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Transforming Irrigated Agriculture in Semi-Arid and Dry Subhumid Mediterranean Conditions: A Case of Protected Cucumber Cultivation

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Abstract: Pressure from population growth and climate change stress the limited water resources in the Mediterranean region and threaten food security and social stability. Enhancing food production requires the transformation of irrigation systems and enhancement of local capacity for sustainable water and soil management in irrigated agriculture. The aim of this work is the conversion of traditional irrigation practices, by introducing the practice of optimal irrigation scheduling based on local ET estimation and soil moisture monitoring, and the use of continuous feeding by fertigation to enhance both water and nutrient use efficiency. For this, two trials were established between August and November 2023 in two different pedoclimatic zones (Serein and Sultan Yacoub) of the inner Bekaa Plain of Lebanon, characterized by semi-arid and dry subhumid conditions and different soil types. Greenhouse cucumber was tested to compare the prevailing traditional farmers' practices with the advanced, technology-based, methods of water management. Results showed a significantly higher amount of water applied by the farmers to the protected cucumber, with a potential for average saving of 105 mm of water applied in each season by improved practices. Water input in the traditional practices revealed potential stress to plants. With more than 20% increase in cucumber yield by the transformed practices, a general trend was observed in the fertilization approach and amounts, resulting in lower nutrient recovery in the farmer's plots. The science-based practices of water and nutrient management showed higher application and agronomic water use efficiency of full fertigation, exceeding 60%, associated with double and triple higher nitrogen use efficiency, compared to those results obtained by the traditional water and fertilizer application methods. The monitored factors can contribute to severe economic and environmental consequences from nutrient buildup or leaching in the soil–groundwater system in the Mediterranean region.

Keywords: continuous fertigation; adapted irrigation scheduling; ET estimation; monitoring of soil moisture; integrated water and nutrient management

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1. Introduction

Drought and water scarcity exert immense pressure on natural resources, compromising crop production and food security [1]. Moreover, the combination of population growth and climate change is placing additional stress on the already limited water resources, particularly in the dry Mediterranean region. This is affecting livelihoods, food security, economic development, and even social stability [2]. Agricultural lands are integral components of natural landscapes, each with specific agro-ecosystems. To achieve food security and meet the Sustainable Development Goals (SDGs), the intensification of sustainable practices must conform to the requirements of low environmental impact and prevention of agricultural land expansion at the expense of natural landscapes [3]. Equally critical is curbing urban expansion into arable lands. Prioritizing this prevents detrimental land use changes that harm biodiversity and disrupt sustainable ecosystems [4].

To enhance food production and meet growing demands, advanced genetic engineering has focused on optimizing shoot–root design and improving beneficial water use in crops [5]. However, inadequate irrigation system performance can hinder water use efficiency and impact food production [6]. Traditional irrigation with a lack of soil moisture monitoring leads to suboptimal irrigation scheduling and reduced water nitrogen use efficiency, factors perceived as major constraints by farmers in irrigated agriculture [7]. Beyond environmental consequences, excessive water pumping from wells contributes to groundwater depletion, limiting water productivity and economic benefits [8].

To mitigate these challenges, research gaps on sustainable land management must be closed to compensate for the low percentage of research and papers addressing land degradation and evidence-based sustainable land management in the region [9]. In this regard, crop diversification should be considered and cash crops in adapted rotations introduced [10]. Sequencing shallow- and deep-rooted crops optimizes water use across different soil layers [11]. Additionally, incorporating crop residues before planting the next crop enhances yield and achieves complementarity in nitrogen and water use [12].

One of major elements of sustainable food production in semi-arid and dry subhumid Mediterranean conditions is the adoption of optimal irrigation scheduling and efficient nutrient management at the farm level. Crop switching and more efficient water and energy use with water and nutrients placement within the root zone increase the benefits of irrigated agriculture with a reduced footprint of water and fertilizer use and gas emissions [13]. Crop productivity in irrigated agriculture is affected by prevailing soil and climatic conditions, cultivars and farming practices. To address yield gaps, it is essential to enhance irrigation and agricultural practices [14]. Numerous factors—biotic, abiotic, and socio-economic—affect crop productivity and the environmental impact of agriculture. Consequently, integrating agriculture with other ecosystems and land uses, as well as adapting to climate change, becomes imperative [15].

Conservation agriculture was suggested for dry Mediterranean conditions as a powerful tool of sustainable land management to achieve higher productivity and income and adapt to climate change and water scarcity [16]. If the irrigation systems are not improved, the Mediterranean region is expected to witness a gross irrigation requirements increase of up to 18% from climate change [17]. Simulation using the process-based eco-hydrological and agro-ecosystem model showed the potential of 35% water saving by the implementation of more efficient irrigation and conveyance systems.

Previous studies conducted on the coastal Lebanese area have demonstrated the benefits of fertigation for protected cucumber cultivation. Improving irrigation efficiency may substantially contribute to decreasing water stress [18]. The farmers' practice in the Bekaa Plain of Lebanon consists of applying fertilizers intermittently in every second irrigation event that contributes to the leaching of nitrates [19] and even less mobile phosphorous [20] within the topsoil and beyond the root zone.

Intermittent application of fertilizers to greenhouse crops in the eastern and southern Mediterranean is justified under saline conditions, if followed by water application, to prevent salt accumulation in the soil [21]. However, with the application of up to 70 mm of leaching water, this approach does not consider the risk to groundwater quality. The use of low salinity irrigation water allows for continuous feeding (fertigation), securing more efficient use of water and nutrients without causing a risk to soil solution salinity rise and reduced biomass production.

The rational application of fertilizers and water with the use of modern/smart technologies in irrigated agriculture are recommended for the countries of the Mediterranean basin to answer food security and secure optimized use of limited resources [22]. However, local farmers apply empirical estimation of crop water demands and apply excess water without appropriate water accounting strategy. Our work is trying to capitalize, and establish a solid link between research and development, by upgrading the modalities of nutrient and water input in continuous feeding to modernize agriculture in Lebanon. The novelty of this approach is the technology and evidence-based estimation of crop water needs and the prevention of salinity rise in the root zone when applying water and nutrients with every irrigation event. Compared to the farmers' practices of double dose of fertilizers, followed by the leaching of salts and nutrients in fresh water application the next irrigation cycle, the advanced approach of SEALACOM prevented water and salinity stress to protected cucumber. An optimized nutrient input and adapted irrigation schedule can sustain plant health and provide higher productivity with reduced energy and fertilizer cost and limited environmental hazards [23].

As protected greenhouses expand into the Bekaa Plain—an elevated inland area ranging between 800 and 1100 m asl—bridging the gap between research and development of remote rural areas becomes crucial through the introduction of more efficient irrigation technology. Analyzing local community performance, particularly farmers' fertilization, and irrigation practices, and energy use is necessary to ensure the proper transformation and sustainability of protected agriculture at higher elevations. Consequently, this work aims to analyze yield gaps, enhance fertilization and irrigation practices, and promote capacity building among local farmers by establishing demonstration sites (DSs) in two pedoclimatic zones within the Bekaa Plain of Lebanon.

2. Materials and Methods

To achieve the project's objectives related to sustainable water use in agriculture with a low energy and environmental footprint, two DSs were selected. These sites represent two pedoclimatic zones within the Bekaa Plain of Lebanon, covering a total area of 86,251.8 ha, with 45.8% representing agricultural land use.

2.1. Geographic Location

The first area is located in Central Bekaa, specifically in Serein village, and the second in Sultan Yacoub village, West Bekaa. Serein exhibits a level plain, while Sultan Yacoub features undulating foot slopes. Both areas are surrounded from east and west by the sloping and steep rocky lands of Mount Lebanon and Anti-Lebanon mountain chain (Figure 1). DS1, located at Serein (Casa of Zahle), stands at an elevation of 950 m asl, while DS2, situated in Sultan Yacoub within the Casa of West Bekaa, is 850 m asl.

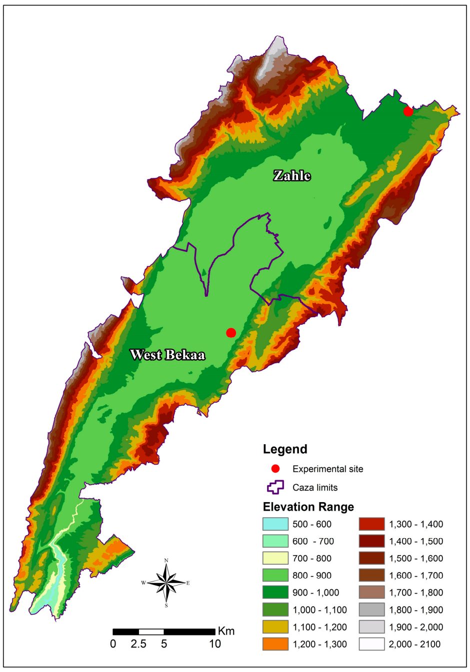

Figure 1. Topographic map of the SEALACOM Demo Sites showing the elevation range derived from DEM.

2.2. Climatic Conditions

The mean annual climatic data were obtained from the climatic stations of Tal-Amara [24]. DS1 falls within the semi-arid climatic zone, receiving 566 mm of annual precipitation, primarily between November and March (Figure 2). The rest of the year remains dry, with mean high and low annual temperature reaching 25.6 °C and 8.5 °C respectively. DS2 belongs to the dry-subhumid climatic zone, with annual rainfall of 700 mm and mean high and low annual temperature reaching 24.56 °C and 10.85 °C.

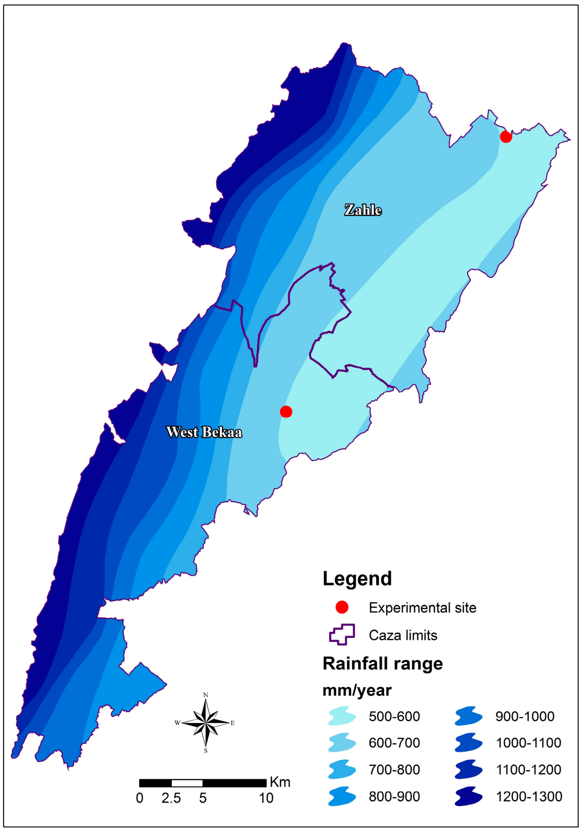

Figure 2. Rainfall map of the SEALACOM Demo Sites showing the 100-precipitation interval.

2.3. Soil Properties

Regarding soil characteristics, both DSs predominantly consist of Cambisols, Regosols, and Luvisols, with the additional presence of Vertisols, Calcisols, Leptosols, Arenosols, and Andosols (Figure 3). DS1's soil is classified as deep Eutric Regosols, characterized by neutral pH and non-saline properties. It exhibits a clay texture with negligible $CaCO_3$ content (Table 1). The soil has an average low organic matter content, is poor in total nitrogen, but enriched in phosphorous, and shows moderately high availability of potassium.

Table 1. Physico-chemical characteristics of the soils of the two DSs before the experiment.

Soil Type	Depth, cm	Total Sand	Silt	Clay	$CaCO_3$ Total	$CaCO_3$ Active	O.M.	EC	pH H_2O	Available Nutrients, ppm		
					%			ds m^{-1}		N	P_2O_5	K_2O
Eutric Regosols DS1-Serein	0–20	36	18	46	5.6	1.9	2.74	0.49	7.6	23.8	354	280
	20–40	30	20	50	3.8	1.3	1.55	0.33	7.4	23.1	305	268
Eutric Cambisols DS2-Sultan Yacoub	0–20	26	12	62	5.8	1.9	1.25	0.34	7.7	32.2	206	578
	20–40	24	16	60	5.8	1.9	1.31	0.3	7.8	27	185	627

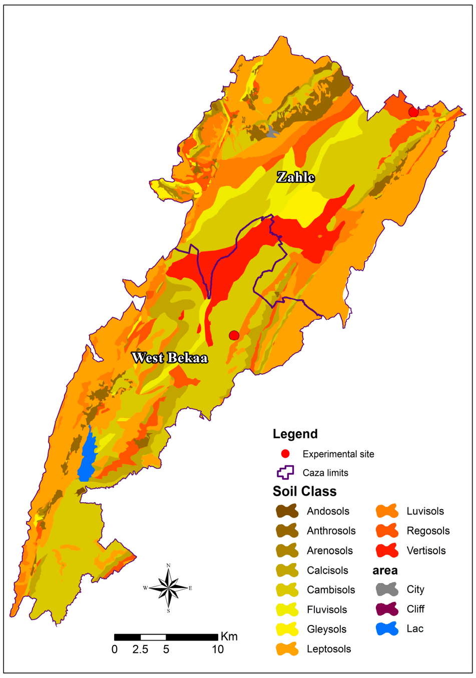

Figure 3. Soil map of the SEALACOM area of study (Source: [25]).

The soil cover of DS2 was classified as Eutric Cambisols. The soil texture is clay, with low organic matter content and a neutral-weakly basic pH (Table 1). DS2's soil is non-saline, poor in nitrogen, enriched with available phosphorous, and highly enriched with potassium. The targeted zone (DS1 and DS2) represents a relatively large area of 120 ha, making it suitable for nontraditional, intensive, protected farming in elevated semi-arid Mediterranean conditions (Figure 4) that do not require heating in winter. Notably Lebanon has experienced significant greenhouse expansion, with a total area of 1560 ha dedicated to greenhouses [25].

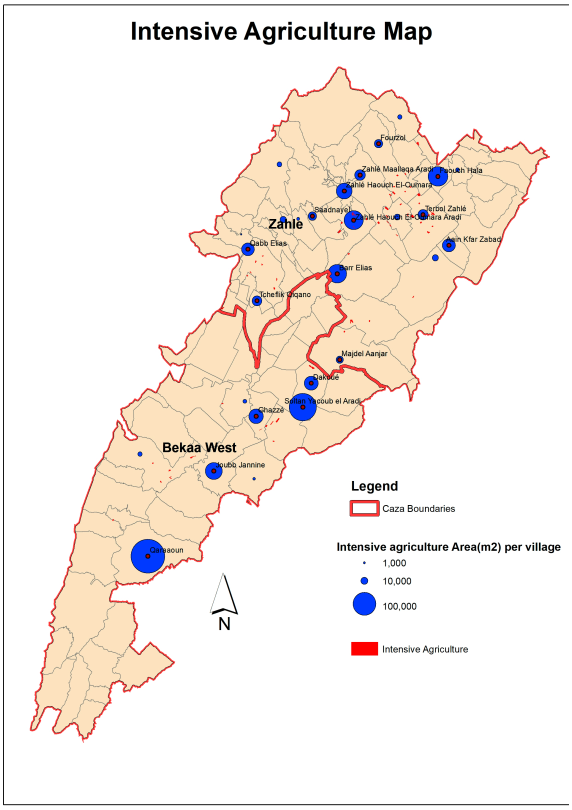

Figure 4. Development of protected agriculture in Central and West Bekaa (Source: [25]).

The selected demonstration sites represent valuable agro-climatic zones with diverse and multiple irrigated cropping systems, characteristic for the dry Mediterranean region, and provide insights into yield gaps and sustainable land management practices and the intricate interactions of water, energy, and food systems, targeted by the SEALACOM project.

2.4. Experimental Design

Field experiments focused on the protected cucumber cultivation in both locations, considering pedoclimatic variability and different farmers' practices. In Serein, three plastic walk-in houses (each measuring 8 × 41.5 m, with a total area of 996 m^2) served as the control treatment group (Figure 5). The project managed three similar, nested, experimental greenhouses.

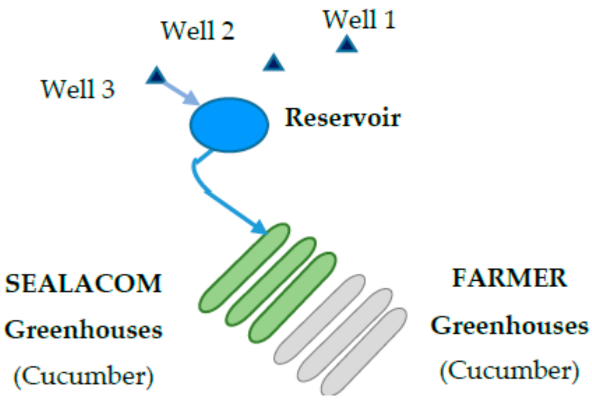

Figure 5. Serein experimental site coordinates 33°52′35″ and 36°02′57″.

In Sultan Yacoub, 4 greenhouses (each measuring 9 × 34 m (Figure 6), with a total area of 612 square meters for the two control houses and similar area for the other two experimental houses) were part of the experiment. In this way, we had two treatments (experimental and control greenhouses), replicated 5 times in 2 locations. In both DSs, farmers managed the control greenhouses as usual, applying fertigation with locally available complex, soluble, fertilizers using traditional closed tanks.

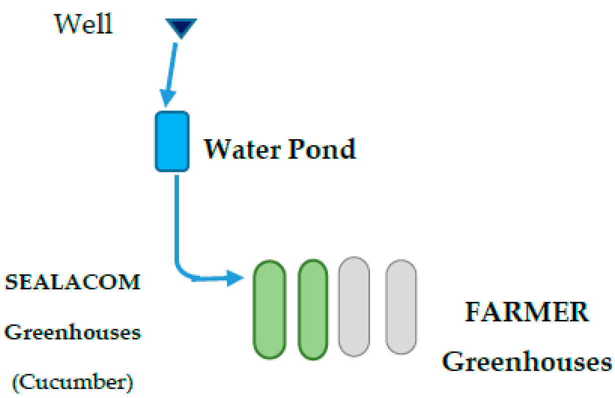

Figure 6. Sultan Yaqoub Experimental Site Coordinates 33°40′20″ and 35°51′41″.

2.5. Modality of Water and Fertilizer Application

Once the irrigation volumes are supplied to the soil, the infiltration and redistribution processes occur and contribute to regulating the water exchange within the soils, plants, and atmospheric system. Thus, the adopted irrigation management strategy, which defines the frequency and interval of the interventions, does nothing but steadily interfere with the soil–water interactions, modifying the readily available soil water and nutrient content [26].

Farmers independently managed the types, amounts, and timing of nutrient and water applications, following traditional irrigation practices with intermittent nutrient delivery that was continuously monitored by the project. We counted the time and amount of applied water, and the quality and quantity of applied fertilizers. In contrast, the SEALACOM project adopted advanced practices of fertigation that were explained and observed by the farmers.

The project estimated the required irrigation water based on ET_0 (reference evapotranspiration) calculations specific to the given site. To calculate reference evapotranspiration (ET_0), the traditional Penman–Monteith equation was applied, which combines multiple climatic variables, including solar radiation, temperature, relative humidity, and wind speed, to estimate ET_0 in open-field conditions. Since the aim was to assess ET_0 under greenhouse condition, where environmental factors differ substantially, the ET_0 value was adjusted by multiplying it by a factor of 0.65. This factor accounts for the lower evapotranspiration demand in greenhouses due to controlled conditions, such as reduced wind and lower direct solar radiation. A crop coefficient (Kc) specific to the plant species was then applied to convert ET_0 to actual crop water needs within the greenhouse environment.

Studies like [27,28] discuss the adjustments to ET_0 estimation when wind speed is minimal or less influential, especially under greenhouse conditions, which allows for modifications to the Penman–Monteith approach by focusing on more stable environmental factors. Instead of using the expensive and highly precise Dosatron injectors, the project employed a feasible venturi system, securing homogeneous and proportional, continuous water and nutrient, application. To ensure proper functioning of the venturi, it is necessary to keep a constant pressure in the system (2 Mbars) with differential pressure at the entry and output of the device. This approach differed from the farmers' intermittent fertigation using the traditional closed tank with instable pressure (Figure 7a,b). While the SEALACOM project controlled the amount and time of water application through the consideration of ETc, crop growth dynamics, and soil moisture, the farmers relied on the visual symptoms of crop and soil water status and plant age to define the onset and duration of irrigation.

(**a**) (**b**)

Figure 7. (**a**) Venturi system for full fertigation mode maintains homogeneous nutrient application. (**b**) Closed tanks do not secure homogeneous nutrient application in time and space.

2.6. Monitoring of Soil Moisture

The SEALACOM team monitored soil moisture using tensiometers to regulate water application and irrigation scheduling. Tensiometers were placed at depths of 20 cm and 40 cm in both the farmers' cucumber test sites and the SEALACOM experimental sites. These devices measured soil head potential (Figure 8), i.e., the negative soil water potential through a ceramic and porous cup, reflecting the conditions of soil moisture. Measurements were taken directly before irrigation and 24 h after each irrigation event, allowing time for gravity water to infiltrate beyond the root zone. Additionally, water meters were used to precisely control water application and measure the cumulative volume of water applied in each greenhouse of both production systems (Figure 9).

Figure 8. Tensiometer to measure soil head potential (soil moisture) and schedule onset of irrigation.

Figure 9. Water meter to control water application, a practice often ignored by local farmers.

2.7. Land Preparation and Cultivation Cycle

The farmers in Serein followed specific practices to prepare their land for cucumber cultivation: Soil plowing at 30 cm depth was followed by surface soil smoothing and irrigation network setting. A total of 100 kg of organic compost was added to each greenhouse, as basic fertilizer equivalent to 3000 kg/ha. Prior to seedling transplant, the soil was irrigated (8320 L/greenhouse of 332 m^2, equivalent to 25 m^3/1000 m^2) and sterilized with fungicide and insecticide.

Cucumber seedlings were transplanted on 18 August 2023, and supported with peat to prevent fungal diseases. The cucumbers were planted at 5 cm depth in double rows, with 45 cm between single rows and 90 cm between double rows. The distance between seedlings was 40 cm (Figure 10). Each greenhouse contained 1040 seedlings, equating to 31,325 seedlings/ha. After transplanting, each greenhouse was irrigated with 4160 L (12.5 m^3/ha). To support the new seedlings, irrigation was carried out 10 min every morning and evening, using 693 L/greenhouse (2.0 m^3/ha) each time.

Land preparation at Sultan Yacoub involved plowing to a depth of 30 cm, chiseling, and applying basic fertilizers. Farmers in Sultan Yacoub typically use 50 Kg of vermicompost and 50 Kg of complex fertilizers (15:15:15). To test the potential of using only organic compost, the project agreed with the farmer to apply only 50 Kg of vermicompost to the SEALACOM managed experimental greenhouse N1, while SEALACOM greenhouse N2 received the usual combination of 50 kg vermicompost and 50 kg complex fertilizers, received by the control house.

Figure 10. Protected cucumbers in Serein.

Cucumbers in Sultan Yacoub were planted on 19 August 2023, one day later than in Serein. The distance between two nested irrigation lines was 45 cm, and the distance between seedlings was 40 cm (Figure 11). The planting depth was 5 cm, and each greenhouse contained 1020 seedlings.

Figure 11. Protected cucumbers in Sultan Yacoub.

2.8. Estimation of Crop Water and Nutrient Demands

Nutrient and water requirements of the protected crops in the farmers' practices relied on individual farmers' skills and knowledge. They were recorded as done by the farmer without any intervention from the experimental team. Water and nutrient demands of protected cucumbers in the SEALACOM plots relied on data received from earlier experiments, using an isotope technique, showing the dynamic of crop consumption [29].

2.9. Statistical Analysis

Statistical analysis was done using descriptive statistics in Excel 2016. The means were calculated, followed by the confidence intervals, considering a 95% significance level. The comparison of the means was done through the confidence ranges obtained as [mean $\pm$ confidence interval]. If two confidence ranges overlapped, then the means were not considered different ($p < 0.05$).

3. Results and Discussion

3.1. Management of Irrigation of Protected Cucumber

While farmers irrigated the crop and determined irrigation duration based on their own skills without measuring soil water status, the SEALACOM project followed a comprehensive approach. The project team applied irrigation events and amounts with reference to climatic conditions, crop growth, production, and other field measurements (Figure 12).

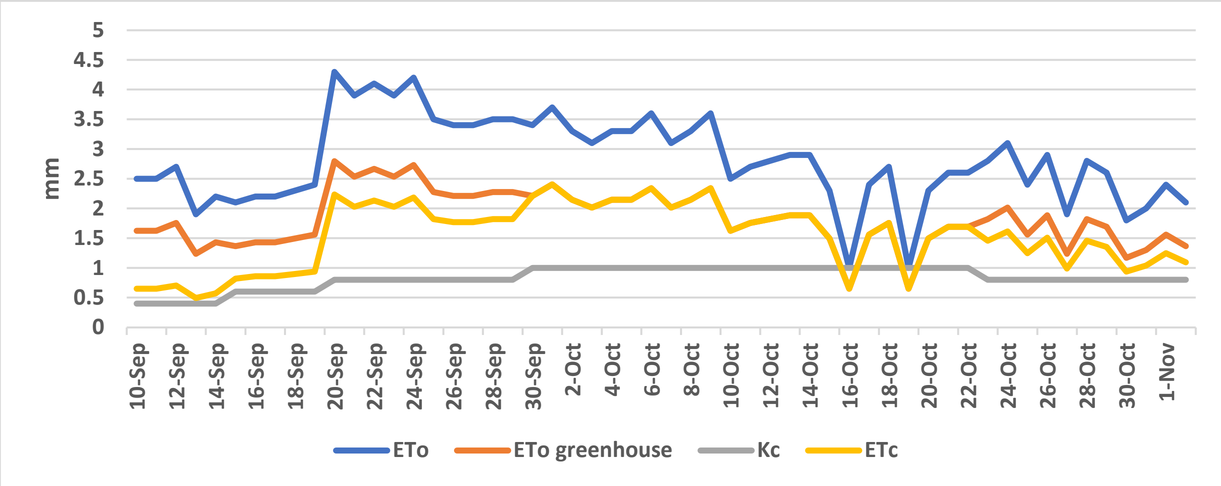

Figure 12. Science-based water application by SEALACOM project to protected cucumbers during the short fall 2023 season in Serein.

The water applied by the farmers throughout the cucumber season in both locations was significantly higher than the amount applied by the SEALACOM project (Table 2). This trend was also observed during the short production cycle of protected cucumbers at both DSs (Figure 13).

Table 2. Amount of water application under protected cucumbers in late summer 2023 by the SEALACOM project and farmers.

Location	Water Application	SEALACOM	Farmer	Difference (Farmers-SEALACOM)	Potential Water Saving from Protected Greenhouses in One Cucumber Season, m^3	
		(mm)			SEALACOM DS (120 ha)	Country Level (1560 ha)
Serein	Whole season	190.0	283.0	93	111,600	1,450,800
Sultan Yacoub		177.70	299.67	121.97	146,335	1,902,732
Serein	Productive period	81.75	157.83	76.08	91,278	1,186,848
Sultan Yacoub		88.83	147.3	58.47	70,150	912,132

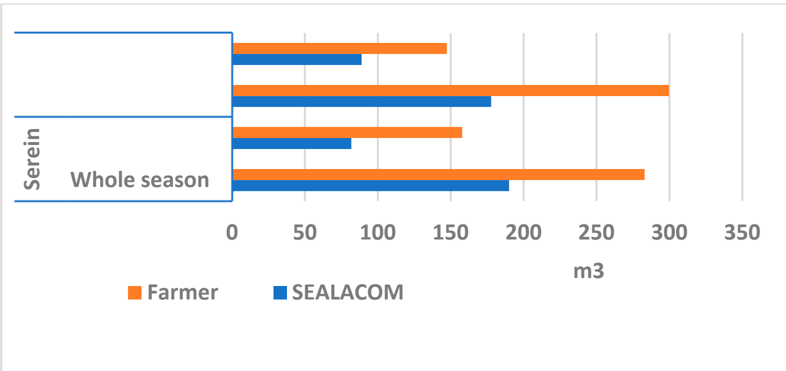

Figure 13. Water application saving potential in protected cucumbers in Bekaa, Lebanon.

The over-irrigation by farmers was evident from the soil head potential levels recorded before and 24 h after irrigation.

Figures 14 and 15 show a higher amplitude of variation in farmers' practices, which can cause stress to cucumbers, characterized by undetermined crop growth pattern before irrigation and water stagnation after irrigation, potentially leading to fungal diseases.

Despite the frequent, day on and day off, irrigation cycles, it is important to notice the larger hydric stress caused by the farmers' practice and its impact on yield. The observed low variation in soil moisture in the SEALACOM approach suggests the provision of better soil moisture conditions for improved crop performance with lower depletion levels prior to the next irrigation event.

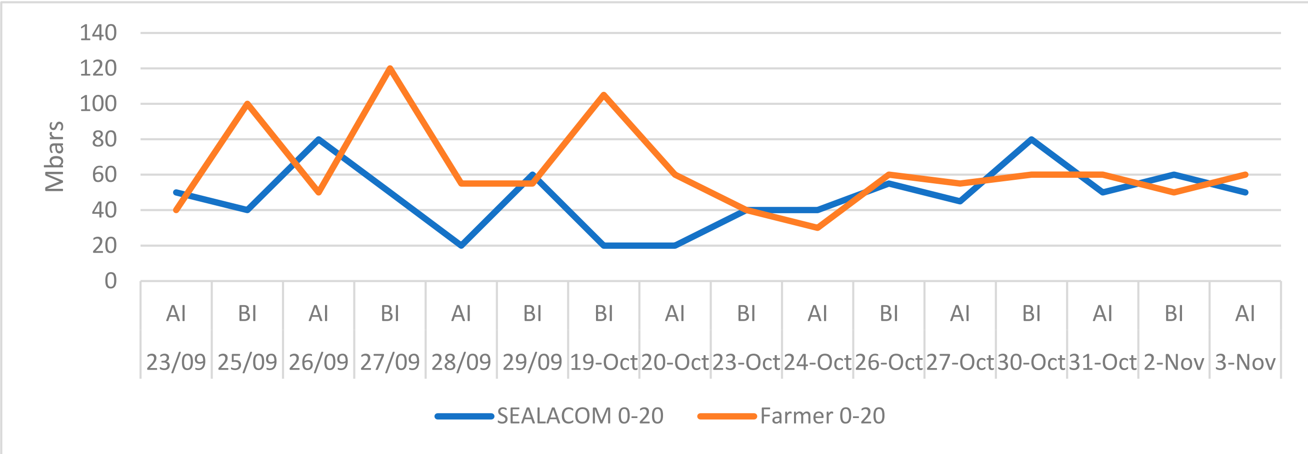

Figure 14. Measured soil head potential at surface soil layer in late fall protected cucumbers in Central and West Bekaa Plain of Lebanon showing water-stressed plants in farming practice during the early stage of growth.

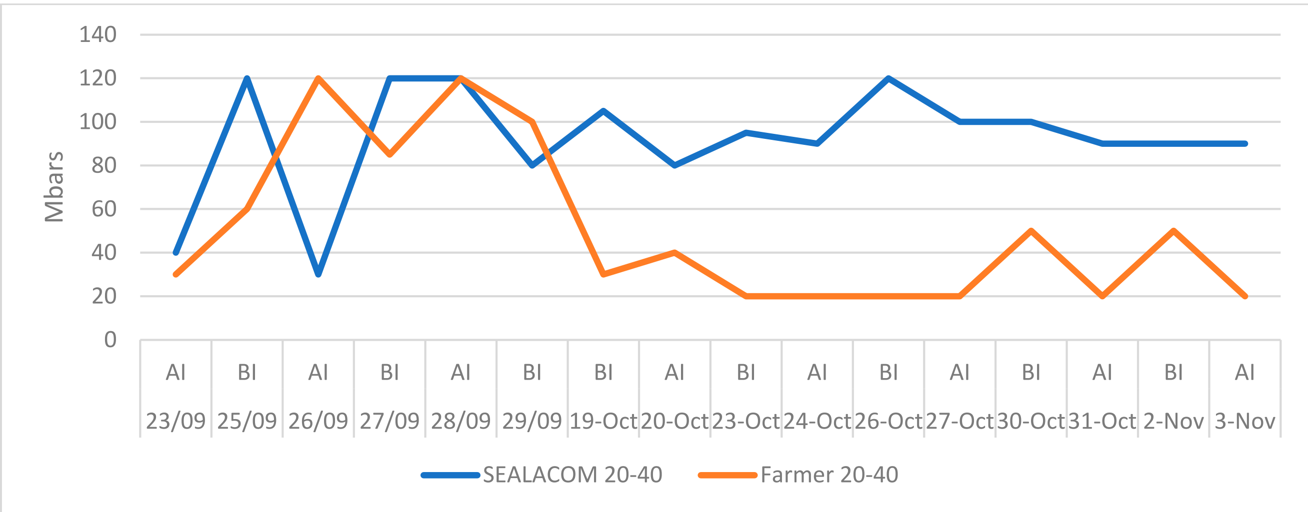

Figure 15. Measured soil head potential in subsoil in late fall protected cucumbers in Central and West Bekaa Plain of Lebanon.

Indeed, the dynamics of water application in the advanced SEALACOM practice better matched the crop productivity along the vegetation cycle (Figure 16) and answered the biological and reproductive water demands of the sensitive to water stress, protected, cucumbers.

These experimental results indicate a high potential for water savings in protected cucumber cultivation in the Central and West Bekaa Plain, and the whole country, with simple capacity building and the adoption of simple and cost-effective IT devices to monitor soil moisture, estimate the right water amount, and regulate the irrigation schedule (Table 2).

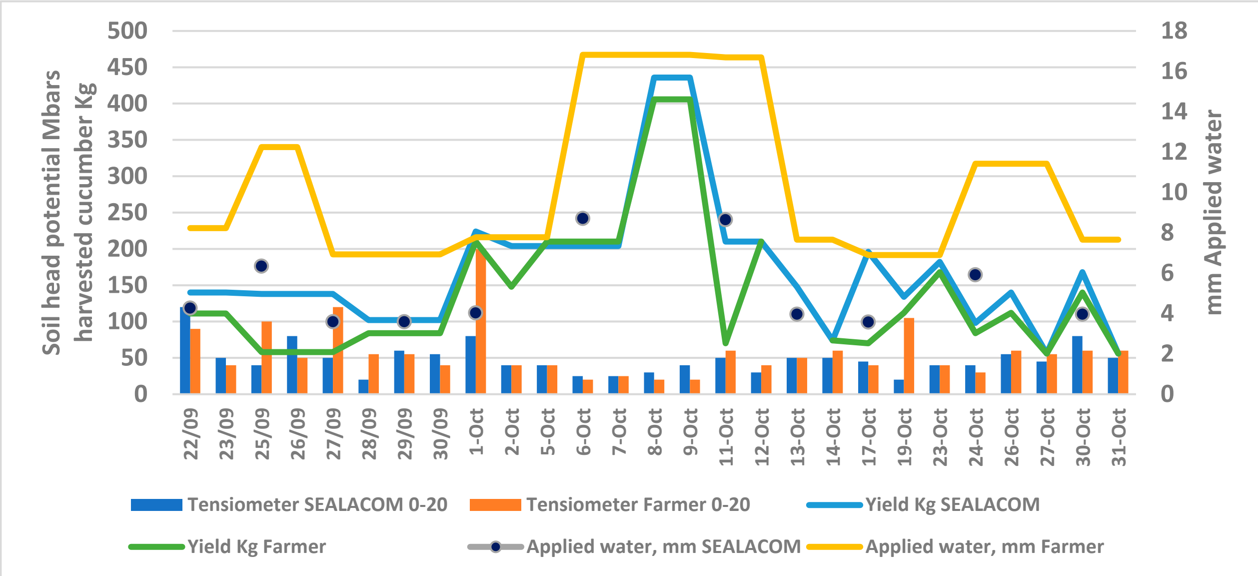

Figure 16. Dynamics of irrigation schedule and amount of water applied to cucumbers, and comparative yield in advanced and farmers' practices.

3.2. Fertilization Practices of Protected Cucumber

The fertilization policy followed by the farmers is not based on soil sampling and analysis to consider the available soil pool and nutrient balance. Additionally, farmers rarely conduct water analysis to check for nutrients like nitrogen derived from nitrates. From primary sources, during the cucumber fall season of 2023, the farmers in Serein applied a total of 27.5 kg N Deca^{-1}, 11.4 kg P_2O_5 Deca^{-1}, and 6 kg K_2O Deca^{-1} (Table 3). Farmers in Sultan Yacoub applied a comparable amount of nutrients, except for phosphorous, using different types and ratios of fertilizers. Except for potassium, these amounts far exceed those applied by the SEALACOM project.

Table 3. Fertilization of protected fall cucumber following the traditional practice (Farmer) or advanced methods (SEALACOM) in Central Bekaa.

Location	Nutrient	Pure Element (Kg Deca^{-1})				Fertilizer Equivalent (Kg Deca^{-1})			
		N	P_2O_5	K_2O	MgO	Amm. Sulfate	MAP	Pot. Sulfate	Mg Sulfate
Serein	Farmer	27.52	11.39	6.05	2.01	131.02	18.66	12.11	13.39
	SEALACOM	10.14	2.41	12.54	0.65	48.27	3.96	25.08	4.36
Sultan Yacoub	Farmer	26.86	73.59	9.80	0.00	127.92	120.65	19.61	0.00
	SEALACOM	11.40	2.51	13.79	1.62	54.30	4.12	27.58	10.77

3.3. Yield of Protected Cucumbers in Traditional and Advanced Practices

The average yield of protected cucumbers obtained from fertigation in Serein during the late fall 2023 production season, using the continuous feeding system (2911.6 Kg Deca^{-1}), exceeded the yield obtained by the farmer's traditional practice (2379.5 Kg Deca^{-1}) by 22.4% (Figure 17).

It is equally important to notice the same trends in cumber yield obtained in Sultan Yacoub with the advantage of continuous feeding of cucumbers based on science-based methods of estimation of crop water and nutrient demands (Figure 18). The exception observed in the lower yield of treatment S-compost can be probably explained by the poor natural soil fertility background and low nitrogen presence in the soils of the arid Mediterranean climate. The combination of compost with basic mineral fertilizer application is a justified pre-sowing practice in the region.

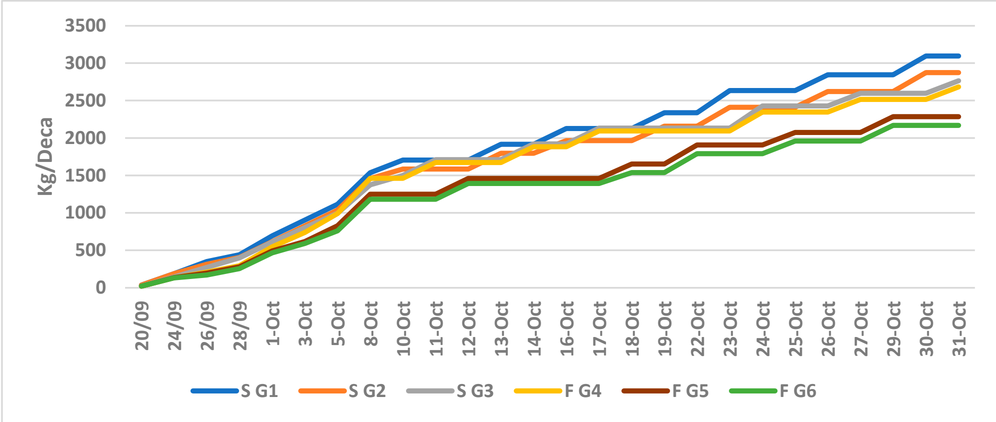

Figure 17. Comparative cumulative yield of protected cucumbers in Serein following farmers' practices (F G4, F G5, and F G6) and SEALACOM approach (S G1, S G2, and S G3).

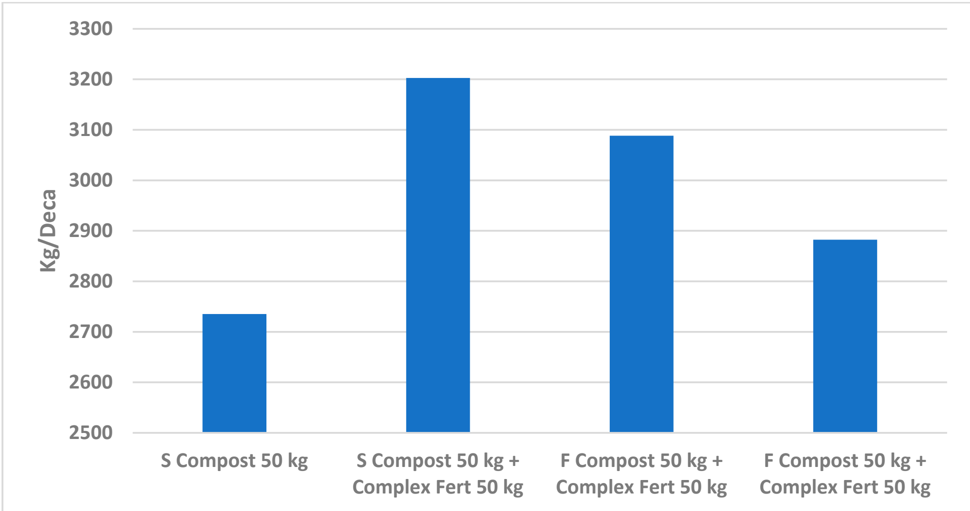

Figure 18. Comparative yield of protected cucumbers in Sultan Yacoub following the farmers' practices (F) and SEALACOM approach (S).

The improved practice produced significantly higher cucumber yield as compared to the farmers' practice within the same location (Serein) in the Bekaa valley (Table 4). In the absence of an overlapping within the confidence range (Table 4), the superior yield within the improved treatment could be validated as significantly different. Within the other location (Sultan Yacoub), yield results could not be validated due to different background fertilization practice based on the testing of soil response to sole application of vermicompost in one of the two SEALACOM greenhouses, which reduced the number of replicates.

Table 4. Cucumber yield and confidence interval obtained from traditional and improved cultivation of protected cucumbers in Bekaa Plain, Lebanon.

Treatment	Mean Yield (kg/deca)	Confidence Interval (ConI)	Range [Mean ± ConI]
Improved practice	2911.6 a	191.2	2911.6 − 191.2 = 2720.4
Farmers practice	2379.5 b	305.0	2379.5 + 305.0 = 2684.5

Different letters indicate significant difference at $p < 0.05$.

Results proved the low natural fertility of the Lebanese soils caused by the low organic carbon content and showed the necessity to increase the soil organic carbon sequestration in the soils of the semi-arid regions to improve their productivity with minimal reliance on mineral fertilizers [27].

3.4. Water Use Efficiency of Protected Cucumbers in Traditional and Advanced Practices

Comparing the application and agronomic water use efficiency between full fertigation and traditional water and fertilizer application during the late fall protected cucumber season showed the clear advantage of modern practices in water and nutrient application to meet the challenges of food security (Table 5).

Table 5. Comparative water use efficiency in farmers' practices versus modern tools of irrigation and fertilization (SEALACOM) for late fall protected cucumbers in Central Bekaa, Lebanon.

Practice	Serein				Sultan Yacoub			
	Total Applied Water, mm	Water Application During the Production Stage, mm	Application Water Use Efficiency, Kg/mm	Agronomic Water Use Efficiency, Kg/mm	Total Applied Water, mm	Water Application During the Production Stage, mm	Application Water Use Efficiency, Kg/mm	Agronomic Water Use Efficiency, Kg/mm
Farmer	283	190.3	8.4	12.5	299.7	147.3	9.96	20.27
SEALACOM	190.3	82.2	15.3	35.4	177.7	88.83	16.7	33.42

Land suitability for large-scale irrigation and adapted cropping patterns was also successfully tested in even more arid conditions using multiscale climate and soil conditions, sustainable water use, topography, and improved land management practices [30]. The sustainability of agricultural production in the country is in direct connection with the environmental performance to reduce water, nutrient, energy, and labor input, and address the need for environmentally friendly practices [31].

Comparing the efficiency of water use in the SEALACOM project with the farmers' practice showed the potential to achieve total cucumber harvests of 2911.6 and 2379.5 Kg deca^{-1}. Our results demonstrated the advantage of the combined use of water and nutrients in continuous feeding mode by full fertigation in a dry Mediterranean area. Indeed, the obtained results show that the efficiency of total applied water by SEALACOM project surpassed the farmers' practices by 1.82 times in Serein and 1.67 times in Sultan Yacoub (Table 4). Using the SEALACOM-adopted methods allowed the achievement of higher agronomic water use efficiency in Serein and Sultan Yacoub equivalent to 2.83 and 1.65 times, respectively. Our findings support the climate proofing Lebanon's Development Plan [32] and National Water Sector Strategy Update [33] to promote agricultural resilience to climate change, mitigate GHG, and improve national and local adaptation, notably, in the integrated management of the irrigation and water sectors.

The same statistical approach was applied to water productivity of both sites and treatments (Table 6). The confidence ranges in Serein (15.30 − 1.01 = 14.29) and in Sultan Yacoub (16.71 − 2.58 = 14.13) showed no overlapping with those obtained in farmers' practices to the confidence interval in Serein (8.41 + 1.08 = 9.49) and Sultan Yacoub (9.96 + 0.67) = 10.63. The same trends were observed for the treatment of improved fertigation versus traditional fertigation, where the values were 14.50 and 10.14, respectively. The absence of overlapping indicates significant difference between the replicates and treatments.

Table 6. Statistical analysis of water productivity in improved fertigation versus farmers' practices.

Treatment	Site	Replicate	Applied Water m^3/Deca	Cucumber Yield Kg/Deca	Water Productivity Kg/m^3	Mean	Confidence Interval	Interval	
								Minimum	Maximum
Improved	Serein	1.1	190.26	3096.39	16.27	15.30 a	1.01	14.29	16.32
		1.2	190.26	2873.49	15.10				
		1.3	190.26	2765.06	14.53				
	Sultan Yacoub	1.4	177.70	2735.29	15.39	16.71 a	2.58	14.13	19.29
		1.5	177.70	3202.61	18.02				
	Mean improved treatment					15.86 a	1.19	14.67	

Table 6. *Cont.*

Treatment	Site	Replicate	Applied Water m^3/Deca	Cucumber Yield Kg/Deca	Water Productivity Kg/m^3	Mean	Confidence Interval	Interval	
								Minimum	Maximum
Farmers	Serein	2.1	283.06	2683.73	9.48	8.41 b	1.08	7.33	9.49
		2.2	283.06	2285.24	8.07				
		2.3	283.06	2169.58	7.66				
	Sultan Yacoub	2.4	299.67	3088.24	10.31	9.96 b	0.67	9.29	10.63
		2.5	299.67	2882.35	9.62				
	Mean farmers treatment					9.03 b	0.97	10.00	

Different letters indicate significant difference at $p < 0.05$.

3.5. Nitrogen Use Efficiency of Protected Cucumbers in Traditional and Advanced Practices

Nutrient use efficiency for applied nitrogen in protected cucumbers was calculated for two different fertilization and watering practices: those experimented by SEALACOM and those implemented by the farmers in the Central and West Bekaa Plain (Table 7).

Table 7. Nitrogen use efficiency in late fall protected cucumbers grown with traditional (Farmer) and advanced methods (SEALACOM) of water and fertilizer application.

Practice	Average Yield, Kg Deca^{-1}		Applied Nitrogen, Kg Deca^{-1}		N Use Efficiency, Kg cucumber/Kg Nitrogen	
	Serein	Sultan Yacoub	Serein	Sultan Yacoub	Serein	Sultan Yacoub
Farmer	2379.5	2969	27.52	26.86	86.5	111.14
SEALACOM	2911.6	2985.3	10.14	11.4	287.1	255.4

The results show that advanced nitrogen management considering the soil and water pools and crop demands, allowed to reach 3.32- and 2.30-times higher nitrogen use efficiency in both locations. Fertigation of protected cucumbers in the coastal area using the isotope ^{15}N showed advantageous nitrogen uptake by the crop, which reduced risks of nitrogen buildup in the soil and limited nitrate leaching into the groundwater [29].

Adapting the methods of advanced irrigation and fertilization practices resulted in large water savings associated with significantly higher cucumber yield and more efficient use of applied nitrogen and phosphorous, ranging between 2.5 and more than 4 times, against 50% higher potassium application in SEALACOM plots (Table 8). This approach is justified by the K regulating functions and provision of plant abiotic stress tolerance [34], which is a kind of adaptation strategy to promote crop resistance to environmental adversities under decreasing late autumn temperature in Mediterranean highlands regions.

Table 8. Applied water, crop yield, and nutrient use efficiency of protected cucumbers grown in dry and subhumid Mediterranean conditions.

Location	Treatment	Applied Irrigation Water, m^3	Crop Yield Kg/Deca	Nutrient Use Efficiency Kg Product/kg Nutrient		
				N	P_2O_5	K_2O
Serein	SEALACOM	190.27	2911.65 a	287.14	1208.15	232.19
	Farmer	283.06	2379.52 b	86.47	208.91	452.81
Sultan Yacoub	SEALACOM	177.70	2968.95 a	255.40	1182.84	215.30
	Farmer	299.67	2985.29 a	111.14	40.56	304.62

Different letters indicate significant difference at $p < 0.05$.

3.6. Effect of Fertigation Practices on Soil Quality

While both fertigation methods caused a slight buildup of salts in the soil, the continuous fertigation slightly increased Soil EC value of the surface layer from 0.49 to 0.64 in Serein while ECe remained within the control level in Sultan Yacoub (Table 9).

Table 9. Post-experiment physico-chemical properties of the soil under protected cucumbers in Serein.

Demo Site	Depth, cm	SEALACOM Practice				Farmers' Practice			
		EC dS/m	pH H_2O	Available Nutrients, ppm		EC dS/m	pH H_2O	Available Nutrients, ppm	
				P_2O_5	K_2O			P_2O_5	K_2O
Serein	0–20	0.64	7.6	233	307	0.39	7.6	232	275
	20–40	0.63	7.6	236	283	0.38	7.6	239	253
Sultan Yacoub	0–20	0.59	7.4	174	830	0.58	7.6	137	831
	20–40	0.51	7.4	200	818	0.34	7.7	101	707

The lower values of soil salinity rise in intermittent fertigation are explained by the potential leaching of salts towards the groundwater [35]. The accumulation of phosphorus and potassium in the soil after the experiment was comparable in the two nutrient application modalities with some accumulation of P_2O_5 in Sultan Yacoub. Results show that continuous fertigation has no direct negative ecological impact, especially if the soil pool is considered in the following cropping season, which might represent economic advantages in water saving and higher water productivity.

The obtained results point to the potential of water saving and meeting the challenges of the SDGs, access to water and food security, without compromising the farmers' incomes or environmental soil and groundwater conditions. The consequent crop of tomato under greenhouse conditions, which is more tolerant to slight salinity, can offset the slight accumulation of salts in the root zone following the continuous fertigation modality. This practice could be economically and environmentally more rewarding than leaching the applied nutrients and salts towards the groundwater.

Transforming the production systems in semi-arid and dry Mediterranean environments requires local capacity building to inoculate the advanced modalities of fertigation and disseminate good agricultural practices. Despite the clogging risks of drip fertigation and system cost, fertigation with continuous feeding secures more synchronized water and nutrient supply, answering the growth and development of agricultural crops, and securing higher productivity and efficiency of agricultural inputs [36]. Advanced field technologies and sustainable management practices have been recommended to boost the economic profit and reduce environmental pollution from the applied fertilizers, notably nitrogen [37]. Upgrading the technical base of sustainable agricultural production and skills of local farmers suggests a more active role from policy makers and authorities to support the emerging agricultural sector, including the financial sustenance to adapt and sustainably manage modern irrigation systems.

Earlier studies conducted in the semi-arid Lebanese region showed salinity development and yield reduction of greenhouse cucumber in traditional fertilizer and water application [38]. A comparable cucumber yield was possible to obtain only under the use of plastic mulch in late summer protected cucumbers [39].

It is possible to obtain better results under protected vegetables on the coastal areas even with the use of slightly saline water in irrigation due to appropriate management of fertigation and irrigation schedule based on the monitoring of soil moisture [29]. Water scarcity in inland Bekaa area and intensive agriculture have been associated with excess pumping from groundwater, causing the depletion of the groundwater table level [19].

Although the experiments were carried out in two pedoclimatic conditions, the greenhouse atmosphere and fertigation practices interfered with the outside ambient conditions and smoothed the difference in background soil fertility. A comparable amount of water and nutrients were applied in the two zones. Despite that, a higher water use efficiency was achieved in the improved practices due to controlled water use according to crop water demands. The onsite estimation of ET_0 and appropriate irrigation schedule, related to soil moisture monitoring, and fertigation following the continuous feeding lead to higher nutrient recovery and cucumber yield. The over-irrigation observed by the farmers, detected from permanently humid subsoil during the production stage (Figures 15 and 16), coupled with intermittent fertilizer application could have contributed to leaching of soluble forms of nitrogen and decreased crop yield. The approach followed by the SEALACOM project has both economic and environmental consequences for mainstreaming sustainable farming in dry lands. For this reason, disseminating good irrigation practices with reliance on combined climatic data, crop cycle and soil moisture to achieve economic yields with less water and fertilizer inputs are important measures to transform traditional practices in the Bekaa into economically sustainable and environmentally sound exercises.

Our results demonstrated the possibility to increase the yield of protected cucumbers with controlled application of fertilizers and water associated with better water accounting and higher water productivity. Extrapolating to the national and regional levels, a significant breakthrough in water saving can be achieved that supports sustainable agriculture and meets the challenges of the SDGs.

Despite the small scale and short duration of the experiments, representing a potential source of error, the results provide room for a deep analysis of the current state of water and fertilizer use in emerging agricultural production of semi-arid and dry subhumid areas, and allow for the prospection of feasible road map for improved practices.

4. Conclusions

Compared to the empirical water and fertilizer application methods commonly used in Lebanon and similar semi-arid and dry subhumid regions, the advanced practices followed by the SEALACOM project have proven to be more efficient. By adequately considering soil and crop conditions, monitoring nutrient and water balance, climatic conditions, measured ET values, and controlling soil moisture for suitable irrigation schedules, significant advantages in water, fertilizer, and energy savings were achieved. Full fertigation of late fall protected cucumbers with continuous feeding using simple modern injectors and soil moisture monitoring resulted in significantly larger yields (2911.65 kg/Deca in SEALACOM plots against 2379.52 kg/Deca in the farmer's plot), associated with better, two to four times higher, water and fertilizer use efficiency. Under the conditions of climate change and water scarcity, achieving water savings of 93 to 122 mm per single, short, fall protected cucumber season is significant for meeting access to water and food security challenges, as well as other objectives of the SDGs. Additionally, the SEALACOM project applied two to five times less nitrogen and phosphorous. Water and nutrient savings positively impacted application and agronomic water use efficiency, and up to four times higher potential of economic profit with the SEALACOM approach compared to the traditional farmer practices. Water and fertilizer savings, combined with better cucumber yields and higher productivity per unit of applied water and nutrients, result in higher returns, lower environmental pollution, and reduced GHG emissions related to the fertilizer industry and use of water pumping using fossil energy that prevails in the region. The obtained results are evidence-based tools to improve policy and close the research gaps to serve sustainable water allocation and water use at the decision making and farmer's levels.

Efforts should focus on capacity building to improve current practices and disseminate effective water and nutrient management at both district and country levels. Upgrading operational infrastructure and introducing IT tools for water and nutrient management, as well as soil and crop monitoring, are crucial for enhancing the technological basis of intensive agriculture. These advancements will help meet the challenges of the SDGs and address socio-economic constraints to achieve sustainable rural livelihoods. This research provides a foundation for deriving practical guidelines and recommendations for farmers, optimizing intensive agriculture to enhance productivity and sustainability. By examining socio-economic benefits, we can offer valuable insights into improving agricultural practices. Looking ahead, it is essential to project the potential expansion of intensive agriculture in response to climate change over the next decade. With anticipated increases in temperature and decreases in rainfall, adaptive strategies focusing on resilient crop varieties, efficient water management, and innovative farming techniques will be vital to achieve sustainable food production. By proactively addressing these challenges, we can support sustainable agricultural growth, ensure food security, and enhance the overall socio-economic well-being of the region. However, it is recommended to undertake further studies of the impact of long-term application of continuous feeding on the soil biome and soil health.

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