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LEMON (CITRUS LIMON L.) GROWTH AND DEVELOPMENT UNDER PROTECTED GROUND: THE EFFECTS OF IRRIGATION AND NUTRITION RATES. A THEORETICAL AND COMPARATIVE ANALYSIS

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Abstract
This theoretical and analytical article presents a systematic analysis of research by foreign and domestic scientists on the effects of irrigation regimes and mineral nutrition (NPK) rates on the growth, development, physiological and biochemical processes, and yield of lemon (Citrus limon L.) grown under protected ground conditions (greenhouses and trenches). Based on comparative analysis, it is theoretically substantiated that keeping pre-irrigation soil moisture at 75–80% of field capacity (FC) in the active root zone (0–50 cm) under greenhouse microclimate conditions, combined with drip irrigation and fertigation, saves 30–42% of water compared with traditional methods and increases nitrogen and phosphorus uptake by 25–35%. It is also shown that feeding at N180–200 P120–150 K100–150 kg/ha against a background of 15–20 t/ha of organic fertilizer (well-rotted manure or biohumus) strengthens the photosynthetic activity of trees, increases yield by 20–35% (to 28.0–31.4 t/ha), and improves fruit quality.

Keywords: Lemon, Citrus limon L., protected ground, greenhouse, theoretical analysis, irrigation regime, field capacity (FC), fertigation, organomineral nutrition, NPK, photosynthesis, yield.

Introduction

Under conditions of global climate change, the steady decline of freshwater resources, and intensive use of agricultural land, ensuring the population's year-round supply of vitamin-rich citrus fruits, including lemon products, has become an urgent task. In the subtropical and semi-arid regions of the world, and under protected ground conditions (greenhouses, trenches, lemon houses), obtaining high-quality citrus yields requires scientifically grounded water and nutrition

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regimes that match the physiological requirements of the plant.

Many scientific studies have been carried out on the water and nutrition requirements of lemon. They report different effects of pre-irrigation soil moisture, irrigation methods, and mineral and organic fertilizer rates on plant growth, yield, and fruit quality. However, these results mostly focus on individual factors or on specific regional conditions, and the question of comparing them within a single scientific system has not been sufficiently studied.

In the sharply continental climate of Uzbekistan, lemon is mainly grown in trenches and greenhouses. Experience with water-saving technologies and nutrition rates in modern greenhouses is growing, but local and foreign data in this area have not yet been brought into a single system. This makes it difficult to scientifically substantiate agrotechnical parameters.

Scientific problem of the study: to determine, on a theoretical and comparative basis, the interaction between irrigation regime and mineral and organomineral nutrition rates under protected ground conditions.

Aim of the study: to carry out a theoretical and comparative analysis of the effects of irrigation regimes and nutrition rates on the growth, development, physiological and biochemical processes, and yield of lemon (Citrus limon L.) under protected ground (greenhouse and trench) conditions, and to develop the scientific basis of an optimal water–nutrient regime.

Objectives of the study: (1) to comparatively analyze the optimal limits of pre-irrigation soil moisture for lemon; (2) to evaluate irrigation methods and water use efficiency; (3) to determine the effects of mineral and organomineral nutrition rates on growth, yield, and fruit quality; (4) to substantiate agrotechnical recommendations for greenhouse conditions based on the data obtained.

Object of the study: lemon (Citrus limon L.) grown under protected ground (greenhouse and trench) conditions.

Subject of the study: irrigation regime, water and nutrient rates, and their effects on plant growth, physiological indicators, yield, and fruit quality.

Research method: systematic analysis of available scientific sources, their comparative evaluation, and application of the water use efficiency (WUE) and agronomic nutrient use efficiency (NUE) criteria for fertilizers.

Scientific novelty: scattered data on pre-irrigation moisture limits, drip irrigation, and fertilization rates for lemon were brought into a single system, and for protected ground conditions a range of optimal indicators with a comparative and theoretical basis was determined (pre-irrigation moisture 75–80% of field capacity; N180–200P120–150K100–150 kg/ha).

Practical significance of the study: the results can be used in designing water-saving irrigation and nutrition regimes and in developing agrotechnical recommendations in greenhouse farms and research institutions.

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2. RESEARCH MATERIALS AND ANALYSIS METHODOLOGY

Sources and scope of the research. This theoretical and analytical study comparatively analyzed nearly 100 fundamental and applied scientific sources on lemon irrigation and nutrition in protected and open ground, published between 1981 and 2024. The sources come from research institutions in the world's leading citrus-growing regions (Spain, Italy, USA, Brazil, Israel, China, India, Turkey) and from the CIS and Central Asia (Uzbekistan, Tajikistan, Russia, Georgia, Azerbaijan), including articles indexed in Scopus and Web of Science, monographs, and journals on the Higher Attestation Commission (OAK) list.

Systematic analysis and grouping methodology. In the course of the scientific sources and comparative analysis, the sources were systematized into three main clusters: 1) the effects of pre-irrigation soil moisture limits (% FC) and evapotranspiration levels (% ETc) on lemon physiology; 2) irrigation methods (traditional furrow irrigation, drip irrigation, and fertigation) and water use efficiency (WUE); 3) the effects of mineral (NPK), organomineral, and microelement nutrition rates on tree biometric indicators, yield, and the biochemical composition of fruit (Table 1).

Table 1 Conceptual classification of research on the water–nutrient regime of lemon in protected ground and intensive orchards

Analysis direction	Studied rates and limits	Main evaluation indicators	Key sources (authors and years)
Direction I: Irrigation regime and water balance (FC and ETc)			
Low moisture (water deficit / RDI)	50–65% FC (50–70% ETc)	Leaf water potential (MPa), stomatal conductance, fruitlet drop (%)	Domingo et al. (1996); García-Sánchez et al. (2007); Zaysev and Kozlova (1984)
Optimal differentiated moisture	75–80% FC (80–100% ETc)	Photosynthetic activity, annual shoot growth (cm), productive fruit set (%)	Faxriddinov (1987); Koo (1985); O‘rinboyev and Khakimova (2022); Soliyev and Qosimov (2024)
High (excess) soil moisture	85–90% FC (>100% ETc)	Soil aeration, nitrate leaching (%), root rot diseases	Boboyeva and Maxmadbekov (2017); Paramasivam et al. (2001); Liu et al. (2021)
Direction II: Irrigation technology and mineral nutrition (NPK) system			
Traditional furrow irrigation and dry fertilization	4800–5400 m³/ha of water; N120P90K60 to N180P135K90	Seasonal water consumption (m³/ha), fertilizer uptake coefficient (%)	Mirzayev and Javakyans (2000); Alva et al. (2006); Qodirov and Jo‘rayev (2021)
Drip irrigation and split fertigation	3100–3500 m³/ha of water; N170–200P90–140K110–180	Water productivity (kg/m³), NPK uptake (%), yield (t/ha)	Bar-Yosef (1999); Quiñones et al. (2007); Wu et al. (2020); Xolmirzayev and Abdullayev (2020)
Organomineral system and microelements	15–20 t/ha manure/biohumus + N180–200P140–150K100–120 + Zn, B, Fe	Soil humus (%), leaf area (m²), yield (t/ha), vitamin C (mg/%)	Islamov and Normuratov (2018); Sattarov and Yuldashev (2019); Toshmatov and Karimov (2021)

Note: The table was compiled by systematizing many years of experimental data from foreign and domestic authors.

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Theoretical calculations and comparative evaluation criteria. To compare the results of studies conducted under different soil, climate, and greenhouse conditions, the criteria of water use efficiency (WUE – Water Use Efficiency, kg/m³) and agronomic nutrient use efficiency (NUE – Nutrient Use Efficiency) were used. In particular, the fruit yield obtained per 1 m³ of irrigation water in the greenhouse was evaluated using the following ratio:

WUE = Y / M (kg/m³)

Here: Y – total lemon yield obtained per hectare (kg/ha); M – total amount of irrigation water used during the growing season (m³/ha). Also, relying on the data of R.C.J. Koo [6], K.T. Morgan et al. [7], and M.Z. Faxriddinov [9], it was accepted as the calculation criterion that 75–80% of the active root system of lemon trees is located in the upper 0–50 cm soil layer.

3. THEORETICAL ANALYSIS RESULTS AND DISCUSSION

3.1. Irrigation regimes and the physiological regularities of water consumption. A systematic analysis of the scientific literature shows that lemon, as an evergreen subtropical crop, does not stop vegetation and transpiration throughout the year, and therefore it is very sensitive to changes in soil and air humidity [4, 6, 14]. M.K.V. Carr [14], summarizing international studies, found that the annual evapotranspiration (ETc) of open-field lemon orchards is 850–1200 mm (8500–12000 m³/ha), while in greenhouse conditions, due to limited solar radiation and wind speed, this indicator is about 450–750 mm (4500–7500 m³/ha). According to the studies of M.Z. Faxriddinov [9], V.B. Zaysev and T.A. Kozlova [8], and M.M. Mirzayev [10], in greenhouses of Uzbekistan and Tajikistan, 16–20 irrigations (4500–5200 m³/ha) per season are required with traditional furrow irrigation to keep soil moisture at 75–80% FC. When modern drip irrigation technology is used, seasonal water consumption falls to 3100–3380 m³/ha (by 34–41%) due to reduced physical evaporation and filtration losses, and the fruit yield obtained per 1 m³ of water (WUE) rises from 4.2 kg to 9.1 kg [12, 19].

3.2. The effects of water and nutrition regimes on the growth and biometric indicators of lemon. Analysis of physiological and agrotechnical studies confirms that soil moisture and mineral fertilizer rates directly affect the vegetative growth of trees, leaf area, and the level of productive fruit set (Table 2).

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Table 2 Effects of different irrigation and nutrition regimes on the biometric and physiological indicators of lemon (based on analysis of scientific sources)

No.	Study region and conditions	Irrigation regime	Fertilization rate (kg/ha)	Annual shoot length, cm	Leaf area (cm² or m²/tree)	Productive fruit set / growth effect	Source (author, year)
1	Spain (greenhouse)	60% FC (deficit)	Standard NPK	32.4	Photosynthesis –22%	Increased fruitlet drop	García-Sánchez et al. [4]
2	Spain (greenhouse)	75–80% FC	NPK + 15% K, Ca	45.0	Water storage +14%	Fruit set +18%	García-Sánchez et al. [4]
3	Tajikistan (lemonhouse)	70% FC (control)	N120P90K60	26.2	21.5 cm²	Productive set 4.5%	Maxmadbekov and Gulov [15]
4	Tajikistan (lemonhouse)	80% FC (optimal)	N200P140K100	38.5	28.4 cm²	Shoot growth +46.9%	Maxmadbekov and Gulov [15]
5	Tashkent region (greenhouse)	70% FC (control)	N120P90K60	27.8	18.2 m²/tree	Photosynthesis 4.1 g/m²·day	Zokirov and Rahimov [18]
6	**Tashkent region (greenhouse)**	**80% FC (optimal)**	**N200P150K120**	**40.4**	**24.6 m²/tree**	**Leaf area +35.1% (5.8 g/m²·day)**	**Zokirov and Rahimov [18]**
7	**Fergana region (greenhouse)**	**75–80–70% FC**	**N200P150K120 + 15 t/ha biohumus**	**42.6**	**25.4 m²/tree**	**Productive set 7.5–8.2%**	**Soliyev and Qosimov [20]**
8	**Average optimal rate**	**75–80% FC**	**N180–200P140–150K100–120**	**38.5–42.6**	**24.6–25.4 m²**	**Productive set 7.4–8.2%**	**Generalized indicator**

The comparative data in Table 2 show that in greenhouse conditions, lowering pre-irrigation soil moisture to 60–65% FC causes water deficit stress in the plant. M.F. Ortuño et al. (2006) and F. García-Sánchez et al. [4] found that when soil moisture drops from 80% FC to 55–60% FC, shoot water potential falls from –0.85 MPa to –1.95 MPa, and stomatal conductance and CO_2 assimilation decrease by 22–35%. As a result, annual shoot length decreases from 45.0 cm to 32.4 cm (by 28%), and the physiological drop of fruitlets increases by 35–40% during flowering and fruit set. The same pattern was proven in the studies of Kh.A. Boboyeva and S. Maxmadbekov [16], where soil moisture above 85–90% FC worsened oxygen exchange in soil pores and increased root rot diseases by 15%.

Conversely, keeping soil moisture at 75–80% FC in a regime differentiated by phenological phases and feeding at N180–200P140–150K100–120 kg/ha maximally improves the biometric indicators of trees [15, 18, 20]. In particular, according to X.X. Zokirov and M.M. Rahimov [18] and A.R. Soliyev and D.X. Qosimov [20], under this optimal water–nutrient regime the total leaf area of one lemon tree increases from 18.2 m² to 24.6–25.4 m² (by 35–39%), the net photosynthetic productivity of leaves rises to 5.8 g/m²·day, and the productive fruit set reaches 7.5–8.2%.

3.3. The effects of irrigation and nutrition rates on lemon yield and fruit quality. Literature analysis shows that the ratio of nitrogen, phosphorus, and potassium, and the timing of their application, play a decisive role in obtaining high-quality lemon yields from trees (Table 3).

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Table 3 Effects of irrigation and nutrition (NPK) rates on lemon yield and fruit quality indicators (comparative literature analysis)

No.	Region and lemon variety	Optimal irrigation and nutrition regime	Average fruit weight, g	Yield, t/ha	Increase vs. control	Dry matter (Brix), %	Vitamin C, mg/%	Juice yield, %
1	Brazil (Siciliano)	Optimal moisture + N240P100K180	138.0	48.5	+55.4%	8.9	49.5	51.0
2	Spain (Fino 49)	80% FC (100% ETc) + N200P80K160	130.5	42.5	+22.1%	8.8	54.2	52.0
3	China (greenhouse, Eureka)	80% ETc + N180P90K150 (fertigation)	136.2	38.6	+28.6%	10.4	51.2	50.4
4	Uzbekistan (trench, Meyer)	75–80% FC + N180P120K90 + manure	132.0	26.5	+25.0%	8.4	46.8	48.0
5	Tashkent region (greenhouse, Tashkent)	70–80–70% FC + N200P150K120 + 20 t manure	140.0	28.8	+34.6%	8.8	49.2	50.5
6	**Fergana region (greenhouse, Meyer)**	**80% FC (drip) + N180P140K100**	**141.5**	**29.6**	**+22.3%**	**8.9**	**48.5**	**51.2**
7	**Fergana region (greenhouse, Meyer)**	**75–80–70% FC + N200P150K120 + biohumus**	**144.0**	**31.4**	**+42.7%**	**9.2**	**51.8**	**52.5**
8	Andijan region (greenhouse, Meyer)	75–80% FC (3100 m³/ha) + N180P130K110	139.4	29.8	+26.8%	9.0	50.1	51.0
9	**Optimal range for greenhouses**	**75–80% FC + N180–200P130–150K100–120**	**135–145**	**28.5–31.4**	**+22–42%**	**8.8–9.2**	**48.5–52.0**	**50.5–52.5**

Note: The table was compiled based on the data of Quaggio et al. [2], Domingo et al. [1], Wu et al. [13], Faxriddinov [9], Islamov and Normuratov [11], Xolmirzayev and Abdullayev [12], Ergashev and Khudoyberdiyev [19], and Soliyev and Qosimov [20].

From the analysis of Table 3, it is seen that in the studies of G. Roccuzzo et al. (2012) and E. Primo-Millo and F. Legaz (2020), when 35–40 tonnes of lemon per hectare were obtained, trees took up 165–185 kg of N, 25–30 kg of P, and 145–160 kg of K over the year, and 62% of the potassium was used directly for fruit formation and juice accumulation. A. Quiñones et al. [3] and B. Martínez-Alcántara et al. (2012), in experiments using the ^{15}N isotope, applied nitrogen fertilizers in portions across phenological phases (spring growth, fruitlet formation, and fruit enlargement) with irrigation water, and found that this raised the nitrogen uptake coefficient from 24.5% to 46–48.2% and reduced nitrate leaching by 40–45%.

Under protected soil conditions in Uzbekistan, long-term intensive irrigation in greenhouses leads to soil compaction (bulk density increasing to 1.35–1.38 g/cm³) and a decline in humus content [11, 17]. For this reason, M.A. Sattarov and G. Yuldashev [17], S.Ya. Islamov and I.T. Normuratov [11], B.Kh. Kholmirzayev and R.M. Abdullayev [12], and N.E. Toshmatov and A.A. Karimov [19] concluded that applying mineral fertilizers at N180–200P140–150K100–120 kg/ha together with 15–20 t/ha of well-rotted cattle manure or biohumus, combined with a 75–80% FC irrigation

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regime, gives the greatest effect. In this organomineral system, average fruit weight reaches 138–144 g, yield rises to 28.8–31.4 t/ha, and 22–42% additional yield is obtained compared with control variants. At the same time, Y. Wu et al. [13] and C.E. Kallsen et al. (2011) showed that excessively raising the fertilizer rate to N240–260 kg/ha causes excessive shoot growth, thickening of the fruit peel, and a 6.2% drop in yield, and noted that over-fertilization is not economically or environmentally justified.

4. CONCLUSIONS

1. Theoretical and comparative analysis of foreign and domestic scientific studies shows that, to ensure normal physiological activity and high productivity of lemon (Citrus limon L.) under protected ground (greenhouse) conditions, the most optimal hydrothermal regime is keeping pre-irrigation moisture in the soil layer where active roots are distributed (0–50 cm) at 75–80% FC, differentiated by phenological phases (75–80% FC during flowering and fruit growth, and 65–70% FC during ripening and the winter rest period).

2. Combining drip irrigation with fractional fertilization in greenhouses (feeding fertilizers together with water) allows saving seasonal water consumption by 30–42% compared with traditional furrow irrigation (from 5000–5400 m^3/ha to 3100–3400 m^3/ha), raising water use efficiency (WUE) to 8.5–9.2 kg/m^3, and increasing the uptake coefficient of nitrogen and phosphorus fertilizers by 25–35%.

3. For maintaining soil fertility in greenhouses on irrigated gray and meadow-gray soils of Uzbekistan, and for obtaining high yields (28.5–31.4 t/ha) of the "Meyer" and "Tashkent" lemon varieties, the most scientifically and practically effective agrotechnical measure is applying mineral fertilizer at N180–200P140–150K100–120 kg/ha, divided into 3–4 applications during the growing season, against a background of 15–20 t/ha of organic fertilizer (well-rotted manure or biohumus). Raising the mineral fertilizer rate above N210–240P160K150–200 kg/ha causes excessive vegetative growth of trees and leads to a decline in generative productivity and fruit quality.

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