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Solar-powered desalination of brackish water with nanofiltration membranes for intensive agricultural use in Jordan, the Palestinian Authority and Israel

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ABSTRACT

Agriculture is a major source of livelihood for rural communities in the Middle East. Lacking freshwater resources, brackish aquifers are often exploited as sources of irrigation water, but the practice is unsustainable. The "Solar-powered desalination of brackish water with nanofiltration membranes for intensive agricultural use in Jordan, the Palestinian Authority and Israel" (AGRISOL) project aims at developing and testing a solar-powered, nanofiltration desalination system for the production of irrigation water and high-value crops in arid environments. Such solution has the potential to reduce groundwater abstraction rates, increase agricultural yields, and enhance farmers' well-being by enlarging their portfolio of crops. Two pilot plants are designed and installed in Israel (Hatzeva) and Jordan (Karama). Agronomic experiments are conducted to determine the technical and economic viability of the new technology. The potential market penetration of desalinated water irrigation is explored through surveys, aimed at eliciting farmers' perceptions and their potential concerns in switching to desalinated water irrigation. This paper presents selected results from the project and highlights additional expected major outcomes. We find that a market potential for the proposed innovation exists both in Israel and Jordan. This is largely determined by the perceived importance by farmers in both countries for sustainable solutions to their irrigation needs, particularly as a result of the observed rising salinity levels in the irrigation water. Moreover, experiments conducted in Hatzeva on strawberry demonstrate the technology's potential to enable the cultivation of salt-sensitive cash crops in the region. We conclude that desalination may be a valuable strategy towards more sustainable water management in the regional arid land agriculture.

Keywords: Arid agriculture; Brackish water; Nanofiltration membranes; Renewable energy; Solar desalination.

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1. Introduction

Agriculture is a major source of livelihood for many rural communities in the Middle East, despite the severe lack of freshwater that affects the region. Brackish groundwater aquifers are often exploited as sources of irrigation water, but the practice is unsustainable due to limitations on marketable yields, choice of crops, and large water use to cope with leaching requirements [1]. Increase in the salinity of the abstracted groundwater over time presents additional challenges to local agriculture [2].

In Jordan, the area of arable land is estimated in 380,000 ha, of which about 19% are irrigated (mostly in the lower Jordan River Basin), primarily with drip irrigation [3,4]. The agricultural sector accounts for 62–65% of the total amount of water consumption in Jordan [3]. The agricultural sector is characterized by very fragmented farm holdings. Most farm units in the Jordan River Valley, for instance, range between 3 and 5 ha in size. The total labor force in agriculture in Jordan is estimated in 120,000 individuals in 2015 (i.e., 5.3% of the total labor force), 66.4% of which are female [5]. Groundwater is a major water resource in many areas in Jordan, especially for agriculture. It is estimated that groundwater is used in 53% of the area under irrigation countrywide [6]. Aquifer exploitation is responsible for the rapid expansion of irrigation in areas such as the highlands and there is evidence that the resources are overexploited [7]. The Ministry of Agriculture estimates that the usable time for groundwater resources in Jordan may be as short as 40 years and increased water salinity is already observed in the Wadi Duhleil and Azraq basins [7]. A total of 67 saline water springs have been identified in Jordan (mostly in the Jordan River and Dead Sea basins) with an estimated total average discharge of 46 MCM/year (out of about 700 MCM/year in the agricultural sector overall) [7].

In Israel, irrigation with brackish water is widely practiced in the Negev and Arava Valley. The Arava basin is extremely arid, with average annual precipitation of about 50 mm. Excluding the city of Eilat, the Arava Valley hosts 20 communities with an estimated population of about 7,800 inhabitants. Economic activities in the region rely heavily on the exploitation of the local brackish aquifers for highly intensive agriculture, and export of off-season horticultural crops, mainly to European markets. Other economic activities include dairy production, aquaculture, tourism, small businesses, and renewable energy production [8]. From a hydro-chemical point of view, one can distinguish three major groundwater types in the Arava Valley: the Northern Arava basin; the Central Arava basin; and the Southern Arava basin [9]. The vast majority of water sources are brackish, with an estimated 53% of the water from local wells, presenting an electro-conductivity (EC) between 2.65 and 3.4 dS/m. Only 3% of the water sources have EC of 1.9 dS/m or less, while 2% have EC equal or higher than 5.2 dS/m. High concentrations of iron (>0.3 mg/L) or hydrogen sulfide (>0.5 mg/L) are found in 7% of the wells. Brackish water irrigation with salinities of 2–3.5 dS/m is practiced as a rule. Areas in the Central Arava are extensively developed for agriculture. Water in the Southern Arava basin is primarily used for aquaculture farms, irrigation of palm trees, and feedwater for the brackish water reverse osmosis (RO) desalination plant in Eilat. Dropping groundwater levels and deteriorating water quality (i.e., increasing salinity) have been documented and can be attributed both to anthropogenic and climatic factors [2].

In the Gaza Strip, severe over-exploitation of the coastal aquifer has altered the normal transport of salts into the sea, leading to a sharp increase in chloride concentration in groundwater, and making the problem of coping with high-salinity water for irrigation and other purposes very actual [10–12]. Demand increase and reduced water availability due to climate change are expected to make the problem even more harshly felt in the future.

The "Solar-powered desalination of brackish water with nanofiltration membranes for intensive agricultural use in Jordan, the Palestinian Authority and Israel " (AGRISOL) project (in.bgu.ac.il/en/bidr/ziwr/AGRISOL/Pages/default.aspx) aims at developing a more resource-efficient and cost-effective alternative to brackish water irrigation by designing, developing and testing an innovative desalination system for application at farm-scale to the production of irrigation water and high-value crops in semi-arid environments. The project aims at advancing high-technology farming practices by developing and testing a new generation of solar-powered, low-pressure membrane desalination plants. The plants are fitted with nanofiltration (NF) membranes that operate at lower pressure than RO membranes, improving the affordability of desalination in agriculture and compensating for the drawbacks of irrigation with RO desalinated water, such as high energy consumption and lack of elements that are essential to the crops like magnesium (Mg^{2+}) and calcium (Ca^{2+}) [1,13,14].

The proposed approach is tested for its potential to reduce the current rates of groundwater abstraction, increase current agricultural yields, and enhance farmers' overall wellbeing by enlarging their currently available portfolio to cash crops with low salinity tolerance. AGRISOL is an ongoing research effort that involves a high degree of collaboration among the partner institutions in Israel, Jordan and Palestinian Authority. This paper presents selected project results concerning: (1) the evaluation of the potential market penetration of the proposed innovation in Israel and Jordan based on (i) the analysis of the respective current brackish water irrigation markets and (ii) the results of two farmers' surveys; and (2) the experimental results obtained in Israel regarding the feasibility of using the proposed technology to introduce in the region the cultivation of strawberry, a high-value, salt-sensitive crop that is not suitable for growth under brackish water irrigation. Additional expected major outcomes of the project are also highlighted.

2. Materials and methods

2.1. Market analysis and final users' surveys

The market potential of the proposed technology is investigated in AGRISOL through a combination of market analysis, cost-benefit analysis, farmers' surveys, and policy analysis. The present paper summarizes the information collected regarding the target markets for brackish water irrigation in Jordan and Israel, with a focus on the identification of their current size, cultivated crops and irrigation water quality. The future prospects as determined by the current trends are also investigated, particularly for what water salinity trends are concerned. Two surveys of the target final users for the proposed innovation were conducted, with the aim to explore their interest and attitude towards the prospective use of (solar) desalination, potential barriers to entry as determined by their stated concerns regarding the transition from brackish to desalinated water irrigation, and general socio-demographic characteristics. The first survey was conducted on a sample of 19 Jordanian farmers in the Jordan River Valley in September 2015. The second one involved a larger sample of 128 farmers in the Israeli Central and Northern Arava Valley in May 2016. A questionnaire was purposely developed for this analysis and translated into Arabic, Hebrew and English. The questionnaire is divided into three major sections. The first set of questions aims at collecting information regarding the current farming practices (e.g., cultivated crops, land ownership, irrigation type, growing method) as well as general socio-demographic information (e.g., income level, education). The second section explores the respondents' awareness and concerns related to their current irrigation practices (e.g., water salinity, water use, concerns about rising water salinity, awareness of the possibility to use desalinated water for crop irrigation). The third section investigates the willingness to switch to desalinated water in the future, concerns in adopting desalinated water irrigation, and preferences with regard to policies that would best address their present concerns. The administration of the questionnaires was done in the context of face-to-face interviews that were conducted by staff of the National Center for Agricultural Research and Extension and the University of Haifa, respectively in Jordan and Israel. The present paper focuses on the critical comparison of the results obtained from the two surveys. Additional details on the questionnaire and a more in-depth analysis of the results of the survey conducted in Israel are provided in [15].

2.2. Pilot solar desalination plants

Experimental investigations involve the construction and evaluation of two pilot solar NF desalination plants, one in Hatzeva, Israel (30°46'37.7''N, 35°14'25.7''E) and one in Karama, Jordan (31°55'39.84''N, 35°34'13.09''E). The two pilot plants are designed to desalinate the local, moderately saline water, which is characterized by EC levels of 2.8 dS/m and 3.1 dS/m, respectively.

The pilot plant in Hatzeva was originally constructed in 2009 and underwent equipment upgrading as part of the AGRISOL project (including replacement of pre- and post-filters, and main water pump). The system is designed to produce 5–6 m^3/d of permeate water with EC = 0.7 dS/m and operate at 80% recovery rate and operating pressure of 4–5 bar (Fig. 1). The system is equipped with an array of photovoltaic (PV) modules with a total capacity of 4.2 kW_p. During the evaluation phase, the pilot NF desalination plant matched or exceeded the expectations in terms of permeate production (6.5 m^3/day on average), specific energy consumption (1.37 kWh/m^3), and permeate water quality [13]. After blending, the EC, sodium adsorption ratio (SAR), and sodium over calcium ratio of the product water were, respectively, equal 0.71 dS/m, 2.9 and 1.78, which are representative of an irrigation water that does not entail a significant risk for reduction of the water infiltration rate in the sandy soil of the Arava [13].

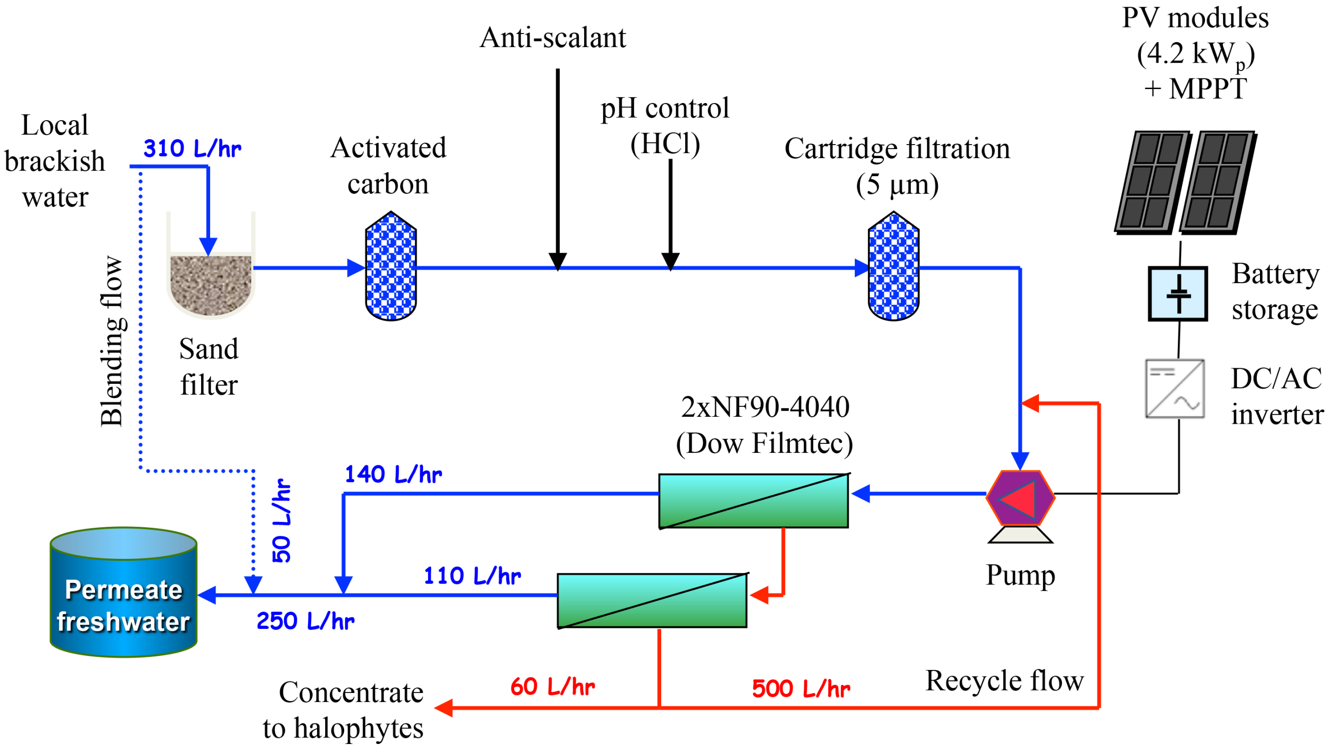

Fig. 1. Design scheme of the pilot solar desalination unit at Hatzeva, Israel.

The pilot desalination plant in Karama was designed using the Reverse Osmosis System Analysis tool by The Dow Chemical Company (ROSA v9.1; www.dow.com/liquidseps/design/rosa.htm) and following the basic configuration of Hatzeva's pilot plant, which involves: two low-pressure membrane elements, arranged in a single-pass configuration within one pressure vessel; a recirculation flow to achieve a high recovery rate of 75–80%; an array of PV modules with nominal peak power equal to 3.65 kW_p; and the blending of the permeate with a small fraction of the feed water to ensure an adequate concentration of Mg^{2+} and Ca^{2+} in the product water while maintaining acceptable values for EC (=1.0 dS/m) and sodium adsorption ratio (SAR) (=2.92). The pilot plant in Karama is currently in the construction phase.

2.3. Agronomic experiments with strawberries

Agronomic experiments with a range of crops are planned in both experimental sites. This paper presents results from the Hatzeva pilot plant regarding the cultivation of strawberry. Strawberry is a highly salt-sensitive crop [16] that cannot currently be cultivated in the Arava with brackish water irrigation due to severe symptoms of chloride toxicity. The experiment was conducted in two tunnel greenhouses covered with polyethylene, each with an area of 500 m^2. Three strawberry varieties (Shani, Maor and Tamir) were planted in soilless cultures (coconut fibers) on October 15, 2015. A steady EC level equal to 0.72 ± 0.03 dS/m was maintained at the outlet of the solar-powered NF desalination plant. The salinity of the irrigation water was dominated by the fertilizer levels, which were applied in accordance to the Israeli Ministry of Agriculture Extension Services guidelines for strawberries. Irrigation and drainage water quality were monitored every 10 d for EC and nitrogen concentration. Harvest started 32 d after planting. Harvested fruits were sorted into A and B fruit qualities, export and local markets, respectively, weighed and incubated under post-harvest simulation conditions, two weeks at 6°C followed by 3 d at 20°C. The brine from the pilot desalination plant (EC = 6.4 ± 0.05 dS/m) was used to irrigate a relatively salt-tolerant tree: date palm. Date palm can produce 50% from its optimal yield under irrigation water salinity of 4.5 dS/m [17]. Sixteen date palms located 250 m NE of the experimental plot were irrigated with a 1:1 mixture of brine and local brackish water (mixture EC = 4.25 dS/m).

3. Results and discussion

3.1. Market and final users' analysis in Jordan and Israel

In Jordan, the Jordan River Valley is of particular appeal to the proposed technology because: (1) estimated 23 saline water springs are located here, which are used to provide irrigation water for agriculture [7]; (2) more than 10,000 farm units, most of which of small to very small extent are located here [18]; (3) this is a key region for the country's agricultural sector (over 60% of the country's agricultural produce is grown here) and in particular for high-value export products, some of which are moderately sensitive crops such as tomatoes (the country's most highly valued export crop, with exports estimated in $225 million in 2011), cucumber (the country's second most highly valued export crop, with exports estimated in $121 million in 2011), and eggplants ($36 million in exports in 2011) [3].

In Israel, according to estimates of the Central and Northern Arava R&D, in May 2013 the population of the Central-Arava basin comprised approximately 700 families, of which 530 are farmers, for a total population of about 3,360 people. In addition, estimated 120 families, of which 110 are farmers, for a total of about 550 people live in the Sodom Valley region in Tamar. The arable land in the 2012/13 season comprised of 3643 hectares, of which 82% were cultivated with vegetables, 16% with fruit trees plantation (mainly dates) and 2% with cut flowers. Bell pepper (*Capsicum annuum*) is the major crop in the region, covering 50% of the total arable land and 66% of the vegetables area. Other crops include melon (13.3% of the vegetables area), watermelon (9%), tomato (4%), cut herbs (3%), eggplant (2%), squash (1.2%), onion (1.1%), and cherry tomatoes (0.7%). Bio-organic farming holds about 10% of the growing area. The majority of the cultivation is carried out in net houses, tunnels and greenhouses, while only a small portion of the crops are cultivated in open fields. The region produces about 60% of the total Israeli export of fresh vegetables and about 10% of cut flowers export.

The comparative analysis of the results of the surveys reveals a degree of similarity among Jordanian farmers in the Jordan River Valley and Israeli farmers in the Central and Northern Arava, in terms of current agricultural practices and perceived concerns for their sustainability, but also significant differences. Farmers in Israel and Jordan appear to be rather conservative in terms of their choices of crops to cultivate, with the majority of respondents (67% in Israel; 83% in Jordan) stating that they have not changed cultivations during the past five years. Most have more than 10 years of experience as brackish water farmers (78% in Jordan; 70% in Israel), with 47% of Israeli farmers having practiced brackish water irrigation for more than 20 years. All respondents practice drip irrigation and most (56% in Israel; 61% in Jordan) state that they are "very concerned" about saving water when irrigating their fields. When it comes to water salinity, respondents are concerned about the increase in the salinity of irrigation water (88% in Israel; 100% in Jordan) and aware of the potential use of desalinated water for irrigation (97% in Israel; 83% in Jordan).

Substantial differences between Israeli and Jordanian farmers are found however along a range of other lines of enquiry. The majority (53%) of Israeli respondents enjoys a higher monthly income than the average Israeli citizen, as opposed to only 8% of Jordanian farmers. About a third of Jordanian respondents (31%) state that their income is "far below" the national average. Israeli respondents tend to be more highly educated, with 39% having received a university degree compared to 11% of Jordanian respondents. The property structure of the cultivated land also differs: while in Jordan only 21% of the respondents own the land they cultivate, this percentage rises to 63% among Israeli respondents. An additional 32% of Israeli respondents own at least part of the land they cultivate. All Jordanian respondents cultivate their crops exclusively in open fields, while greenhouses, net houses, and tunnels are more frequently used in Israel. Only 20% of Israeli respondents rely entirely on open field cultivation.

The identified differences between Israeli and Jordanian respondents may be useful in understanding their different attitudes with respect to the perception of the potential use of desalination in agriculture. After being reminded about the costs of desalination and potential advantages of using desalinated water, about half of Israeli respondents state that they are either already planning to switch to desalinated water or intend to do so over the next few years (Fig. 2). In Jordan, only 18% of the respondents share this opinion, while 41% state that at this stage they are not interested in desalination. In both countries, the majority of respondents (76% in Israel; 70% in Jordan) list economic factors among their primary concerns with respect to using desalinated water (Fig. 3). Among respondents who are concerned with the disposal of the desalination brine, the preferred solution is the cultivation of halophytes (43% in Israel; 90% in Jordan). At grid parity, 77% of the Israeli respondents would be interested in exploring solar desalination options. Out of these, 64% estimate to have enough land available to locate the PV panels.

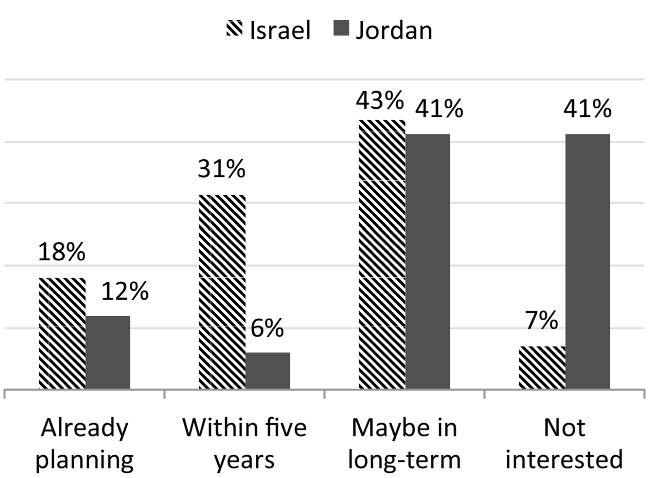

Fig. 2. Responses of Israeli and Jordanian farmers regarding their willingness to switch to desalinated water irrigation.

3.2. Agronomic experiments with desalinated water

Figs. 4 and 5 show, respectively, the EC and nitrogen concentrations of the irrigation and drainage water as measured during the growing period, and the time series of the cumulative total yield of strawberry, inclusive of both A and B fruit qualities.

The harvest rate was slow during the late fall 2015 and the winter 2016, followed by a steep rise in the accumulated yield, of about 350 kg a week. The total yield of Tamir (88.1 ton/ha) and Maor varieties (91.4 ton/ha) was 16% smaller than the yield of Shani (113.9 ton/ha). Fruit quality after the shelf-life simulation is shown in Fig. 6.

In general, fruit softness steadily increased since the mid-January 2016, due to the shifting in the annual paradigm of the temperature. Maor variety had higher fruit hardness than the other varieties. The seasonal irrigation water quantity applied in the experiment was 785 mm. The total desalinated water for the plot was 125 m^3, and the

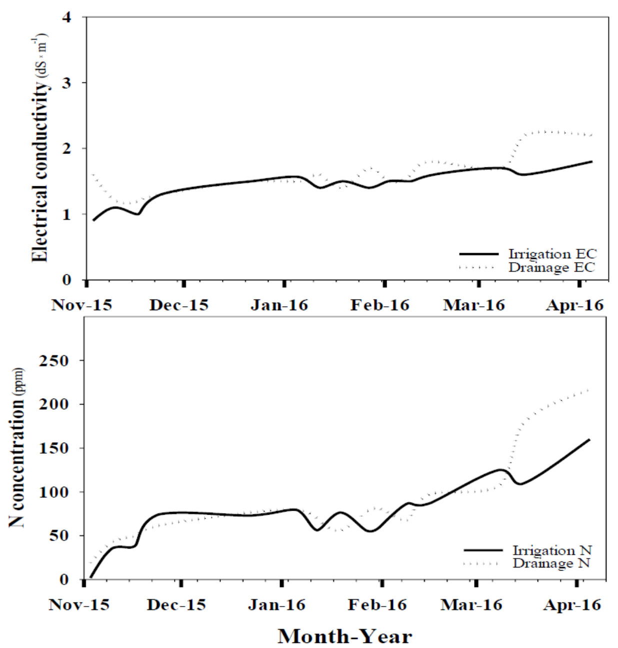

Fig. 4. EC and nitrogen concentration in the water sampled from the irrigation system and from the drainage.

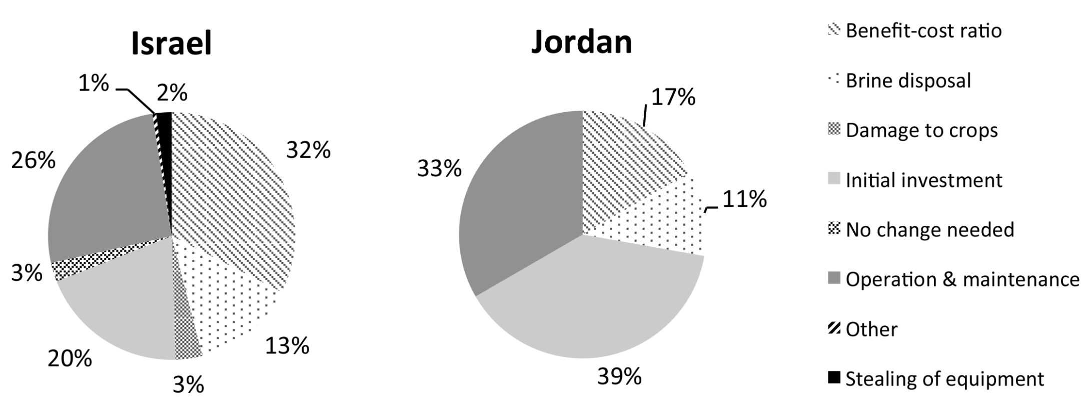

Fig. 3. Responses of Israeli and Jordanian farmers regarding their willingness to switch to desalinated water irrigation.

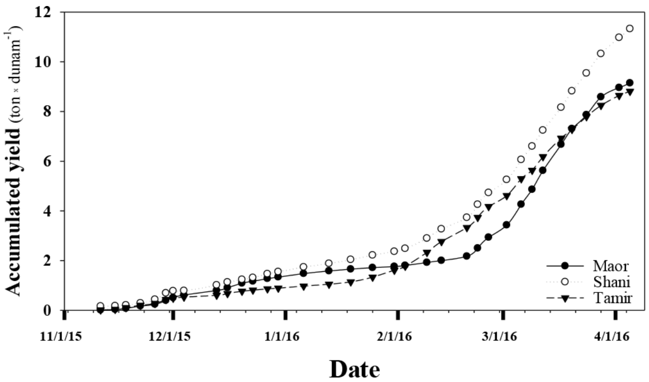

Fig. 5. Time series of accumulated total yield for three strawberry varieties, including both export and local market quality.

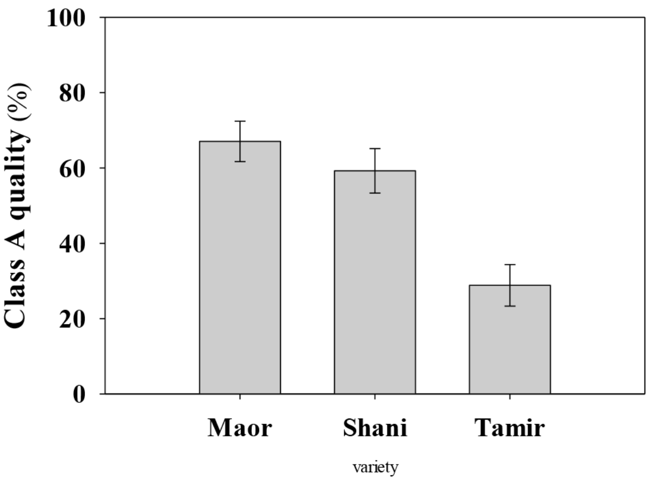

Fig. 6. Fruit hardness percentage after incubation under post-harvest simulation conditions.

brine water quantity was 38 m^3. The experiment showed the possibility of growing strawberries in the region using desalinated water by the solar-powered NF plant. The yield that was measured for each of the varieties was in agreement with Israeli commercial plots existing in the western Negev desert. The climate conditions in the Arava during late autumn until early spring, bring an opportunity to develop its potential agro-economic benefits in this region. Already a number of local farmers in the Arava expressed their interest in the project.

4. Conclusions

Overall, the findings of the AGRISOL project, as presented here, support the notion that the introduction of solar-powered brackish water desalination may be a valuable strategy toward a more sustainable agricultural water management in arid regions of Israel, Jordan and Palestinian Authority. The results presented in this paper indicate that there is a market potential for the proposed innovation both in Israel and Jordan. Brackish water irrigation is widely practiced in the region. The local farmers appear to be well aware of the limitations of the current practices and the risks entailed in the rising salinity of their irrigation water. Bearing in mind the limitations involved in the small size of the surveyed sample of Jordanian farmers, it appears that, mainly in virtue of the higher socio-economic standards, different land property structure, and more technology-intensive growing methods, Israeli farmers in the Central and Northern Arava are more readily willing to switch to desalinated water irrigation than their Jordanian counterparts. The experiments conducted in Hatzeva on strawberry demonstrate that the investigated solar desalination technology has the potential to enlarge the portfolio of crops that are currently available to the local farmers, by enabling the cultivation of salt-sensitive cash crops. The extent to which the relatively conservative farmer communities would embrace the shift towards new cultivations remains however to be established. Overall, the dissemination of scientific information regarding the safe and effective use of desalinated water in agriculture and its impacts on the environment remains fundamental to raise awareness of sustainability issues in agriculture among the farmers.

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