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Agrochemical Characterization and Nutrient Dynamics in West Kazakhstan Agricultural Soils: Implications for Sustainable Crop Productivity Under Irrigated and Rainfed Systems

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THE PRESENT study aims at analyzing the application of modern tools for nutrient status check of farmlands. The process constituted an automatic sampler, a digital server, and Offline Maps software using geopositioning and geodata files in KML format. Now, following the method, the latest phase will likely have synergy with soil sampling, chemical analysis, statistics in data processing, and digital mapping further allowing modern agrochemical assessments with time and cost reductions. A method of use of the automated sampler was created to investigate the benefits of digital technologies and automation in improving soil agrochemical study efficiency. Thematic digital maps for irrigated and non-irrigated arable soils in Western Kazakhstan were developed to represent the spatial distribution of nitrate nitrogen, available phosphorus and potassium, sulfur content, organic matter, and pH of soils at each sampling point. The carbon content of irrigated plots was very low, situated in the range of 0.93-1.62%. The nitrate Nigeria contents of soils were very low, situated within the range of 1,19-2,82 mg/kg. Available forms of phosphorus also registered low levels within the range of 7.54-11.82 mg/kg, while the available form of potassium registered considerably higher values, within the range of 496.7-751.5 mg/kg. Considerably less carbon content was found in our plots that were not treated with irrigation, ranging between 1.4 and 1.9%. Nitrate nitrogen contents ranged between 0.96 and 6.69 mg/kg, while the amount of available phosphorus was quite low and varied between 3.0 and 6.0 mg/kg. Available potassium levels, however, were extremely high, from 633.8 to 952.9 mg/kg. A strong and statistically significant correlation was identified between carbon and available phosphorus content ($R = 0.83$, $p < 0.05$). Utilization of electronic soil maps per plot allows exact separation for application of fertilization with regard to the content of plant nutrients, organic matter content and pH of the individual plots. Cartograms are the keystone of precision agriculture, laying a solid basis for the resource effective application of fertilizers and higher yields.

Keywords: Digital technologies, Agrochemical analysis, Geodata, Precision agriculture, Fertilizer optimization, Western Kazakhstan.

1. Introduction

In recent years, the overall development of Kazakhstan has decelerated because agricultural development grew slowly. Agricultural crop production has gone down tremendously. This downturn has been partly attributed to the improper application of mineral fertilizers, as recommended usage norms were not followed, leading to a significant reduction in their utilization (Kenzhebekov, et al., 2020).

The Ministry of Agriculture of Kazakhstan reported that the total amount of grain and legume crops sown for harvesting in 2023 was 17.38 million hectares. Soil surveys in 2021 were done by the Committee on Land Resources Management of the Ministry of Agriculture, which revealed approximately 29 million hectares of fertile land in Kazakhstan had degraded (Kozbagarova and Alimzhanov, 2021). In 2023, Kazakhstan experienced a decline in its grain exports, highlighting the pressing need to address soil health and productivity.

To improve crop yields, the implementation of both organic and mineral fertilizers is crucial, as indicated by the results of agrochemical surveys and the analysis of soil nutrient maps. These findings emphasize the importance of aligning fertilization practices with the specific nutrient needs of the soil to ensure sustainable agricultural production (Olsson and Johansson, 2018).

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The United Nations has established 17 Sustainable Development Goals (SDGs), a detailed blueprint for creating a more desirable world society, with the ultimate aim of improving the standard of life for all. Ending poverty and hunger is a high-ranking priority among these goals. Kazakhstan, besides fulfilling its own demand for food grains, also plays a vital role in the global food market by exporting large quantities of grains and value-added agricultural products (FAO, 2021).

The issue of soil fertility restoration has reached the critical stage. To accelerate the field part of agrochemical surveys of arable lands, it is recommended to use a diversity of soil samplers. Soil sampling for agrochemical surveys was previously carried out manually using a hand drill. However, the application of automatic samplers has significantly increased the productivity of operations (Mann and White, 2019).

The key to solving the food program issue is connected with soil fertility. Humus composition, soils' pH, and the content of available forms of nitrogen, phosphorus, potassium, and sulfur determine in a decisive way the yield of crops. Soil formation in western Kazakhstan's dry steppe region is conducted under unfavorable climatic conditions with an annual precipitation of 200- 250 mm on average. Such quantities of precipitation mean that achieving stable and high yields is unlikely. Moreover, soil formation takes place where vegetation is sparse, whose height and density only sometimes exceed 25 to 35 cm. The cover of vegetation covers up to a depth of 60 to 65% in the ground. Plant residue is minimal, leading to the formation of few organic carbon and nutrient components. Chestnut soils predominantly form on loess-like loams (Ivezić, et al., 2022).

Systematic decline of soil carbon stocks in Kazakhstan is primarily driven by existing land use patterns in agriculture. It is not an exclusive case; Australian researchers have also attributed a significant decrease in soil carbon content. It is a common understanding that soil is among the biggest carbons (C) reservoirs in the biosphere of the planet. These small variations in soil carbon stocks can lead to large differences in CO_2 concentrations in the atmosphere and have a quantitatively significant impact on climate systems in the world. Soil carbon loss has been extensively observed in the literature. For instance, studies in Australia have quantified a cumulative loss of approximately 51% of carbon in the soil over more than 40 years in the upper 0.1 meters of soil (Luo et al., 2010).

Soil organic carbon plays a crucial role in soil fertility improvement. Fertilizer application is considered as being among the most significant soil fertility drivers in China. A long-term field experiment was employed to compare five fertilizer application patterns. The findings indicated that OFM (organic fertilizer management) treatment and the combination of chemical fertilizers with bio-organic fertilizers (OFB) were the most excellent, accounting for 84.35% and 81.26% of the variation in soil carbon sequestration, respectively (Yang et al., 2024).

Moreover, nitrogen, phosphorus, and potassium (NPK) treatments had greater performance in enhancing soil carbon sequestration than the farmers' practice (FP) fertilizer regime that is conventionally used by local farmers (Tian, K., et al., 2015).

Organic carbon loss rate also varies depending on the crop. Thai scientists have been found to obtain that SOC loss was greater for maize than in upland rice. SOC stocks declined with increasing years of cultivation in both cropping systems. Significantly, SOC loss rate was always greater for maize cultivation **(**Pansak et.al. (2008).

This accelerated loss in maize fields is attributed to increased soil surface exposure and lower root-derived carbon inputs, which contribute to the rapid depletion of soil organic matter (SOM). The decomposition rate constant (based on first order kinetics) for plant derived SOM was found to be higher in maize fields than in upland rice fields or forest fallow systems. It is hypothesized that these conditions promote faster decomposition of organic matter in maize-dominated systems (Vityakon et al., 2000; Kongchum et al., 2011; Six et al., 2002).

Conversely, SOC stocks were observed to increase with the length of the fallow period, consistent with the slower decomposition of C_4 plant-derived SOM in forest fallow. Continuous maize cultivation was associated with substantial SOM loss, whereas forest fallow and mountain rice systems were shown to mitigate these losses effectively. These results underscore the importance of crop selection and land management practices in maintaining soil carbon levels (Fujii et al., 2021).

The enhancement of soil organic carbon (SOC) stocks in croplands is achievable through the implementation of targeted soil management strategies that not only improve soil fertility but also contribute to climate change mitigation. One such promising approach is the incorporation of cover crops, which has been shown to facilitate SOC sequestration (Seitz et al., 2022; Bruni et al., 2022).

While the processes governing the stabilization and destabilization of soil organic carbon (SOC) have been extensively studied, the determinants of SOC content across various spatial scales remain insufficiently understood. Previous research has established that soil texture and geochemistry significantly influence SOC levels (Six et al., 2002; Kögel-Knabner, 2002).

Several studies have also demonstrated the effectiveness of phosphorus and potassium fertilizers in enhancing alfalfa yields. For instance (Lissbrant et al. 2009). Indicated a remarkable increase in alfalfa biomass upon application of these macronutrients. In another work, United States researchers showed that potassium fertilization notably increased multiple agronomic traits of alfalfa, including shoot biomass, nodule, and rate of net nitrogen fixation. Application of 448 kg/ha of potassium provided a 166% increase in shoot mass per plant in silty loam and 178% increase in sandy soil (Darapuneni et al., 2024).

Although application of phosphorus increased shoot biomass, its effect was less compared to potassium. For example, simultaneous application of phosphorus and sulphur boosted nodule count on sandy but not silty loam soils. Nitrogen fixation activity increased 2.8 times in sandy and 1.7 times in silty loam soil at application 224 kg/ha, whereas the effect in silty loam was dependent on phosphorus. Sulphur alone did not influence shoot biomass but was implicated in increased nodule formation in alfalfa from sandy soils (Collins et al., 1986).

In addition to nutrient management, understanding spatial variability in soil properties is critical for achieving sustainable agricultural production in dryland environments. A study conducted by Iranian researchers focused on the spatial prediction and mapping of key soil attributes soil organic carbon (SOC), particle size distribution (clay, sand, and silt fractions), and calcium carbonate equivalent (CCE) in an arid region of Iran. The study integrated a variety of environmental covariates derived from digital elevation models (DEM) and remote sensing data to develop predictive models using advanced machine learning algorithms, including Cubist, Random Forest, and C5.0 (Copper). Furthermore, synthetic soil images (SySI) were generated by processing multi-temporal Landsat imagery (from satellites 4, 5, 7, and 8) in conjunction with DEM-based bare soil pixel data to enhance spatial resolution and model accuracy (Naimi et al., 2022).

As previously indicated, Kazakhstan holds one of the largest expanses of land resources globally, which necessitates the application of advanced technologies and methodologies for the accurate evaluation of soil cover structure. According to (Bratney et al. 2003), numerous international organizations are actively exploring the integration of innovative information technologies and scientific approaches into soil survey practices. A key advancement in this domain is the adoption of Geographic Information Systems (GIS) for soil resource assessment. This approach facilitates the generation of digital maps representing soil properties and classification, thereby significantly reducing the reliance on extensive field surveys and subsequent laboratory analyses.

The main objectives of this study were to assess the agrochemical properties of soils under potato and barley cultivation in West Kazakhstan, evaluate the availability of key nutrients (N, P, K, S, and organic carbon) in irrigated and non-irrigated soils, identify nutrient deficiencies that limit crop productivity, analyze the impact of irrigation on soil fertility and nutrient dynamics and examine correlations among soil properties to support sustainable nutrient management.

2. Materials and Methods

The study took place during the years 2019 and 2020 within a dry steppe landscape in western Kazakhstan. Chestnut soil represents the predominant zonal soil type in the region. What defines the area is a non-leaching water regime, wherein precipitation is insufficient to percolate through and leach the soil layers. Consequently, soluble salts accumulate along the entire soil profile. Further, their concentration increases with depth. Winter is really cold with temperatures almost dropping to -40°C while summer is quite warm with temperatures soaring to +40°C. Precipitation is low during winter, snowfall being roughly between 15 to 25 cm, whereas summer temperatures are usually above +35°C. Most annual precipitation levels are concentrated in autumn and winter.

In soil sampling through points for agrochemical surveys, the Offline Maps software platform was pertinent. The geospatial data files in Keyhole Markup Language (KML) format were uploaded on a digital server. KML is one of the most accepted formats for visualization of geospatial data in applications such as Google Earth. The offline function allows planning of routes and location identification in the absence of internet, all based on GPS geolocation. Sampling points were georeferenced and visualized on a digital map (Figure 1).

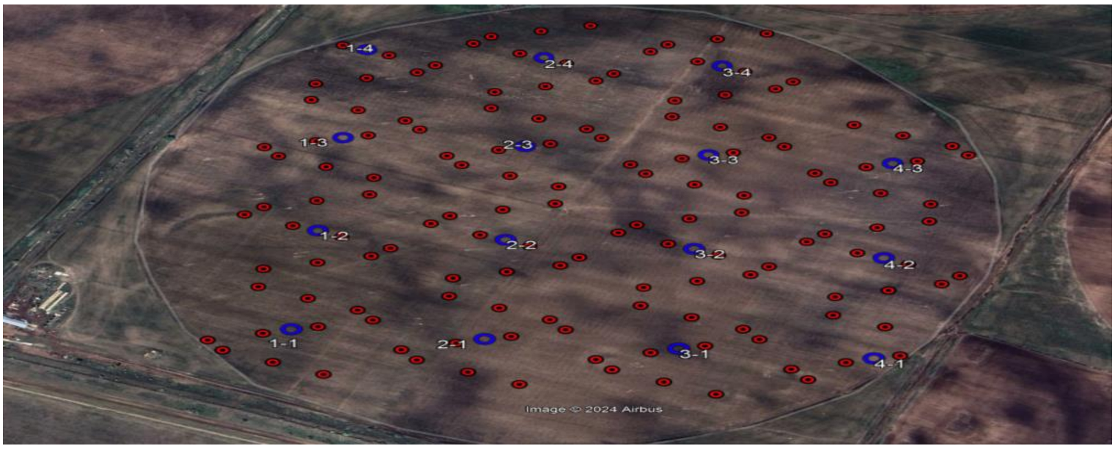

Fig. 1. Spatial distribution of georeferenced soil sampling points visualised using KML-based data in Offline Maps software with GPS-supported positioning.

Downloaded application Offline Maps on the smartphone was used to facilitate georeferenced soil sampling. Each sampling point has a unique identifier and is accurately positioned on the application's interface. After the agrochemical analyses, these points are located, i.e., geotagged on the electronic map, to allow spatial referencing. A available mapping system operates based on the eXtensible Markup Language (XML) standard, which applies a hierarchical tag-based structure of nested elements and associated attributes to encode geospatial information. During the commencement of the field survey, the desired sampling depth is calibrated on the automatic soil sampler; meanwhile, the operator remains inside the vehicle, observing the sampling operation. Samples are collected from 8 to 12 predetermined points along the designated transect. After completing it, the operator leaves the vehicle to collect the sampled soil. The soil is transferred from the sampler's collection box into pre-labelled sampling bags for analysis figure 2 (Chaudhary et al., 2019. and Adamchuk et al., 2004)

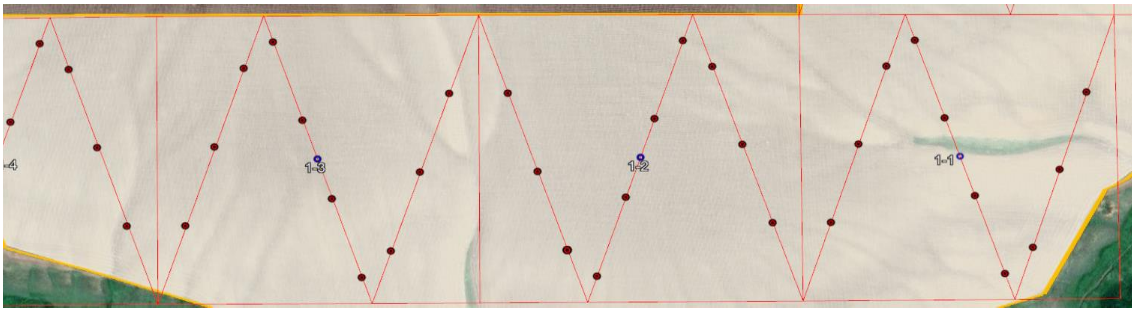

Fig. 2. Soil sampling route as displayed on the digital map using GPS-based geolocation.

Soil sampling for the agrochemical survey was conducted at a depth of 0–20 cm using the Wintex Agro 2000 automated soil sampler figure 3.

Fig. 3. Wintex Agro 2000 automated soil sampler for 0–20 cm sampling.

Operation of the automatic soil sampler greatly improves field efficiency through decreased sample collection time. Specifically, collection of a 20 cm deep soil core at one sampling point ranges from 25 to 30 seconds. Under normal operating conditions, the system enables about 800 to 1,000 hectares per day to be covered with a capacity of collecting 32 to 40 representative soil samples (Wintex Agro; Falcon Soil Technologies).

Agrochemical survey was carried out on non-irrigated and irrigated field pieces. For non-irrigated fields, the sampling field was marked off into 25-hectare square units, while irrigated field pieces were subdivided into 5-hectare units. Each unit consisted of samples obtained by adopting a zigzag sampling pattern for spatial representativeness. A composite sample was made up from each 25 hectares of non-irrigated land and each 5 hectares of irrigated land.

Due to the dry-steppe zone's arid nature, potato cultivation is not feasible without irrigation. Hence, potatoes were cultivated in irrigated land of 80 hectares and barley in non-irrigated land of 375 hectares. 16 samples were collected from irrigated land and 15 from non-irrigated land.

Soil was sampled at 0–20 cm depth for the assessment of available pools of nitrogen (NO_3^-), phosphorus (P), potassium (K), and sulphur (S), soil pH, and carbon (C) content in soil. Approximately 300 grams of soil per sample were sampled, placed in labeled polythene bags, and transported to the laboratory. Samples were air-dried in a ventilated room, sieved, and cleared of plant residues. For organic carbon analysis, the samples were sieved through 1 mm; for all the other parameters, sieving was carried out through 0.25 mm.

Soil pH was determined potentiometrically using a soil-to-water ratio of 1:5, employing a combined glass electrode, according to the protocol of (Van Reeuwijk, 1992). Organic carbon content was determined using the dichromate oxidation method as described by (Walkley and Black, 1934).

Pearson correlation analysis was performed to examine the linear relationships among the measured parameters using STATISTICA software version 10. Statistical significance was assessed at the 0.05 level. Correlation coefficients deemed statistically significant were automatically highlighted in the software interface to facilitate interpretation. For instance, a correlation coefficient of 0.83 was found to be statistically significant at the $p < 0.05$ threshold as showed in table 1 (StatSoft, Inc., 2011)

Table 1. Pearson correlation coefficients among soil chemical properties.

	C	**NO_3**	**Available potassium**
C	1		
NO_3	0.31	1	
Available phosphorus	0.83	0.59	1

To evaluate the strength and direction of the relationships among selected variables, scatter plots were generated using the "Pearson Correlations" dialog within the 2M Scatterplot module in the STATISTICA software (StatSoft, Inc., 2011). Each plot displayed a linear regression line, the associated regression equation, and 95% confidence interval bands. These graphical elements aid in visualizing the linear association and interpreting its statistical significance, figure 4. (Licht, 2014).

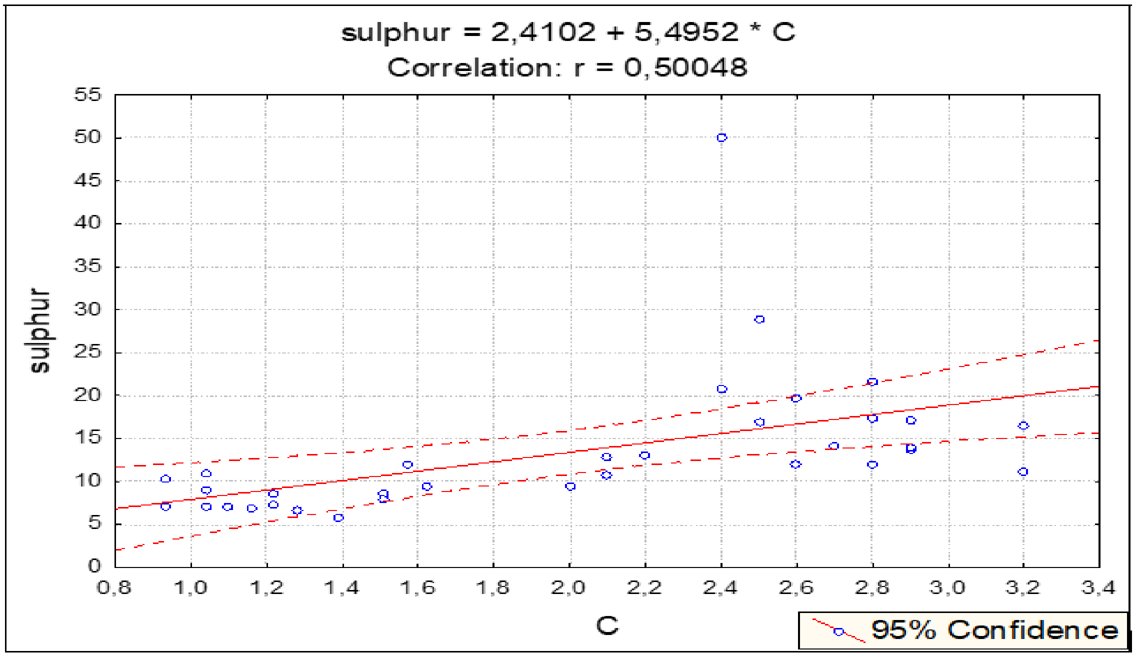

Fig. 4. Regression between soil organic carbon and sulphur.

3. Results

3.1. Soil Characterization

The methodology integrates georeferenced sampling, automated data collection, and digital mapping using KML files and Offline Maps software. This approach enables precise identification of nutrient deficiencies and supports site-specific fertilizer recommendations, which are fundamental principles of precision agriculture.

Typically, alkaline (pH 7.2–7.5), the chestnut soils of West Kazakhstan region Organic carbon content varied from 0.93% to 1.62%; nitrate nitrogen concentrations ranged from 1.19 to 2.82 mg/kg. Available phosphorus concentration ranged from 7.54 to 11.82 mg/kg; available potassium from 496.7 to 751.5 mg/kg. Sulfur levels ranged from 5.8 to 12 mg/kg. Soil pH was also uniformly alkaline (7.4–7.5). Measurements of yields showed higher productivity in the irrigated fields, with more nutrient depletion. Organic matter content was higher in barley fields compared to potato fields.

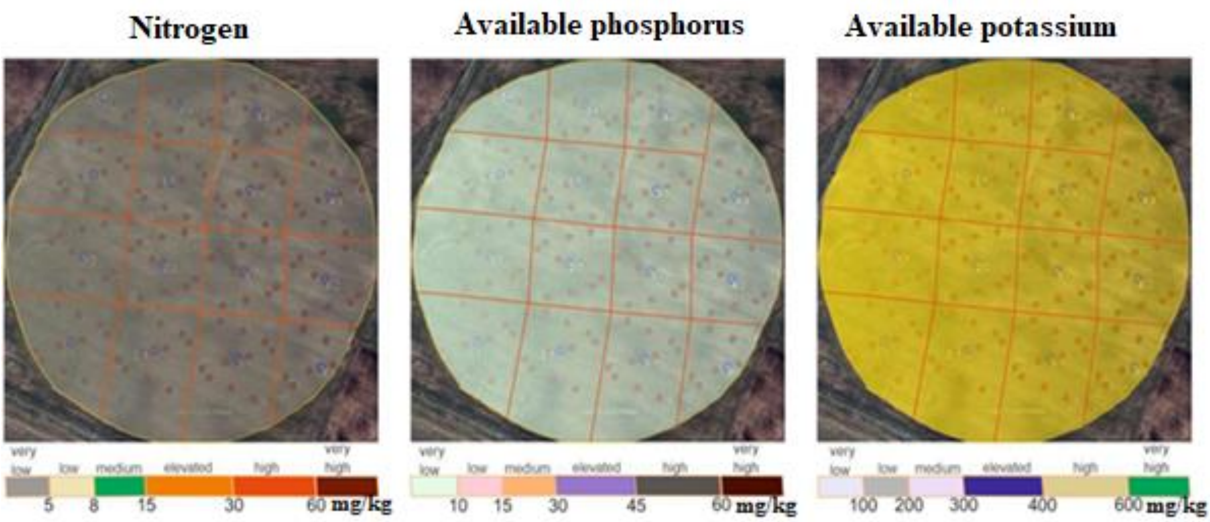

Fig. 5. Nutrient Element Availability in Soils under Potato Cultivation.

Additional samples had organic carbon ranging from 1.4% to 1.9%, nitrate nitrogen ranging from 0.96 to 6.69 mg/kg, available phosphorus ranging from 3.0 to 6.0 mg/kg, and available potassium ranging from 633.8 to 952.9 mg/kg. Sulfur was low (1.1 to 5.0 mg/kg), and soil pH ranged from 7.25 to 8.01. Historical yields for grain crops have stayed below 10 centners/ha and dropped to 2–3 in drought years. However, barley grown after irrigated potato crops yielded 65–70 quintals/ha due to residual moisture.

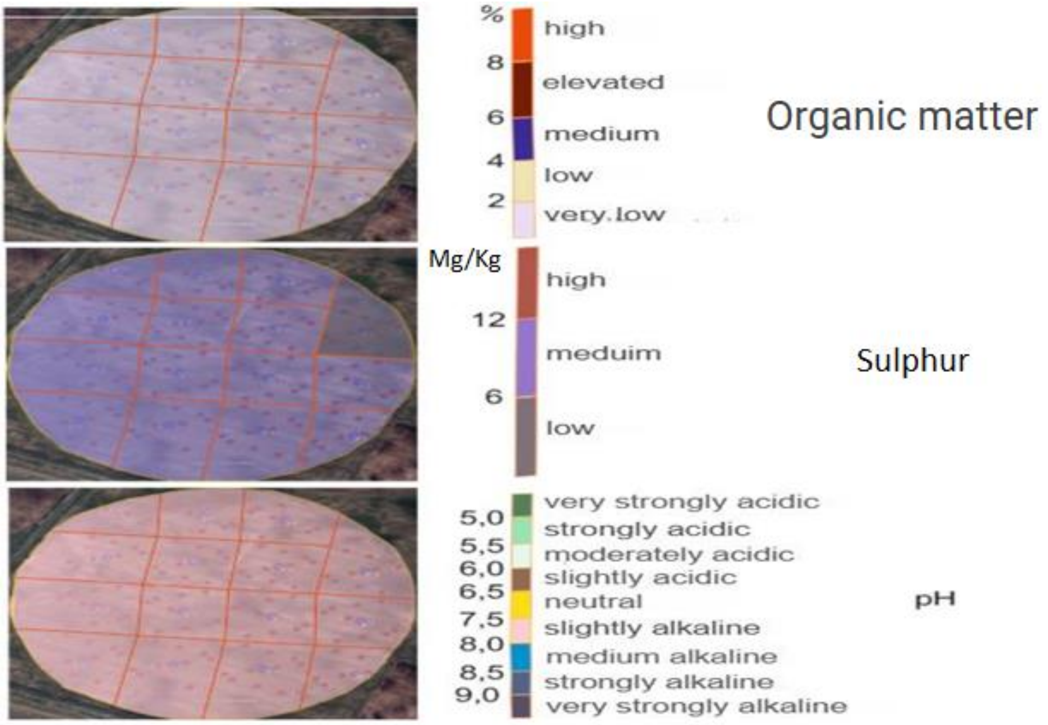

Fig. 6. Organic Carbon, Nutrient Availability, and pH in Soils under Potato Crops.

The low nitrogen, phosphorus, and organic carbon conspicuously measured go well with the dry steppe climatic condition of West Kazakhstan, comprising low rainfall of 200–250 mm a year and sparse vegetation cover. Such restrictive environmental conditions impede nutrient cycling and organic matter deposition, which results in the documented low fertility status. Permitting the agrochemical findings to be interpreted in terms of climatic and environmental characteristics of the environment stresses the importance of the findings to sustainable arid land control.

3.2 Statistical Data

shows descriptive statistics for irrigated soils, with averages and ranges for each agrochemical parameter in table 2 and presents descriptive statistics for non-irrigated soils showed in table 3.

Table 2. Descriptive Statistics of Agrochemical Parameters in Irrigated Soils.

Variables	Average	Fiduciary	Fiduciary	Minimum	Maximum	Standard deviation
C	1.24	1.11	1.37	0.93	1.62	0.23
NO_3	1.71	1.44	1.98	1.19	2.82	0.49
Available phosphorus	9.13	8.30	9.95	7.51	11.82	1,49
Available potassium	602	558	646	496	751.50	79.22
Sulphur	8.29	7.31	9.28	5.80	12.0	1.78
Ph	7.44	7.41	7.47	7.40	7.50	0.05

Table 3. Descriptive Statistics of Agrochemical Parameters in Rainfed Soils.

Variables	Average	Fiduciary	Fiduciary	Minimum	Maximum	Standard deviation
C	1.62	1.53	1.71	1.40	1.90	0.17
NO_3	3.14	2.14	4.13	0.96	6.69	1.80
Available phosphorus	4.13	3.65	4.61	3.00	6.00	0.87
Available potassium	739	684	794	633	952	99.40
Sulphur	1.90	1.36	2.44	1.10	5.00	0.97
pH	7.61	7.50	7.72	7.25	8.01	0.20

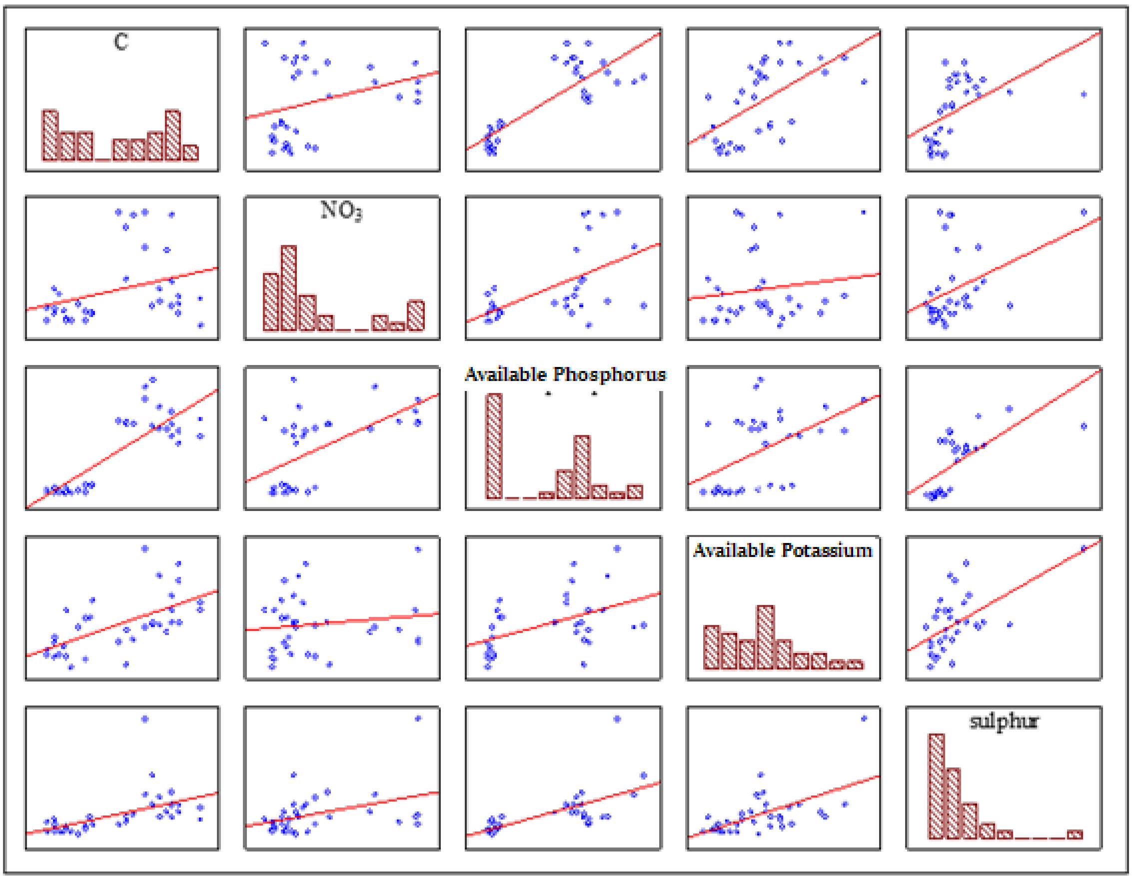

Fig. 7. Correlation Matrix Plot of Agrochemical Soil Properties.

Table 4. Pearson Correlation Matrix.

	C	NO_3	Available phosphorus	Available potassium	Sulphur
C	1				
NO_3	0.31	1			
Available phosphorus	0.83	0.59	1		
Available potassium	0.61	0.14	0.49	1	
Sulphur	0.50	0.40	0.66	0.59	1

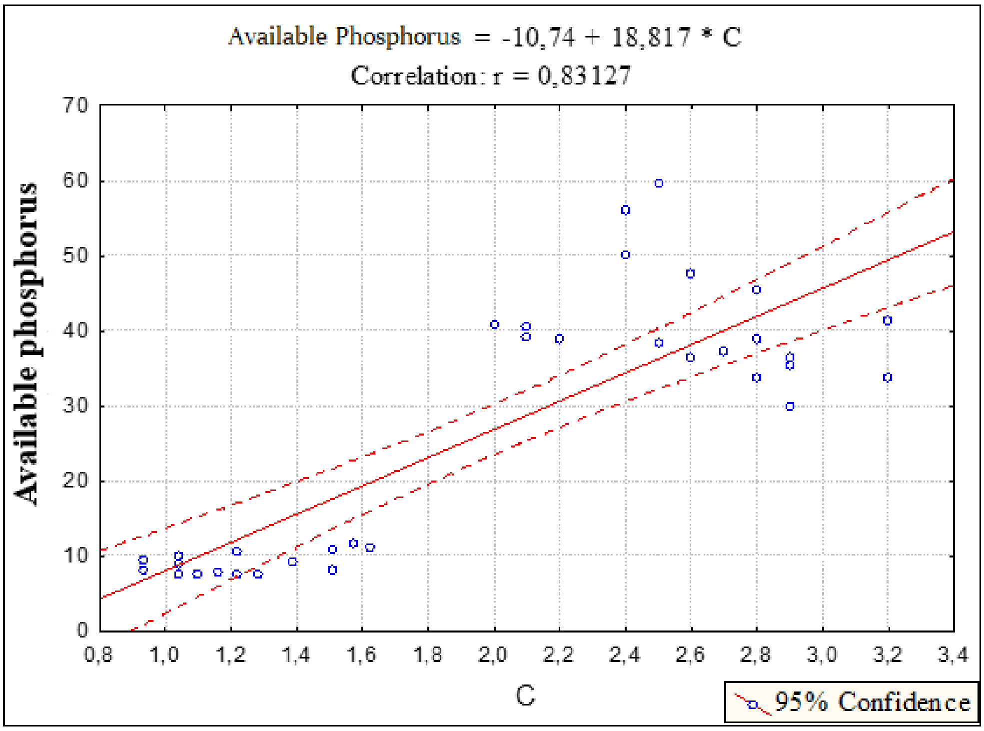

Fig. 8. Scatter Plot and Linear Regression Between Organic Carbon and Available Phosphorus in Soil Samples.

4. Discussion

The agrochemical analysis of the soils of West Kazakhstan was able to demarcate patterns of fertility that differ between irrigated and rainfed agricultural systems. The region, largely comprising alkaline chestnut soils having a pH ranging between 7.2 and 8.01, has the auspices of moderately to highly base saturation mainly due to the presence of exchangeable calcium and magnesium, which favor crop productivity. Alkalinity, therefore, impacts much on the bioavailability of certain micronutrients, most especially iron and manganese, as they tend to precipitate into insoluble hydroxides or oxides at high pH levels (Lindsay and Norvell, 1978; Marschner, 2012). Furthermore, phosphorus availability significantly decreases due to fixation with calcium in form of insoluble phosphate compounds such as hydroxyapatite, especially in case where the soil is poorly buffered (Havlin et al., 2013; Frossard et al., 2000). The problem is compounded by a low OM content (< 2%) in the region generally due to continuous cropping, little stubble retention, and low organic amendments (Buttar et al., 1991a). Concurrently, low OM also functions as a bottleneck for soil fertility by decrease in the activity of soil microbes, thereby limiting nutrient cycling, which secondarily may lead to soil structure deterioration and water retention capacity in the soil (Lal, 2004; Six et al., 2002). Together, these factors emphasize that better soil management practices including application of organic amendments, micronutrient supplementation, pH adjustment operations are necessarily required to improve nutrient availability and to maintain crop productivity in the area.

Clear differences in the content of OC were registered for rainfed and irrigated soils in West Kazakhstan - levels of 1.40% 1.90% (mean -1.62%), and 0.93% - 1.62% (mean 1.24), respectively. This difference is likely due to differences in soil moisture regimes and biotic factors. Lower microbial mineralization rates related to a wetting limitation of soil, limiting microbial turnover in rainfed systems can lead to greater organic matter retention, whereas a reduction in the intensity of leaching may lead to carbon inputs being retained in the soil surface, (Six et al., 2002; Lal, 2004). Conversely, irrigated systems tend to encourage heightened microbial respiration and decomposition of organic matter, especially under warm and wet conditions, resulting in rapid carbon loss (Glenn et al., 1993).

Interestingly, strong positive correlation was also found between OC and available phosphorus (P_2O_5; r = 0.83), indicating that organic matter is vital in maximizing phosphorus bioavailability in alkaline soils through the formation of soluble organic-P complexes and by buffering pH near root zones (Frossard et al., 2000; Stevenson and Cole, 1999). These results emphasize how important organic carbon is for reducing phosphorus fixation in calcareous soils and reinforce the need of organic additions as a strategy to sustain soil fertility under semi-arid circumstances.

Across West Kazakhstan's agricultural soils, nitrogen availability showed significant spatial variation; rainfed soils had a bigger range of nitrate-nitrogen (NO_3^--N) levels (0.96–6.69 mg/kg; mean: 3.14 mg/kg) than irrigated soils (1.19–2.82 mg/kg; mean: 1.71 mg/kg). Dare to compare these more narrowly distributed levels. In rainfed environments, moisture limited microbial activity may explain this variability; hence, nitrification is slowed and residual NO_3^--N buildup in surface horizons is maintained (Campbell et al., 1993; Wang et al., 2014). However, in some rainfed areas with higher NO_3^--N levels, real plant intake is still limited since drought stress impairs root function and restricts nitrogen absorption (Xu and Zhou, 2006). Significantly, mean NO_3^--N levels in both systems fall below agronomic thresholds needed for optimal potato production (usually 150–200 kg N/ha, equivalent to ~5–8 mg/kg NO_3^--N in soil), pointing to a widespread nitrogen deficiency (FAO, 2006; Westermann, 2005). These results highlight the need of site-specific nitrogen management methods that consider both nutrient condition and water availability in order to improve nitrogen use efficiency and crop yield.

Phosphorus and potassium dynamics in West Kazakh soils show different patterns under irrigation and rainfall systems. Available phosphorus (P_2O_5) content remained below agronomic sufficiency levels (<15 mg/kg) at all locations, with irrigated soils having somewhat higher values (7.51–11.82 mg/kg; mean: 9.13 mg/kg) than rainfed soils (3.0–6.0 mg/kg; mean: 4.13 mg/kg). The relatively low phosphorus availability, especially in the rainfed system, corresponds with the phosphorus fixation under alkaline conditions and the absence of conventional phosphorus applications (Havlin et al., 2013; Frossard et al., 2000). Also, in such soils, the low organic matter content limits P mineralization by microbial types of activity and reduces the P solubility. Whereas potassium (K_2O) content was found to be substantially higher in rainfed soil (633.9–52.9 mg/kg; mean: 739.16 mg/kg) when compared to irrigated soil (496.7–751.5 mg/kg; mean: 602.29 mg/kg). Such a variation might be correlated with the higher leaching loss in irrigated soils, mainly those with sandy texture and low CEC, common in semi-arid steppe zones (Sparks, 2003; Brady and Weil, 2016).

Frequent irrigation events help potassium move in such soils, therefore encouraging downward dislocation beyond the root zone. These results highlight the importance of nutrient management plans that are balanced, especially in irrigated systems phosphorus enrichment and potassium conservation.

Sulfur (S) availability in soils of West Kazakhstan ranged widely across agroecosystems, with a significant difference noted in higher concentrations in irrigated soils (5.80–12.00 mg/kg; mean: 8.29 mg/kg) as compared to rainfed soils (1.10–5.00 mg/kg; mean: 1.90 mg/kg). This difference was presumably due to more significant mobilization of sulfur brought on by irrigation apart from other probable sources of sulfur fertilizers and accelerated mineral weathering under moist conditions (Eriksen, 2009; Tisdale et al., 1985). In a rainfed system, limited rainfall coupled with the presence of low organic matter can hamper sulfur mineralization and retention and therefore lessen S availability. In a surprising manner, moderate positive correlations of sulfur with P_2O_5 ($r = 0.66$) and K_2O ($r = 0.59$) suggested the possibility of synergistic associations in nutrient cycling. Sulfur is valuable for phosphorus elemental use efficiency and potassium uptake by certain degrees in the synthesis of sulfur amino acids and nutrient metabolism enzymes (Scherer, 2001; Marschner, 2012). We do want to stress that nitrogen assimilation and protein biosynthesis of crops are maximized by good sulfur levels, so integrating sulfur into the wider nutrient scheme. Such findings demand integrating sulfur diagnostics into fertilizer management strategies particularly under irrigation where sulfur mobility and macronutrient interactions seemingly play key roles in soil fertility.

The contrasting nutrient dynamics between irrigated and rainfed systems in West Kazakhstan highlight the need for system-specific nutrient management approaches. While irrigated agriculture supports higher crop productivity, this comes at the cost of accelerated nutrient depletion, particularly of nitrogen, phosphorus, and potassium, due to increased biomass export and intensified cultivation cycles (Fixen et al., 2015; Cassman et al., 2002). Balanced fertilization to meet site specific crop demand and soil nutrient supply is hence important to sustain yield and prevent long term loss of fertility. This is in contrast to rainfed systems with greater organic carbon (OC) and potassium (K_2O) storage from lower harvest indices, smaller biomass removals, and little external application of inputs. These conditions promote nutrient conservation but often limit productivity potential. Regression analyses from the current study confirmed that OC is a strong predictor of available phosphorus (P_2O_5) availability ($p < 0.01$), underscoring the role of organic matter in enhancing phosphorus bioavailability through chelation, microbial mineralization, and buffering of soil pH (Stevenson and Cole, 1999; Frossard et al., 2000). Therefore, organic matter enrichment via manure application, crop residue retention, or cover cropping emerges as a critical strategy for mitigating phosphorus limitations, particularly in alkaline, low-OM soils typical of the region.

Spatial distribution data showen in maps (Figures 5 and 6) reveal limited variability in nutrient availability throughout the study area. This narrowed range reflects the inherent homogeneity of chestnut soils and the uniform land management currently followed in this region. Although visual backdrops are subtle, statistical tools (e.g., coefficient of variation, spatial autocorrelation) support that under marginal conditions, even small differences in nutrient levels can become agronomically significant.The map legends and color scales have been enhanced to better illustrate these differences. Similar studies conducted in arid and semi-arid regions have reported comparable challenges regarding low nutrient variability and soil fertility constraints. This consistency reinforces the relevance of digital mapping and automated sampling tools for improving nutrient management in such environments.

5. Conclusion and Recommendations

The study accentuates the peculiarities of nutrient stock dynamics, as well as those of soil fertility, in irrigation and rainfed agriculture in Western Kazakhstan. Low organic carbon and phosphorus were reported to be the commonality of both systems, with higher potassium and sulfur contents being manifested in the irrigated soils, probably due to fertilization and irrigation practices. A marked positive correlation was revealed between organic carbon and available phosphorus and confirmed the very important role of organic matter in nutrient availability, mainly in alkaline soils. Addressing the constraints identified above would improve soil fertility in a sustainable manner and would involve strategies adapted to the conditions of each system. In rainfed areas, priority should be given to practices that increase soil organic matter, including incorporation of crop residues, application of organic amendments, and conservation tillage, in order to promote phosphorus bioavailability and nutrient cycling. In irrigated systems, however, these must be complemented by precision nutrient management approaches to maximize fertilizer use efficiencies, preempt nutrient depletion, and minimize nontarget nutrient losses through leaching. The digital soil mapping integrated with automated soil sampling technology as developed in this study comprises a set of promising tools providing an excellent basis for site-specific nutrient assessment and decision-making. Future research should address the long-term monitoring of nutrient dynamics in soils under different management regimes and the development. Additional use of machine learning approaches and synthetic soil images is also recommended for increased mapping accuracy as well as rendering informed agrochemical assessments.

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

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