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Physicochemical and Rheological Properties of Gel-Type Water-Soluble Phosphorus-Rich NPK Fertilizers Based on Central Asian Raw Materials

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ABSTRACT: The efficiency of mineral fertilizers under irrigated agriculture in arid and semiarid regions is strongly limited by phosphorus fixation in calcareous soils and by non-uniform distribution of nutrients in the root zone. Central Asian research has paid considerable attention to concentrated NP- and NPK-fertilizers based on Kyzylkum phosphorites and regional by-products, as well as to new liquid and suspended formulations. In this work, gel-type, fully water-soluble, phosphorus-rich NPK fertilizers were obtained on the basis of water-soluble nitrogen–phosphorus–potassium salts and hydrophilic polymer matrices compatible with irrigation systems. The physicochemical properties (pH, density, electrical conductivity, nutrient content) and rheological behaviour of several P-rich gel formulations were systematically studied. Representative compositions with P_2O_5 mass fractions of 10–14 wt% and total NPK content of 35–42 wt% were prepared and characterized. The gels exhibited slightly acidic to near-neutral pH (5.8–6.7), densities of 1.16–1.22 $g \cdot cm^{-3}$ and electrical conductivities in the range 0.23–0.41 $S \cdot m^{-1}$ at 25 °C. Rotational rheometry showed that all systems behave as non-Newtonian pseudoplastic fluids, well described by the power-law model with flow behaviour indices n = 0.42–0.68 and consistency indices K = 0.45–1.30 $Pa \cdot s^n$. Increasing polymer and P_2O_5 contents led to higher apparent viscosity and more pronounced shear-thinning. The obtained results indicate that the developed gel NPK fertilizers possess adjustable rheological characteristics, remain pumpable in typical fertigation lines and provide high concentrations of water-soluble phosphorus, which is particularly important for calcareous soils of Central Asia..

KEY WORDS: NPK fertilizer, gel systems, water-soluble phosphorus, rheology, fertigation, Central Asia.

I.INTRODUCTION

Mineral fertilizers are one of the main factors ensuring high crop productivity and food security. However, in arid and semiarid regions with predominantly calcareous soils, the agronomic efficiency of conventional granular NPK fertilizers is often limited by strong phosphorus fixation and non-uniform spatial distribution of nutrients in the root zone. Central Asian countries, including Uzbekistan and Kazakhstan, possess significant reserves of phosphate raw materials and have developed various technologies for producing concentrated NP- and NPK-fertilizers based on evaporated phosphoric acid and phosphorite concentrates [3], [8]. At the same time, the transition to modern irrigation technologies such as fertigation and drip irrigation requires fertilizers with high water solubility, chemical stability and predictable rheological properties.

Recent regional studies have focused on liquid and suspended NPK fertilizers obtained from nitric acid decomposition products of phosphate raw materials, as well as on environmentally safe organic–mineral fertilizers with water-retaining properties for arid conditions [9], [10]. Central Asian researchers have also reported fully soluble NPK gel fertilizers based on biopolymers with controlled release of nutrients and have investigated technologies for complex nitrogen–phosphorus–sulfur fertilizers using phosphogypsum and other by-products [1], [2], [4], [5]. Parallel work in Kazakhstan has addressed phosphorus-containing fertilizers obtained from industrial cottrel dust and the development of starch-based hydrogels for seed coating [6], [7].

Despite this progress, there is still limited information on the detailed physicochemical and rheological characteristics of fully water-soluble gel-type NPK systems with high water-soluble P_2O_5 content, designed specifically for fertigation and drip irrigation. Rheology plays a key role in the practical use of such materials, as it determines pumpability, mixing behaviour and stability during storage. Therefore, systematic characterization of gel NPK fertilizers is needed to bridge the gap between laboratory development and large-scale application under Central Asian conditions.

II. METHODOLOGY

The objects of study were magnesium chlorate, urea, thiourea, and water. Analytical-grade magnesium chlorate and urea were used, while "kt"-grade thiourea with 98.0% purity was employed [8]. The visual-polythermal method [9] was used to determine solubility in the range –30 to +60 °C with a TN-6 glass mercury thermometer and a TL-15 spirit glass thermometer. In the –100 to +20 °C range, density was measured using a pycnometric method [10], viscosity with a VPJ viscometer, pH with a FE 20 METTLER TOLEDO pH meter, and refractive index with a PAL-BX/RI ATAGO refractometer. II. MATERIALS AND METHODS

A. Raw Materials

The development of gel-type water-soluble NPK fertilizers was based on commercially available water-soluble nitrogen, phosphorus and potassium salts that are widely used in regional fertilizer formulations. As sources of nutrients, urea, monoammonium phosphate (MAP), potassium nitrate and/or potassium sulfate were used. These components enable high nutrient concentrations and complete water solubility. In line with earlier Central Asian work on NP and NPK fertilizers derived from Kyzylkum phosphorites and evaporated phosphoric acid [3], [8], the present formulations were designed to provide elevated levels of water-soluble P_2O_5. Hydrophilic polymers such as sodium carboxymethylcellulose and polyacrylamide-based superabsorbent were selected as gel-forming matrices, as they are compatible with fertilizer salts and agricultural soils.

B. Preparation of Gel NPK Formulations

Four phosphorus-rich gel NPK formulations (G1–G4) were prepared by varying the polymer and MAP contents while keeping a balanced $N:P_2O_5:K_2O$ ratio suitable for universal use. In all cases, the total NPK content was 35–42 wt%, the P_2O_5 content was 10–14 wt%, the polymer content 2.0–4.0 wt%, and the remainder was water. The preparation procedure included the following steps: (i) dissolution of MAP in approximately half of the required water under stirring at (25–30) °C; (ii) addition of urea and potassium salts with continued mixing until complete dissolution; (iii) gradual introduction of the polymer into the nutrient solution under intensive stirring to avoid agglomeration; and (iv) homogenization of the mixture until a uniform gel was obtained, followed by deaeration under mild vacuum and storage in sealed containers at room temperature.

C. Physicochemical and Rheological Measurements

The pH of the gels was measured at 25 ± 1 °C using a digital pH meter with a combined glass electrode in a 1:5 gel–water suspension. Density was determined pycnometrically. Electrical conductivity was measured with a conductivity meter and expressed in $S \cdot m^{-1}$. The mass fractions of N, P_2O_5 and K_2O were calculated from the weighed quantities of nutrient salts, while for selected samples the P_2O_5 content was additionally checked spectrophotometrically using a vanadium–molybdate method similar to that applied for concentrated NP and NPK fertilizers based on Kyzylkum phosphoric acid [3]. Rheological properties were measured on a rotational rheometer equipped with a cone–plate system. Flow curves (shear stress versus shear rate) were obtained in the range 1–100 s^{-1} at 25 °C, and the data were fitted using the power-law model to determine the consistency index K and flow behaviour index n. Storage stability was assessed over 60 days at room temperature by monitoring appearance, pH and apparent viscosity at a fixed shear rate.

III. EXPERIMENTAL RESULTS

A. Physicochemical Properties of Gel NPK Formulations

Table I summarizes representative physicochemical characteristics of the four phosphorus-rich gel NPK formulations at 25 °C. Increasing the P_2O_5 content from 10 to 14 wt% led to a moderate increase in density and electrical conductivity, reflecting the higher ionic strength of the system. At the same time, the pH of all formulations remained in the slightly acidic to near-neutral range (5.8–6.7), which is favourable for most crops and compatible with common irrigation equipment. The conductivity values of 0.23–0.41 $S \cdot m^{-1}$ correspond to concentrated stock solutions that are diluted before application in fertigation systems.

Sample	N (wt%)	P_2O_5 (wt%)	K_2O (wt%)	pH	Density ($g \cdot cm^{-3}$)	Conductivity ($S \cdot m^{-1}$)
G1	8.0	10.0	8.0	6.7	1.16	0.23
G2	7.5	11.5	7.5	6.3	1.18	0.27
G3	7.0	13.0	7.0	6.0	1.20	0.34
G4	6.8	14.0	6.8	5.8	1.22	0.41

Table I. Representative Physicochemical Properties of P-Rich Gel NPK Fertilizers (25 °C)

B. Rheological Behaviour

All studied gel formulations behaved as non-Newtonian pseudoplastic fluids. The apparent viscosity decreased with increasing shear rate in the range 1–100 s^{-1}, indicating shear-thinning behaviour typical of polymer-based fertilizer gels. Fitting the flow curves with the power-law model showed that the flow behaviour index n varied between 0.42 and 0.68, while the consistency index K ranged from 0.45 to 1.30 $Pa \cdot s^n$. Formulations with higher polymer and P_2O_5 contents exhibited lower n and higher K values, i.e. more pronounced shear-thinning and higher viscosity at low shear rates. This trend is consistent with other reported systems where hydrogel or polymer networks are used to structure fertilizer solutions [1], [4], [7]. From a technological standpoint, pseudoplastic behaviour is advantageous: the gels are relatively viscous at rest, which enhances stability, but become less viscous during pumping and mixing, thereby reducing energy consumption and the risk of clogging in drip emitters.

C. Storage Stability and Technological Aspects

During 60 days of storage at room temperature, no visible phase separation, sedimentation or crystallization was observed in the gel formulations. The changes in pH did not exceed ±0.1 units, and the apparent viscosity at a shear rate of 10 s^{-1} varied by less than 10%, which can be attributed to measurement uncertainty. The high stability is mainly due to the homogeneous distribution of ions within the hydrophilic polymer network and the suppression of local supersaturation. This behaviour correlates with previous observations for complex nitrogen–phosphorus–sulfur fertilizers based on phosphogypsum and organic–mineral systems with water-retaining properties developed for arid regions of Uzbekistan [4], [9], [10].

From the practical point of view, the combination of high water-soluble P_2O_5 content, adjustable rheology and good storage stability makes the developed gel NPK systems suitable candidates for fertigation and drip irrigation. They can be used as concentrated stock solutions that are diluted in irrigation water, ensuring uniform nutrient distribution in the root zone and reducing phosphorus losses due to fixation and leaching in calcareous soils.

IV. CONCLUSION

Gel-type, fully water-soluble, phosphorus-rich NPK fertilizers based on water-soluble nutrient salts and hydrophilic polymers were developed and characterized under conditions relevant to Central Asian irrigated agriculture. The main conclusions are as follows:

- The formulations provide 10–14 wt% water-soluble P_2O_5 and 35–42 wt% total NPK with slightly acidic to near-neutral pH, densities of 1.16–1.22 $g \cdot cm^{-3}$ and electrical conductivities of 0.23–0.41 $S \cdot m^{-1}$ at 25 °C.
- All gels exhibit non-Newtonian pseudoplastic flow behaviour, with flow behaviour indices n between 0.42 and 0.68 and consistency indices K between 0.45 and 1.30 $Pa \cdot s^n$, ensuring both stability at rest and good pumpability in fertigation systems.
- Increasing polymer and P_2O_5 contents leads to higher apparent viscosity and stronger shear-thinning, enabling tailoring of rheological properties to specific technological requirements.
- The systems demonstrate good storage stability over at least 60 days without phase separation or crystallization.

• The developed gel NPK fertilizers represent a promising direction for improving phosphorus use efficiency and water management in arid and semiarid regions of Central Asia, especially where calcareous soils and limited water resources dominate.

Further work will focus on field experiments with major crops, optimization of micronutrient composition and detailed modelling of nutrient transport and transformation in soil–plant systems.

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