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Effects of Controlled Environment Agriculture and Nutrient Sources on the Production of Eggplants (*Solanum melongena* var. *esculenta* L.)

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Abstract. **Production of eggplant (*Solanum melongena* var. *esculenta* L.) was systemically evaluated under various controlled environments and nutrient supplies to produce novel information on factors affecting eggplant growth and productivity traits. Treatments of three environmental conditions (fully controlled, semicontrolled, and uncontrolled) and four nutrient sources [i.e., eggplants grown in pots with peatmoss and 100% inorganic fertilizer supply, 100% compost, 50% mix of the two, and control (e.g., peatmoss without any nutrient supply)] were replicated four times under a split-plot design. Smart agricultural tools were used for system automation and data collection. Higher light intensity in the conventional greenhouse (30 μmol/m^2/day), variations in its air temperature (25 to 30 °C), and active pollination led to its higher fruit yield (20.2 mg·ha^{-1}), which was significantly ($P \leq 0.05$) greater and statistically different from the fruit yield of the fully controlled smart greenhouse (11.2 mg·ha^{-1}) and uncontrolled open field cultivation (14.1 mg·ha^{-1}). However, the smart greenhouse showed the best water use efficiency (33 L·kg^{-1}) among the other environmental treatments because of lower irrigation water requirements. This study's significance lies in its systematic evaluation of eggplant production under various controlled environment agriculture settings to produce Qatar-specific data for the first time in the literature. The study findings suggested that conventional greenhouse cultivation could be an economically feasible (based on the benefit-to-cost ratio), energy efficient, and environmentally friendly method of producing eggplants in arid regions and agricultural conditions resembling those used in this study provided that precision agriculture practices are adopted.**

Controlled environment agriculture can contribute to food security initiatives for the growing world population (Gu et al. 2021) because of its productivity potential in the face of economic expansion, climate change, and dwindling arable lands (Ragaveena et al. 2021). Precision agriculture technologies must support controlled environment agriculture to boost food production under controlled or semicontrolled environments (Al-Naemi and Al-Otoom 2023; Taghizadeh-Hesary et al. 2019).

With the potential to improve food security and maintain a low ecological footprint, controlled environment agriculture has received significant coverage in the recent literature (Lin et al. 2022). It supports the small-scale local production of vegetables, in addition to large-scale commercial productions, for both consumption and regional market needs through urban, greenhouse, in-home, roof-top, and backyard farming (Gómez et al. 2019). It helps to manage crop irrigation in areas with scarce irrigation supply, where water is one of the most limiting factors for crop production, in particular for vegetables such as eggplant that require large amounts of water and good quantities of nutrients (Ji et al. 2022; Karam et al. 2011; Lovelli et al. 2007). However, other than the crop inputs, the challenges of maintaining a controlled environment for agriculture involve greenhouse cooling/heating, humidity control, and ventilation. A temperature integration principle of a greenhouse simultaneously depends on controlling the mean temperature of a greenhouse, rather than its instantaneous temperature (Körner and Challa 2003), through proper ventilation control systems (Bot 2001). The mean greenhouse temperature is controlled through heating and ventilation in cold regions (Cockshull et al. 1982; Hurd and Graves 1984). The hot region greenhouses require cooling and exhaust systems to control the greenhouse mean temperature (Al-Naemi and Al-Otoom 2023). This may hinder optimal plant growth because lowering temperature increases relative humidity (Körner and Challa 2003). The increased greenhouse humidity poses numerous challenges for crop growth in greenhouses due to the water vapor pressure deficit between greenhouse air and a greenhouse crop unless an efficient humidity-control system is in place (Goddek et al. 2023; Li et al. 2021; Mortensen 1986).

Numerous studies have been reported in the literature on the use of controlled environment agriculture and environmental variables to produce eggplant seedlings and plants (Uzun 2007). For example, Kurunç and Ünlükara (2009) evaluated the controlled environmental conditions for eggplant roots (i.e., plant pots of varying capacity from 3.6 to 52 L) on selective plant growth and productivity traits and reported that the size of plant root confinement significantly affected eggplant traits. Kakahy and Alshamary (2020) used a greenhouse to study the effects of plant spacing and chemical fertilizer concentrations on eggplant growth and reported that the plant growth traits and fruit yield were significantly affected by the interaction of their experimental treatments. Okosa et al. (2022) studied the growth and yield of eggplants under partially shaded solar greenhouse and water management and reported that climatic control and water management influence the quality of fruits rather than the plant growth parameters. Similar findings were concluded for tomatoes by Dumas et al. (2003) and Fanasca et al. (2006). Katsoulas et al. (2009) compared the performance of a greenhouse having a controlled humidity of 80% with an uncontrolled humidity greenhouse on eggplant crop growth under Mediterranean summer conditions. They reported that the greenhouse cooling for humidity control resulted in 13% lesser crop transpiration. Savvas et al. (2008) reported that the reduced crop transpiration and/or crop water requirements, in a soilless culture of a greenhouse may reduce plant nutrient requirements as well as nutrient-related physiological disorders in greenhouse plants. Frankenberger and Abdelmagid (1985) investigated nitrogen mineralization in soil from organic fertilizers and recommended mixing organic fertilizers with inorganic fertilizers because, according to the researchers, the incorporation of only organic fertilizer in soil may not provide the necessary nutrients to plants. Combining inorganic fertilizer (75% urea) with goat manure (25%), Maghfoer et al. (2015) reported a higher yield of eggplants than their other treatments of various combinations of nitrogen sources.

Other than fertilizers, irrigation water is one of the important crop inputs. Crop irrigation requirements are calculated using standard methods reported in the literature. For example, McNaughton and Jarvis (1984)

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mentioned the Penman–Monteith method as the most efficient and standard method to estimate potential evapotranspiration (ET_0) that calculates irrigation water requirements of crops using coefficient factors of specific crops (Kc). Several weather parameters (temperature, moisture content, wind velocity, and solar radiation) are needed for the calculations of this method. However, Hargreaves (Hargreaves and Samani 1985), Blaney–Criddle (Allen and Pruitt 1986), and FAO-56 (Allen et al. 1998a) were suggested for a limited requirement of input data and in the absence of the above-listed meteorological data. Hafeez et al. (2020) found the Hargreaves method to perform better for ET_0 estimation than the Blaney–Criddle and FA0-56 methods because it required only daily maximum (T_{max}) and minimum (T_{min}) temperature data.

Indian eggplant (*Solanum melongena* var. *esculenta* L.) belongs to the *Solanaceae* family like tomatoes and potatoes and is considered a vegetable also called brinjal (Oliveira et al. 2009). It is used as a medicinal plant due to its nutritional properties of reducing cholesterol and controlling cardiovascular diseases (Gonçalves et al. 2006). It is a warm-climate crop whose plants grow 0.4 to 1.5 m tall having fruits of high economic importance and is one of the essential components of the daily diet in numerous Asian, Mediterranean, and Central European countries (Caruso et al. 2017). There are no reports in the literature on the systematic evaluation of production and growth variables of *S. melongena* var. *esculenta* L. under controlled environmental agriculture that is now increasingly practiced in the Middle East and arid regions where field agriculture is challenging. Therefore, an organized evaluation of the effects of controlled environment agriculture and nutrient sources on the production of eggplants is needed. Bridging this knowledge gap, we evaluated the effects of fully controlled, semicontrolled, and uncontrolled environments on the physiological growth and productivity of *S. melongena* var. *esculenta* L. under four nutrient source treatments. Recommendations for a suitable system are based on thorough experimental assessments and benefit-to-cost ratios of crop cultivation systems that consider total costs and gross income.

Materials and Methods

Experimental area and facilities. These experiments were carried out in Qatar (lat. 25.286106°N, long. 51.534817°E) about 50 to 100 m above sea level at the University of Doha for Science and Technology (UDST) research facilities. Qatar experiences arid climatic conditions, being the world's driest area (Abbas et al. 2023) with annual rainfall averaging below 100 mm (Baalousha and Ouda 2017; Bilal et al. 2021). Its mean relative humidity from November to February, which is a general growing season for horticultural crops in Qatar, ranges 60% to 65% (Karanisa et al. 2021). It experiences ∼40 °C as the maximum average temperature and ∼30 °C as the minimum average temperature during the summer. The maximum and the minimum temperatures are ∼22 and ∼14 °C, respectively, during the winter (Abbas et al. 2023).

The experimental facilities at UDST include a smart greenhouse, a conventional greenhouse of ∼20 m, and a wood-fenced open field in front of them with an area of 125 m^2. The smart greenhouse mimicked a fully controlled environment of agriculture, having a sensor-based drip irrigation system and solar-powered air conditioning and exhaust fans to control inside temperature, humidity, and dew point (Al-Naemi and Al-Otoom 2023). The conventional greenhouse is a semicontrolled environment agriculture facility in the shape of a nethouse having walls and a roof structure of used metal pipes/rods welded to form a frame covered with a thick green plastic net. The open field was fenced with recycled wood logs.

The WatchDog 1650 micro station (Spectrum Technologies Inc., Aurora, IL, USA) was installed at the three experimental facilities and configured to collect air temperature from the wired temperature sensors mounted at about 1.5 m in the center of the experimental facilities. The WatchDog micro stations were also connected to the WaterScout SM-100 soil moisture sensors (Spectrum Technologies Inc.) and temperature sensors installed at a depth of 10 to 15 cm in representative plant pots of the three environmental treatments. The micro stations had built-in sensors to record relative humidity values on a time-series basis. The meteorological and substrate temperature and volumetric water content data were logged onto the micro station logger and received using a field laptop, a data transmission cable (3661U), and SpecWare 9 software (Spectrum Technologies Inc.).

Experimental design and treatments. The experimental design consisted three environmental treatments (E1 to E3) that were considered as the main plots and four nutrient treatments (N1 to N4) that served as subplots. The plant pots were arranged in a completely randomized design with a split-plot scheme in which the four nutrient treatments were replicated four times. The experimental facilities served as three environmental treatments including E1 (smart greenhouse), E2 (nethouse), and E3 (open field). Nitrogen supplies to the soil substrate (peatmoss) of the plant pots formed four nutrient treatments including N1, in which the nutrients were supplied from the synthetic fertilizer; compost (N2); the combination of synthetic fertilizer and compost (N3); and peatmoss only without any nutrient supply (N4) to form a control treatment. Resultantly, the N1 treatment had 2.0 g of N/plant calculated from 20 g of inorganic fertilizer applied to the plant for an overall recommended rate of inorganic fertilizer application of 320 kg·ha^{-1}. The N2 treatment had 2.0 g of N per plant calculated from 200 g of compost applied to the plant for an overall recommended rate of compost application of 3.52 t·ha^{-1}. Likewise, N3 treatment had a 50% supply of nitrogen from inorganic fertilizer and the remaining 50% from compost to have 2.0 g of N/plant calculated from a mixture of application of 160 kg·ha^{-1} and 1.76 t·ha^{-1} of inorganic fertilizer and compost, respectively. Lastly, the control treatment N4 did not receive any external application of nitrogen but its natural nutrient concentration (Table 1).

Seeds for *S. melongena* var. *esculenta* L. were planted on 8 Feb 2023, and 3-week-old seedlings were transferred to the experimental facilities, about 21 d after sowing (DAS) on 1 Mar 2023. The eggplant seedlings were prepared by packing 1.5 kg of sphagnum peatmoss and accordingly mixed with inorganic fertilizer, compost, or a mixture of the two for their respective nutrient treatments. The substrate was tapped from the sides of the pots gently but continuously during the packing and merely pressed to achieve the bulk density value mentioned in Table 1. Bulk density of 0.161, 0.152, 0.158 and 0.156 g·cm^{-3} and total porosity of 74.4, 76.0, 74.9, and 75.2% for the respective treatments of N1, N2, and N3 were achieved and calculated using standard methods that considered 0.63 g·cm^{-3} as the particle density of the sphagnum peatmoss (Bigelow et al. 2004; Grossman and Reinsch 2002; Heiskanen 1995). With a control treatment, these trials had 36 eggplant pots (21.2 L each, calculated from 30-cm height and 15-cm diameter), of which 12 pots were placed at each of the three environmental treatments: smart greenhouse, nethouse, and open field.

S. melongena var. *esculenta* L., which is one of the nontuberous oval-shaped species of the nightshade family Solanaceae (Kantharajah and Golegaonkar 2004), was selected for these experiments because it is a perennial variety, as well as an annual crop cultivated in various parts of the world including the Middle East (Costa et al. 2013). The same eggplant variety of intermediate fruit size that matures in 70 to 100 d was cultivated in all three environmental conditions.

Cultural practices. According to Rajam and Kumar (2007), the eggplant crop has several stages of growth including seeding, germination (7 to 14 DAS), developing the true first leaves (15 to 21 DAS), the early growth stage (22 to 41 DAS), and the vegetative growth stage (6 to 10 weeks; 42 to 70 DAS). At its vegetative stage, the eggplant produces more leaves, gains length, and attains strength through thickening its diameter. During the vegetative growth, the plants start flowering simultaneously (10 to 12 weeks; 70 to 84 DAS), and pollination followed by fruiting occurs from week 14 to 15 (98 to 105 DAS) followed by ripening/harvesting of fruits throughout weeks 15 to 18 (105 to 126 DAS). Various crop care activities including irrigation, supplemental doses of NPK, staking, hoeing, and cleaning were performed during these stages.

For irrigation water requirements, Hargreaves method was used to estimate the ET_0 from T_{max} and T_{min} with the following equation:

$$ET_0 = 0.408(0.0023) \times (17.8 + T_{mean}) \times (T_{max} - T_{min})^{0.5} \times R_a \quad [1]$$

Table 1. Content and properties of the materials used in experimental treatments of inorganic fertilizer, compost, mixed fertilizer, and substrate used in this study forming the four nutrient treatments: N1, N2, N3, and N4.

Content and properties of the materials used in experimental treatments, units	N1: Inorganic fertilizer	N2: Compost	N3: Mixed fertilizer	N4: Substrate (control)
Chemical properties				
Total nitrogen (N) (TKN for OC)[i], g/100 g	12.0	1.21	6.00	0.74
Nitrate nitrogen (NH_3_N), g/100 g	8.90	–	–	–
Ammonium nitrogen (NH_4_N), g/100 g	3.10	–	1.55	–
Phosphorus pentoxide (P_2O_5), g/100 g	10.0	0.01	5.50	0.02
Potassium oxide (K_2O), g/100 g	18.0	0.33	9.15	0.09
MCDHS urease inhibitor, g/100 g	10.1	–	5.00	–
Carbon nitrogen ratio	–	29:1	15:1	–
Organic carbon, g/100 g	–	29.1	14.5	–
EC (1:5 water/compost extract), $dS \cdot cm^{-1}$	–	2.80	–	2.85
pH 25 at °C	–	6.90	–	–
Physical properties				
Water, g/100 g	23.0	23.8	23.4	Dry
Organic matter (LOI[i]), g/100 g	–	71.1	35.6	70.0
Bulk density, $g \cdot cm^{-3}$	0.161	0.151	0.158	0.156
Total porosity, %	74.4	76.0	74.9	75.2

[i] TKN as the sum of ammonia nitrogen and organic nitrogenous compounds.
[ii] LOI at 550 °C (Navarro et al. 1993).
EC = electrical conductivity, LOI = loss on ignition, MCDHS = Monocarbamide dihydrogen sulphate, OC = organic compound, TKN = total Kjeldahl nitrogen.

where 0.408 is an empirical factor to convert MJ/m^2 units of extraterrestrial radiation (R_a), which is solar radiation at the top of the earth's atmosphere. The daily values of the estimated ET_0 were multiplied with the Kc of eggplants (Allen et al. 1998b) for its various stages of crop-specific evapotranspiration (ETc) that were considered the irrigation water requirements for eggplants as:

$$ETc = ET_0 \times Kc \quad [2]$$

Historical data of T_{max}, T_{min}, and R_a were obtained from the Qatar Environment and Energy Research Institute database. The resultant irrigation water requirements were 286, 438, and 600 $m^3 \cdot ha^{-1}$ for plants in the smart greenhouse, conventional greenhouse, and open field, respectively. All irrigations were supplied at a preferred time of 5:00 to 6:00 PM, when humidity in Doha is lower than most of the day hours, to avoid loss of water from evapotranspiration during the hot hours of the day and rising of local (experimental location-specific) humidity conditions that hinder plant development (Mishra et al. 2020; Sawan 2018).

Equal quantities of nitrogen were applied to all nutrient treatments except for the control treatment. Nitrogen concentrations of the nutrient sources mentioned in Table 1 were used to calculate inorganic, organic, and mixed fertilizers for the N1, N2, and N3 treatments. However, the total supplies of inorganic fertilizer were portioned into four applications and applied at fortnight intervals after transporting the seedlings to the UDST experimental facilities. The available nutrients in the eggplant seeds and the substrate were considered enough and equal for all the first 3 weeks of seedling growth.

Agronomic treatments were performed as necessary. For example, at the stage of fruiting, the plants were supported with the help of ropes tied gently from various parts of the plant stems to wooden stakes that helped the plants carry the weight of their fruit. Gentle hoeing was manually performed to depths of ~10 cm in all treatment pots. A UDST weather station, stationed about 100 m away from the experimental facilities, was consulted for any rain and the daily values of extreme temperatures for the period of March to Jun 2023.

Experimental factors/variables and data collection. These experiments had two independent variables/factors including environment and nutrient source. The environment factor comprised three subfactors: a fully controlled environment provided by a smart greenhouse, a semicontrolled environment in the shape of the conventional greenhouse, and an uncontrolled environment under open field termed as treatments E1, E2, and E3, respectively. The nutrient source independent

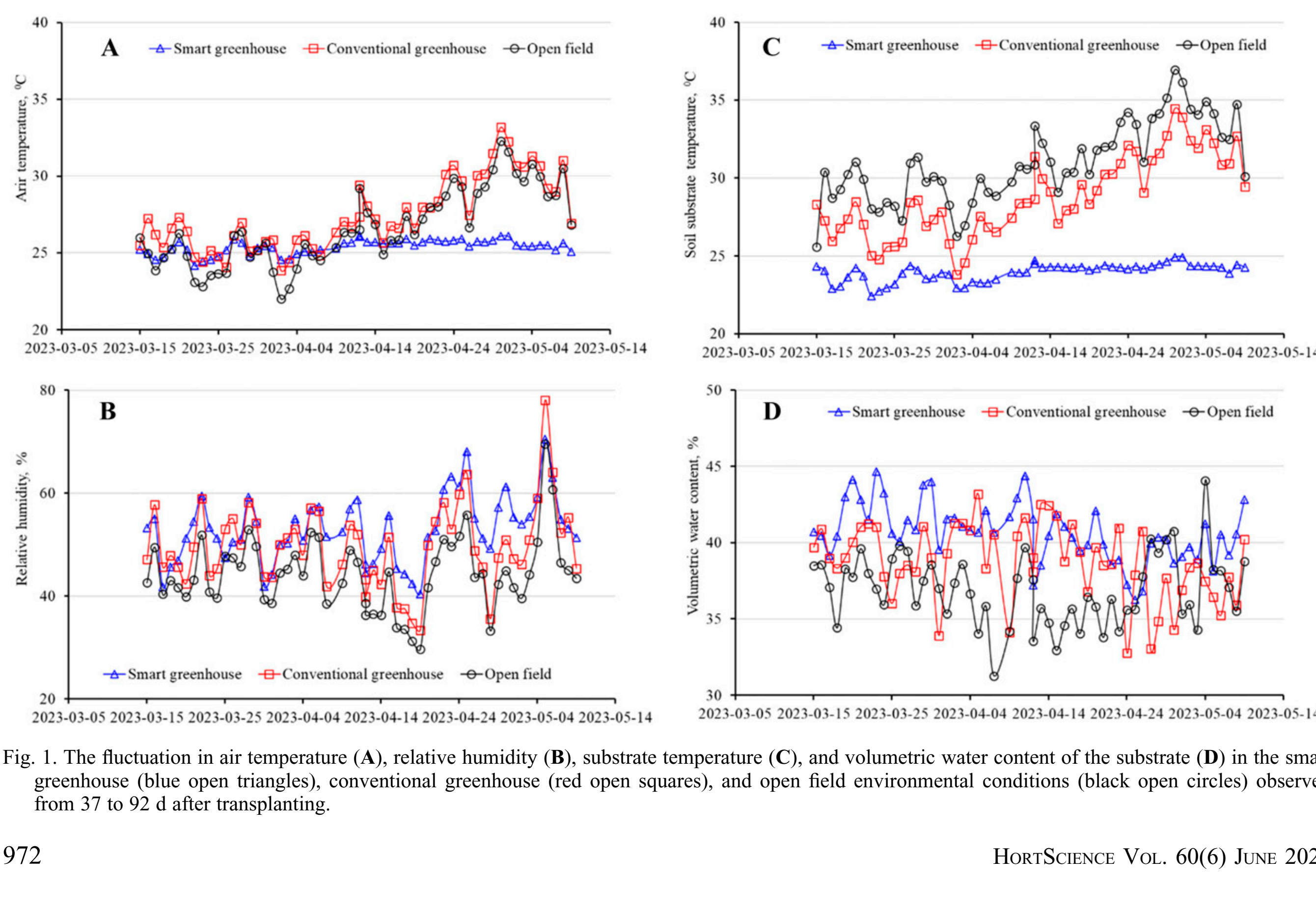

Fig. 1. The fluctuation in air temperature (**A**), relative humidity (**B**), substrate temperature (**C**), and volumetric water content of the substrate (**D**) in the smart greenhouse (blue open triangles), conventional greenhouse (red open squares), and open field environmental conditions (black open circles) observed from 37 to 92 d after transplanting.

Table 2. Effects of environmental conditions and nutrient source treatments on selected plant characteristics.

Treatment	Plant height, cm	Plant stem diameter, mm	Height-to-diameter ratio, cm/mm	Days after sowing to flowering	Days after sowing to fruiting
Environmental conditions					
Greenhouse (E1)	59.4 A	12.1 A	4.90 A	86 A	100 A
Nethouse (E2)	62.3 A	12.6 A	4.97 A	82 B	95.0 B
Open field (E3)	65.1 A	12.6 A	5.17 A	81 B	93.2 C
Nutrient sources					
Inorganic fertilizer (N1)	65.3 a	13.2 ab	5.00 A	84.0 a	94.8 b
Compost (N2)	63.0 a	12.2 b	5.22 A	82.8 ab	95.8 ab
Mixed fertilizer (N3)	69.3 a	14.0 a	4.98 A	83.8 a	96.8 a
Control (N4)	51.2 b	10.3 c	5.03 A	81.7 b	97.0 a
Combinations					
E1 × N1	62.7 *ab*	12.7 *abc*	4.98 *a*	84.5 *abc*	98.5 *ab*
E1 × N2	61.0 *abc*	12.2 *abcd*	5.00 *a*	86.0 *ab*	100 *a*
E1 × N3	69.4 *ab*	13.7 *ab*	5.07 *a*	86.8 *a*	101 *a*
E1 × N4	44.7 *c*	9.80 *d*	4.56 *a*	87.2 *a*	101 *a*
E2 × N1	68.6 *ab*	13.1 *ab*	5.25 *a*	81.0 *de*	94.0 *cd*
E2 × N2	59.1 *abc*	12.2 *abcd*	4.91 *a*	81.2 *de*	94.2 *cd*
E2 × N3	71.1 *a*	14.0 *a*	5.16 *a*	83.0 *bcd*	93.8 *cd*
E2 × N4	50.4 *bc*	11.1 *bcd*	4.57 *a*	72.7 *cde*	94.0 *cd*
E3 × N1	65.9 *ab*	14.0 *a*	4.78 *a*	79.7 *e*	91.7 *d*
E3 × N2	69.1 *ab*	12.1 *abcd*	5.75 *a*	81.2 *de*	93.2 *cd*
E3 × N3	67.3 *ab*	14.2 *a*	4.71 *a*	81.7 *cde*	93.8 *cd*
E3 × N4	58.5 *abc*	10.1 *cd*	5.95 *a*	82.0 *cde*	94.0 *cd*
Environmental conditions	≤0.148	≤0.435	≤0.471	≤0.000	≤0.000
Nutrient sources	≤0.000	≤0.000	≤0.889	≤0.000	≤0.000
Environmental conditions × nutrient sources	≤0.205	≤0.471	≤0.219	≤0.907	≤0.907
Alpha	0.05				

The environmental conditions were: E1, smart greenhouse; E2, conventional greenhouse; and E3, open field. The nutrient sources were: N1, inorganic fertilizer; N2, compost; N3, mixed fertilizer; and N4, substrate only/control. The mean values have been compared within the variable type, where the values labeled with the same letter (A, B, or C for environmental treatments and a, b, c, or d for nutrient source treatments) are not statistically different according to Tukey's least significant difference test. The homogeneous group format cannot be used because of the pattern of significant differences.

factor had four subfactors including N1, N2, N3, and N4.

The effects of the independent variables were investigated on various dependent variables belonging to environmental conditions (e.g., temperature, humidity, and dew point) and crop growth variables including plant leaf number, plant height, plant chlorophyll content, stem diameter, plant height/plant diameter ratio, dry root biomass, dry aboveground plant shoot biomass, plant root/shoot biomass ratio, total dry biomass, days to flowering, days to fruiting, fruit diameter at the largest point, fruit length, fruit individual weight, fruit weight per plant, fruits count per plant, and fruit yield.

The number of days to flowering was determined when a plant had at least one full open flower, and the number of days to fruiting was determined when a plant had a fruit of at least 1 cm in diameter (Costa et al. 2013). Biweekly observations were made for plant leaf number, plant height from the substrate surface to the plant tip using a measuring tape, stem diameter at 1 cm height from the substrate surface using a vernier caliper (Altraco Inc., Sausalito, CA, USA), plant height/plant diameter ratio, dry root biomass after the fruit final harvest, dry aboveground plant shoot biomass after the fruit final harvest, plant root/shoot biomass ratio, total dry biomass, days to flowering, days to fruiting, fruit diameter at the largest point, fruit length, fruit weight, and fruit yield pooled from individual fruit harvests that were weighed separately for each treatment, as were the plant dry biomass samples, using a calibrated digital balance with ±2-mg error. Fruit harvesting started on 106 DAS in the open field, 110 DAS in the conventional nethouse, and 116 DAS in the smart greenhouse and continued until 121, 128, and 135 DAS in the three sites, respectively. The nethouse and open field had four harvestings, and the smart greenhouse had five harvestings. The experiment ended on 1 Jul 2023. The dry biomass values of the plant root and shoots were made after drying plant samples separately in an oven at 60 °C for about 72 h, at which point the dry weights became unchanged by further drying and were finally weighed accordingly (Williams et al. 2013). During the same hours and intervals, the photosynthetic photon flux density values were measured using LightScout Quantum PAR meters (Spectrum Technologies Inc.) to calculate daily light integral.

Economic analysis. For economic analysis, a benefit-to-cost ratio was considered by dividing the total return (market price of eggplants in Qatar; $/ha) by the total cost (fixed and operational costs of the infrastructure and the injection units; $/ha) as described by Cetin et al. (2004). Fixed costs included the expenditures (materials plus labor) to build the smart greenhouse (including a solar system), the nethouse structure, and open field fencing. The operational costs comprised crop inputs (seeds/seedlings, chemicals, labor for seedbed preparation, injection system installation, and crop care) and energy charges (for greenhouse cooling and running irrigation networks). The lifetime for the infrastructure (smart greenhouse and nethouse structures) and the injection units (such as irrigation pump, engine, and components of drip irrigation system) were considered as 20 and 10 years, respectively with 3% of maintenance cost for all infrastructure and equipment (Gül et al. 2022).

Statistical analysis. SPSS (Statistical Package for Social Sciences) software (version 28.01; IBM SPSS Statistics, Armonk, NY, USA) (Kremelberg 2010) was used to conduct statistical analysis on the experimental data. The individual effects of environmental control and interactive effects of environment and nutrient source treatments were considered using one-way and two-way analyses of variance, respectively, to evaluate plant growth conditions (e.g., temperature, humidity, and dew point) and crop growth variables including plant leaf number, plant height, plant chlorophyll content, stem diameter, plant height/plant diameter ratio, dry root biomass, dry aboveground plant shoot biomass, plant root/shoot biomass ratio, total dry biomass, days to flowering, days to fruiting, fruit diameter at the largest point, fruit length, fruit weight, and fruit yield. A significance level of 95% was considered for an effect of independent variables on dependent variables; i.e., the effect of independent variables was considered significant on dependent variables at $P \leq 0.05$ and nonsignificant at $P > 0.05$. All significant effects were distinguished with Tukey's mean separation [least significant difference (LSD)] test. The mean values were compared within the variable type, where the values labeled with the same or combination of letters (A, B, or C for environmental treatments and a, b, c, or d for nutrient source treatments) were not considered statistically different according to Tukey's LSD test hypothesis. Pearson correlation test was also conducted to find a correlation between plant growth and plant productivity variables represented by the coefficient of correlations (R), which ranges between −1 and +1; a value of R close to +1 represents a strong correlation and vice versa.

Results

Meteorological variables and substrate conditions. Meteorological variables including air temperature (Fig. 1A) and relative humidity (Fig. 1B) varied with environmental treatments reflecting lesser fluctuations in air temperature values of the fully controlled smart greenhouse (24.2 to 26.1 °C) than in the semicontrolled conventional greenhouse (23.9 to 32.3 °C) and uncontrolled open field (20.0 to 33.2 °C) conditions. The mean values of air temperature for the three environmental treatments were 25.4 ± 0.47, 26.4 ± 2.52, and 27.5 ± 2.34 °C, respectively. The smart

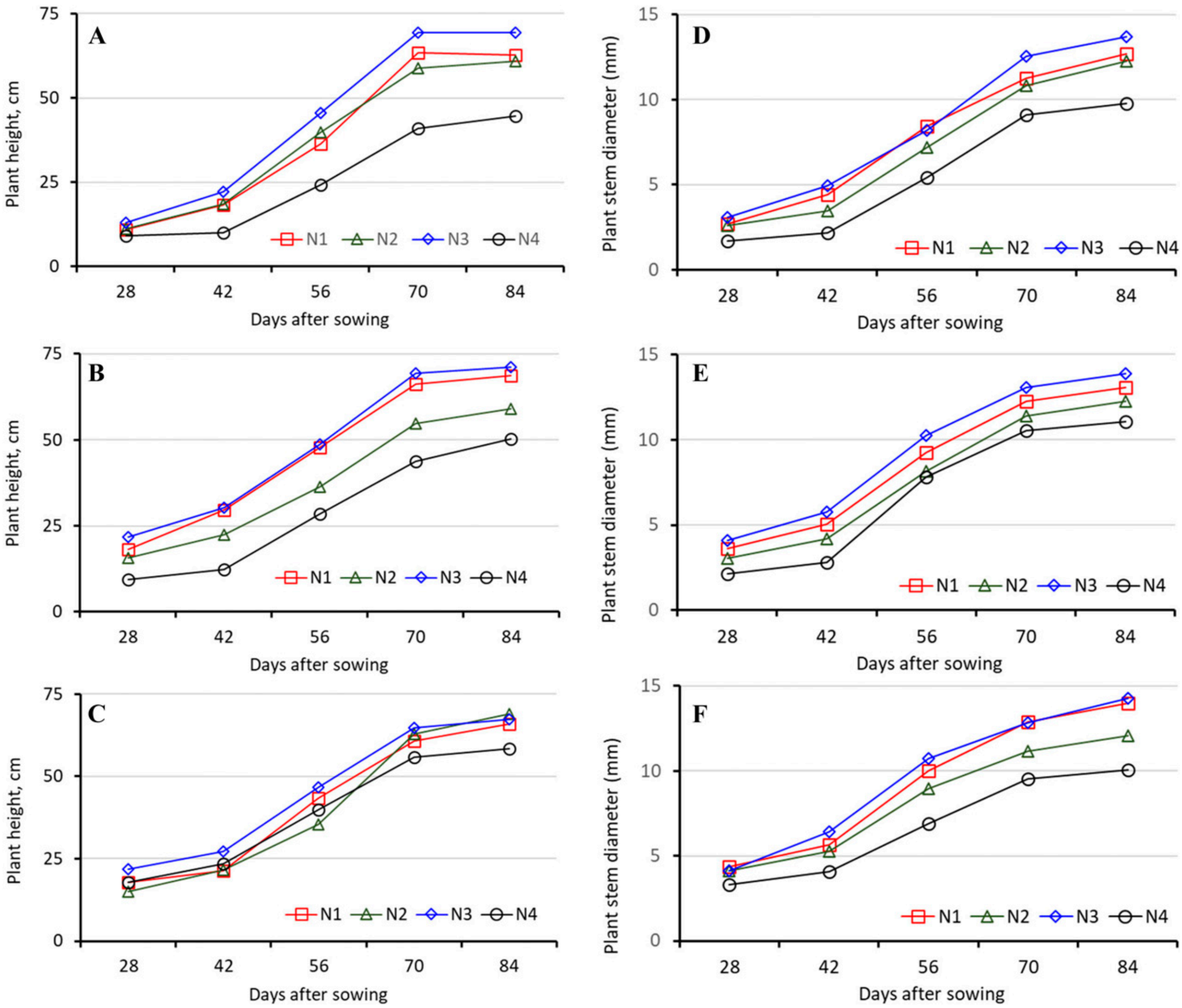

Fig. 2. Overtime (28 to 84 d after sowing) increases in the height (**A–C**) and stem diameter (**D–F**), of eggplants grown in the smart greenhouse (**A**, **D**), conventional greenhouse (**B**, **E**), and open field (**C**, **F**) environmental conditions under the effects of nutrient treatments. N1 = inorganic fertilizer, N2 = compost, N3 = mixed fertilizer, N4 = substrate only (control).

greenhouse treatment had the lowest standard deviation from the mean of its air temperature, reflecting more stability in the smart greenhouse temperature than in the temperature of the other two environmental conditions. More than 2 °C higher standard deviations from the means of conventional greenhouse (i.e., 2.52 °C) and open field (i.e., 2.34 °C) resulted in the mean air temperatures of these environmental treatments exceeding about 5 °C from the mean air temperature of the smart greenhouse.

The open field environmental treatment had lesser relative humidity than the smart and conventional greenhouses (Fig. 1B). The mean values of relative humidity for the three environmental treatments were 52.9 ± 6.57%, 49.7 ± 8.06%, and 44.3 ± 7.17%, respectively. The open field environmental treatment experienced 19.4% and 12.1% lesser relative humidity than the smart and conventional greenhouse, respectively. Relative humidity for the three respective environmental treatments ranged 40.4% to 70.5% (smart greenhouse), 33.4% to 78.1% (conventional greenhouse), and 29.6% to 69.5% (open field), resulting in the lowest fluctuations in the open field (22.5%) compared to the smart greenhouse (30.1%) and conventional greenhouse (44.7%) treatments.

The air temperature of the three environmental conditions directly affected the temperature of the soil substrates placed inside these environments to grow eggplant (Fig. 1C). In all three environmental conditions, the trends were different because the temperature of the substrate remained lower than the ambient temperature in the smart greenhouse treatment pots (24.0 ± 0.58 °C), whereas the former was higher than the latter in the conventional greenhouse (28.8 ± 2.61 °C) and open field (31.0 ± 2.48 °C) treatment pots. The conventional greenhouse and open field treatment pots experienced 20.3% and 22.8% higher temperatures than the smart greenhouse pots, which had the lowest range of minimum to maximum temperatures (i.e., 22.4 to 24.9 °C) as evidenced by the temperature ranges of the conventional greenhouse (23.8 to 34.5 °C), and open field (25.6 to 36.9 °C) treatment pots. The substrate temperatures of the smart greenhouse treatment pots were 4.86 and 7.06 °C, respectively, lower than the substrate temperatures of conventional greenhouse and open field pots. Both air and soil substrate temperatures of the three environmental conditions directly affected the dynamics of substrate moisture content of the three environmental treatments (Fig. 1D). The mean soil moisture content in E1 treatment pots (40.7% ± 1.93%) were higher, due to lower evapotranspiration rates from smart greenhouse pots than those from E2 and E3 treatment pots (38.7% ± 2.48% and 36.9% ± 2.33%, respectively), which experienced higher evapotranspiration because of comparatively higher air temperatures (Fig. 1A).

Plant growth traits. Environmental conditions had a nonsignificant ($P > 0.05$) individual effect on plant height, stem diameter, and the ratio of the former to the latter plant growth traits. However, the nutrient source treatments significantly ($P \leq 0.05$) independently affected plant height and stem diameter but had a nonsignificant interactive effect on the two variables (Table 2). The treatment of mixed fertilizer (N3) produced the tallest plants (69.3 cm), followed by N2 (compost treatment), which produced 63.0-cm-tall plants; N1 (synthetic fertilizer treatment) and N4 (control) produced 65.3- and 51.2-cm-tall

Table 3. Effects of environmental and nutrient source treatments on selected plant growth variables including plant leaf number, number of days after sowing to flowering and fruiting, biomass of dry shoot and root, shoot-to-root weight ratio, and total plant dry biomass contents.

Treatment	Leaf number	Dry shoot weight, g	Dry root weight, g	Shoot-to-root weight ratio	Total dry biomass, g
Environmental conditions					
Greenhouse (E1)	12.4 A	27.7 A	15.9 A	1.74 A	43.7 A
Nethouse (E2)	12.4 A	17.9 B	10.0 C	1.79 A	27.9 B
Open field (E3)	12.2 A	17.1 B	10.6 B	1.62 B	27.8 B
Nutrient sources					
Inorganic fertilizer (N1)	13.1 ab	19.2 b	10.9 d	1.76 b	30.2 d
Compost (N2)	11.3 ab	22.2 a	13.1 a	1.68 b	35.4 a
Mixed fertilizer (N3)	14.2 a	22.3 a	12.0 c	1.86 a	34.4 b
Control (N4)	10.8 b	19.9 b	12.6 b	1.57 c	32.5 c
Combinations					
E1 × N1	12.5 *a*	24.7 *c*	14.4 *c*	1.71 *bc*	39.1 *c*
E1 × N2	13.0 *a*	31.6 *a*	18.5 *a*	1.71 *bc*	50.1 *a*
E1 × N3	13.3 *a*	29.4 *b*	15.7 *b*	1.88 *ab*	45.2 *b*
E1 × N4	10.7 *a*	25.2 *c*	15.1 *bc*	1.67 *bc*	40.2 *c*
E2 × N1	13.3 *a*	17.3 *efg*	9.22 *f*	1.88 *ab*	26.5 *gh*
E2 × N2	11.3 *a*	18.2 *de*	10.7 *de*	1.70 *bc*	28.9 *def*
E2 × N3	14.5 *a*	17.8 *ef*	9.10 *f*	1.96 *a*	31.0 *d*
E2 × N4	10.0 *a*	18.1 *def*	11.1 *de*	1.63 *c*	28.0 *efg*
E3 × N1	13.5 *a*	15.7 *g*	9.30 *f*	1.69 *bc*	25.0 *h*
E3 × N2	9.75 *a*	16.9 *efg*	10.3 *ef*	1.64 *c*	27.2 *efg*
E3 × N3	14.8 *a*	19.7 *d*	11.3 *de*	1.75 *abc*	26.9 *fgh*
E3 × N4	11.5 *a*	16.2 *fg*	11.7 *d*	1.40 *d*	28.0 *efg*
Environmental conditions	=0.972	≤0.000	≤0.000	≤0.004	≤0.000
Nutrient sources	=0.023	≤0.000	≤0.000	≤0.000	≤0.000
Environmental conditions × nutrient sources	=0.664	≤0.000	≤0.000	≤0.017	≤0.000
Alpha	0.05				

The environmental conditions were: E1, smart greenhouse; E2, conventional greenhouse; and E3, open field. The nutrient sources were: N1, inorganic fertilizer; N2, compost; N3, mixed fertilizer; and N4, substrate only/control. The mean values have been compared within the variable type, where the values labeled with the same letter (A, B, or C for environmental treatments and a, b, c, or d for nutrient source treatments) are not statistically different according to Tukey's least significant difference test.

plants, respectively (Table 2). The height of individual control treatments of all nutrients remained lower than the other three nutrient treatments, possibly because of an insufficient supply of nutrients (Fig. 2A–C). Similar trends were noticed in the case of plant stem diameter; N3 treatments, with a mixed fertilizer supply available for plants, had the largest final diameter, followed by N1, N2, and N4 (Fig. 2D–F). Doan et al. (2013) also reported thicker stem diameters of the experimental tomatoes grown under mixed fertilizer treatment, arguing that the inorganic component of their mixed fertilizer treatment could have supplied the required nutrients during the early stages of plant growth and the compost could have done the job during the latter growth stages.

The days after sowing to flowering and fruiting had individual significant effects of environment and nutrient source treatments ($P \leq 0.05$) but a nonsignificant interactive effect of the two treatments (Table 2). The plant length and stem diameter rapidly grew during the vegetative growth stage from 42 to 70 DAS (Fig. 2). Similar trends were noticed in the plants grown under all environmental control and nutrient supply treatments as the growth of plant height and stem diameter remained slow during the early growth stage and stabilized during the fruit development stage. Due to open and semicontrolled conditions, the plants under treatments E2 and E3 took fewer days to flower (82 and 81, respectively) than those of E1 treatment (86 d) following the trends of healthier plants observed in E2 and E3 treatments than those found in E1 treatments. For N1, N2, N3, and N4, the plants respectively took about 84, 82, 84, and 82 d to flower. The sequence of blossoming of flowers led to similar trends of fruiting in all experimental treatments accordingly, as the first mature fruit was harvested after 93 DAS from the open field treatment followed by the harvesting from a semicontrolled conventional greenhouse (95 DAS) and smart greenhouse (100 DAS). These three values for DAS for fruiting are significantly ($P \leq 0.05$) different from one another, which is demonstrated by their P values and the different Tukey's LSD letters to distinguish their mean separated values (Table 2).

There were significant ($P \leq 0.05$) individual effects of environmental condition treatments and their interactive effect with nutrient source treatments on plant vegetative, root, and total dry biomasses, and the ratio of vegetative to root dry biomass, but not on leaf number ($P > 0.05$) (Table 3). However, the nutrient source treatments had significant individual effects on all of these variables. Plants of the mixed fertilizer treatment N3 maintained the highest number of leaves (14 leaves/plant) that were significantly greater than the leaves of the plants of the control treatment (10 leaves/plant) but not statistically different from the synthetic fertilizer (13 leaves/plant) and compost (11 leaves/plant) treatments (Table 3).

Significant effects of environment and nutrient treatments on the plant lengths and diameters led to significant ($P \leq 0.05$) variations in the vegetative (above and below ground, i.e., shoot and root, respectively) characteristics including dry biomasses (shoot, root, and total) and ratios of shoot-to-root dry biomasses among all experimental treatments (Table 3). Masses of the dry shoots of plants grown under semicontrolled environmental conditions (E2) in a conventional greenhouse and uncontrolled open environment conditions (E3) were significantly ($P \leq 0.05$) different and about 37% greater than the mass of the dry plant shoots grown under fully controlled environmental conditions (E1) in a smart greenhouse. There was no significant difference ($P > 0.05$) between the dry shoot mass of the plants harvested from E2 and E3 treatments as represented by the similar Tukey's LSD letters (Table 3). On the other hand, the dry shoots of the plants from the N2 (compost) and N3 (mixed fertilizer) treatments weighed more than the dry shoots of the plants from the N1 (synthetic fertilizer) and N4 (control) treatments. However, the dry root mass of the plants from the E1 and E2 treatments was greater than the mass of the dry roots of the open field treatment. The mass of roots of the N4 treatment plants was lower than the masses of the other three nutrient source treatment plants. The values of masses of dry shoots and roots were according to the literature (Kurunç and Ünlükara 2009) for the similar size of plant pot size and directly influenced the ratios of dry root-to-shoot biomass and the total biomass (Table 3). The total plant dry biomass values of this study ranged from 27.8 to 43.7 g/plant and matched the range of values (27.4 to 47.9 g/plant) of the whole plant dry weight reported by Kirnak et al. (2001) for their various water application treatments.

Plant productivity traits. Except for fruit length, the mean values of plant productivity traits including fruit count per plant, fruit length, fruit yield per plant, total yield per ha, and water use efficiency were significantly ($P \leq 0.05$) different under the individual effects of environmental condition and nutrient source treatments (Table 4). The E2 treatments inside the conventional greenhouses produced significantly more fruits (i.e., 8.1 fruits/plant) that were statistically greater than the mean number of fruits produced by each plant of treatments E1 (6.0 fruits/plant) and E3 (6.5 fruits/plant). The mixed fertilizer treatment N3 produced the maximum number of mean fruits (9 fruits/plant), and the control treatment produced the lowest number of fruits/plant (5.25 fruits/plant). The lengths of fruit from the nethouse and open field treatments were not statistically different from one another but significantly larger than the fruits of smart greenhouse treatment as reflected by the different Tukey's LSD letters used to distinguish their mean values. The mean fruit lengths of the four nutrient treatments were significantly different from one another under the individual effects of nutrient source treatments. With a nonsignificant difference between the mean fruit diameter values of E1

Table 4. Effect of environmental and nutrient source treatments on fruit characteristics, plant productivity, total yield, and water use efficiency.

Treatment	Fruit characteristics			Fruit yield		Water use efficiency, L·kg^{-1}
	Fruit count	Length, cm	Diameter, cm	kg/plant	mg·ha^{-1}	
Environmental conditions						
Greenhouse (E1)	6.00 B	8.05 B	5.58 A	0.67 C	11.2 C	33.0 B
Nethouse (E2)	8.12 A	8.47 A	5.29 AB	1.21 A	20.2 A	35.3 B
Open field (E3)	6.50 B	8.38 A	5.11 B	0.84 B	14.1 B	59.0 A
Nutrient sources						
Inorganic fertilizer (N1)	6.67 b	8.70 b	5.64 ab	0.82 b	13.7 b	41.1 b
Compost (N2)	6.58 b	7.39 c	5.08 bc	0.89 b	14.9 b	42.5 b
Mixed fertilizer (N3)	9.00 a	9.96 a	5.88 a	1.27 a	21.2 a	26.1 c
Control (N4)	5.25 c	7.15 d	4.70 c	0.64 c	10.7 c	60.0 a
Combinations						
E1 × N1	6.00 *bc*	8.36 *c*	5.84 *ab*	0.61 *d*	10.3 *c*	31.9 *bcd*
E1 × N2	5.50 *bc*	7.52 *d*	5.22 *abc*	0.68 *d*	11.4 *c*	33.9 *bcd*
E1 × N3	7.25 *bc*	9.13 *b*	6.21 *a*	0.80 *cd*	13.2 *c*	21.5 *cd*
E1 × N4	5.25 *bc*	7.22 *d*	5.04 *abc*	0.58 *d*	9.75 *c*	44.5 *abcd*
E2 × N1	8.00 *b*	8.92 *b*	5.61 *abc*	1.10 *bc*	18.4 *b*	32.0 *bcd*
E2 × N2	8.25 *b*	7.37 *d*	5.36 *abc*	1.27 *b*	21.1 *b*	27.6 *bcd*
E2 × N3	7.25 *bc*	10.4 *a*	5.81 *ab*	1.82 *a*	30.3 *a*	19.3 *d*
E2 × N4	4.50 *c*	7.17 *d*	5.04 *abc*	0.66 *d*	11.0 *c*	62.3 *ab*
E3 × N1	6.00 *bc*	8.84 *bc*	5.48 *abc*	0.75 *d*	13.5 *c*	59.3 *abc*
E3 × N2	6.00 *bc*	7.29 *d*	4.66 *bc*	0.73 *d*	12.2 *c*	66.0 *ab*
E3 × N3	8.00 *b*	10.4 *a*	5.63 *abc*	1.20 *b*	20.1 *b*	37.5 *bcd*
E3 × N4	6.00 *bc*	7.08 *d*	4.66 *bc*	0.68 *d*	11.4 *c*	73.1 *a*
Environmental conditions	≤0.000	≤0.472	≤0.043	≤0.000	≤0.000	≤0.008
Nutrient sources	≤0.000	≤0.134	≤0.000	≤0.000	≤0.000	≤0.000
Environmental conditions × nutrient sources	≤0.000	≤0.518	≤0.669	≤0.000	≤0.000	≤0.319
Alpha	0.05					

The environmental conditions were: E1, smart greenhouse; E2, conventional greenhouse; and E3, open field. The nutrient sources were: N1, inorganic fertilizer; N2, compost; N3, mixed fertilizer; and N4, substrate only/control. The mean values have been compared within the variable type, where the values labeled with the same letter (A, B, or C for environmental treatments and a, b, c, or d for nutrient source treatments) are not statistically different according to Tukey's least significant difference test.

and E2 treatments, these mean diameter values of the fruits of open field E3 plants were significantly smaller than that of E1 treatment. Within the environmental conditions and nutrient source treatments, the ranges of mean fruit diameter were 5.11 to 5.58 cm and 4.70 to 5.88 cm, respectively (Table 4).

Regarding the mean weights of fruit, the E2 treatment plants produced more yield per individual plant with the largest load of fruits (1.21 kg/plant) as compared with the load of fruits of E1 treatment plants (0.67 kg/plant) and E3 treatment plants (0.84 kg/plant). Similarly, N3 treatment plants had a mean load of 1.27 kg/plant, which was the largest and significantly different from the rest of environmental condition treatments. The other three nutrient treatment plants had a fruit load of less than 1 kg/plant.

The total yield of eggplant fruits converted into yield per hectare was the largest for E3 treatment (21.2 mg·ha^{-1}), which was significantly different and greater than the yield of other treatments and about twice the yield of the control treatment (10.7 kg·ha^{-1}). Therefore, the smart greenhouse and the control treatment (i.e., plant grown without nutrient application) produced 50% lesser yield than the respective best-performing treatments (E2 and N3). Statistical analyses showed that the environmental conditions and nutrient source treatments significantly ($P \leq 0.5$) affected the water use efficiency under the individual effects of these treatments (Table 4). However, there was no interactive effect of these treatments on the water use efficiency.

Statistical analyses (Tables 2–4) revealed nonsignificant ($P > 0.05$) interactive effects of environmental conditions and nutrient source treatments on plant height, stem diameter, plant height-to-diameter ratio, days after sowing to flowering and fruiting, plant leaf number, count, length and diameter of fruits, and the water use efficiency. However, significant ($P \leq 0.5$) interactions of the experimental treatments were calculated for shoot dry biomass, root dry biomass, shoot-to-root dry biomass ratio, total plant dry biomass, fruit yield per plant, and the fruit yield per hectare.

Outcomes of economic analysis. Total costs for the smart greenhouse, conventional nethouse, and open field were 39,515, 28,265, and 28,098 $/ha comprising (1) fixed costs of 10,000 $/ha (for 20 years of lifetime of greenhouse), 5000 $/ha (for 10 years of lifetime of nethouse), and 5000 $/ha (for 15 years of lifetime open field) and (2) operating costs of 38,200 $/ha/year (for two possible growing cycles in the greenhouse), 27,100 $/ha/year (for one possible growing cycles in the nethouse), and 28,100 $/ha/year (for one possible growing season in the open field). The operating costs comprise the individual costs for the components of energy, seeds/seedlings, labor, and chemicals (pesticides and fertilizers). Total returns, calculated from multiplying the eggplants' market price in Qatar (i.e., 3.5 $/kg) with crop yield (Table 4), when divided by the total cost (Table 5), resulted in benefit-to-cost ratios of 1.98 (smart greenhouse), 2.50 (conventional nethouse), and 1.76 (open field). These results agree with the findings of Moursy et al. (2023), who reported that the benefit-to-cost ratios of greenhouses and open fields of their studies ranged from 1.96 to 2.14 and 1.71 to 1.81, respectively. This economic analysis leads to the recommendation of the conventional nethouse as the best production system to cultivate eggplants in arid regions as compared with the smart greenhouse and open field conditions tested in this study.

Discussion

The controlled temperature of the smart greenhouse resulted in less evapotranspiration than that from the other two environmental treatment plants. Therefore, the values of

Table 5. Results of the economic analysis for eggplant production under three environmental treatments including a smart greenhouse, conventional nethouse, and open field.

Environmental treatments	Greenhouse	Nethouse	Open field
Fixed cost, $/ha/year	1,000	1,000	833
Operating cost, $/ha	38,200 for 2 years	27,100 for 1 year	27,100 for 1 year
Total cost, $/ha	39,515 for 2 years	28,265 for 1 year	28,098 for 1 year
Total income, $/ha	78,400 for 2 years	70,700 for 1 year	49,350 for 1 year
Benefit-to-cost ratio	1.98	2.50	1.76

daily substrate water content averaged over the growing cycle were 40.7% ± 1.93%, 38.7% ± 2.48%, and 36.9% ± 2.33% in the smart greenhouse, conventional greenhouse, and open field pots, respectively. The experimental pots of the open field treatments could retain lesser moisture content because of higher daily means of temperature (27.5 ± 2.34 °C) than that of the smart (25.4 ± 0.47 °C) and conventional (26.6 ± 2.52 °C) greenhouses and thus evapotranspiration rates and lower relative humidity rates under the open conditions than in the other two environmental condition treatments. These meteorological variables, in addition to nutrient treatments, affected plant growth variables. However, despite the significant effects of environmental and nutrient treatments, because of similar trends in the increases of plant height and stem diameter throughout DAS 28 to 84, the plant height-to-stem diameter ratio remained statistically similar ($P > 0.05$) for all the environmental conditions (E1 to E3) and nutrient source type (N1 to N4) treatments as shown by the similar Tukey's LSD letters to distinguish their mean values (Table 2). Flower settings during these experiments (i.e., 81 to 86 DAS) in different environmental treatments were in the range of 70 to 90 DAS reported in the literature (Kowalska 2008) as it depends mainly on environmental conditions (Kowalska 2003; Sun et al. 1990).

The E1 and E2 treatments (smart and conventional greenhouses, respectively) produced significantly larger and different lengths of plants (59.4 and 62.3 cm, respectively) than that of the E3 treatment of the open field uncontrolled environment treatment (55.1 cm) (Table 2). These plant lengths accord with the lengths of eggplants recorded by Kirnak et al. (2001) and by Kakahy and Alshamary (2020) in their greenhouse experiments for the effect of fertilizers and irrigation levels on eggplant growth traits. The E3 treatment produced the largest mean stem diameter of plants (14.7 ± 0.51 mm), which was significantly greater than the mean diameter values of plants of E1 treatment (12.6 ± 0.51 mm) and E2 (13.6 ± 0.51 mm). The length and stem diameter values were in concurrence with the observations of Kirnak et al. (2001) and Kurunç and Ünlükara (2009) who studied the effects of pot size on plant growth and productivity traits. Controlled environment agriculture cultivates plants in pots, limiting growth and spread on plant roots. Restrictions on roots' liberty to move freely into their root zone affect other plant growth variables, including plant height, diameter, and dry weights of shoots and roots (Kurunç and Ünlükara 2009). However, the restriction of roots within a limited space (i.e., size of the growing pads or pots) affects the plant growth and productivity traits including plant height, stem diameter, dry biomass of shoots and roots, and fruit yield that increases with an increase in size of plant pots for eggplants and okra (Kurunç and Ünlükara 2009) and for starfruit (*Averrhoa carambola* L.) as reported in the literature (Ismail and Noor 1996).

The trends in the increase in plant height and stem diameter values resulted in straight lines when plotted against each other for all environmental conditions and nutrient source treatments (Fig. 3A–C). However, the increases in plant height were greater than the increase in stem diameter as depicted from the positions of their data values and regression lines falling above the 1:1 line in Fig. 3A–C. The regression models established from these data sets can precisely estimate one characteristic of the eggplant shoots from the other (height from stem diameter) and vice versa (stem diameter from height) with goodness of fit (i.e., R^2, the coefficient of regression) values close to unity. Therefore, the height-to-diameter ratios for both environmental conditions and nutrient source treatments became horizontal straight lines when plotted against DAS (Fig. 3D–F) as the height-to-diameter ratios had nonsignificant ($P > 0.05$) effects of the experimental treatments (Table 2). These ranges of height-to-diameter ratios (measured in cm/mm) concur with the results (4.6 to 4.7 cm/mm) of Díaz-Pérez and Eaton (2015), who monitored eggplant growth parameters under the effect of five irrigation levels.

The possible reason for the lower yield in the E1 treatment may be the lower temperature amplitude in the smart greenhouse than the other two environmental conditions treatments (Wu et al. 2022; XiaoYing et al. 2011) as depicted in Fig. 1. The plants in the smart greenhouse were deprived of natural sunlight, whereas the other two treatment plants were exposed to varying sunlight, leading to higher fruit yield in the E2 and E3 treatments than the E1 treatments. The other possible reason the control environment had a lesser yield than the open field may be the limited pollination and light in the smart greenhouse compared to the open field (Kittas et al. 2006; Manrique 1993; Nguyen et al. 2022). Furthermore, the slow development of plant fruits resulted in additional harvesting in the smart greenhouse (i.e., five harvests in the smart greenhouse and four harvests each in the nethouse and the open space). On the other hand, the results of higher yield from the plants of N3 treatment than the other nutrient source treatments support the findings of Frankenberger and Abdelmagid (1985), who investigated N mineralization in soil from inorganic fertilizers and recommended mixing of organic fertilizers with inorganic fertilizers because, according to their conclusion, the incorporation of only organic fertilizer in soil may provide the necessary nutrients to plants.

Different irrigation water requirements and the fruit yield from the experimental treatments influenced the water use efficiency [i.e., liters of irrigation water needed to produce 1 kg of fruit ($L \cdot kg^{-1}$)] of the experimental treatments. For example, ~52% and ~27% lower water was required by the plants of the smart greenhouse (286 $m^3 \cdot ha^{-1}$) and conventional greenhouse (438 $m^3 \cdot ha^{-1}$) than by the plants of the open field treatment (600 $m^3 \cdot ha^{-1}$), resulting in 44.1 and 40.2% higher water use efficiency of the smart greenhouse plants (33.0 $L \cdot kg^{-1}$) and conventional greenhouse plants (35.3 $L \cdot kg^{-1}$) than that of the plants of the open field treatment (59 $L \cdot kg^{-1}$). In contrast, the fruit yield dominated in the calculation for water use efficiency for the nutrient source treatments, where the mixed fertilizer treatment needed the least amount of irrigation water (26.1 $L \cdot kg^{-1}$), and the control treatment consumed the most amount of irrigation water (60.0 $L \cdot kg^{-1}$) to produce the same yield of fruits (Table 4). The individual inorganic (N1) and compost (N2) treatments had respectively 57% and 62% lower water use efficiencies than the mixed treatments of inorganic and compost treatment (E3). These findings support the reports of Abd El-Mageed et al. (2021), who reported about 32 to 64% increases in the water use efficiency of their eggplant treatments of compost mixed with other fertilizers.

Statistical analyses of the data showed that other than environmental conditions and nutrient sources, the eggplant yield was correlated to the plant growth traits including plant height and stem diameter as shown in Table 6, which also gauged the correlation among plant growth variables. The strongest correlation was found between plant height and stem diameter ($R = 0.46$), followed by fruit yield and stem diameter ($R = 0.45$) and plant height and plant yield ($R = 0.34$).

One of the novel points of this work is the systematic evaluation and the first-time reporting of Qatar-specific data about eggplant production under various environment and nutrient supply settings leading to the findings that the combination of inorganic and organic nutrient supply sources produced the optimum yield under semicontrolled conventional greenhouse settings. The study findings suggested that conventional greenhouse cultivation could be an economically feasible, energy-efficient, and environmentally friendly method for producing eggplants in arid regions and agricultural conditions resembling those used in this study. The outcomes of the economic analysis support these findings based on the benefit-to-cost ratios of 1.98, 2.50, and 1.76 for the smart greenhouse, conventional nethouse, and open field cultivations, respectively. This confirms the reports of Abbas et al. (2024) about the best performance of a semicontrolled conventional nethouse as the best option to cultivate horticultural crops in arid regions.

Conclusions

This study systematically evaluated plant growth and productivity traits across three distinct environmental settings: a fully controlled smart greenhouse, a semicontrolled conventional greenhouse, and uncontrolled open-space cultivation. These environmental conditions were treated as blocks, while four nutrient source treatments, encompassing plant nitrogen supply through inorganic fertilizer, compost, a mix of inorganic fertilizer and compost, and a control treatment, were designated as split-plot treatments.

The results indicated that under the interactive effects of environmental conditions and nutrient sources, the eggplants cultivated

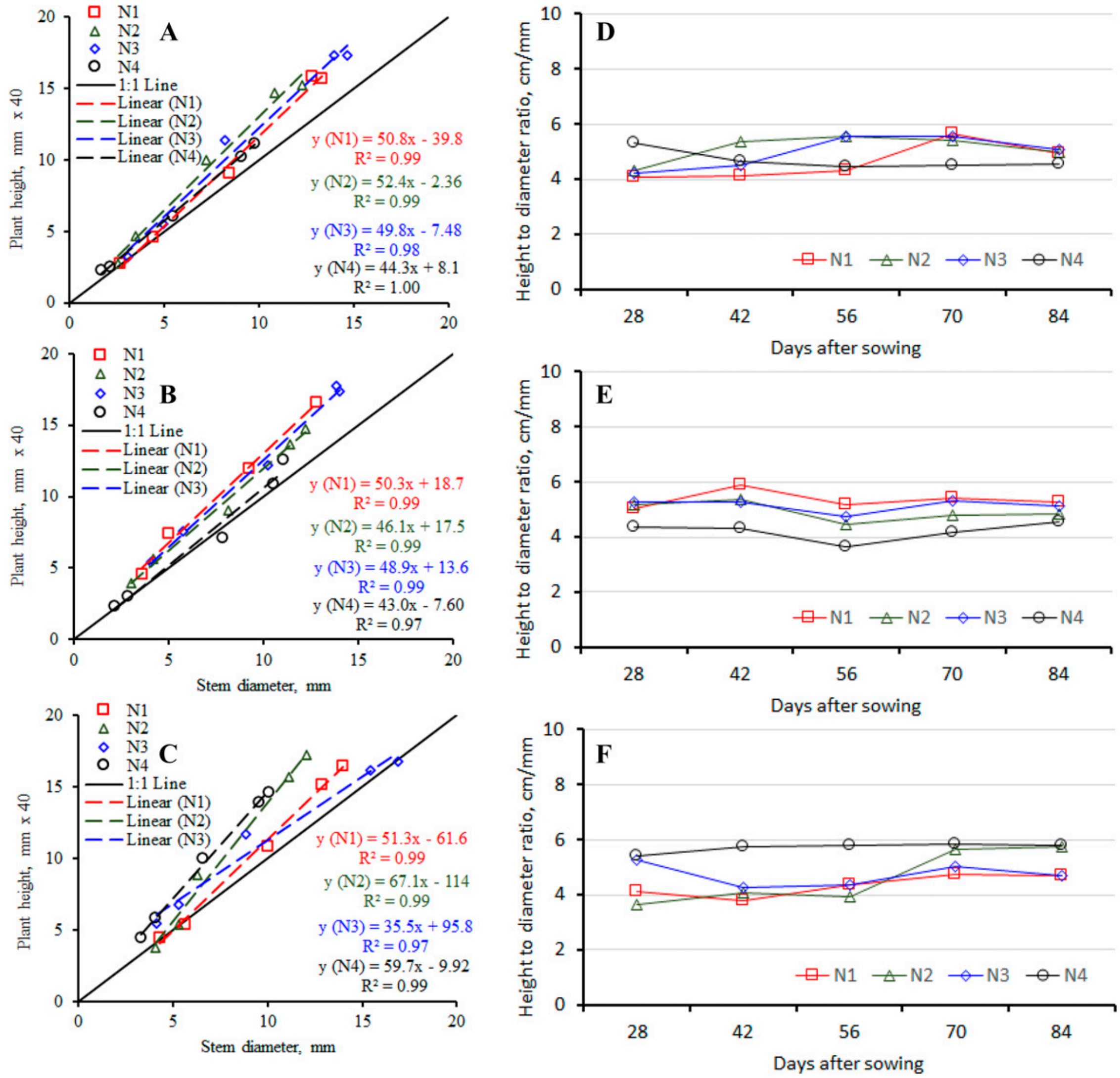

Fig. 3. Relationships of plant height and stem diameter (**A–C**) and variations of plant height to diameter ratio with 28 to 84 d after sowing (**D–F**) of eggplants grown in the smart greenhouse (**A**, **D**), conventional greenhouse (**B**, **E**), and open field (**C**, **F**) environmental conditions under the effects of nutrient treatments. N1 = Inorganic fertilizer, N2 = compost, N3 = mixed fertilizer, N4 = substrate only (control).

Table 6. Results of Pearson correlation test showing the values of coefficient of correlation (R) among plant height, stem diameter, and fruit yield.

	Plant height	Stem diameter	Fruit yield
Plant height	1		
Stem diameter	0.46	1	
Fruit yield	0.34	0.45	1

in a semicontrolled conventional greenhouse, when supplied with nitrogen using mixed fertilizers, statistically outperformed other treatments and their combinations. This suggested that these practices could be deemed optimal for efficient eggplant cultivation, especially in regions with agricultural and environmental characteristics akin to Qatar, including those within the Gulf Cooperation Council (i.e., Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates) countries and arid zones.

In terms of water use efficiency, the smart greenhouse emerged as the most effective option for conserving water, despite a disparity in fruit yield when compared with other environments. The year-round potential for multiple crop cycles in the smart greenhouse enhances its economic viability and environmental sustainability. Further enhancement of crop productivity in the smart greenhouse could be achieved by upgrading its heating, ventilation, and air conditioning system and implementing a supplemental lighting system tailored to the specific light requirements and daily light integral.

Despite the experimental and economic analysis–based recommendations of conventional nethouse as the best choice for arid regions, the findings of this study underscore the potential for smart greenhouses for these regions with strategic improvements in its environmental control technologies that could optimize both fruit yield and water use efficiency. The comprehensive data set and statistically analyzed results generated by this study provide a foundational resource for subsequent in-depth investigations, including controlled environment agriculture experimentation and crop growth modeling simulations.

References Cited

Abbas F, Al-Naemi S, Farooque AA, Phillips M. 2023. A review on the water dimensions, security, and governance for two distinct regions. Water. 15(1):208. https://doi.org/10.3390/w15010208.

Abbas F, Al-Otoom A, Al-Naemi S, Ashraf A, Mahasneh H. 2024. Experimental and life cycle assessments of tomato (*Solanum lycopersicum*) cultivation under controlled environment agriculture. J Agric Food Res. 18:101266. https://doi.org/10.1016/j.jafr.2024.101266.

Abd El-Mageed TA, Abdelkhalik A, Abd El, Mageed SA, Semida WM. 2021. Co-composted poultry litter biochar enhanced soil quality and eggplant productivity under different irrigation regimes. J Soil Sci Plant Nutr. 21(3):1917–1933. https://doi.org/10.1007/s42729-021-00490-4.

Allen RG, Pereira LS, Raes D, Smith M. 1998. Crop evapotranspiration—Guidelines for computing crop water requirements—FAO irrigation and drainage paper 56. FAO, Rome, 300(9): D05109.

Allen RG, Pruitt WO. 1986. Rational use of the FAO Blaney–Criddle formula. J Irrig Drain Eng. 112(2):139–155. https://doi.org/10.1061/(ASCE)0733-9437(1986)112:2(139).

Al-Naemi S, Al-Otoom A. 2023. Smart sustainable greenhouses utilizing microcontroller and IOT in the GCC countries: Energy requirements & economical analyses study for a concept model in the state of Qatar. Results Eng. 17:100889. https://doi.org/10.1016/j.rineng.2023.100889.

Baalousha HM, Ouda OK. 2017. Domestic water demand challenges in Qatar. Arab J Geosci. 10(24):537. https://doi.org/10.1007/s12517-017-3330-4.

Bigelow CA, Bowman DC, Cassel DK. 2004. Physical properties of three sand size classes amended with inorganic materials or sphagnum peat moss for putting green rootzones. Crop Sci. 44(3):900–907. https://doi.org/10.2135/cropsci2004.9000.

Bilal H, Govindan R, Al-Ansari T. 2021. Investigation of groundwater depletion in the state of Qatar and its implication to energy water and food nexus. Water. 13(18):2464. https://doi.org/10.3390/w13182464.

Bot GP. 2001. Developments in indoor sustainable plant production with emphasis on energy saving. Comput Electron. Agric. 30(1–3):151–165. https://doi.org/10.1016/S0168-1699(00)00162-9.

Caruso G, Pokluda R, Sękara A, Kalisz A, Jezdinský A, Kopta T, Grabowska A. 2017. Agricultural practices, biology and quality of eggplant cultivated in Central Europe: A review. Hortic Sci. 44(4):201–212. https://doi.org/10.17221/36/2016-HORTSCI.

Cetin B, Yazgan S, Tipi T. 2004. Economics of drip irrigation of olives in Turkey. Agric Water Manage. 66(2):145–151. https://doi.org/10.1016/j.agwat.2003.10.004.

Cockshull KE, Hand DW, Langton FA. 1982. The effects of day and night temperature on flower initiation and development in chrysanthemum. Acta Hortic. 125:101–110. https://doi.org/10.17660/ActaHortic.1982.125.12.

Costa E, Durante LGY, Santos AD, Ferreira CR. 2013. Production of eggplant from seedlings produced in different environments, containers and substrates. Hortic Bras. 31(1): 139–146. https://doi.org/10.1590/S0102-05362013000100022.

Díaz-Pérez JC, Eaton TE. 2015. Eggplant (*Solanum melongena* L.) plant growth and fruit yield as affected by drip irrigation rate. HortScience. 50(11):1709–1714. https://doi.org/10.21273/HORTSCI.50.11.1709.

Doan TT, Ngo PT, Rumpel C, Van Nguyen B, Jouquet P. 2013. Interactions between compost, vermicompost and earthworms influence plant growth and yield: A one-year greenhouse experiment. Sci Hortic. 160:148–154. https://doi.org/10.1016/j.scienta.2013.05.042.

Dumas Y, Dadomo M, Di Lucca G, Grolier P. 2003. Effects of environmental factors and agricultural techniques on antioxidantcontent of tomatoes. J Sci Food Agric. 83(5):369–382. https://doi.org/10.1002/jsfa.1370.

Fanasca S, Colla G, Rouphael Y, Saccardo F, Maiani G, Venneria E, Azzini E. 2006. Evolution of nutritional value of two tomato genotypes grown in soilless culture as affected by macrocation proportions. HortScience. 41(7): 1584–1588. https://doi.org/10.21273/HORTSCI.41.7.1584.

Frankenberger WT, Abdelmagid HM. 1985. Kinetic parameters of nitrogen mineralization rates of leguminous crops incorporated into soil. Plant Soil. 87(2):257–271. https://doi.org/10.1007/BF02181865.

Goddek S, Körner O, Keesman KJ, Tester MA, Lefers R, Fleskens L, Joyce A, van Os E, Gross A, Leemans R. 2023. How greenhouse horticulture in arid regions can contribute to climate-resilient and sustainable food security. Glob Food Sec. 38:100701. https://doi.org/10.1016/j.gfs.2023.100701.

Gómez C, Currey CJ, Dickson RW, Kim H-J, Hernández R, Sabeh NC, Raudales RE, Brumfield RG, Laury-Shaw A, Wilke AK, Lopez RG, Burnett SE. 2019. Controlled environment food production for urban agriculture. HortScience. 54(9):1448–1458. https://doi.org/10.21273/HORTSCI14073-19.

Gonçalves MDCR, Diniz MDF, Borba JDC, Nunes XP, Barbosa-Filho JM. 2006. Eggplant (*Solanum melongena* L.): Myth or reality in the fight against dyslipidemia? Rev Bras Farmacogn. 16:252–257.

Grossman RB, Reinsch TG. 2002. Bulk density and linear extensibility, p 201–228. In: Dane JH, Topp GC (eds). Methods of soil analysis: Physical methods. Soil Science Society of America, Madison, WI, USA.

Gu D, Andreev K, Dupre ME. 2021. Major trends in population growth around the world. China CDC Wkly. 3(28):604–613. https://doi.org/10.46234/ccdcw2021.160.

Gül M, Değirmenci N, Şirikçi BS, Kadakoğlu B. 2022. Cost and profitability analysis of greenhouse eggplant production: A case study of Antalya Province, Turkey. Custos e Agronegocio. 18(2):440–457.

Hafeez M, Gulshan AB, Basit A, Chattha ZA, Khan AA, Majeed MA, Tahira F. 2020. Penman and Thornthwaite equations for estimating reference evapotranspiration under semi-arid environment. J Plant Sci. 8(5), 146–151. https://doi.org/10.11648/j.jps.20200805.16.

Hargreaves GH, Samani ZA. 1985. Reference crop evapotranspiration from temperature. Appl Eng Agric. 1(2):96–99. https://doi.org/10.13031/2013.26773.

Heiskanen J. 1995. Water status of sphagnum peat and a peat–perlite mixture in containers subjected to irrigation regimes. HortScience. 30(2):281–284. https://doi.org/10.21273/HORTSCI.30.2.281.

Hurd RG, Graves CJ. 1984. The influence of different temperature patterns having the same integral on the earliness and yield of tomatoes. Acta Hortic. 148:547–554. https://doi.org/10.17660/ActaHortic.1984.148.69.

Ismail MR, Noor KM. 1996. Growth and physiological processes of young starfruit (*Averrhoa carambola* L.) plants under soil flooding. Sci Hortic. 65(4):229–238. https://doi.org/10.1016/0304-4238(96)00897-7.

Ji T, Guo X, Wu F, Wei M, Li J, Ji P, Wang N, Yang F. 2022. Proper irrigation amount for eggplant cultivation in a solar greenhouse improved plant growth, fruit quality and yield by influencing the soil microbial community and rhizosphere environment. Front Microbiol. 13: 981288. https://doi.org/10.3389/fmicb.2022.981288.

Kakahy AN, Alshamary WF. 2020. The effect of drip irrigation, plant spacing and chemical fertilizers on some characteristics of eggplant *Solanum melongena* L. grown inside a greenhouse. IOP Conf Ser Earth Environ Sci. 553(1): 12005.

Karanisa T, Amato A, Richer R, Abdul Majid S, Skelhorn C, Sayadi S. 2021. Agricultural production in Qatar's hot arid climate. Sustainability. 13(7):4059. https://doi.org/10.3390/su13074059.

Kantharajah AS, Golegaonkar PG. 2004. Somatic embryogenesis in eggplant. Sci Hortic. 99(2): 107–117. https://doi.org/10.1016/S0304-4238(03)00090-6.

Karam F, Saliba R, Skaf S, Breidy J, Rouphael Y, Balendonck J. 2011. Yield and water use of eggplants (*Solanum melongena* L.) under full and deficit irrigation regimes. Agric Water Manag. 98(8):1307–1316. https://doi.org/10.1016/j.agwat.2011.03.012.

Katsoulas N, Savvas D, Tsirogiannis I, Merkouris O, Kittas C. 2009. Response of an eggplant crop grown under Mediterranean summer conditions to greenhouse fog cooling. Sci Hortic. 123(1):90–98. https://doi.org/10.1016/j.scienta.2009.08.004.

Kittas C, Tchamitchian M, Katsoulas N, Karaiskou P, Papaioannou CH. 2006. Effect of two UV-absorbing greenhouse-covering films on growth and yield of an eggplant soilless crop. Sci Hortic. 110(1):30–37. https://doi.org/10.1016/j.scienta.2006.06.018.

Kowalska G. 2008. Flowering biology of eggplant and procedures intensifying fruit set–review. Acta Sci Polonorum Hortorum Cultus. 7(4): 63–76.

Kirnak H, Kaya C, Tas I, Higgs D. 2001. The influence of water deficit on vegetative growth, physiology, fruit yield and quality in eggplants. Bulg J Plant Physiol. 27(3–4):34–46.

Körner O, Challa H. 2003. Process-based humidity control regime for greenhouse crops. Comput Electron Agric. 39(3):173–192. https://doi.org/10.1016/S0168-1699(03)00079-6.

Kowalska G. 2003. The effect of pollination method and flower hormonization on yielding of eggplant (*Solanum melongena* L.) grown in a plastic tunnel. Folia Hortic. 15/2:77–87.

Kremelberg D. 2010. Practical statistics: A quick and easy guide to IBM® SPSS® Statistics, STATA, and other statistical software. SAGE Publications, New York, NY, USA.

Kurunç A, Ünlükara A. 2009. Growth, yield, and water use of okra (*Abelmoschus esculentus*) and eggplant (*Solanum melongena*) as influenced by rooting volume. NZ J Crop Hortic Sci. 37(3):201–210.

Li H, Guo Y, Zhao H, Wang Y, Chow D. 2021. Towards automated greenhouse: A state of the art review on greenhouse monitoring methods and technologies based on internet of things. Comput Electron Agric. 191:106558. https://doi.org/10.1016/j.compag.2021.106558.

Lin T, Goldsworthy M, Chavan S, Liang W, Maier C, Ghannoum O, Cazzonelli CI, Tissue DT, Lan Y-C, Sethuvenkatraman S, Lin H, Jia B, Chen Z-H. 2022. A novel cover material improves cooling energy and fertigation efficiency for glasshouse eggplant production. Energy. 251:123871. https://doi.org/10.1016/j.energy.2022.123871.

Lovelli S, Perniola M, Ferrara A, Di Tommaso T. 2007. Yield response factor to water (Ky) and water use efficiency of *Carthamus tinctorius* L. and *Solanum melongena* L. Agric Water Manag. 92(1–2):73–80. https://doi.org/10.1016/j.agwat.2007.05.005.

Maghfoer MD, Soelistyono R, Herlina N. 2015. Growth and yield of eggplant (*Solanum melongena* L.) on various combinations of N-source and number of main branch. Agrivita J Agric

Sci. 36(3):285–294. https://doi.org/10.17503/Agrivita-2014-36-3-285-294.
Manrique LA. 1993. Greenhouse crops: A review. J Plant Nutr. 16(12):2411–2477. https://doi.org/10.1080/01904169309364697.
McNaughton KG, Jarvis PG. 1984. Using the Penman–Monteith equation predictively. Agric Water Manag. 8(1–3):263–278. https://doi.org/10.1016/0378-3774(84)90057-X.
Mishra V, Ambika AK, Asoka A, Aadhar S, Buzan J, Kumar R, Huber M. 2020. Moist heat stress extremes in India enhanced by irrigation. Nat Geosci. 13(11):722–728. https://doi.org/10.1038/s41561-020-00650-8.
Mortensen LM. 1986. Effect of relative humidity on growth and flowering of some greenhouse plants. Sci Hortic. 29(4):301–307. https://doi.org/10.1016/0304-4238(86)90013-0.
Moursy MAM, Kareem NS, A, Mustafa EF, ElFetyany M. 2023. Assessing the application of modern irrigation systems under greenhouse and open field conditions on the productivity of different crops (eggplants case). Alexandria Eng J. 77:435–442. https://doi.org/10.1016/j.aej.2023.07.006.
Navarro AF, Cegarra J, Roig A, Garcia D. 1993. Relationships between organic matter and carbon contents of organic wastes. Bioresour Technol. 44(3):203–207. https://doi.org/10.1016/0960-8524(93)90153-3.
Nguyen GN, Lantzke N, van Burgel A. 2022. Effects of shade nets on microclimatic conditions, growth, fruit yield, and quality of eggplant (*Solanum melongena* L.): A case study in Carnarvon, Western Australia. Horticulturae. 8(8):696. https://doi.org/10.3390/horticulturae8080696.
Okosa I, Ndukwu MC, Horsfall IT, Igbojionu DO. 2022. The combined effect of water management and environmental control on the planting of two varieties of garden egg in a partially shaded greenhouse: An energy and yield indicator analysis. Energy Nexus. 7:100132. https://doi.org/10.1016/j.nexus.2022.100132.
Oliveira AB, Hernandez FFF, de Assis Júnior RN. 2009. Nutrients absorption of eggplant seedlings cultivated in green coconut coir fibre. Rev Caatinga. 22(2):139–143.
Ragaveena S, Shirly Edward A, Surendran U. 2021. Smart controlled environment agriculture methods: A holistic review. Rev Environ Sci Biotechnol. 20(4):887–913. https://doi.org/10.1007/s11157-021-09591-z.
Rajam MV, Kumar SV. 2007. Eggplant, p 201–219. In: Transgenic crops IV. Springer, Berlin, Heidelberg.
Savvas D, Ntatsi G, Passam HC. 2008. Plant nutrition and physiological disorders in greenhouse grown tomato, pepper and eggplant. Eur J Plant Sci Biotechnol. 2(1):45–61.
Sawan ZM. 2018. Climatic variables: Evaporation, sunshine, relative humidity, soil and air temperature and its adverse effects on cotton production. Inf Proc Agric. 5(1):134–148. https://doi.org/10.1016/j.inpa.2017.09.006.
Sun W, Wang D, Wu Z, Zhi J. 1990. Seasonal change of fruit setting in eggplants (*Solanum melongena* L.) caused by different climatic conditions. Sci Hortic. 44(1–2):55–59. https://doi.org/10.1016/0304-4238(90)90016-8.
Taghizadeh-Hesary F, Rasoulinezhad E, Yoshino N. 2019. Energy and food security: Linkages through price volatility. Energy Policy. 128:796–806. https://doi.org/10.1016/j.enpol.2018.12.043.
Uzun S. 2007. Effect of light and temperature on the phenology and maturation of the fruit of eggplant (*Solanum melongena*) grown in greenhouses. NZ J Crop Hortic Sci. 35(1):51–59. https://doi.org/10.1080/01140670709510167.
Williams JD, McCool DK, Reardon CL, Douglas CL, Albrecht SL, Rickman RW. 2013. Root:Shoot ratios and belowground biomass distribution for Pacific Northwest dryland crops. J Soil Water Conserv. 68(5):349–360. https://doi.org/10.2489/jswc.68.5.349.
Wu Y, Yan S, Fan J, Zhang F, Zhao W, Zheng J, Guo J, Xiang Y, Wu L. 2022. Combined effects of irrigation level and fertilization practice on yield, economic benefit and water-nitrogen use efficiency of drip-irrigated greenhouse tomato. Agric Water Manag. 262:107401. https://doi.org/10.1016/j.agwat.2021.107401.
XiaoYing L, ShiRong G, ZhiGang X, XueLei J, Tezuka T. 2011. Regulation of chloroplast ultrastructure, cross-section anatomy of leaves, and morphology of stomata of cherry tomato by different light irradiations of light-emitting diodes. HortScience. 46(2):217–221. https://doi.org/10.21273/HORTSCI.46.2.217.