Synthesis and Evaluation of Organo-Mineral Phosphatic Fertilizers from the Agricultural and Agro-Industrial Wastes to Improve the Phosphorus Use Efficiency of Bell Pepper (Capsicum Annuum)

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The conversion of animal waste and agricultural by-products into organ mineral fertilizers is the best way to manage animal waste and use them as soil amendments to improve soil health and enhance nutrient availability. Animal waste can cause serious environmental consequences if not managed properly. This study was planned to convert animal waste into valuable and nutritional fertilizer for plants. We used cow dung, poultry manure, and different ratios of elemental sulfur and humic acid for the preparation of Organo-mineral Phosphatic fertilizer (OMPF). Di-ammonium phosphate was also used as a mineral source of Phosphorus (P). A total of six treatments (4 of OMPF with 5% humic acid, 5% elemental sulfur, 2.5% humic acid with 2.5% elemental sulfur, and only OMPF, 1 of DAP, and 1 as a control with no P) were evaluated under a pot trial using Bell pepper (*Capsicum Annuum*) as a test crop. Treatments were applied according to a complete randomized design (CRD) with three replications, and achieved 20% higher PUE as compared to DAP. It is concluded that application of P as OMPF can significantly enhance shoot fresh weight, root fresh weight, and chlorophyll content with 45 %, 52.6%, and 21%, respectively. And OMPF performs more significantly than the control treatment and positively effect on plant nutrients availability. However, more field studies are needed for broader applications of this technology.

Keywords: Organo-Mineral Phosphatic Fertilizer, Animal Manure, Phosphorus Use Efficiency, Phosphorus Uptake

Introduction:

Phosphorus is a critical macronutrient for plant growth and development and plays a key role in numerous physiological processes as photosynthesis, energy transfer, and nucleic acid synthesis [1]. Phosphorus is an important element that contributes to plant physiological regulation and enhances plant tolerance to abiotic stresses such as salinity, drought, waterlogging, elevated CO_2, and heavy-metal toxicity, such as salinity, drought, water-logging, high CO_2, and heavy metals toxicity [2]. To adequately feed the projected global population of 10 billion by 2050, global food production should increase by at least 70% [3]. However, the traditional practice of increasing food production without improving the efficiency of food systems is no longer sustainable. Phosphorus is a non-renewable and necessary resource, which is very important in agricultural production. About 40% (3.1 billion individuals) of the global population is unable to consume a wholesome diet (FAO, 2021). Global phosphorus reserves are being depleted, and extracting them is becoming increasingly difficult [4]. A total of about 67% of land under crop production in the world is under phosphorus deficiency [5]. It has been estimated that agricultural soils worldwide will be depleted by between 4 and 19 kg P ha^{-1} $year^{-1}$, with losses due to erosion by water contributing to over 50% of the total P losses [6]. The fixation process causes a large proportion of phosphorus-based fertilizers to become immobilized in the soil, making them inaccessible to plants. [7].

Techniques to improve Phosphorus Availability:

To enhance the efficiency of phosphatic fertilizers, it is quite necessary to create innovation and low-cost strategies with a view to the scenario mentioned above. Improving the availability of phosphorus to the plants is something that can be achieved in many ways. The grouping of PSB and AMF possesses an effective ability to transform insoluble phosphate present in soil either into a soluble form or readily available to be taken up by plants [8]. Phosphate-solubilizing microorganisms (PSM) consist of a collection of organisms that belong to actinobacteria, bacteria, fungi, and arbuscular mycorrhizae, as well as cyanobacteria that contain the capacity to hydrolyze organic as well as inorganic phosphorus into soluble forms, thus making phosphorus bioavailable to plants [9]. Slow-release fertilizers coat the fertilizer with a biodegradable organic or inorganic polymer that retards the rate of fertilizer release, resulting in an overall higher crop yield per pound of fertilizer applied. Therefore, the technique of slow-release fertilizers is termed a best management practice (BMP) instrument in crop production. Organo-mineral fertilizer (OMF) preparation is probably the most effective method to achieve the optimal agronomic efficiency and crop productivity without compromising the sustainable soil health and fertility [10]. A combination of organic matter and phosphorus mineral sources increases the amount of soil fertility and guarantees the continuous availability of nutrients. The addition of organic matter in the fertilizer will help to condense the soil and increase water retention during the duration of the use period [11]. It also increases positive microbial action within the ground, which causes augmented nutrient circulation and accessibility to the vegetation. Moreover, slow-release characteristics of the OM fertilizers facilitated the distribution of the nutrients in time [10].

An OMF product has numerous benefits than a single application of mineral fertilizer in the agricultural field in terms of FUE, soil aggregation, soil biochemistry, and microbial diversity [5]. A number of studies have established that using OMF has had an impact on the soil chemical characteristics, that is, pH, cation exchange capacity, organic carbon, exchangeable acidity, base saturation, basic nutrients, total nitrogen, and available phosphorus. The organo-mineral types of fertilizers make nutrient release slowly as and when it is needed by the plant during the growing season, and this helps the plant to absorb nutrients more effectively, leading to greater growth and development of the plant [12].

Materials and Methods:

Organic Waste Collection and Conversion:

For the preparation of organ-mineral phosphatic fertilizer, animal manure, poultry manure, and compost were used as organic waste. The cow dung and poultry manure were collected from the dairy farm and hen shop, respectively. Press mud was purchased from the local supplier industrial site of Multan, Pakistan. After the collection of these organic wastes, we dried them in sunlight for 5–6 days to remove moisture. The dried material was then ground and passed through a <2 mm sieve. to ensure uniform particle size. The water holding capacity of organic waste material was determined as the mass of water retained per mass of dry material. The electrical conductivity and pH were measured by an EC meter [ADVANCED (TDS & EC)], a pH meter [PH-009(I)A]. By adding OMPF in distilled water at a ratio of 1:10 (w/v), followed by shaking on a mechanical shaker for 30 minutes [13].

Furthermore, the digestion of OMPF was done using hydrogen peroxide (H_2O_2) and sulfuric acid (H2SO4) for the estimation of P, K, Zinc (Zn), Copper (Cu), and Iron (Fe) in the Muhammad Nawaz Sharif University of Agriculture, Multan, Pakistan.

Preparation of OMPF:

Organ-mineral phosphatic fertilizer was produced by enriching organic waste with (both use 5%). Diammonium phosphate (DAP) was also used as a mineral source. For the preparation of different OMPF, we used Organic waste mixture (OWM) and DAP in a 1:1 (50%:50%) ratio with the 5 % elemental sulfur and humic acid. So, according to these ratios

OMPF1 = 230g OWM + 230g DAP + 24g H.A
OMPF2 = 230g OWM + 230g DAP + 24g E.S
OMPF3 = 230g OWM + 230g DAP + 12g E.S & 12g H.A
OMPF4 = 250g OWM + 250g DAP only

Table 1. Organo-Mineral Phosphatic Fertilizer preparation (%)

OMPF	**Fertilizer Doses (%)**
OMPF1	47% OWM + 47% DAP + 5% H. A
OMPF2	47% OWM + 47% DAP + 5% E. S
OMPF3	47% OWM + 47% DAP + 2.5% E.S & 2.5% H. A
OMPF4	50% OWM + 50% DAP

Table 2. Physico-chemical Characteristics of soil used for pot experiment.

Parameters	Value	Unit
Textural class	Clay loam	-
Organic matter	0.38	%
pH	8.22	-
EC	1.77	ds m^{-1}
Total N	0.027	%
Available P	8.20	mg/kg
Extractable K	80	mg/kg
Zinc	0.15	mg/kg
Copper	0.06	mg/kg
Iron	0.17	mg/kg
Manganese	0.24	mg/kg

Experimental design and Plant material:

A pot trial was conducted during the spring season (2025), in greenhouse conditions near Academic Block-B (30 9'36" N and 71 27'1" E) of MNS-University of Agriculture, Multan, Pakistan. Total six treatments (T1-T6) were evaluated in this experiment including control (T1), recommended P from DAP (T2), OMPF1 with 5% humic acid (T3), OMPF2 with 5% of elemental sulfur (T4), OMPF3 with 2.5% of humic acid and 2.5% of elemental sulfur (T5) and solo application of OMPF4 (T6). Treatments were arranged according to a complete randomized design (CRD) with three replications of each treatment. The P levels were determined by dividing the recommended dose (40 kg/acre) of inorganic fertilizer (DAP). The recommended dose of nitrogen (60 kg/acre) and potassium (30 kg/acre) was added to all the treatments. Each treatment (OMPF) was mixed in 10 kg of soil, then filled into an earthen pot (1 foot in height and 8 inches in diameter). *Capsicum Annuum* was raised in peat moss trays for one month, and then the seedlings were transplanted into each pot (one plant per pot). According to crop requirements and weather conditions, measured irrigation was equally supplied throughout the experimental period. The other management practices (hoeing, pest management, and disease control) were also kept constant throughout all treatments.

Pre-Analysis of Experimental Soil:

A soil sample was randomly collected from a depth of 0–15 cm in the experimental field area of MNS University of Agriculture, Multan, Pakistan. The soil was air-dried and passed through a <2 mm sieve before analysis for selected physico-chemical properties. Soil texture was determined using the hydrometer method, while pH and EC were measured in a 1:1 (w/v) soil–water suspension. Organic matter was analyzed using the Walkley–Black method. Total nitrogen was determined using the Kjeldahl distillation method, and available phosphorus was measured spectrophotometrically. Extractable potassium was analyzed using the ammonium acetate extraction method as described by [14]. Micronutrients (Zn, Cu, Fe, and Mn) were extracted using the DTPA method and quantified using Atomic Absorption Spectroscopy (AAS) [novAA, Analytik Jena].

Determination of Plant Parameters:

The crop was harvested at the stage of maturity, and the data regarding growth attributes were recorded. Chlorophyll content in bell pepper leaves was measured by using a SPAD meter 502 plus. The shoot length (cm) was measured by measuring tape. A similar procedure was also used for measuring the root length. A digital balance [JJ324BC] was used to take the fresh weight of root and shoot (g). In order to determine their dry weights (g), samples were oven dried at 105 for 2 hours, and then the dry weight was measured with a digital balance. Moreover, the dried and ground plant leaf samples were used to measure the elemental analysis. For the determination of P content in bell pepper leaves, digestion was done in Hydrogen peroxide (H2O2) and sulfuric acid (international standard) (H2SO4), followed by Spectrophotometer [UH5300, HITACHI] measurement of P at the wavelength of 410 nm [15]. The digestion sample was analyzed to detect extractable K content by using a flame photometer [BWB Technologies], and N content was determined by using the Kjeldahl apparatus [16].

Calculation of phosphorus use efficiency (PUE):

Phosphorus uptake by bell pepper plants was calculated using the following formula:

P uptake (g plant^{-1}) = P content (%) in grain/straw × grain/straw yield (g plant^{-1}). (1)

Phosphorus use efficiency (PUE) was then calculated using the formula:

PUE (%) = \ (P uptake in treatment pot (mg) – P uptake in control pot (mg)\) ÷ P dose applied (g) × 100. (2)

Statistical analysis:

The recorded data was determined by using the analysis of variance (ANOVA) technique following CRD. Means were compared by using the least significant difference (LSD) test at 5% level of significance. Statistic 8.1 software was used for statistical analysis of the data.

Results:

Response of Crop Growth Parameters to OMPF:

Plant height is an important indicator of plant growth during the growth period. It is more of a varietal characteristic, but it may be modified by different agronomic practices. The data regarding plant height indicates a progressive increase in shoot length. The best plant height was recorded in OMPF2 (44 cm), showing a 51.7% increase over the control (29 cm), indicating a substantial improvement in vegetative growth due to the synergistic effect of elemental sulfur and organic waste mixture that likely enhanced phosphorus solubility and root activity. The T3 contain 50% OWM and 50% DAP with 5% ES. The shoot fresh weight of bell pepper was markedly influenced by different phosphorus treatments. Compared to the control, the highest shoot fresh weight was observed in T3 (OMPF2 + elemental sulfur) with a 45% increase. The fresh root and dry root weight showed similar patterns; the result showed that T3 (OMPF with 5% elemental sulfur) gave the best results. The root fresh weight also increases in treatment T3, with the maximum increase 52.6%. Chlorophyll content was highest in the T4 treatment, which increased by 21% over the control, followed by T3 and T5. The lowest SPADE value was observed in T5, highlighting the differential response of chlorophyll content to OMPF application.

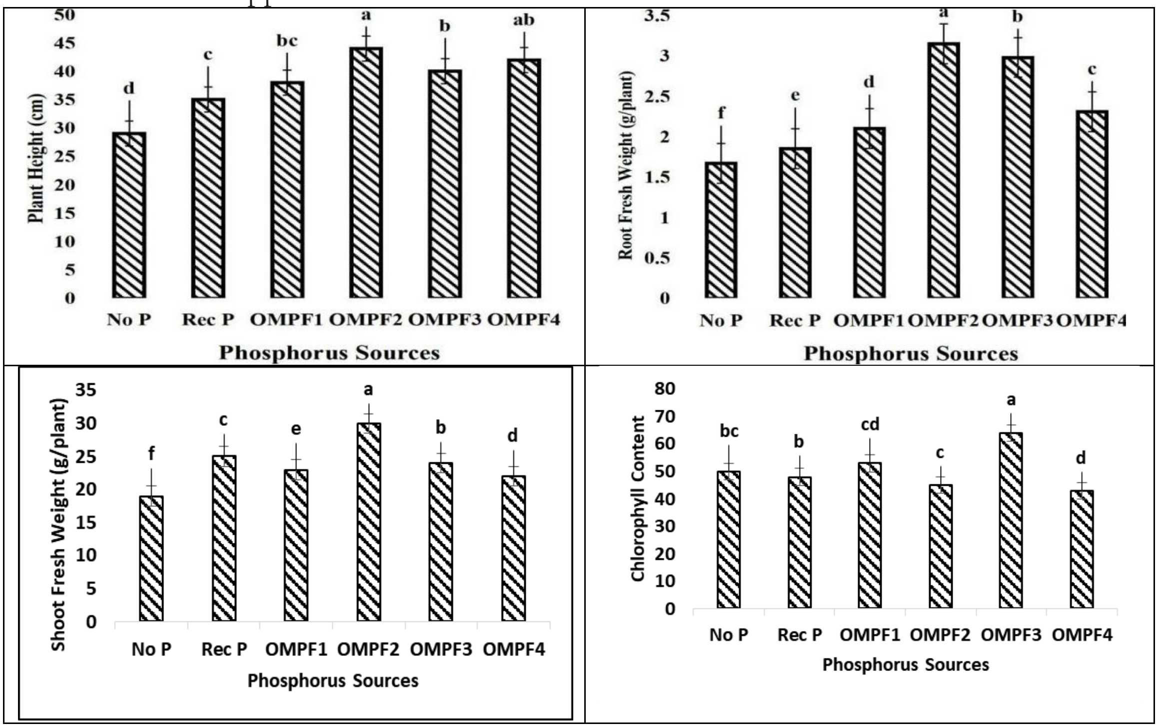

Figure 1. Effect of different Phosphorus sources on (A) plant height, (B) shoot fresh weight, (C) root fresh weight, (D)chlorophyll content of Bell Pepper under pot experiment. The treatment bars showing different letters are significantly different ($P<0.05$) from others (Error bars = Mean ± S.E)

Response of Nutritive Parameters to OMPF:

Nitrogen Content (%) and Uptake (mg/pot):

Nitrogen concentration in bell pepper plants varied significantly among treatments, indicating a clear influence of organ mineral phosphatic fertilizer (OMPF) formulations on plant nitrogen status. While the highest concentration **(**3.5%**)** was recorded in OMPF2**,** showing a 45.8% increase over the control. Nitrogen uptake increased by up to 46% increase over the No P control and a 13% increase over the Rec P treatment.

Phosphorus Content (%) and Uptake (mg/pot):

Phosphorus concentration in bell pepper tissue showed a marked increase under organ mineral phosphatic fertilizer (OMPF) treatments compared to both control and inorganic phosphorus sources. The highest concentration was observed in T3 (OMPF2) with a 66.7% increase over the control, followed closely by T5 (0.69%; 64.3%**)**. The OMPF2 treatment achieved a peak uptake of 0.172 mg, which is 72% higher than the control and 48% higher than the Rec P treatment.

Potassium Content (%) and Uptake (mg/pot):

Potassium concentration also responded favorably to organ mineral fertilizer applications. The control treatment (No P) had 2.56% K, while OMPF2 showed the highest content of 3.5%**,** corresponding to a 36.7% increase over the control. The highest (1.058 mg) occurred in OMPF2**,** showing a 106.7% increase compared to the control.

Phosphorus Use Efficiency % (PUE):

Phosphorus use efficiency (PUE) indicates how effectively plants convert P into yield or biomass. It is the plant biomass produced per unit of P absorbed by the plants. Among the tested formulations, OMPF2 showed the highest PUE (35.70%), which was 15-20% than the T1 treatment. In the bell pepper, the PUE enhances significantly and shows the best response of OMPF.

Table 3. Effect of different P fertilizers on the NPK contents of Bell pepper

Treatments	N Uptake (mg)	N Content (%)	P uptake (mg)	P Content (%)	K Uptake (mg)	K Content (%)	PUE (%)
No P	0.68e	2.8f	0.1d	0.15c	0.5d	2.5f	0f
Rec DAP	0.7d	3.1e	0.13cd	0.26bc	0.7b	2.57e	10e
OMPF1	0.7d	3.5c	0.13c	0.3ab	0.6c	2.7d	20d
OMPF2	1.3a	4.3a	0.23a	0.38a	1.1a	3.3a	35a
OMPF3	0.8c	3.1d	0.17b	0.31b	0.5b	2.4c	26d
OMPF4	0.8b	3.6b	0.14b	0.34b	0.57c	2.5b	28b
LSD	0.0149	0.03	0.022	0.014	0.157	0.034	0.457

Means values having different letters are statistically significant according to the LSD test at $P < 0.05$.

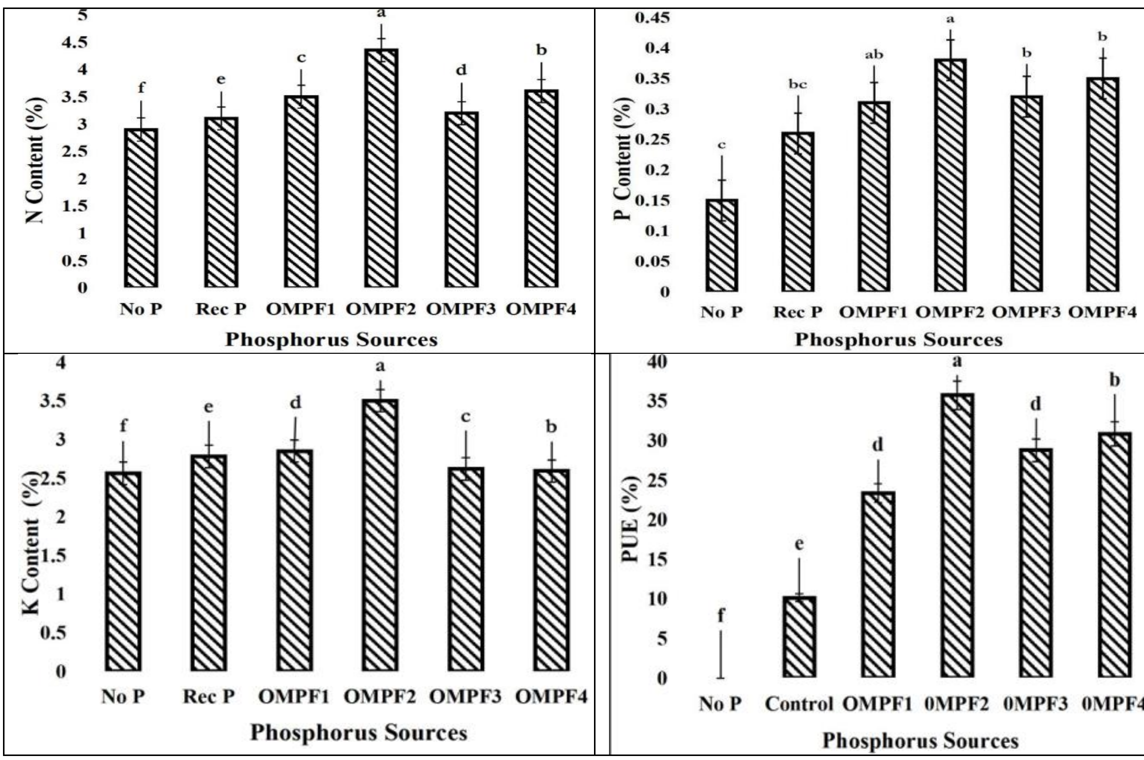

Figure 2. Effect of different Phosphorus sources on (A) Nitrogen content, (B) Phosphorus content, (C) Potassium content, (D) Phosphorus use efficiency of Bell Pepper under pot experiment. The treatment bars showing different letters are significantly different ($P<0.05$) from others (Error bars= Mean ± S.E)

Discussion:

The experiment focused on phosphorus use efficiency and overall nutrient availability to plants. The results indicated remarkable trends with respect to the varying doses of OMPF with different ratios of humic acid and elemental sulfur. This study explored the potential of organo- mineral phosphatic fertilizer (OMPF) synthesized from agricultural and agro-industrial wastes to enhance phosphorus use efficiency (PUE) and crop performance in bell pepper (*Capsicum annuum*). The findings support the hypothesis that organo- mineral fertilizers, especially when supplemented with elemental sulfur and humic substances, can significantly improve plant growth and productivity compared to conventional phosphorus sources such as diammonium phosphate (DAP).

The treatment T3 (OMPF2 with elemental Sulfur), comprising 100% phosphorus, outperformed all others in terms of growth parameters such as plant height, shoot fresh weight, shoot dry weight, root fresh weight, root dry weight, and number of leaves. This result suggests a synergistic effect between the slow-release nature of organo-mineral matrices and the enhanced solubilization of phosphorus mediated by sulfur oxidation. Sulfur, particularly in its elemental form, is known to stimulate microbial populations such as *Thiobacillus* species, which oxidize sulfur to produce sulfuric acid, thereby decreasing rhizosphere pH and promoting the release of bound phosphates from soil minerals.

The superior performance of T3 over the DAP treatment (T1) also highlights the inefficiency of conventional phosphate fertilizers in certain soil conditions. DAP, while soluble and readily available, tends to get rapidly fixed in the soil as calcium or iron phosphates, particularly in calcareous or acidic soils, respectively. In contrast, the organo-mineral fertilizers appear to maintain phosphorus in a more bioavailable form over a prolonged period, likely due to the organic matter complexing with P ions and preventing fixation.

Conclusion:

The study concludes that OMPFs derived from organic waste, when enriched with both humic acid and elemental sulfur, can serve as superior alternatives to conventional phosphorus fertilizers. Treatment T3 emerged as the most effective formulation, demonstrating the best performance in plant height. The combination of humic acid and sulfur appears to enhance phosphorus solubilization and uptake, offering a promising strategy for sustainable phosphorus management in crop systems.

Investigate the microbial and biochemical mechanisms behind the synergistic effects of humic substances and sulfur on phosphorus dynamics. Standardize OMPF formulations based on different organic waste types and their nutrient-release fertilizer. Explore multi-season and multi-crop trials to assess long-term soil and productivity impacts. Encourage adoption of enriched OMPF to reduce dependency on synthetic fertilizers and improve soil health. Support the local production and distribution of OMPF using regionally available agro-waste. Invest in training programs to educate farmers on the use and benefits of customized slow-release fertilizers.

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Data Availability

The original contributions and data availability in this research can be directed to the corresponding author.

Conflict of Interest

No any conflicts of interest declare by author.

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