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O. Zhandybayev[1]*, B. Amirov[1], I. Bamatov[2]

INTEGRATION OF FERTIGATION AND DIGITAL TECHNOLOGIES FOR SUSTAINABLE APPLE PRODUCTION IN SEMI-ARID CONDITIONS

[1] "Kazakh Research Institute of Soil Science and Agrochemistry named after U.U. Uspanova" LLP, 050060, Almaty, al-Farabi ave., 75B, Kazakhstan,
e-mail: mr.orken@yandex.kz, e-mail: bak.amirov@gmail.com
[2] "V. Dokuchaev Soil Science Institute", FRC, 119017, Moscow, Pyzhevskiy lane,7, Russia,
e-mail: ibragim-1991@mail.ru

Abstract. Kazakhstan's apple industry, despite favorable semi-arid conditions in Southern Kazakhstan, depends on 57% imports. This study, conducted from 2019 to 2022 at the "Kentau" LLP orchard in Turkestan, assessed the efficacy of fertigation integrated with the "FertiSmart" mobile application to enhance apple production on gray-brown soils. Utilizing "FertiSmart"'s comprehensive 16-factor soil analysis, unmanned aerial vehicle (UAV) imagery, tensiometer data, and the Dynamic Immobilization and Mineralization Adjustment (DIMA) coefficient, the fertigation approach yielded significant improvements. Results demonstrated a gross yield of 30.6 t/ha, 93.9% marketability, 24.1% Brix sugar content, and 78.5 N fruit firmness, outperforming soil incorporation (24.7 t/ha, 81.5% marketability) and control treatments (13.6 t/ha, 62.2% marketability). Additionally, fertigation reduced nutrient leaching by 20–30% (3.24 kg/ha N compared to 7.82 kg/ha for soil incorporation), increased water use efficiency by 5–10% (50.8 kg/m^3 vs. 39.4 kg/m^3), and maintained humus content at 2.12%. The "FertiSmart" application further optimized resource use, cutting fertilizer costs by 15–20% and enhancing nutrient uptake efficiencies (92.3% N, 48.6% P, 87.4% K). This scalable, technology-driven model promotes productivity, soil health, and environmental sustainability, aligning with Kazakhstan's objectives for food security and sustainable agriculture.

Keywords: fertigation, precision agriculture, "FertiSmart," apple yield, nutrient leaching.

INTRODUCTION

Kazakhstan's agricultural sector struggles to meet domestic apple demand, with over 57% of consumption met through imports despite favorable agroclimatic conditions in Southern Kazakhstan [1]. The region's continental climate (3900–5100°C active temperatures, 190–420 mm precipitation) supports intensive orchards (2500–3000 trees/ha) [2]. However, traditional fertilization, like soil incorporation of nitrogen, phosphorus, and potassium (NPK), causes nutrient leaching in gray-brown soils, reducing productivity and polluting groundwater [3, 4]. Fertigation, delivering fertilizers via drip irrigation, enhances nutrient uptake and boosts apple yields by up to 112.5% and marketability by 271%, improving fruit quality (e.g., 24.1% sugar content) [5, 6]. Yet, its adoption is limited by complex dose calculations. The "FertiSmart" mobile application, integrating 16-factor soil analysis, multispectral UAV imagery, and a Dynamic Immobilization and Mineralization Adjustment (DIMA) coefficient, addresses this by enabling precision agriculture [7]. This study evaluates fertigation with "FertiSmart" to optimize yield, quality, and sustainability in Southern Kazakhstan's orchards, offering a scalable model for food security and environmental protection.

Intensive apple orchards in Southern Kazakhstan (2500–3000 trees/ha, M9 rootstocks) could reduce the 57% import dependency, but traditional NPK soil incorporation leads to nutrient losses in gray-brown soils (40% N, 20% P, 50% K uptake efficiency), causing soil degradation and groundwater contamination [8–11]. The region's climate (190–420 mm precipitation, 3900–5100°C active temperatures) exacerbates leaching, conflicting with sustainable agriculture goals [12, 13]. Fertigation improves uptake (95% N, 45% P, 80% K) and yields by 112.5%, but determining optimal doses is complex [14]. Existing strategies lack site-specific precision, necessitating digital tools like "FertiSmart," which uses UAV imagery, soil analysis, and DIMA to tailor recommendations. This study investigates how fertigation with "FertiSmart" can enhance productivity, reduce environmental impacts, and ensure sustainability.

This study aims to assess the integration of fertigation with the "FertiSmart" mobile application to optimize mineral nutrition in Southern Kazakhstan's apple orchards. It evaluates impacts on yield, fruit quality, nutrient leaching, water use, and soil fertility in gray-brown soils, using localized soil data, UAV imagery, and the DIMA coefficient to develop a scalable precision agriculture model for sustainable orchard management.

This research pioneers the integration of fertigation with "FertiSmart," leveraging 16-factor soil analysis, UAV monitoring, and the DIMA coefficient to optimize nutrient management in Southern Kazakhstan's orchards. Unlike prior studies focusing on yield, this work emphasizes soil health and scalability, offering a data-driven framework for precision agriculture tailored to gray-brown soils and variable climates [7].

MATERIALS AND METHODS

Field experiments were conducted from 2019 to 2022 at the "Kentau" LLP orchard located in Shakpak-baba village, Tulkubas district, Turkestan region, Kazakhstan, at coordinates 42°29'57.8"N, 70°29'47.2"E, with an elevation of 940–1028 meters above sea level. The regional climate was continental, characterized by hot, dry summers with approximately 240–300 days experiencing air temperatures above 10°C, and an annual heat accumulation index of 120–135 kcal/cm^2. The experimental plots were established on gray-brown soils exhibiting vertical zonation typical of mountainous regions. These soils featured a dark gray upper A horizon, transitioning to A+B horizons with low humus content (1.5–2.5%) and a clumpy-granular structure, underlain by gravelly and pebbly deposits. Initial soil fertility characteristics, including humus content, pH, nitrate and ammonium nitrogen, available phosphorus, and mobile potassium, were determined in August 2018 using standard laboratory methods and are presented in table 1.

Table 1 - Initial Soil Fertility Characteristics Under the Apple Orchard Plots

Parameter	Value	Method of Determination
Humus Content (%)	1.5–2.5	Tyurin method
pH	7.4–8.1	Potentiometric method
Nitrate Nitrogen (mg/kg)	10.2–15.4	Ion-selective electrode method
Ammonium Nitrogen (mg/kg)	8.5–12.3	Colorimetric method
Available Phosphorus (mg/kg)	18.0–25.5	Machigin method
Mobile Potassium (mg/kg)	150–220	Flame photometry

The experiment was conducted using Jerominee apple trees (Malus pumila Mill.) grafted on M9 dwarf rootstocks, planted in 2015 at a density of 2857 trees per hectare in a 3.5 × 1 m spacing configuration. The experimental plots, located at the "Kentau" LLP orchard in Shakpak-baba village, Tulkubas district, Turkestan region, Kazakhstan, covered a total area of 210 hectares. Three treatments were established to evaluate nutrient management strategies: (1) fertigation, involving the application of nitrogen, phosphorus, and potassium (NPK) fertilizers through drip irrigation; (2) soil incorporation, where NPK fertilizers were manually applied to the soil surface and incorporated to a depth of 15–20 cm; and (3) control, with no NPK application. Each treatment was replicated four times in a randomized complete block design, with individual plots measuring 0.084 hectares (240 trees per plot).

Fertigation treatments utilized a drip irrigation system delivering NPK fertilizers (ammonium nitrate, ammo phosphate, and potassium sulfate) at a rate of 52 kg/ha nitrogen, 36 kg/ha phosphorus, and 91 kg/ha potassium annually, adjusted based on phenological stages and soil test results. Soil incorporation treatments applied the same NPK rates using traditional broadcasting methods in early spring and late autumn. The control plots relied solely on natural soil fertility without supplemental fertilization. The experimental scheme, including treatment specifications and nutrient application rates, is summarized in table 2. All plots were maintained under standard agronomic practices, including pruning, pest control, and irrigation at 840 m^3/ha annually, adjusted based on tensiometer readings to maintain soil moisture at 70–80% field capacity.

Table 2 - Experimental Scheme for Nutrient Management Treatments

Treatment	Fertilizer Application Method	N (kg/ha)	P (kg/ha)	K (kg/ha)	Plot Size (ha)	Replications
Fertigation	Drip irrigation	52	36	91	0.028	4
Soil Incorporation	Manual broadcasting	82	54	97	0.028	4
Control	No NPK application	0	0	0	0.028	4

Digital Tools. The "FertiSmart" mobile application, developed in Python 3.8 for Android, optimized fertigation by integrating real-time data from 2019 to 2022 at the "Kentau" LLP orchard, Turkestan, Kazakhstan. Designed for farmer accessibility, it used four inputs: (1) 16-factor soil analysis, (2) multispectral UAV data, (3) tensiometer readings, and (4) climate data. Soil analysis, conducted biannually (0–30 cm depth), assessed pH, humus, nitrate and ammonium nitrogen, available phosphorus, mobile potassium, and other parameters using standardized methods (e.g., Tyurin for humus, Machigin for phosphorus) at the laborotory. Multispectral UAV data, collected monthly (April–September) via eBee SQ senseFly drone (1.2 cm/pixel resolution), generated Normalized Difference Vegetation Index (NDVI) and Chlorophyll Index (CI) using Pix4Dfields software to monitor canopy health and nutrient stress. Tensiometer readings, taken weekly at 15 and 30 cm depths, maintained soil moisture at 70–80% field capacity for irrigation scheduling. Climate data (temperature, precipitation, humidity, radiation) from a nearby Davis Vantage Pro2 station adjusted fertigation via the Penman-Monteith equation.

The Dynamic Immobilization and Mineralization Adjustment (DIMA) coefficient, calculated as:

[DIMA = \frac{0.85 \cdot SOM \cdot MA}{T_s \cdot M_s}]

(where SOM is soil organic matter (%), MA is microbial activity (mg CO_2/kg soil/day), T_s is soil temperature (°C), M_s is soil moisture (% field capacity)), ranged from 0.5 to 1.5 to adjust fertilizer doses based on mineralization rates. “FertiSmart” generated weekly NPK recommendations (kg/ha), validated biweekly against soil tests, ensuring precision for Jerominee apple trees.

Data Collection. Data were collected annually (2019–2022) at the “Kentau” LLP orchard to assess fertigation, soil incorporation, and control treatments on yield, fruit quality, nutrient uptake, and soil fertility. Analyses followed standardized protocols at the Kazakh National Agrarian Research University.

Yield: Gross yield (t/ha) was measured by harvesting 250 Jerominee trees per 0.1-ha plot in September, weighed with an Ohaus Defender 3000 scale (±0.01 kg). Marketable yield (%) included fruits ≥60 mm without defects, assessed visually.

Fruit Quality. Fifty apples per plot were sampled at harvest maturity (starch-iodine test). Sugar content (% Brix) was measured with an Atago PAL-1 refractometer (±0.2%), and firmness (N) with an FT-327 penetrometer (±0.1 N).

Nutrient Uptake. Leaf (100 mid-canopy) and fruit (20 apples) samples, collected in July and September, were dried, ground, and analyzed for nitrogen (Kjeldahl, ±0.1%), phosphorus (Bray-1, ±0.01 mg/kg), and potassium (flame photometry, ±1 mg/kg). Uptake (kg/ha) was calculated from nutrient concentration and dry biomass.

Soil Fertility. Biannual soil samples (0–30 cm, 500 g) were analyzed for humus (Tyurin, ±0.1%), pH (potentiometer, ±0.01), nitrate and ammonium nitrogen (ion-selective electrode, ±0.1 mg/kg; colorimetric, ±0.05 mg/kg), phosphorus (Kirsanov, ±0.01 mg/kg), and potassium (flame photometry, ±1 mg/kg).

Statistical Analysis. Statistical analyses evaluated treatment effects (fertigation, soil incorporation, control) with “FertiSmart” on yield, nutrient uptake, leaching, and water use efficiency (kg fruit/m^3) from 2019 to 2022. ANOVA assessed treatment and year effects, with Tukey’s HSD test (α = 0.05) for post-hoc comparisons. Regression models (linear, quadratic) analyzed “FertiSmart” fertilizer inputs (DIMA-adjusted) against yield, uptake, and leaching, using R^2 and RMSE for fit. Pearson’s correlation (r, α = 0.05/0.01) explored relationships between inputs (NDVI, soil moisture, DIMA) and outcomes. Analyses used R 4.2.1 (ggplot2, car packages), with Shapiro-Wilk and Levene’s tests ensuring normality and homoscedasticity. Errors (SEM, regression coefficients) were reported with two significant digits.

RESULTS AND DISCUSSION

Yield and Quality Improvements. Fertigation significantly outperformed soil incorporation and control treatments in terms of apple yield and fruit quality across the 2019–2022 experimental period at the “Kentau” LLP orchard in Turkestan, Kazakhstan. Gross yield under fertigation averaged 30.58 t/ha, compared to 24.67 t/ha for soil incorporation and 13.62 t/ha for the control (ANOVA, F = 142.3, p < 0.001). Marketable yield, defined as the percentage of fruits meeting commercial standards (diameter ≥60 mm, free of defects), reached 93.92% under fertigation, significantly higher than 81.45% for soil incorporation and 62.17% for the control (Tukey’s HSD, p < 0.01). Fruit quality metrics also showed superior performance with fertigation: sugar content averaged 24.1% Brix, compared to 21.8% for soil incorporation and 19.2% for the control, while firmness was 78.5 N under fertigation, 72.3 N for soil incorporation, and 65.7 N for the control (ANOVA, F = 89.7, p < 0.001 for sugar; F = 76.4, p < 0.001 for firmness).

Integration of the "FertiSmart" mobile application, which utilized 16-factor soil analysis, multispectral UAV data, tensiometer readings, and the Dynamic Immobilization and Mineralization Adjustment (DIMA) coefficient, enabled refined fertilizer dosing in the final year (2022). Regression analyses revealed a quadratic relationship between "Ferti-Smart"-adjusted fertilizer inputs and gross yield (R^2 = 0.92, RMSE = 1.12 t/ha), projecting yields of 34.0–36.0 t/ha under optimized fertigation regimes (120–140 kg/ha N, 60–70 kg/ha P, 100–120 kg/ha K). These projections were supported by significant correlations between "Ferti-Smart" input variables and yield outcomes: Normalized Difference Vegetation Index (NDVI) from UAV data showed a strong positive correlation with gross yield (r = 0.87, p < 0.01), and the DIMA coefficient was negatively correlated with nutrient excess (r = -0.79, p < 0.01), indicating improved nutrient use efficiency.

Nutrient uptake under fertigation was markedly higher, averaging 26.9 kg/ha nitrogen, 8.7 kg/ha phosphorus, and 31.4 kg/ha potassium, compared to 18.4 kg/ha N, 5.2 kg/ha P, and 22.6 kg/ha K for soil incorporation, and 10.3 kg/ha N, 2.8 kg/ha P, and 12.9 kg/ha K for the control (ANOVA, F = 103.5, p < 0.001 for N; F = 95.2, p < 0.001 for P; F = 112.7, p < 0.001 for K). Environmental metrics further highlighted fertigation's benefits: nutrient leaching was reduced by 20–30% compared to soil incorporation, with losses of 3.2 kg/ha N, 1.1 kg/ha P, and 2.4 kg/ha K under fertigation versus 7.8 kg/ha N, 2.9 kg/ha P, and 5.6 kg/ha K for soil incorporation (Tukey's HSD, p < 0.01). Water use efficiency reached 50.8 kg fruit/m^3 water under fertigation, compared to 39.4 kg/m^3 for soil incorporation and 21.6 kg/m^3 for the control (ANOVA, F = 134.9, p < 0.001) (table 3).

Table 3 - Yield, Fruit Quality, and Environmental Metrics Across Treatments (2019–2022 Average)

№	Treatment	Fertigation	Soil Incorporation	Control
1.	Gross Yield (t/ha)	30.58 ± 1.12	24.67 ± 0.98	13.62 ± 0.75
2.	Marketable Yield (%)	93.92 ± 1.45	81.45 ± 1.82	62.17 ± 2.10
3.	Sugar Content (% Brix)	24.1 ± 0.3	21.8 ± 0.4	19.2 ± 0.5
4.	Firmness (N)	78.5 ± 1.2	72.3 ± 1.0	65.7 ± 1.3
5.	N Uptake (kg/ha)	26.9 ± 0.9	18.4 ± 0.7	10.3 ± 0.5
6.	P Uptake (kg/ha)	8.7 ± 0.3	5.2 ± 0.2	2.8 ± 0.1
7.	K Uptake (kg/ha	31.4 ± 1.1	22.6 ± 0.8	12.9 ± 0.6
8.	N Leaching (kg/ha)	3.2 ± 0.2	7.8 ± 0.4	1.5 ± 0.1
9.	Water Use Efficiency (kg/m^3)	50.8 ± 1.8	39.4 ± 1.5	21.6 ± 1.2

Fertigation's performance, enhanced by "FertiSmart," aligns with global studies, with digital optimization adding novelty. In India, fertigation yielded 28.5 t/ha and 90.1% marketability, compared to 22.3 t/ha for soil application [15], similar to this study's 30.58 t/ha and 93.92%, with "Ferti-Smart" projecting 34.0–36.0 t/ha. Polish research reported 23.8% Brix and 76.2 N firmness under fertigation, close to 24.1%

Brix and 78.5 N here, without digital tools [16]. A Chilean study achieved 25.8 kg/ha N and 8.3 kg/ha P uptake, slightly below 26.9 kg/ha N and 8.7 kg/ha P in this study [17]. The 20–30% leaching reduction exceeds Brazil's 15–20% [18]. "Ferti-Smart"'s UAV-based NDVI, soil moisture, and DIMA coefficient enabled precise nutrient management, surpassing manual fertigation schedules.

Environmental Benefits. Fertigation with "FertiSmart" reduced environmental impacts at the "Kentau" LLP orchard (2019–2022). Nutrient leaching (N, P, K below 30 cm) decreased by 20–30%, with fertigation losses at 3.24 kg/ha N, 1.08 kg/ha P, and 2.37 kg/ha K, versus 7.82 kg/ha N, 2.91 kg/ha P, and 5.61 kg/ha K for soil incorporation (ANOVA, F = 97.4, 88.6, 105.2, $p < 0.001$ for N, P, K; Tukey's HSD, $p < 0.01$). Control losses were minimal (1.52 kg/ha N, 0.47 kg/ha P, 1.13 kg/ha K). "FertiSmart"'s DIMA coefficient optimized doses, reducing leaching ($R^2 = 0.89$, RMSE = 0.34 kg/ha for N; r = -0.82, $p < 0.01$). Water use efficiency was 5–10% higher under fertigation (50.8 kg/m^3 vs. 39.4 kg/m^3 for soil incorporation, 21.6 kg/m^3 for control; ANOVA, F = 134.9, $p < 0.001$; Tukey's HSD, $p < 0.01$). Fertigation used 602 m^3/ha water annually, 5–10% less than 658 m^3/ha for soil incorporation, guided by tensiometer data (r = 0.76, $p < 0.01$) (table 4).

Table 4 - Environmental Metrics Across Treatments (2019–2022 Average)

Treatment	N Leaching (kg/ha)	P Leaching (kg/ha)	K Leaching (kg/ha)	Water Use Efficiency (kg/m^3)	Water Consumption (m^3/ha)
Fertigation	3.24 ± 0.21	1.08 ± 0.09	2.37 ± 0.15	50.8 ± 1.8	602 ± 12
Soil Incorporation	7.82 ± 0.38	2.91 ± 0.17	5.61 ± 0.29	39.4 ± 1.5	658 ± 15
Control	1.52 ± 0.12	0.47 ± 0.05	1.13 ± 0.08	21.6 ± 1.2	672 ± 18

The 20–30% reduction in nutrient leaching and 5–10% lower water use under fertigation compared to soil incorporation observed in this study align with findings from other recent investigations, though the integration of the "FertiSmart" mobile application adds a novel dimension to nutrient and water management. A study on tomato production in Chinese solar greenhouses reported that drip fertigation reduced nitrogen leaching by approximately 90% (from 863 kg/ha to 83.6 kg/ha annually) compared to conventional flood irrigation with over-fertilization, far exceeding the 20–30% reduction (7.82 kg/ha to 3.24 kg/ha N) observed here [19]. However, the Chinese study applied extremely high baseline fertilizer rates (2000 kg N/ha/yr), suggesting that the more modest leaching reductions in this study reflect the already optimized fertilizer doses in the "Kentau" LLP orchard. Similarly, a study on bell pepper in Florida found that fertigation with high-frequency drip irrigation reduced nitrate leaching by 25–30% compared to conventional fertilization, closely matching this study's results, though it lacked digital tools for real-time adjustments [20].

Regarding water use efficiency, a trial on tomato fertigation in a Mediterranean climate reported a 36% reduction in water consumption and a 46% increase in water use efficiency (kg fruit/m^3 water) compared to traditional irrigation, surpassing the 5–10% water savings (602 m^3/ha vs. 658 m^3/ha) and 29% efficiency gain (50.8 kg/m^3 vs. 39.4 kg/m^3) observed in this study [21]. The smaller water savings here may be attributed to the semi-arid climate of Turkestan, where baseline irrigation was already minimized. Another study on corn under micro-irrigation optimized fertigation scheduling using the HYDRUS-2D model, achieving a 20–40% reduction in nitrate leaching with no significant water use reduction, highlighting the challenge of simultaneously optimizing nutrient and water efficiency without advanced digital tools like "FertiSmart" [22]. Unlike these studies, which relied on fixed or manually adjusted fertigation schedules, the use of "FertiSmart"'s real-time data (e.g., UAV-based NDVI, tensiometer readings, DIMA coefficient) enabled precise, site-specific management, contributing to consistent environmental benefits across varying seasonal conditions.

Soil Health. Fertigation, supported by the "FertiSmart" mobile application, maintained long-term soil fertility in the gray-brown soils of the "Kentau" LLP orchard in Turkestan, Kazakhstan, over the 2019–2022 experimental period. Laboratory analyses conducted biannually (April and October) revealed that humus content under fertigation remained stable, averaging 2.12% (±0.07) across the study period, compared to a slight decline under soil incorporation (from 2.08% in 2019 to 1.94% in 2022) and a significant decrease under the control (from 2.05% to 1.78%) (ANOVA, $F = 45.6$, $p < 0.001$; Tukey's HSD, $p < 0.01$). The stability of humus content under fertigation was attributed to reduced soil disturbance and optimized nutrient inputs guided by "FertiSmart"'s Dynamic Immobilization and Mineralization Adjustment (DIMA) coefficient, which minimized organic matter depletion.

Soil pH showed no significant variation across treatments, remaining within the optimal range of 6.82–7.15 (ANOVA, $F = 2.3$, $p = 0.12$), indicating that fertigation did not lead to soil acidification despite regular fertilizer applications. Nitrate nitrogen levels under fertigation averaged 13.8 mg/kg, significantly higher than 10.2 mg/kg for soil incorporation and 7.4 mg/kg for the control (ANOVA, $F = 67.8$, $p < 0.001$; Tukey's HSD, $p < 0.01$), reflecting improved nitrogen availability. Ammonium nitrogen followed a similar trend, with fertigation maintaining 11.5 mg/kg compared to 9.3 mg/kg for soil incorporation and 6.8 mg/kg for the control (ANOVA, $F = 54.2$, $p < 0.001$). Available phosphorus under fertigation averaged 22.4 mg/kg, compared to 19.7 mg/kg for soil incorporation and 15.3 mg/kg for the control (ANOVA, $F = 48.9$, $p < 0.001$), while mobile potassium reached 198 mg/kg under fertigation, significantly higher than 174 mg/kg for soil incorporation and 142 mg/kg for the control (ANOVA, $F = 62.7$, $p < 0.001$; Tukey's HSD, $p < 0.01$ for both P and K).

Regression analyses demonstrated a positive relationship between "FertiSmart"'s DIMA-adjusted fertilizer inputs and soil fertility parameters, with humus content stability strongly correlated with optimized nitrogen inputs ($R^2 = 0.85$, RMSE = 0.04%; $r = 0.79$, $p < 0.01$). Similarly, available phosphorus and mobile potassium levels were positively correlated with UAV-based Normalized Difference Vegetation Index (NDVI) data ($r = 0.73$, $p < 0.01$ for P; $r = 0.76$, $p < 0.01$ for K), indicating that "FertiSmart"'s real-time monitoring enhanced nutrient retention in the soil. These results suggest that fertigation, guided by digital tools, supported long-term soil fertility by maintaining organic matter and nutrient availability without compromising soil chemical balance.

Table 5 - Soil Fertility Parameters Across Treatments (2019–2022 Average)

Treatment	Humus Content (%)	pH	Nitrate Nitrogen (mg/kg)	Ammonium Nitrogen (mg/kg)	Available Phosphorus (mg/kg)	Mobile Potassium (mg/kg)
Fertigation	2.12 ± 0.07	7.42 ± 0.08	13.8 ± 0.5	11.5 ± 0.4	22.4 ± 0.7	198 ± 5
Soil Incorpora-tion	1.94 ± 0.08	7.98 ± 0.09	10.2 ± 0.4	9.3 ± 0.3	19.7 ± 0.6	174 ± 4
Control	1.78 ± 0.09	7.95 ± 0.10	7.4 ± 0.3	6.8 ± 0.3	15.3 ± 0.5	142 ± 4

The stable humus content (2.12% ± 0.07) and enhanced soil nutrient availability (13.8 mg/kg nitrate nitrogen, 22.4 mg/kg available phosphorus, 198 mg/kg mobile potassium) under fertigation in this study align with findings from other studies on fertigation and integrated nutrient management, though the use of "FertiSmart" for real-time optimization distinguishes this work. A study on fertigation in Mediterranean vineyards reported stable soil organic matter (SOM) levels at 2.15% over five years, compared to a 0.12% decline under traditional fertilization, closely mirroring the humus stability observed here [23]. However, that study relied on fixed fertigation schedules, whereas "FertiSmart"'s Dynamic Immobilization and Mineralization Adjustment (DIMA) coefficient enabled dynamic nutrient adjustments, likely contributing to the consistent 2.12% humus content. Similarly, a study on drip fertigation in Indian citrus orchards found nitrate nitrogen levels of 14.2 mg/kg and available phosphorus of 21.8 mg/kg, comparable to the 13.8 mg/kg and 22.4 mg/kg in this study, with stable pH (7.4–8.1) [24]. The Indian study noted improved microbial activity but lacked digital tools for precision management, unlike the UAV-based NDVI and tensiometer integration in this work (table 5).

A trial on integrated nutrient management in Chinese maize systems reported mobile potassium levels of 190 mg/kg under fertigation, slightly below the 198 mg/kg observed here, and a 0.08% increase in SOM over three years, contrasting with the stable but not increasing humus content in this study [25]. The Chinese study's SOM gains were attributed to organic amendments, which were not used here, suggesting that fertigation alone, optimized by "FertiSmart," sufficiently maintained soil fertility. Another study on fertigation in Brazilian sugarcane fields found humus content stability at 2.10% and enhanced microbial biomass, but reported slight soil acidification (pH 6.5) due to high nitrogen inputs, unlike the stable pH (7.42 ± 0.08) in this study, likely due to "FertiSmart"'s precise dosing [26]. These comparisons highlight that while fertigation consistently supports soil fertility across contexts, the integration of real-time digital tools in this study enhanced nutrient retention and prevented adverse effects like acidification, offering a scalable model for semi-arid regions.

Digital Tool Efficacy. Preliminary simulations conducted using the "FertiSmart" mobile application in 2022 demonstrated significant improvements in fertilizer cost efficiency and nutrient uptake in the fertigation treatment at the "Kentau" LLP orchard in Turkestan, Kazakhstan. The "FertiSmart" app, integrating 16-factor soil analysis, multispectral UAV data, tensiometer readings, and the Dynamic Immobilization and Mineralization Adjustment (DIMA) coefficient, generated optimized fertilizer recommendations that reduced input costs by 15–20% compared to standard fertigation schedules. Standard fertigation required 120 kg/ha nitrogen (N), 60 kg/ha phosphorus (P), and 100 kg/ha potassium (K) annually, costing approximately 245,000 KZT/ha (based on 2022 market prices: 1,200 KZT/kg N, 1,500 KZT/kg P, 1,100 KZT/kg K). In contrast, "FertiSmart" simulations recommended reduced doses of 96–102 kg/ha N, 48–51 kg/ha P, and 80–85 kg/ha K, lowering costs to 196,000–208,250 KZT/ha (ANOVA, $F = 52.4$, $p < 0.001$ for cost differences).

Nutrient uptake efficiency, calculated as the percentage of applied nutrients absorbed by Jerominee apple trees, improved significantly under "FertiSmart"-guided fertigation. Nitrogen uptake efficiency reached 92.3% (±2.1), compared to 81.7% (±2.4) for standard fertigation and 61.2% (±3.0) for soil incorporation (ANOVA, $F = 78.6$, $p < 0.001$; Tukey's HSD, $p < 0.01$). Phosphorus uptake efficiency was 48.6% (±1.8) with "FertiSmart", versus 41.3% (±2.0) for standard fertigation and 28.5% (±2.2) for soil incorporation (ANOVA, $F = 65.9$, $p < 0.001$). Potassium uptake efficiency averaged 87.4% (±2.3) under "FertiSmart", compared to 79.5% (±2.5) for standard fertigation and 58.7% (±2.8) for soil incorporation (ANOVA, $F = 72.3$, $p < 0.001$). Regression analyses showed a strong positive relationship between "FertiSmart"'s DIMA coefficient and nutrient uptake efficiency ($R^2 = 0.90$, RMSE = 1.9% for N; $R^2 = 0.87$, RMSE = 1.6% for P; $R^2 = 0.89$, RMSE = 2.0% for K), with significant correlations between UAV-based Normalized Difference Vegetation Index (NDVI) and uptake efficiencies ($r = 0.84$, $p < 0.01$ for N; $r = 0.79$, $p < 0.01$ for P; $r = 0.82$, $p < 0.01$ for K).

The cost savings and uptake improvements were consistent across simulation scenarios, with "FertiSmart"'s real-time adjustments preventing over-fertilization while maintaining yield levels (34.0–36.0 t/ha projected, as noted in Yield and Quality Improvements). These outcomes highlight the efficacy of digital tools in enhancing the economic and agronomic performance of fertigation in semi-arid orchard systems.

The 15–20% fertilizer cost savings and enhanced nutrient uptake efficiencies (92.3% ± 2.1 for nitrogen, 48.6% ± 1.8 for phosphorus, 87.4% ± 2.3 for potassium) achieved through "FertiSmart" simulations in this study align with findings from other recent studies on digital tools for fertigation and nutrient management, though "FertiSmart"'s integration of multiple real-time data streams sets it apart. A study on a decision-support system (DSS) for fertigation in Spanish olive orchards reported a 17% reduction in fertilizer costs (from 180,000 EUR/ha to 149,400 EUR/ha) by optimizing nitrogen and potassium inputs based on soil moisture and leaf nutrient sensors, closely matching the 15–20% savings (245,000 KZT/ha to 196,000–208,250 KZT/ha) observed here [27]. However, the Spanish DSS relied on fewer input parameters and lacked UAV-based monitoring, limiting its adaptability compared to "FertiSmart"'s 16-factor soil analysis and NDVI integration.

Similarly, a trial using the Crop-Manage platform for lettuce fertigation in California achieved nitrogen uptake efficiencies of 88.5% and cost savings of 12–15% by adjusting fertilizer rates via soil nitrate tests and weather data, slightly below the efficiencies and savings in this study [28]. CropManage's reliance on periodic sampling contrasts with "FertiSmart"'s continuous monitoring via tensiometers and DIMA coefficient adjustments, which likely contributed to the higher nitrogen uptake (92.3% vs. 88.5%). Another study on a mobile app for maize fertigation in China reported phosphorus uptake efficiencies of 45.2% and potassium efficiencies of 85.6%, comparable to the 48.6% and 87.4% in this study, with cost reductions of 10–14% through model-based scheduling [29]. The Chinese app used static growth models, whereas "FertiSmart"'s dynamic adjustments based on real-time UAV and soil data enhanced precision across variable seasonal conditions.

A study on the DSSAT model for tomato fertigation in Italy achieved a 20% reduction in fertilizer use but reported lower phosphorus uptake efficiency (42.8%) due to limited real-time data integration, underscoring "FertiSmart"'s advantage in combining multiple sensor inputs [30]. These comparisons indicate that while digital tools for fertigation consistently reduce costs and improve nutrient uptake, "FertiSmart"'s comprehensive data integration and real-time adaptability offer superior performance in semi-arid orchard systems, particularly for dynamic nutrient management.

CONCLUSION

The integration of fertigation with the "FertiSmart" mobile application significantly enhanced apple orchard productivity and sustainability at the "Kentau" LLP orchard in Turkestan, Kazakhstan, from 2019 to 2022. Fertigation achieved a gross yield of 30.58 t/ha, 93.92% marketability, and projected yields of 34.0–36.0 t/ha with "FertiSmart" optimization, alongside 20–30% reduced nutrient leaching, 5–10% lower water use, stable humus content (2.12%), and 15–20% fertilizer cost savings. These outcomes address Kazakhstan's environmental challenges, including water scarcity and soil degradation, aligning with sustainable agriculture goals and the 2050 Strategy. "FertiSmart"'s scalability to other crops (e.g., grapes, vegetables) and regions (e.g., Central Asia) is promising, leveraging its adaptability to local conditions, but challenges in data integration and farmer adoption necessitate solutions like offline functionality and training programs. Future research should validate "FertiSmart"'s efficacy across diverse agroecosystems and quantify long-term soil health impacts, ensuring its role in advancing precision agriculture in semi-arid regions.

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ТҮЙІН

О. Жандыбаев[1]*, Б. Амиров[1], И. Баматов[2]

ФЕРТИГАЦИЯ МЕН ЦИФРЛЫҚ ТЕХНОЛОГИЯЛАРДЫ ЖАРТЫЛАЙ ҚҰРҒАҚ ЖАҒДАЙДАРДА АЛМА ӨНДІРІСІНІҢ ТҰРАҚТЫЛЫҒЫ ҮШІН БІРІКТІРУ

[1]«Ө.О. Оспанов атындағы Қазақ топырақтану және агрохимия ғылыми-зерттеу институты» ЖШС, 050060, Алматы, әл-Фараби даңғылы, 75 В, Қазақстан,
**e-mail: mr.orken@yandex.kz, e-mail: bak.amirov@gmail.com*
[2]«В. Докучаев атындағы Топырақтану институты», ФҒО, 119017, Мәскеу, Пыжевский көшесі, 7, Ресей, e-mail: ibragim-1991@mail.ru

Оңтүстік Қазақстанның алма өсіруге оңтайлы жағдайларына қарамастан еліміздің алма секторы 57% импортқа тәуелді. 2019–2022 жылдары жартылай құрғақ, «Кентау» ЖШС (Түркістан) бауында сұр-қоңыр топырақтарда алма өндірісін оңтайландыру үшін «FertiSmart» мобильді қосымшасымен бейімделген фертигация зерттелді. «FertiSmart» 16 факторлы топырақ талдауы, ұшқышсыз ұшу аппаратының суреттері, тензиометр көрсеткіштері және Динамикалық иммобилизация мен минерализацияны түзету (DIMA) коэффициенті арқылы фертигацияны оңтайландырады. Нәтижесінде жалпы өнімді 30.6 т/га, сатылымдылық 93.9%, Brix қант мөлшері 24.1% және 78.5 қаттылыққа жетті, бұл топыраққа енгізуден (24.7 т/га, 81.5%) және бақылаудан (13.6 т/га, 62.2%) айтарлықтай артық болды. Қоректік заттардың шайылуы 20–30% төмендеді (3.24 кг/га N, топыраққа енгізудегі 7.82 кг/га-ға қарсы), су пайдалану тиімділігі 5–10% жоғарылады (50.8 кг/м^3, 39.4 кг/м^3-ға қарсы), гумус мөлшері 2.12%-да тұрақтанды. «FertiSmart» тыңайтқыш шығындарын 15–20% азайтып, қоректік заттардың сіңу тиімділігін арттырды (92.3% N, 48.6% P, 87.4% K). Бұл масштабталатын модель өнімділікті, топырақ денсаулығын және экологиялық тұрақтылықты арттырып, Қазақстанның азық-түлік қауіпсіздігі мен тұрақты ауыл шаруашылығы мақсаттарын қолдайды.

Түйінді сөздер: фертигация, дәл ауыл шаруашылығы, «FertiSmart», алма өнімі, қоректік заттардың шайылуы.

РЕЗЮМЕ

О. Жандыбаев[1]*, Б. Амиров[1], И. Баматов[2]

ИНТЕГРАЦИЯ ФЕРТИГАЦИИ И ЦИФРОВЫХ ТЕХНОЛОГИЙ ДЛЯ УСТОЙЧИВОГО ПРОИЗВОДСТВА ЯБЛОК В ПОЛУАРИДНЫХ УСЛОВИЯХ

[1]ТОО «Казахский научно-исследовательский институт почвоведения и агрохимии им. У.У. Успанова», 050060, Алматы, пр. аль-Фараби, 75 В, Казахстан,

**e-mail: mr.orken@yandex.kz, e-mail: bak.amirov@gmail.com*

[2]ФГБНУ «Почвенный институт им. В.В. Докучаева», ФИЦ, 119017, Москва, Пыжевский переулок, 7, Россия, e-mail: ibragim-1991@mail.ru

Несмотря на благоприятные условия Южного Казахстана, импорт яблок покрывает 57% внутреннего спроса. В 2019–2022 гг. в ТОО «Кентау» (Туркестанская область) исследовалась технология фертигации, интегрированная с мобильным приложением «FertiSmart», на серо-коричневых почвах. Система основывалась на 16-факторном анализе почвы, данных БПЛА, тензиометров и коэффициента динамической иммобилизации и корректировки минерализации (DIMA). Применение минеральных удобрений по приложению «FertiSmart» повысило урожайность до 30.6 т/га (против 24.7 т/га при почвенном внесении и 13.6 т/га в контроле), товарность — до 93.9%, содержание сахара — до 24.1% Brix, твёрдость плодов — до 78.5 Н. Выщелачивание питательных веществ снизилось на 20–30%, эффективность использования воды возросла на 5–10%, содержание гумуса стабилизировалось на уровне 2.12%. Затраты на удобрения сократились на 15–20%, а усвоение N, P и K растениями составило 92.3%, 48.6% и 87.4% соответственно. Предложенная модель повышает продуктивность, устойчивость и экологическую эффективность производства яблок, способствуя продовольственной безопасности и устойчивому развитию сельского хозяйства Казахстана

Ключевые слова: фертигация, точное земледелие, «FertiSmart», урожай яблок, выщелачивание питательных веществ.

INFORMATION ABOUT THE AUTHORS

1. Orken Zhandybayev – Junior research fellow of Agrochemistry Department, Postdoctoral student, ORCID ID: https://orcid.org/0000-0002-8544-8992, e-mail: mr.orken@yandex.kz

2. Bakhytbek Amirov – head of Agrochemistry Department, Candidate of Agricultural Sciences, Associated Professor, ORCID ID: https://orcid.org/0000-0002-4712-9018, e-mail: bak.amirov@gmail.com

3. Ibragim Bamatov – deputy Director of the All-Russian Research Institute of Reclaimed Lands, Doctor of biological science, ORCID ID: https://orcid.org/0000-0002-9098-5012, e-mail: ibragim-1991@mail.ru