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ORIGINAL PAPER

Sheep Wool-Derived Organomineral Fertilizer: Main and Residual Effects in Maize-Maize and Sunflower-Maize Systems

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Abstract
The low efficiency of fertilizer utilization has resulted in resource waste and environmental pollution, therefore, developing effective alternative organomineral fertilizers (OF) has become essential. Waste sheep wool (SW) was used as an organic material to develop an OF, and its effects on plants and soil were compared with diammonium phosphate (DAP). Sheep wool was first hydrolyzed with KOH, and the hydrolysate was then neutralized with H_3PO_4 to obtain an OF (W-NPK). Before the experiment, W-NPK was characterized using Scanning electron microscope (SEM), Fourier Transform Infrared (FTIR) spectroscopy, and X-ray diffraction (XRD) techniques. Maize and sunflower plants were grown under four treatments: control, DAP, W-NPK, and a half dose of W-NPK. To determine the residual effects, maize was then grown in the same pots without further fertilization. W-NPK showed a heterogeneous structure, containing both granular and crystalline inorganic particles within an organic matrix. Fourier Transform Infrared spectroscopy and XRD analyses confirmed distinct functional groups and crystalline phases. Across all cropping cycles, W-NPK at both doses performed as well as or better than DAP in increasing plant dry weight. Residual effect of W-NPK was especially clear in the second maize, where it outperformed DAP. Although N and K concentrations decreased due to dilution effect, N, P, and K uptake increased under all fertilizer treatments. W-NPK resulted in higher P concentration and higher K uptake than DAP. Soils treated with W-NPK showed higher N, plant available P and K in most cases. W-NPK is a sustainable and efficient alternative to conventional chemical fertilizers.

Keywords Circular economy · Waste management · Organomineral fertilizers · Keratin · Maize · Sunflower

1 Introduction

The rapid growth of the global population and increasing pressure on agricultural production systems have intensified the need for sustainable, resource efficient fertilization strategies. Conventional nitrogen (N) and phosphorus (P) fertilizers, such as diammonium phosphate (DAP), are widely used to support crop productivity; however, their production relies heavily on non-renewable mineral resources, high energy inputs, and imported raw materials (Chojnacka et al. 2020; Manning 2018). Moreover, the agronomic efficiency of chemical fertilizers is often low, commonly below 50% (Fixen et al. 2015; Barlog 2023; Singh et al. 2025), meaning that a substantial portion of applied nutrients is not taken up by plants but lost through leaching, fixation, volatilization, or runoff. These inefficiencies not only reduce fertilizer use efficiency but also contribute to environmental problems, including nutrient leaching, greenhouse gas emissions, and long-term soil degradation (Abay et al. 2025). Consequently, there is growing interest in developing alternative fertilizers derived from renewable, locally available waste materials, aligning with circular economy principles.

Among organic wastes, sheep wool (SW) is produced in substantial quantities worldwide, with global raw wool production estimated at approximately 1–2 million tons per year. Despite this large volume, a significant portion of wool is not used in high-value textile applications. Mixed or low-quality wool often becomes waste or is discarded due to processing difficulties and limited market demand (Akca et al. 2023; Taskin 2024; Camilli et al. 2025;

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Szczecina et al. 2025). Consequently, large amounts of SW from small ruminant production are annually discarded because of low commercial value, contamination, and industrial limitations (Midolo et al. 2024; Camilli et al. 2025). This underlines the considerable potential of SW as a resource for alternative valorization strategies, such as organomineral fertilizer (OF) production, within a circular economy framework.

Agronomically, SW is a promising raw material because of its high keratin content, which contains substantial N in the form of amino acids such as cysteine, methionine, lysine, and arginine (Petek and Marinšek Logar 2021; Akca et al. 2023). However, natural SW degradation is extremely slow due to disulfide bonds and high structural stability, limiting its direct use as a fertilizer (Broda et al. 2016; Rom et al. 2024; Sahin et al. 2025a). To overcome these limitations, chemical hydrolysis particularly alkaline hydrolysis has emerged as an efficient method to break down the keratin matrix and convert wool into plant-available N (Colla et al. 2014; Sahin et al. 2025b). Alkaline hydrolysis using KOH not only solubilizes keratin but also introduces potassium (K) ions into the solution, enabling the formation of K-containing organic complexes. Subsequent acid neutralization with H_3PO_4 facilitates P incorporation, producing an organomineral composite containing N, P, and K. This strategy is particularly valuable given the low efficiency of conventional fertilizers: by combining organic matrices with mineral nutrients, fertilizers with higher nutrient-use efficiency, improved soil retention, and reduced nutrient losses can be developed.

Organomineral fertilizers derived from waste biomaterials offer several advantages over conventional mineral fertilizers. They provide a more gradual nutrient release pattern, contribute organic carbon to the soil, enhance microbial activity, and improve nutrient retention due to the presence of organic functional groups (Liu et al. 2024; Uddin et al. 2025). Moreover, combining organic and mineral nutrient sources can enhance soil cation exchange capacity, increase P availability through organic–inorganic interactions, and reduce nutrient losses via leaching. Such fertilizers are increasingly recognized as effective tools to improve soil fertility while reducing the environmental footprint of agricultural inputs.

In this study, waste SW was hydrolyzed with KOH and subsequently neutralized with H_3PO_4 to produce a nutrient-rich OF containing N, P, and K. This approach valorizes an abundant agricultural waste while producing a fertilizer consistent with circular economy and sustainable nutrient management principles. The research hypothesis of this study is that hydrolyzed and phosphoric acid neutralized SW (W-NPK) can act as an effective OF, providing both immediate and residual nutrient supply to crops, with performance comparable to conventional DAP fertilizer, even at reduced application rates. Greenhouse experiments were conducted using maize and sunflower as representative crops. The fertilizer was applied at nutrient levels equivalent to DAP (matched for P) as well as at half-dose applications, allowing direct comparison with a chemical fertilizer. After the initial cropping cycle, a second maize crop was grown without additional fertilization to evaluate residual effects. Plant N, P, and K uptake were measured for each crop, and soil chemical properties including pH, electrical conductivity (EC), total N, and available P and K were determined after both harvests to assess changes in nutrient dynamics. By integrating plant responses with soil chemistry data, this study provides a comprehensive evaluation of both immediate and residual fertilization effects of the newly developed organomineral product.

2 Materials and Methods

2.1 Preparation and Characterization of W-NPK

The SW used in our study was sourced from a specialized livestock farm. It was first washed and then dried in a thermoventilated oven at 65 °C. A 200 g portion of SW was weighed and mixed with 500 mL of 2 N KOH, and the mixture was allowed to react for 30 min. The mixture was then autoclaved for 90 min at 125 °C under 1 bar pressure. After cooling to room temperature, the solution was combined with 500 mL of 4 N H_3PO_4 (85%, d = 1.71 g cm^{-3}) to enrich it with P. Finally, the resulting mixture was dried in a thermoventilated oven at 65 °C and ground into a powder for subsequent analyses and experimental use. The total N concentration of the W-NPK fertilizer was determined following Bremner (1965), while total P, K, Ca, Mg, Fe, Zn, Cu and Mn concentrations were measured using ICP-OES according to Temminghoff and Houba (2004). The total organic carbon (TOC) content of SW and W-NPK was estimated from the loss-on-ignition (LOI) at 550 °C, and the obtained value was divided by 2.24 to calculate the organic carbon content, based on the assumption that soil organic matter contains approximately 58% organic carbon (Van Bemmelen factor) (Nelson and Sommers 1996). Selected chemical and physical properties of SW and W-NPK are presented in Table 1. The surface morphology of W-NPK was examined using a Zeiss Evo40 scanning electron microscope (SEM) operating at 20 keV. Structural analysis was performed by powder X-ray diffraction (XRD) using Cu-Kα radiation (λ = 0.15406 nm) on an EQUINOX X-ray

diffractometer. XRD patterns were recorded at ambient temperature with a scan step of 0.02° over a 2θ range of 10–60°. Functional groups of W-NPK were characterized by Fourier transform infrared (FTIR) spectroscopy. FTIR spectra were collected over the 4000–500 cm^{-1} range using a Shimadzu Infinity FTIR spectrometer equipped with three reflective ATR units. SEM, XRD, and FTIR analyses were conducted at the Earth Sciences Application and Research Centre (YEBIM) of Ankara University.

2.2 Experimental Design and Treatments

In this experiment, the effects of the organomineral fertilizer W-NPK on the dry weight, as well as N, P and K concentrations and uptake of sequentially grown maize-maize plants following maize and sunflower were investigated. For this purpose, plants were cultivated in plastic pots (16 cm depth, 18 cm top diameter, and 12 cm bottom diameter) which contains 2 kg soil from the plow layer of the experimental field at the Department of Field Crops, Ankara University (39°57′53″ N, 32°51′31″ E; altitude 846 m). The main properties of the soil were determined according to Page and Keeney (1982), and the results are presented in Table 1. The study was conducted under naturally illuminated greenhouse conditions at the Department of Soil Science and Plant Nutrition, Ankara University (39°57′47″ N, 32°51′48″ E; altitude 849 m). The first experiment (maize-sunflower) was carried out between April 30 and July 5, 2024. and the second experiment (maize-maize) between July 12 and September 7, 2024. The maize-maize and sunflower-maize sequences were selected to evaluate both continuous and rotational cropping systems. Maize-maize represents a continuous cereal system to assess the residual nutrient availability of W-NPK, while sunflower-maize allows assessment of fertilizer effects on maize following a broadleaf crop with different nutrient dynamics. The treatments applied were: (i) control (no P), (ii) 100 mg P kg^{-1} from DAP (18–46–0), (iii) 100 mg P kg^{-1} from W-NPK (4.83–15.2–16.6), and (iv) 50 mg P kg^{-1} from W-NPK (4.83–15.2–16.6). All fertilizers were thoroughly mixed with the soil, and 10 seeds of maize (*Zea mays* L. cv. Pioneer P0900) or sunflower (*Helianthus annuus* L. cv. 361 Thype) were sown per pot. After emergence, plants were thinned to 3 per pot. One month after emergence, 100 mg N kg^{-1} was applied to all pots as top-dressing using ammonium nitrate (33% N). At the end of the 10-week growing period, first plants were harvested and no basal fertilizer applied to pots for second crops. Second experiment (maize-maize) was carried out between July 12 and September 7, 2024 at the same pots and one month after emergence only top-dressing fertilizer (100 mg kg^{-1} N, ammonium nitrate 33% N) applied to related pots. Nutrient balance table showing total N, P and K inputs per treatment (Table 2). During the experiments, pots were weighed daily, and tap water was added to maintain 70% of field capacity. At the end of each experiment, harvested plants dried in a thermoventilated oven at 65 °C until moisture was completely removed, and their dry weights were recorded. All plant samples were then ground to a fine powder (200 µm) for subsequent chemical analyses.

Table 1 Some physical and chemical properties of the experimental soil, sheep wool (SW) and organomineral fertilizer produced from chemically hydrolyzed and phosphoric-acid-neutralized wool (W-NPK)

Properties (Method)	Soil	SW	W-NPK
Texture (Bouyoucos)	SCL	-	-
$CaCO_3$ (Scheibler), g kg^{-1}	74.1	-	-
pH (1:2.5 water/1:5 water)	7.88	9.55	6.04
EC (1:2.5 water/1:5 water), mS cm^{-1}	0.38	13.7	41.6
Organic matter (Walkley-Black/Weight loss), g kg^{-1}	10.5	827	529
Organic carbon, g kg^{-1}	-	369	236
C/N	-	3.76	4.89
Total-N (Kjeldahl), g kg^{-1}	0.60	98.0	48.3
P ($NaHCO_3$-extractable), mg kg^{-1}	7.77	-	-
Total-P (ICP-OES), g kg^{-1}	-	1.30	66.4
K (NH_4OAc-extractable), mg kg^{-1}	178	-	-
Total-K (ICP-OES), g kg^{-1}	-	54.0	137
Ca (NH_4OAc-extractable) mg kg^{-1}	4900	-	-
Total-Ca (ICP-OES), g kg^{-1}	-	16.8	5.10
Mg (NH_4OAc-extractable), mg kg^{-1}	500	-	-
Total-Mg (ICP-OES), g kg^{-1}	-	3.70	1.10
Zn (DTPA-extractable), mg kg^{-1}	0.54		-
Total-Zn (ICP-OES), mg kg^{-1}	-	118	35.9
Fe (DTPA-extractable), mg kg^{-1}	4.39	-	-
Total-Fe (ICP-OES), mg kg^{-1}	-	4241	1289
Cu (DTPA-extractable), mg kg^{-1}	1.75	-	-
Total-Cu (ICP-OES), mg kg^{-1}	-	14.6	4.44
Mn (DTPA-extractable), mg kg^{-1}	3.09	-	-
Total-Mn (ICP-OES), mg kg^{-1}	-	117	35.6

Table 2 Nutrient balance table used in the experiments depending on treatments for first and second crops

Crops	Treatments	Basal Fertilizers			Top-Dressing Fertlizers
		N mg kg^{-1}	P mg kg^{-1}	K mg kg^{-1}	N mg kg^{-1}
First Crops	Control	0	0	0	100
	DAP	89	100	0	100
	W-NPK	72	100	206	100
	½ W-NPK	36	50	108	100
Second Crops	Control	0	0	0	100
	DAP	0	0	0	100
	W-NPK	0	0	0	100
	½ W-NPK	0	0	0	100

2.3 Mineral Element Determination in Plants

Plant samples were digested with 4:1 acid mixture (HNO_3-$HClO_4$, Merck, EMSURE, Darmstadt, Germany) until 1 mL aliquot remains on the hot plate (Gerhardt HT 43) with a temperature of 100 °C and finally diluted to 50 ml with reverse osmosis water (18.2 MΩ). While total N was determined by a micro-Kjeldahl method according to Bremner (1965); total P was determined according to Barton (1948) and total K was determined according to Pratt (1965). Nitrogen, P and K uptake of plants were calculated to multiple with element concentrations and plant dry weights.

2.4 pH, EC, Total Nitrogen and Available Phosphorus and Potassium Concentrations of Bulk Soils

After harvest of plants, 50 g of bulk soil was collected from the pots and firstly air-dried, and then sieved to a size of 2 mm. pH was determined through a bench pH meter (Orion STAR A211), according to Jackson (1958) and EC was measured using an EC-meter (WTW Cond 720) according to Richards (1954) in the same soil solution, respectively. The concentration of plant-available P was determined according to Olsen et al. (1954). Total N concentration of bulk soils were determined according to Bremner (1965) and exchangeable K was measured according to Pratt (1965).

2.5 Statistical Analysis

The experiment was conducted in a completely randomized design with four replications for each treatment. The significance of treatments was determined with one-way ANOVA using OriginPro2021 (OriginLab, Northampton, MA) and significant differences among treatment means were calculated by Tukey HSD test ($P<0.05$) and also compared by descriptive statistics (±SE).

3 Results

3.1 Characterization of W-NPK

The organomineral fertilizer (W-NPK) obtained from waste SW has a pH of 6.04, organic matter content of 529 g kg^{-1}, total N concentration of 48.3 g kg^{-1}, total P concentration of 66.4 g kg^{-1}, total K concentration of 137 g kg^{-1}, total Ca concentration of 5.10 g kg^{-1}, total Mg concentration of 1.10 g kg^{-1}, and total Fe, Zn, Cu, and Mn concentrations of 1289, 35.9, 4.44, and 35.6 mg kg^{-1}, respectively (Table 1).

In the SEM image of W-NPK, both very small and larger irregularly shaped particles are observed. The larger particles exhibit angular and crystalline-like structures, whereas the smaller particles appear more irregular and granular. The image suggests that inorganic particles are embedded or dispersed within the organic matrix. There is no homogeneous distribution; different particle sizes and compositions coexist, and the surfaces are generally rough and microporous (Fig. 1). In the XRD analysis of the material, prominent peaks were obtained at 17, 23.86, 27.70, 30.38, 34.03, 38.0, 46.39, 58.42, 63.84 and 74.39° two-theta (Fig. 2). In the FTIR analysis of W-NPK, distinct peaks were detected at 887, 1026, 1076, 1288, 1396, 1558, and 1647 cm^{-1} (Fig. 3).

3.2 Dry Weight of Plants

In the first crops, maize and sunflower, dry weights increased with all fertilizer applications compared to the control. Both the full and half doses of W-NPK (equivalent to the full and half DAP rates) produced dry weights comparable to those obtained with DAP (Table 3).

For the second maize crop grown after the first maize crop, dry weights were higher in all fertilizer treatments compared with the control. Both the full and reduced doses of W-NPK resulted in higher dry weights than DAP, indicating a strong residual effect. Similarly, in maize grown after sunflower, all fertilizer treatments significantly increased dry weight relative to the control, regardless of the fertilizer type (Table 3).

3.3 Nitrogen, Phosphorus and Potassium Concentration and Uptake of Plants

Due to the substantial increases in dry weight resulting from fertilizer applications, a dilution effect occurred; thus, especially N and K concentrations appeared to decrease with fertilization. For this reason, it was considered more appropriate to present N, P, and K concentrations together with their uptake values (dry weight x concentration).

In both the first and second crops, N concentrations generally decreased with fertilizer applications compared with the control, except for the first sunflower crop. Despite this, N uptake increased significantly under all fertilizer treatments due to higher biomass production (Table 3).

Plant P concentrations increased significantly in both the maize-maize and sunflower-maize cropping systems relative to the control. The highest P concentrations and P

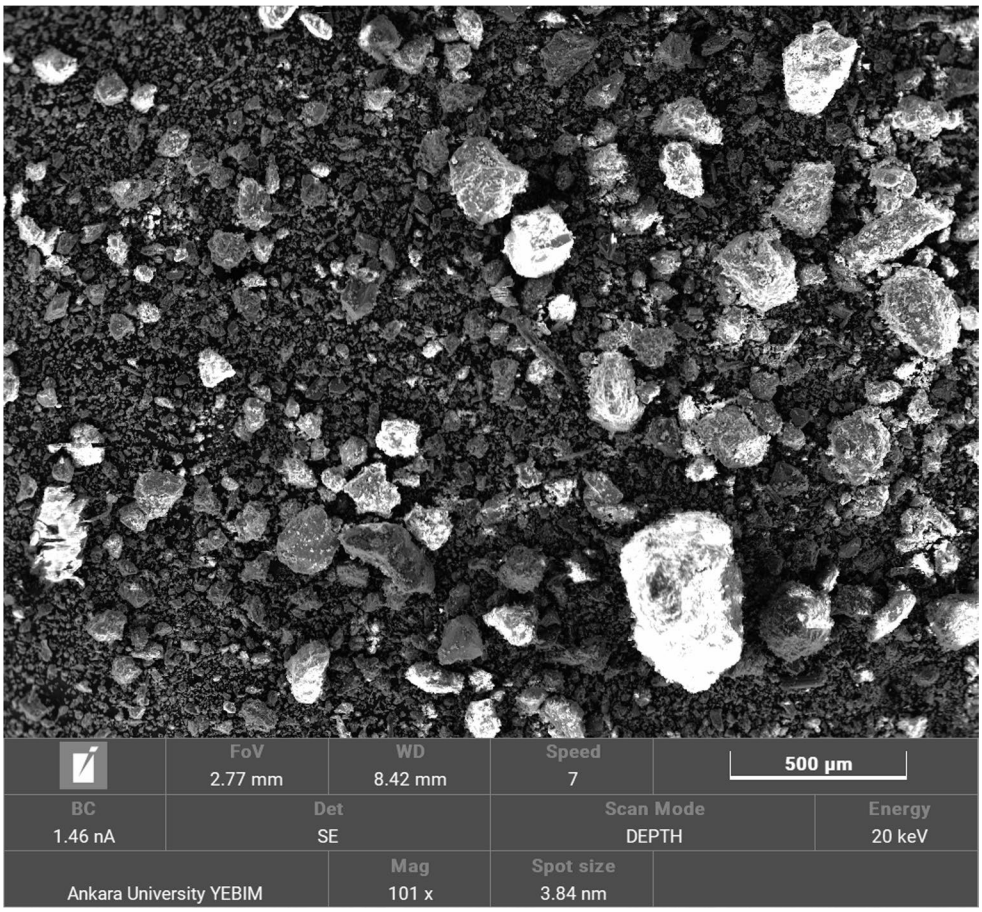


Fig. 1 Scanning electron microscope (SEM) image of organomineral fertilizer produced from chemically hydrolyzed and phosphoric-acid-neutralized wool (W-NPK)

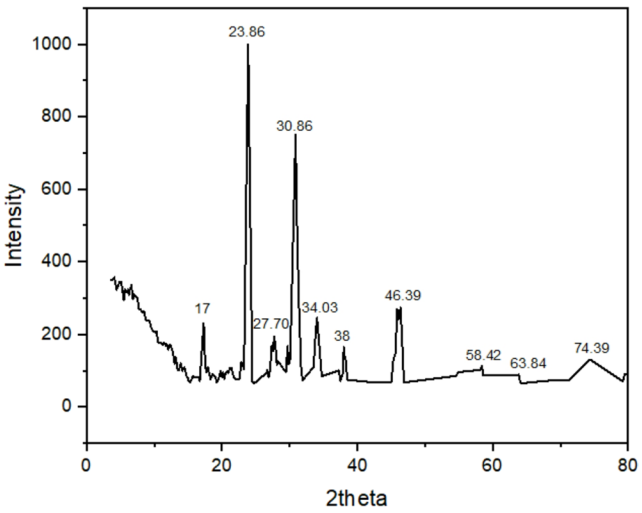


Fig. 2 X-ray diffraction (XRD) pattern of organomineral fertilizer produced from chemically hydrolyzed and phosphoric-acid–neutralized wool (W-NPK)

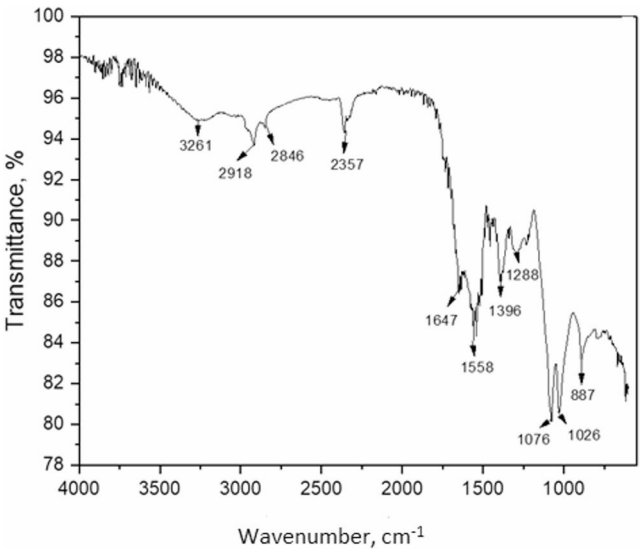


Fig. 3 Fourier Transform Infrared (FTIR) spectra of organomineral fertilizer produced from chemically hydrolyzed and phosphoric-acid-neutralized wool (W-NPK). FTIR spectra showing the transmittance (%) as a function of wavenumber (cm^{-1})

uptake were observed with the full dose of W-NPK, while even the reduced dose of W-NPK produced higher P concentrations and uptake than the DAP treatment (Table 4).

Potassium concentrations decreased in the second maize crop following maize compared with the control. However, in all crops, both full and reduced doses of W-NPK resulted in higher K concentrations than DAP. Similarly, K uptake was significantly enhanced by W-NPK treatments in all

Table 3 Effect of organomineral fertilizer produced from chemically hydrolyzed and phosphoric-acid-neutralized wool (W-NPK) treatments on dry weight, N concentrations and N uptake of subsequently grown plants

Treatments	Dry Weight, g pot^{-1}	*N*, g kg^{-1}	*N* uptake, mg pot^{-1}
	First Crop Maize		
Control	5.51 ± 0.75 b	16.7 ± 0.65 a	93.2 ± 15.1 b
DAP	15.8 ± 0.59 a	13.5 ± 0.19 b	214 ± 6.59 a
W-NPK	17.9 ± 0.84 a	12.4 ± 0.39 b	221 ± 6.24 a
½ W-NPK	15.4 ± 0.15 a	12.2 ± 0.24 b	188 ± 2.25 a
F value	75.3**	25.8**	43.9**
	First Crop Sunflower		
Control	6.09 ± 0.52 b	20.0 ± 0.37	121 ± 9.18 b
DAP	13.9 ± 0.18 a	19.5 ± 0.90	271 ± 9.68 a
W-NPK	14.0 ± 0.21 a	19.0 ± 0.30	265 ± 7.77 a
½ W-NPK	13.3 ± 0.24 a	18.8 ± 0.35	249 ± 6.78 a
F value	141**	1.07^{ns}	70.3**
	Second Crop Maize after Maize		
Control	4.56 ± 0.69 c	19.2 ± 0.31 a	87.1 ± 12.6 b
DAP	14.9 ± 0.41 b	11.2 ± 0.36 b	167 ± 2.45 a
W-NPK	18.8 ± 0.56 a	10.6 ± 0.46 b	198 ± 6.18 a
½ W-NPK	18.1 ± 0.79 a	10.1 ± 0.09 b	183 ± 8.12 a
F value	109**	167**	36.3**
	Second Crop Maize after Sunflower		
Control	10.8 ± 0.33 b	15.9 ± 0.25 a	171 ± 2.87 b
DAP	20.7 ± 0.24 a	10.6 ± 0.41 b	220 ± 5.75 a
W-NPK	21.5 ± 1.00 a	11.0 ± 0.35 b	236 ± 11.9 a
½ W-NPK	21.0 ± 0.67 a	10.9 ± 0.12 b	229 ± 9.55 a
F value	65.7**	70.6**	12.7**

The values are means of four replicates ± standard error. Different letters in each column represent significant difference at $p < 0.05$ level based on Tukey HSD test. ns: non significant; $^{**}p < 0.01$

cases, while DAP showed less pronounced effects compared with the control (Table 4).

3.4 Soil pH, EC, N, and Plant-Available P and K Concentrations After Harvest

After harvest, soil pH did not show any pronounced changes. Only after the first crop sunflower was a slight decrease in pH observed in response to fertilizer applications, while in the second maize grown after maize, slight increases were recorded compared with the control. Soil EC generally did not change significantly with fertilizer applications; a decrease was observed only in the soil of the second maize grown after maize compared with the control (Table 5).

Soil N concentrations after the harvest of the first maize and sunflower crops were higher in the W-NPK treatments compared with the control and DAP. In the maize grown after maize, N concentration did not change markedly, and similarly no change was observed in the maize grown after sunflower. Soil P concentration after all crop harvests was highest in the full dose of W-NPK, followed by the reduced

Table 4 Effect of organomineral fertilizer produced from chemically hydrolyzed and phosphoric-acid-neutralized wool (W-NPK) treatments on P and K concentrations and P and K uptake of subsequently grown plants

Treatments	*P*, g kg^{-1}	*P* uptake, mg pot^{-1}	K, g kg^{-1}	K uptake, mg pot^{-1}
	First Crop Maize			
Control	0.73 ± 0.04 c	4.07 ± 0.72 d	47.3 ± 0.89 b	260 ± 35.8 d
DAP	1.38 ± 0.02 b	21.9 ± 0.83 c	32.7 ± 0.66 c	517 ± 22.5 c
W-NPK	2.96 ± 0.12 a	53.3 ± 4.23 a	51.2 ± 1.07 a	917 ± 45.9 a
½ W-NPK	2.62 ± 0.14 a	40.4 ± 2.28 b	46.0 ± 0.71 b	710 ± 7.04 b
F value	118**	76.1**	90.2**	79.4**
	First Crop Sunflower			
Control	0.95 ± 0.04 d	5.82 ± 0.68 d	45.3 ± 1.43 a	277 ± 27.8 c
DAP	2.67 ± 0.03 c	37.2 ± 0.67 c	34.6 ± 0.59 b	481 ± 8.45 b
W-NPK	5.21 ± 0.13 a	72.8 ± 2.61 a	48.9 ± 0.81 a	683 ± 21.5 a
½ W-NPK	3.78 ± 0.09 b	50.1 ± 1.72 b	45.7 ± 0.42 a	607 ± 11.5 a
F value	460**	293**	47.8**	87.7**
	Second Crop Maize after Maize			
Control	0.86 ± 0.06 c	3.97 ± 0.69 d	30.6 ± 1.29 a	137 ± 15.4 c
DAP	0.99 ± 0.05 bc	14.8 ± 0.33 c	12.4 ± 0.45 d	186 ± 6.74 c
W-NPK	1.48 ± 0.06 a	27.9 ± 1.59 a	22.5 ± 0.46 b	423 ± 16.2 a
½ W-NPK	1.18 ± 0.03 b	21.4 ± 0.69 b	17.9 ± 0.44 c	325 ± 17.7 b
F value	29.1**	115**	105**	79.9**
	Second Crop Maize after Sunflower			
Control	0.73 ± 0.03 d	7.78 ± 0.22 d	33.2 ± 1.22 a	357 ± 18.5 c
DAP	0.99 ± 0.05 c	20.6 ± 1.16 c	17.7 ± 0.50 c	367 ± 11.4 c
W-NPK	1.71 ± 0.06 a	36.5 ± 1.21 a	31.8 ± 0.41 a	685 ± 40.7 a
½ W-NPK	1.25 ± 0.03 b	26.3 ± 1.33 b	23.9 ± 0.38 b	504 ± 21.4 b
F value	79.8**	124**	101**	36.3**

The values are means of four replicates ± standard error. Different letters in each column represent significant difference at $p < 0.05$ level based on Tukey HSD test. ns: non significant; $^{**}p < 0.01$

W-NPK dose and then DAP. Plant-available K concentration in the soil was highest in the W-NPK treatments after the first maize and sunflower harvests. In the second maize grown after maize, the highest K concentration was found in the control, whereas in the maize grown after sunflower, the highest available K was again obtained from the full dose of W-NPK. In all cases, even the reduced dose of W-NPK supplied more plant-available K than DAP.

Table 5 Effect of organomineral fertilizer produced from chemically hydrolyzed and phosphoric-acid-neutralized wool (W-NPK) treatments on pH, EC, total N, available P and K concentrations of soils taken after harvest of subsequently grown plants

Treatments	pH	EC, µS cm^{-1}	*N*, g kg^{-1}	*P*, mg kg^{-1}	K, mg kg^{-1}
	First Crop Maize				
Control	8.31 ± 0.07	526 ± 89.7	0.87 ± 0.03 b	5.10 ± 0.31 d	194 ± 4.91 b
DAP	8.33 ± 0.04	482 ± 20.5	0.90 ± 0.02 b	20.2 ± 1.34 c	149 ± 1.96 c
W-NPK	8.23 ± 0.02	507 ± 11.7	1.04 ± 0.02 a	79.6 ± 6.22 a	239 ± 8.54 a
½ W-NPK	8.34 ± 0.01	501 ± 8.35	1.02 ± 0.03 a	45.2 ± 2.92 b	197 ± 10.6 b
F value	1.28^{ns}	0.15^{ns}	11.2^{**}	86.3^{**}	25.8^{**}
	First Crop Sunflower				
Control	8.31 ± 0.02 a	584 ± 25.4	0.84 ± 0.02 c	4.90 ± 0.26 d	206 ± 6.09 c
DAP	8.24 ± 0.02 b	602 ± 18.1	0.89 ± 0.03 bc	24.6 ± 1.81 c	169 ± 1.09 d
W-NPK	8.17 ± 0.01 b	643 ± 27.3	1.09 ± 0.03 a	112 ± 4.63 a	382 ± 8.09 a
½ W-NPK	8.23 ± 0.01 b	567 ± 13.2	1.03 ± 0.05 ab	52.4 ± 2.56 b	257 ± 5.14 b
F value	10.6^{**}	2.23^{ns}	11.4^{**}	277^{**}	264^{**}
	Second Crop Maize after Maize				
Control	8.20 ± 0.04 c	782 ± 58.9 a	0.87 ± 0.01 ab	4.13 ± 0.62 d	172 ± 4.64 a
DAP	8.41 ± 0.01 a	565 ± 21.0 b	0.83 ± 0.02 b	11.3 ± 0.56 c	141 ± 1.75 c
W-NPK	8.30 ± 0.01 b	620 ± 14.6 b	0.92 ± 0.01 a	43.9 ± 1.59 a	154 ± 1.18 b
½ W-NPK	8.36 ± 0.01 ab	605 ± 10.6 b	0.84 ± 0.01 b	23.3 ± 2.52 b	153 ± 1.90 bc
F value	16.2^{**}	8.68^{**}	6.92^{**}	126^{**}	21.4^{**}
	Second Crop Maize after Sunflower				
Control	8.32 ± 0.02	629 ± 44.5	0.85 ± 0.01	2.94 ± 0.11 d	151 ± 1.05 b
DAP	8.33 ± 0.01	627 ± 8.39	0.87 ± 0.02	12.4 ± 0.43 c	137 ± 1.89 c
W-NPK	8.29 ± 0.01	597 ± 13.7	0.88 ± 0.01	43.1 ± 0.98 a	167 ± 1.24 a
½ W-NPK	8.33 ± 0.02	634 ± 20.8	0.88 ± 0.03	20.3 ± 1.12 b	156 ± 4.41 b
F value	1.44^{ns}	0.43^{ns}	0.43^{ns}	484^{**}	23.1^{**}

The values are means of four replicates ± standard error. Different letters in each column represent significant difference at $p < 0.05$ level based on Tukey HSD test. ns: non significant; $^{**}p < 0.01$

4 Discussion

The present study demonstrates that the OF produced from chemically hydrolyzed and phosphoric-acid–neutralized wool (W-NPK) possesses physicochemical characteristics of a nutrient-rich material capable of enhancing crop growth and soil fertility. SEM analysis revealed a heterogeneous structure composed of fine granular particles and larger angular crystalline fragments embedded within an organic keratin matrix. The angular, crystalline particles likely represent mineral components, whereas the irregular, rough particles correspond to the organic fraction. This structural heterogeneity, combined with rough and microporous surfaces, may influence interactions with soil moisture and microorganisms and could potentially affect nutrient availability in soil, although such processes were not directly measured in the present study.

XRD analysis further supported these findings. The small peak at about 20° indicates partial preservation of crystalline regions within the keratin structure, suggesting that some organic N-bearing peptides remain intact. Peaks around 27° correspond to calcium pyrophosphate ($Ca_2P_2O_7$) and potassium phosphate. Peaks between 30–34° indicate hydroxyapatite ($Ca_5(PO_4)_3OH$) and dicalcium phosphate ($CaHPO_4$), while peaks between 34–38° represent hydroxyapatite together with tricalcium phosphate ($Ca_3(PO4)_2$) and potassium phosphate ($KHPO_4$). The peak near 40° corresponds to potassium phosphate and hydroxyapatite, while peaks at around 45° and 58° correspond to additional hydroxyapatite phases (Karampas and Kontoyannis 2013; Zhang et al. 2025). These crystalline phases indicate that P in W-NPK occurs in multiple mineral forms that may differ in their solubility characteristics. However, because nutrient dissolution kinetics and phase-specific solubility were not directly measured in the present study, the direct influence of these phases on nutrient release dynamics or plant uptake cannot be conclusively determined.

Together, the FTIR and XRD results confirm that W-NPK contains both keratin-derived organic functional groups and mineral components (P, K, and residual minerals), demonstrating its organomineral character. Similar structural integration has been reported in hydrolyzed wool and feather-based fertilizers, where organic-inorganic interactions enhance nutrient retention and reduce leaching. FTIR analysis confirmed the preservation of the organic keratin matrix. The band at 1647 cm^{-1} corresponds to the C=O stretching of Amide I, while the band at 1558 cm^{-1} represents N-H bending and C-N stretching of Amide II, characteristic of protein/peptide structures. Bands in the 1288–1396 cm^{-1} region, associated with Amide III vibrations and partially overlapping with P-O bonds, indicate the coexistence of organic and phosphate-related structures

(Metomo et al. 2024; Sahin et al. 2025a, c; Gunes et al. 2025). The strong P-O stretching band at 1026 cm^{-1} confirms the successful incorporation of phosphate into the matrix during phosphoric acid neutralization, while the peak at 887 cm^{-1} corresponds to P-O bending or low-frequency phosphate vibrations (Luna-Zaragoza et al. 2009; Gong et al. 2024). The presence of these functional groups suggests that the keratin matrix may contribute to nutrient retention and interactions with soil ions.

The growth responses of maize and sunflower support the agronomic potential of W-NPK. In all cropping cycles, W-NPK applied at both full and half doses performed comparably to, and sometimes better than, conventional DAP in promoting plant biomass production. The superior dry weights observed in the second maize crop indicate a residual fertilization effect. However, it should be noted that the present study did not directly quantify nutrient mineralization rates, soil inorganic N fractions, or P fractionation. Therefore, the mechanisms underlying the observed residual effects cannot be demonstrated mechanistically and are inferred from plant growth responses and soil nutrient measurements. The improved performance in the second maize crop may be associated with gradual mineralization of keratin-derived organic N and the presence of mineral P forms with differing solubility characteristics in the organomineral matrix. Nevertheless, these interpretations remain inferential and require confirmation through direct measurements of nutrient release kinetics and soil nutrient transformations. Such residual responses are commonly reported for organic and OF rich in proteinaceous materials, which may mineralize progressively and contribute nutrients over multiple cropping cycles (Diacono and Montemurro 2010; Uddin et al. 2025). This contrasts with conventional fertilizers such as DAP, which typically dissolve rapidly and may exhibit relatively lower nutrient-use efficiency, with global N and P uptake rates often reported below 50% (Fixen et al. 2015; Barlog 2023; Singh et al. 2025).

In addition to these findings, the C/N ratio is an important indicator of organic fertilizer quality, influencing N mineralization dynamics. In this study, the C/N ratio of SW (3.76) was slightly lower than that of W-NPK (4.89); however, both values fall well below the commonly accepted threshold (< 10–12) for high-quality organic amendments (Mohanty et al. 2013; Lal et al. 2020; El-mrini et al. 2022). This indicates that both materials are N-rich and unlikely to cause N immobilization in soil. The slightly higher C/N ratio of W-NPK may be attributed to the incorporation of mineral components during processing and may contribute to a more moderated N release compared to raw SW. The C/N ratio of W-NPK conforms to quality standards for organomineral fertilizers and supports its potential for efficient nutrient supply.

The nutrient concentration results showed lower N concentrations in plant tissues under fertilization, consistent with a dilution effect caused by enhanced biomass production (Igarashi et al. 2021; Shi et al. 2025). However, nutrient uptake data demonstrated that all W-NPK treatments substantially increased N and K uptake compared with the control, confirming effective nutrient delivery despite reduced concentrations. Phosphorus responses were particularly notable: both full and reduced W-NPK doses resulted in higher plant P concentrations and uptake than DAP. Although this response may indicate improved P availability in the soil-plant system, the present dataset does not allow attribution of this effect to specific mineral phases identified in the XRD analysis. Similarly, increased K uptake indicates that K incorporated during alkaline hydrolysis contributed to plant nutrition during the cropping cycles.

Soil analyses also support the agronomic behavior of W-NPK. Soil pH and EC showed minimal changes, indicating that W-NPK does not induce acidification or salinity risks, a benefit commonly associated with organically buffered fertilizers. The increased soil N concentrations following the first harvest in W-NPK treatments suggest partial retention of organic N fractions in the soil. Nevertheless, because soil N mineralization dynamics and inorganic N pools were not directly quantified, the progressive release of N from the keratin matrix cannot be confirmed mechanistically and should be interpreted cautiously. Soil P concentrations were consistently highest in W-NPK-treated soils, while plant-available K also remained higher under W-NPK than DAP, indicating that the material contributed to maintaining soil nutrient availability during successive crops.

5 Conclusion

This study demonstrates that waste sheep wool (SW) can be effectively converted into a nutrient-rich organomineral fertilizer (W-NPK) through alkaline hydrolysis followed by phosphoric acid neutralization. The mixed organic–inorganic structure of W-NPK appears to support gradual nutrient release, which resulted in plant growth and nutrient uptake comparable to those obtained with conventional diammonium phosphate (DAP) under the controlled conditions of a short-term greenhouse pot experiment using a single calcareous, sandy clay loam soil. In several treatments, W-NPK, even at reduced application rates, maintained biomass production and enhanced phosphorus (P) and potassium (K) uptake across cropping cycles. Soil analyses indicated that W-NPK increased plant-available P and K and provided residual fertility benefits without causing significant changes in soil pH or salinity. These findings suggest that W-NPK may have potential as a sustainable fertilizer

option that could contribute to improved nutrient use efficiency while valorizing SW waste; however, claims regarding field-scale applicability, sustainability, and replacement of conventional fertilizers should be considered preliminary. Further studies under diverse soil types, field conditions, and strictly equivalent nutrient comparisons are needed to more precisely evaluate its agronomic performance relative to conventional mineral fertilizers.

Author Contributions Mehmet Burak Taskin: Formal analysis, Investigation, Review & editing; Kiymet Deniz Yagcioglu: Formal analysis; Yusuf Kagan Kadioglu: Review & editing; Aydin Gunes: Conceptualization, Investigation, Methodology, Supervision, Writing - original draft, and Review & editing.

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Data Availability The data supporting the findings of this study are available from the corresponding author, Aydin Gunes, upon reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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