Through Distillation

To address the challenge associated with transportation costs, distillation methods have been explored to reduce the volume of DD by separating water based on differences in boiling points (Puglia *et al.* 2021). Although distillation retains most of the beneficial compounds within DD, it is an energy-intensive process (Halvorsen & Skogestad 2011; Guerini Filho *et al.* 2018). To improve energy efficiency, vacuum distillation has been suggested as a more efficient alternative, though it requires significant upfront investment in specialized equipment (Iakovlieva *et al.* 2017). Previous work by the authors introduced a modified distillation process that produces condensed DD with minimal energy consumption and lower capital investment (Sahakyan *et al.* 2023). This innovation significantly reduces transportation costs and the environmental impact, thereby making DD a more cost-effective and sustainable option for soil amendment.

Soil Improvement with the DD Application

The application of DD at a dose of 1,500 m^3/ha has demonstrated positive effects on the physical and chemical properties of Semi-desert brown soils in Armenia, which are characterised by low fertility. A reduction in total carbonate content by 1.03%, an increase in sand-sized micro aggregates, and a decrease in clay particle size suggest that DD can improve soil structure. These changes likely contribute to enhanced soil aeration, water retention, and soil health. Additionally, the increase in exchangeable magnezium content, coupled with the displacement of potassium and sodium ions, indicates a significant improvement in soil fertility, which benefits plant growth (Khaleel *et al.* 1981). These findings highlight the potential of DD to amend soils in arid and semi-arid regions, where soil fertility and structure are critical obstacles to agricultural productivity.

Impact on EC and Crop Growth

The observed reduction in EC following DD application indicates a decrease in soil salinity, a factor that plays a critical role in preventing adverse effects on plant growth. Excessive soil salinity can severely restrict crop yields, and the amelioration observed in this study indicates that DD can support healthier plant development. The positive impact of DD on alfalfa growth was also evident, with an average 22% increase in yield.

Statistical Significance of Available Nutients and Alfalfa Yield Improvements

Statistical evidence strongly supports the effectiveness of DD in enhancing soil fertility and crop performance. Significant increases in nitrogen and phosphorus availability were observed in DD-treated plots, as indicated by a t-value of 4.3 ($p = 0.0025$) for nitrogen and 2.7 ($p = 0.026$) for phosphorus (Table 8). These enhancements in nutrient content likely contributed to the improved plant growth observed.

Alfalfa DW in the treated area was also significantly higher than in the control, with a t-value of 6.5 ($p = 1.9 \times 10^{-4}$), confirming the positive impact of DD on biomass accumulation. Treated plants exhibited greater height, fresh mass, and dry matter, suggesting that DD application not only improves nutrient availability but also promotes overall crop vigour.

These findings reinforce the potential of DD as a viable soil amendment, particularly for degraded or saline soils where traditional fertilisers may be less effective. The statistical robustness of the results further underscores the practical applicability of DD in improving agricultural productivity within sustainable land management frameworks.

Economic and Practical Considerations

While DD offers significant environmental and agricultural benefits, the high transportation costs remain a notable challenge. Transporting 1,500 t/ha of DD would require approximately 60 trips using 25-ton trucks, incurring costs of around USD 3,000 (in Armenia). However, using a five-fold concentrated form of DD reduces the volume of material required, thereby lowering transportation costs to approximately USD 600. This approach enhances the economic feasibility of DD while preserving its benefits for soil improvement and crop yield enhancement. The concentration of DD thus provides a more cost-effective solution for utilizing brandy production waste in agriculture. This strategy aligns with the recommendations of other studies (Larney & Angers 2012; Cao *et al.* 2024), which suggest that concentrated organic amendments can provide both economic and environmental benefits.

CONCLUSIONS

This study demonstrates that DD can represents an effective and sustainable solution for improving the quality of SDB soils in Armenia. DD contributes to increasing soil fertility and mitigating salinity issues by reducing carbonate content and enhancing soil structure. The application of DD resulted in substantial improvements to key soil quality indicators in semi-desert brown (SDB) soils. Total carbonates were reduced by an average of 13.2%, while the soil's aggregate composition improved, marked by a 15.3% increase in sand-sized aggregates and a corresponding decrease in clay-sized particles. Exchangeable sodium percentage (ESP) declined by 28.8%, and electrical conductivity (EC) decreased by 16.2% on average, relative to the control. In addition, the application of DD significantly enhanced soil fertility: humus content increased by 45%, nitrogen by 55% and phosphorus by 49% on average compared to the untreated variant. These findings indicate a significant improvement in the availability of key soil nutrients essential for plant growth. These improvements were shown to positively influence alfalfa growth, with a 22% increase in yield, thereby highlighting DD's potential to foster healthier crop development in degraded soils. While the high transportation costs associated with DD's water content pose a challenge, the study highlights that distillation processes to concentrate DD can substantially reduce these costs, making its use as a soil amendment more economically viable. This approach not only alleviates waste from brandy production but also offers an environmentally sustainable alternative to chemical fertilisers, supporting circular and eco-friendly agricultural practices. The findings underscore the value of DD as a cost-effective resource for enhancing soil health and boosting agricultural productivity, particularly in regions struggling with waste management and soil degradation. This research contributes to the global movement towards waste recycling and sustainable farming, offering practical solutions that can be applied in areas with similar environmental conditions. Future research should focus on further optimizations of the distillation process and evaluate the long-term impact of DD on both soil and crops across different climates and regions.

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