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Towards Balanced Fertilizer Management in South China: Enhancing Wax Gourd (*Benincasa hispida*) Yield and Produce Quality

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Abstract: Balanced fertilizer management promotes plant growth, enhances produce quality, minimizes inputs, and reduces negative environmental impacts. Wax gourd (*Benincasa hispida*) is an important vegetable crop species in China and in South Asia. Two crop nutrition options, NPK and the natural mineral polyhalite, were tested, separately and combined, with the aim of enhancing wax gourd yield and quality and simultaneously to increase nutrient use efficiency and reducing inputs. The experiments tested the optimization of NPK by reducing the proportion of phosphorus (P), and the effect of enriching the soil with essential macronutrients by the use of the supplementary mineral fertilizer polyhalite containing magnesium (Mg), calcium (Ca) and sulfur (S). Two experiments were carried out in Foshan County, Guangdong, China, in 2018 and 2019. Experiments included four treatments: (1) Conventional NPK (15:15:15); (2) Optimized NPK (16:8:18); (3) Conventional NPK + polyhalite; (4) Optimized NPK + polyhalite. Fertilizers were applied prior to planting. While optimized NPK alone had no effects on fruit yield and quality, supplementary polyhalite resulted in a 10–17% increase in yield and significantly improved produce quality due to increased nutrient uptake from polyhalite, resulting in better foliar biomass. We conclude that the combined crop nutrition options improved yield and quality, enhanced nutrient use efficiency, and reduced risks of nutrient pollution. Inclusion of polyhalite in balanced fertilization practices as a supplementary source of secondary macronutrients seems promising. Nevertheless, plenty of space remains open for further adjustments of NPK application management, focusing on reduced rates, optimized ratio, and accurate timing of application for each nutrient.

Keywords: fruit quality; calcium; magnesium; nutrient recovery; optimized nutrient uptake; phosphorus; polyhalite

1. Introduction

Wax gourd (*Benincasa hispida*), which belongs to the Cucurbitaceae family, is a fast-growing and long season vegetable, widely consumed in Asia and other subtropical countries [1–3]. The fruit, the major edible organ of the wax gourd, are consumed baked, fried, boiled, pickled or candied/preserved [4,5]. Wax gourd fruit has a very long storage life, and as it is available even when other crops are not, it plays an important role ensuring year-round supply of vegetables to households [6]. Traditionally, wax gourd is recommended for treatment of peptic ulcer, hemorrhages from internal organs, epilepsy and the other neurological disorders [7]. The fresh juice is reported to effectively prevent morphine withdrawal symptoms in mice [8,9]. In spite of its high economic importance, research on wax gourd, particularly on mineral nutrition and fertilizer management, is scarce.

In recent years, wax gourd average yields in South China have tended to stagnate. Amongst other factors, one possible reason may be the farmers' conservative practice of fertilizer management. Most of the farmers in South China excessively use compound fertilizers with N-P_2O_5-K_2O ratio of 15:15:15 [10]. This type of composite fertilizers provides all three macronutrients: nitrogen (N), phosphorus (P), and potassium (K) at a relatively low cost. Nitrogen benefits the growth of vegetative organs, which is positively reflected in the photosynthetic and yield capacity of plants [11–13]. Phosphorus, essential for energy transformation and metabolic regulation, is mainly involved in root development and in the initiation of reproductive organs [14,15]. Potassium, which is significant to carbon assimilation, translocation, and management in the plant [12], is involved in regulating many biochemical pathways [16,17], and increases the yield and post-harvest quality of fruit [18].

Beyond adequate NPK supply, the ratio of these nutrients may be fundamental to setting up a normal course of crop development. There are significant interactions between these nutrients: excess or inadequate supply of one nutrient might promote or limit the uptake or utilization of the others [12]. Thus, a NPK ratio of 15:15:15 does not necessarily meet the requirements of every given crop species. In most of melons which belong to Cucurbitaceae family, nutrient requirements and NPK ratio vary significantly, depending on the melon type and cultivar, soil mineral status, and on the crop developmental stage [19,20]. Imbalanced mineral nutrition might bring about inadequate productivity as well as poor quality [19].

Optimum NPK ratio requirements considerably differ among cucurbitaceous crop species [18,19]. Thus, P is especially required for seedling establishment (root growth), and later on, at early reproductive steps (bloom and seed development) [14,15,20,21]. Nitrogen is essential during the vegetative phase for the buildup of adequate canopy and leaf area to ensure yield capacity. However, excess N availability during the reproductive phase promotes undesired competition between fruit and vegetation that might reduce produce quality [22]. Potassium, in contrast, is particularly essential during later stages of fruit development, supporting sugar translocation and accumulation [18,19,21–24].

Furthermore, improper fertilization approaches also have serious environmental consequences. A recent countrywide meta-analysis [25] and several earlier studies of N and P fertilization in vegetable production systems in China revealed excessive application of these nutrients with consequent significant losses through runoff and leaching [26–31]. Optimizing fertilizer application in crop production is, therefore, of great importance not only for maximizing crop yields but also for reducing environmental pollution and its subsequent hazards to human health [32].

In addition, solid composite NPK fertilizers usually lack other essential nutrients, such as magnesium (Mg), calcium (Ca) or sulfur (S). Magnesium, quite often supplied separately through $MgSO_4$, is a pivotal part of the chlorophyll molecule and is therefore essential for photosynthesis. Magnesium plays an important role in the formation and transfer of metabolites to fruits [33–35]. At the canopy level, Mg increases N, P and K uptake, thereby increasing yield and quality [36–39]. Calcium is responsible for proper plant cell division and for strengthening cell walls [40,41]. This nutrient has beneficial effects on fruit firmness and alleviating influence on physiological as well as pathogenic disorders in fruit [42–44]. Sulfur is essential to metabolism of amino acids [45] and interacts with N in protein synthesis and accumulation [46,47].

Improving resource utilization efficiency has recently been determined as the major strategic goal of vegetable production, and this requires a holistic, systematic approach [48], which has been applied to cereals [49], and to bitter gourd [29]. Thus, instead of focusing on one nutrient at a time, balanced fertilizer management must consider nutrient rates, composition, ratio, and formulation together, including all required macro and micronutrients. The duration of nutrient availability after application should be addressed as well. Slow-release fertilizers that exhibit low solubility, therefore providing gradual nutrient supply for a prolonged period of time, seem to have considerable potential to improve nutrient use efficiency and reduce negative environmental impacts [50].

The need to improve fertilizer management by inclusion of essential macronutrients other than N, P, and K and the motivation to extend nutrient availability in the soil set the stage for new fertilizers. Polyhalite, a new commercial fertilizer marketed as Polysulphate® (ICL Fertilizers, Cleveland, UK), is a natural hydrated sulfate of K, Ca, and Mg with the formula: $K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$. The purity of the product is very high (95% polyhalite) with <5% sodium chloride (NaCl) and traces of boron (B) and iron (Fe) at 300 and 100 ppm, respectively. Polyhalite is composed of 48% sulfur trioxide (SO_3), 14% potassium oxide (K_2O), 6% magnesium oxide (MgO), and 17% calcium oxide (CaO). Serving as a suitable fertilizer to supply 4 nutrients, polyhalite is less water soluble than the more conventional sources [51–54]. Comparisons between polyhalite and other K and Mg fertilizers showed that polyhalite was at least as effective as potassium sulfate (K_2SO_4) as a source of K, and at least as effective as potassium chloride (KCl) plus magnesium sulfate ($MgSO_4$) as a source of K and Mg [51]. Calcium, the least soluble nutrient in polyhalite [54], can provide available Ca at rates equivalent to those of gypsum [55]. An increasing number of studies examining the effects of polyhalite application on the performance of various crop species has appeared in recent years [56,57].

We hypothesized that balanced fertilization that included all essential macronutrients and an optimized NPK ratio, would simultaneously improve wax gourd fruit yield and quality and increase nutrient use efficiency. The objective of the present study was to examine, separately and combined, the effects of two crop nutrition options to enhance crop performance: (1) optimization of NPK ratio; (2) supplementary application of polyhalite as the source of Mg, Ca, S, and K (in part). Biomass production and distribution, nutrient uptake, and nutrient allocation between plant organs, as well as fruit firmness, acid, sugar, nutrient ratio, were determined in order to elucidate and explain the effects of the different approaches.

2. Materials and Methods

2.1. Site Description

Two field experiments were carried out in Foshan county (22.98° N; 112.88° E), Guangdong, China, in 2018 (27 March–25 June) and in 2019 (27 March–22 June). The climate of this region is subtropical marine monsoon and precipitation during the growing period was 890 and 1065 mm, in 2018 and 2019, respectively. The mean daily temperature during the growing seasons ranged from 17–32 °C and from 16–33 °C, with daily averages of 25.3 and 24.6 °C, in 2018 and 2019, respectively. Soil chemical properties prior to planting each year are detailed in Table 1.

2.2. Experimental Design

Experiments included four treatments of fertilizer management: 1. Conventional farmers' fertilization practice in the region, assigned FP NPK; 2. Fertilizer applied at an optimum NPK ratio, assigned Opt NPK; 3. Conventional practice, fortified using polyhalite, assigned FP NPK + polyhalite; 4. Optimal NPK ratio, fortified using polyhalite, assigned Opt NPK + polyhalite. A detailed description of the treatments is given in Table 2.

Table 1. Chemical properties of the top of the soil profile (20 cm depth), measured prior to sowing in years 2018 and 2019.

Soil Property	2018	2019
pH	6.3	6.2
Ammonium N (mg kg^{-1})	0.01	0.01
Nitrate N (mg kg^{-1})	32.3	31.2
P (Olsen) (mg kg^{-1})	22.3	8.07
Available K (mg kg^{-1})	204.8	105.9
Exchangeable Ca (mg kg^{-1})	1792	1711
Exchangeable Mg (mg kg^{-1})	191.8	186.0

Table 2. Nutrient application rates according to the four fertilizer treatments of the experiments.

Treatment	Nutrient Input (kg ha^{-1})					
	N	P_2O_5	K_2O	CaO	MgO	SO_3
FP NPK	401	401	401	0	0	0
Opt NPK	427	214	481	0	0	0
FP NPK + polyhalite	401	401	401	404	143	1140
Opt NPK + polyhalite	427	214	481	404	143	1140

In all treatments, 40% of the fertilizer was applied pre-planting and 60% was applied after planting, in accordance with local farmers' practice. The FP NPK and Opt NPK treatments were applied with the solid composite NPK fertilizers 15:15:15 and 16:8:18, respectively. The optimum dose and NPK ratio for the Opt NPK treatment was based on comprehensive information gathered from soil tests, literature [58], and expert recommendations. Since polyhalite includes a considerable K_2O portion (14%), other fertilizers were used to ensure NPK dose and ratio for the remaining treatments were consistent: urea was used to supply N, mono-ammonium phosphate supplied N and P, and potassium sulphate (K_2SO_4), as well as polyhalite supplied K and S. Polyhalite added Mg and Ca. The experiments were designed in complete random blocks with four replications. The dimensions of each experimental plot were 3.5 m by 5.6 m. Ridges, 300 cm wide and 30 cm high, were prepared and two 50 cm wide furrows were opened. Wax gourd seedlings were transplanted in two rows with a spacing of 250 cm and 70 cm between rows and plants in a row, respectively. Plots were hand weeded, and disease and pest management was executed whenever required according to the local recommendations.

2.3. Sampling and Measurements

Three months after transplanting, fruit was harvested, and fruit yield was determined. Eight representative fruit were sampled from each treatment and used to determine physical and nutritional parameters. Fruit firmness was measured using FHM-5 durometer (Takemura Electric Works Co., Ltd., Tokyo, Japan) with a conical probe (tip diameter 12 mm, height 10 mm). External firmness was determined by two readings taken from each fruit at two pared surfaces on the equator to 1 cm depth. For internal (pulp) firmness, about 1 cm^2 was peeled from two locations on the fruit equator and the durometer was employed to 1 cm depth. Titratable acid (TA) was determined using sodium hydroxide titration [59]. Total soluble sugars (TSS) were determined using anthrone colorimetry [60]. Fruit peel color was determined using CM-600d Spectrophotometer (Konica-Minolta Sensing Americas, Ltd., Ramsey, NJ, USA) and the results were expressed in parameters L, a, and b, related to visual perception [61].

At harvest, all aboveground organs were collected from each plot, separated to leaves, petioles, and stems, and weighed to determine fresh weight. Samples were taken from each organ (including fruit), weighed, dried at 105 °C until a constant mass was reached, and weighed to determine dry matter content. The distribution of dry matter among all plant organs was calculated.

Dried plant material was ground to a fine powder. Fifty mg samples of each organ, five replicates per plot, were predigested using HNO_3 and H_2O_2, and then microwaved for 2 h. The amounts of P, K, Mg, Ca, and S in the extracts were determined using ICP-AES, and N was assayed colorimetrically with a discrete auto-analyzer (SmartChem200, WestCo, Westborough, MA, USA). The quantities of N, P, K, Mg, Ca, and S in each plant organ were calculated, giving the nutrient uptake by the crop (kg ha^{-1}), and nutrient distribution among the plant organs. Nutrient recovery rate was calculated for N, P, and K through dividing nutrient uptake by application rates, expressed as a percentage.

2.4. Statistical Analyses

Data were subjected to one-way analysis of variance (ANOVA) using SPSS Version 21 software package. In case of significant treatment effects, a comparison of means was performed using Duncan's multiple range test method at a significance level of 5%.

3. Results

3.1. Fruit Yield

Wax gourd fruit yield under farmers' usual fertilization practice (Treatment FP NPK) was 108 and 87 Mg ha^{-1}, in 2018 and 2019, respectively (Figure 1). When NPK ratio was changed from 15:15:15 and optimized to 16:8:18 (Treatment Opt NPK), fruit yields rose by 2–3%, which was statistically insignificant. When polyhalite was supplemented to the farmers' fertilization practice, the increase in fruit yield was significant, increased by 16 and 9% in 2018 and 2019, respectively. The combination of optimized NPK ratio and supplemental polyhalite gave rise to a slight, insignificant, further yield rise (Figure 1).

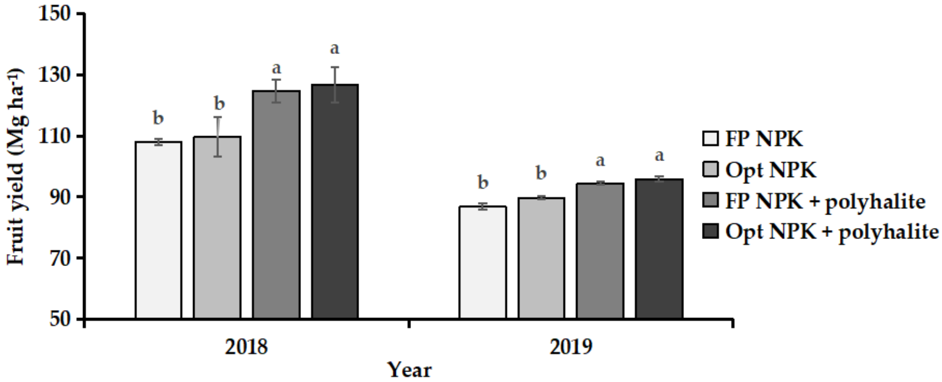

Figure 1. Effects of modified fertilizer NPK ratio and supplemental polyhalite on wax gourd fruit yields in 2018 and 2019. Please refer to Table 2 for a detailed description of fertilizer treatments. Different letters indicate statistical differences between treatments within a year ($p < 0.05$).

3.2. Fruit Quality

External fruit firmness at harvest was significantly increased in response to polyhalite application, while NPK optimization had no effect (Table 3). Effects on the internal fruit firmness, which was considerably lower than the external firmness, displayed a similar pattern; it was significantly increased by polyhalite application, while an obvious advantage from NPK optimization was only recorded when combined with polyhalite (Table 3).

Polyhalite application resulted in a significant reduction in the titratable acid, as well as a significant increase in the total soluble sugars, at harvest (Table 3).

In contrast, no significant influence of NPK optimization could be observed. Consequently, the sugar/acid ratio under supplemented polyhalite was 20–21, much higher than under the two NPK controls.

Table 3. Effects of modified fertilizer NPK ratio and supplemental polyhalite on wax gourd fruit quality parameters at harvest. Values are means of two-year measurements. Means followed by different letters indicate significant differences within a column ($p < 0.05$; n = 8).

Treatment	Firmness (kg)		Titratable Acid (%)	Total Soluble Sugars (%)	Sugar/Acid Ratio
	External	Internal			
FP NPK	2.62 ± 0.04 b	1.11 ± 0.05 c	0.43 ± 0.06 a	4.70 ± 0.05 b	10.93 b
Opt NPK	2.63 ± 0.02 b	1.17 ± 0.03 c	0.37 ± 0.06 ab	4.96 ± 0.32 b	13.40 b
FP NPK + polyhalite	3.05 ± 0.07 a	1.38 ± 0.03 b	0.29 ± 0.02 b	5.86 ± 0.31 a	20.20 a
Opt NPK + polyhalite	3.13 ± 0.03 a	1.48 ± 0.02 a	0.27 ± 0.02 b	5.73 ± 0.27 a	21.22 a

Color parameters (L, a, b) of FP NPK fruit at harvest differed significantly from those of the other treatments (Figure 2); these fruit tended to lighter (Figure 2A), greener (Figure 2B) and towards the more yellow (Figure 2C) edges of the color scale. Optimized NPK application significantly shifted fruit color to the red and blue edges of the scale (less green and yellow), while polyhalite application enhanced this tendency only in 2018 (Figure 2B,C). Overall, optimized NPK treatments, and to a lesser extent polyhalite application, displayed inhibiting effects on some external ripening symptoms, manifested by fruit appearance (Figure 2D).

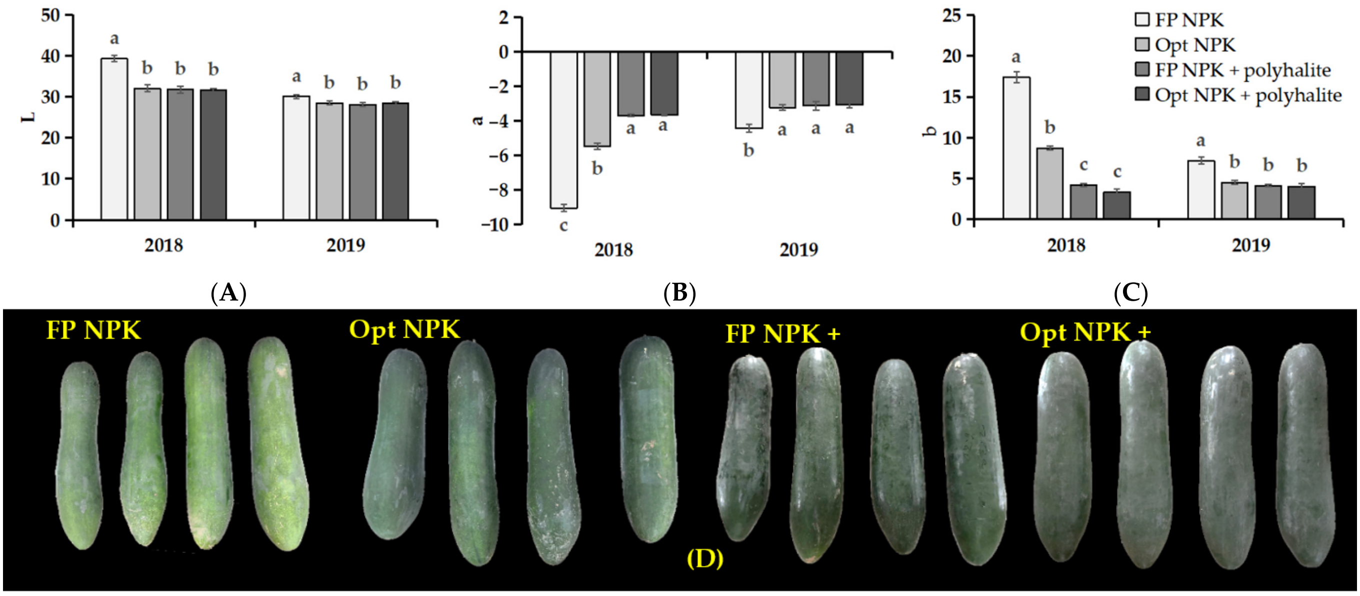

Figure 2. Effects of modified fertilizer NPK ratio and supplemental polyhalite on wax gourd fruit color (L, a, b parameters) at harvest, in 2018 and 2019. Parameter L stands for lightness (**A**); a stands for a scale of change from green (−) to red (+) (**B**); b presents a scale of change from blue (−) to yellow (+) (**C**). Representative fruit for each treatment (**D**). A detailed description of fertilizer treatments is given in Table 2. Different letters indicate statistical differences between treatments within a year ($p < 0.05$).

3.3. Crop Aboveground Biomass and Dry Matter Partitioning

Optimizing NPK ratio alone resulted in an insignificant tendency to increase the total aboveground dry matter production, as determined at harvest (Figure 3A). In contrast, supplementary polyhalite application caused a significant increase in dry matter production, about 40% more than under the FP NPK control. A similar pattern was recorded for the dry matter in leaves, which increased by more than 30% in response to polyhalite, but it was hardly affected by NPK optimization (Figure 3B). In contrast, fertilization treatments did not bring about any significant change in the dry matter of stems and petioles (Figure 3C,D). Polyhalite influence was most evident on the fruit dry matter, which increased by 49%

compared to the FP NPK treatment. Optimizing NPK only produced a slight rise in fruit dry matter, 8–11%, which was statistically insignificant; however, both changes together induced a 57% increase in the dry matter allocated to fruit (Figure 3E). As a result, the harvest index rose from 0.637 to 0.701, mainly due to the polyhalite impact, and to a lesser extent, to the modified NPK ratio (Figure 3F).

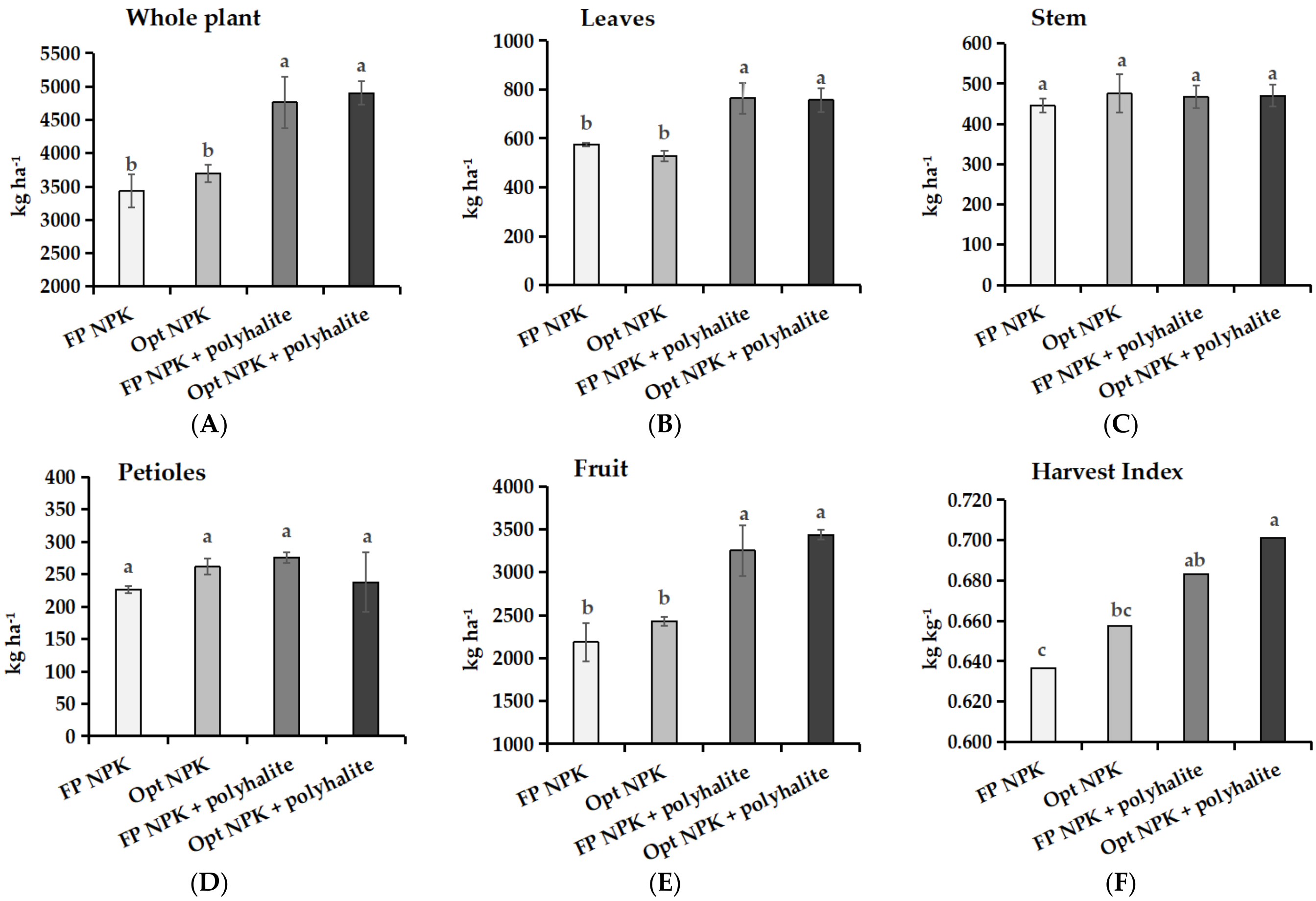

Figure 3. Effects of modified fertilizer NPK ratio and supplemental polyhalite on dry matter production (**A**) and partitioning between leaves (**B**), stems (**C**), petioles (**D**), fruit (**E**), and harvese index (**F**) in wax gourd crop. Different letters indicate statistical differences between treatments ($p < 0.05$).

3.4. Nutrient Uptake and Recovery

Nutrient concentrations in the dry matter of plant organs at harvest were used to calculate nutrient uptake (Figure 4). Supplementary polyhalite caused an increase in N uptake from 75 to 105 kg ha^{-1} (Figure 4A); however, this response completely corresponded with the increase in biomass production (Figure 4G). Modified NPK ratio had no significant effect on N uptake. Similar response patterns to application of polyhalite were observed for most other nutrients: considerable increases in P, K, Mg, and Ca uptake, and a slighter increase in S uptake (Figure 4B–F). In contrast to the poor response of most nutrient uptake from the modified NPK ratio, P uptake, and furthermore, K uptake, did rise, but to a much smaller extent. In general, nutrient uptake/biomass growth ratio of P, K, and S declined from 1.00 (FP NPK control) to 0.90–0.95 in response to the fertilizer treatments, Mg remained stable at 1.00, and Ca increased to about 1.05 (Figure 4G).

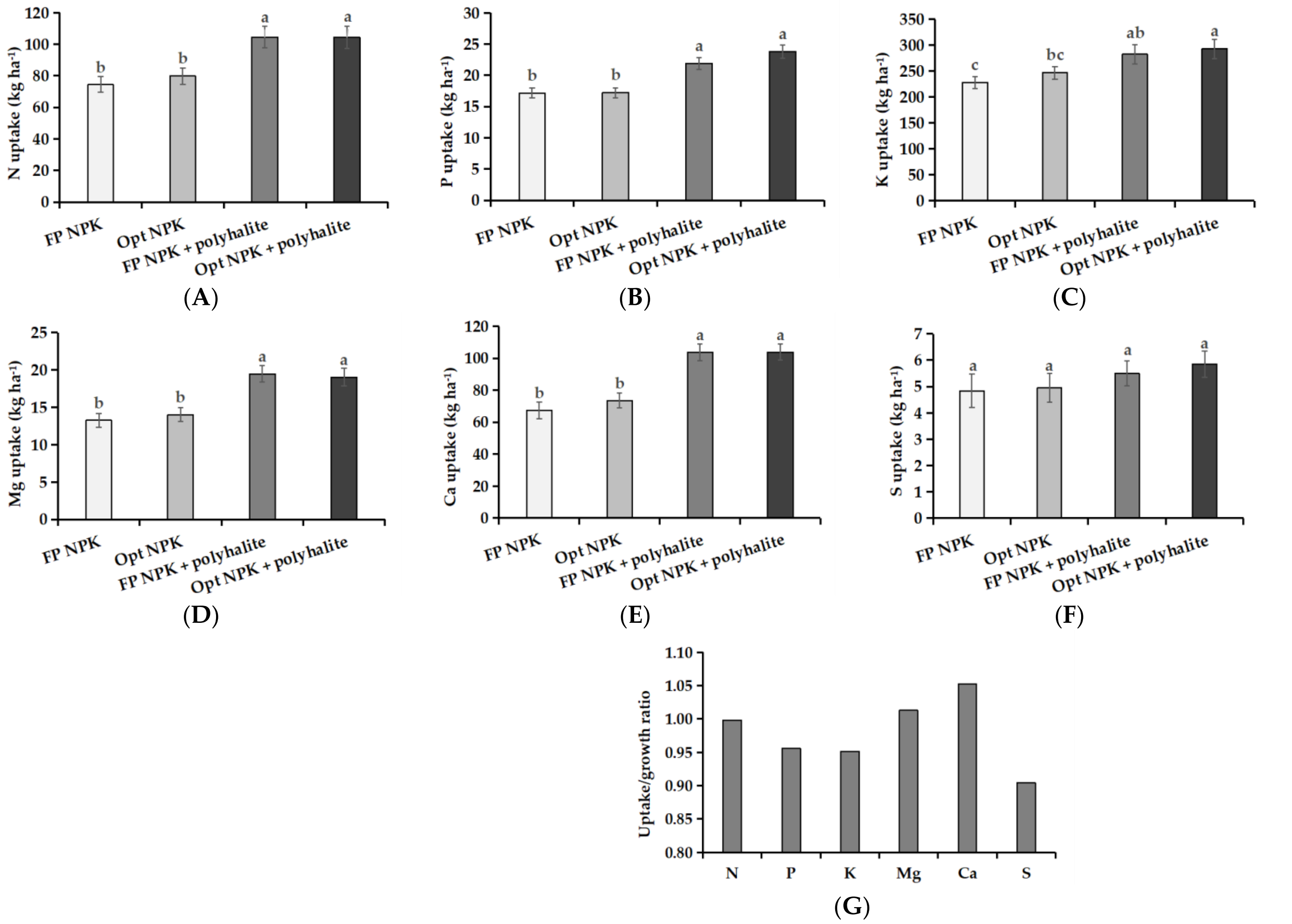

Figure 4. Effects of modified NPK fertilizer ratio and supplementary polyhalite on nutrient uptake (**A**–**F**) and on the ratio between nutrient uptake and biomass growth (**G**) in wax gourd at harvest. Different letters indicate statistical differences between treatments ($p < 0.05$).

Nitrogen recovery by wax gourd was hardly affected by the modified NPK ratio, remaining below 20%, but it increased considerably to about 25% in response to polyhalite application (Figure 5A). In contrast, P recovery was much more sensitive to the modified NPK ratio and was less affected by polyhalite. P recovery doubled in the optimized NPK treatment, despite the reduction in the proportion of p applied, while polyhalite contribution to the rise in P recovery was smaller (Figure 5B). Potassium recovery in the present experimental system varied in the range 50–70%, much higher than the rates of N and P. Interestingly, the optimized NPK ratio slightly reduced K recovery, whereas polyhalite application promoted its increase (Figure 5C).

3.5. Nutrient Allocation

The general pattern of nutrient allocation between fruit, leaves, stems and petioles, the main aboveground plant organs is shown and compared to dry matter allocation in Figure 6. Among the six nutrients examined, Mg and Ca allocation differed substantially from the dry matter allocation. Magnesium and Ca accumulated in wax gourd leaves (33 and 58%, respectively) and in the petioles (11 and 11%, respectively) at the expense of the fruit (51 and 25%, respectively) and stems (5 and 6.5%, respectively). Dry matter allocation to fruit, leaves, stem, and petioles was 67, 16, 11, and 6%, respectively (Figure 6A). Potassium was allocated to petioles (10%) at the expense of leaves (9.5%). Nitrogen, P, and S allocation corresponded to that of dry matter, with slight deviations (Figure 6A).

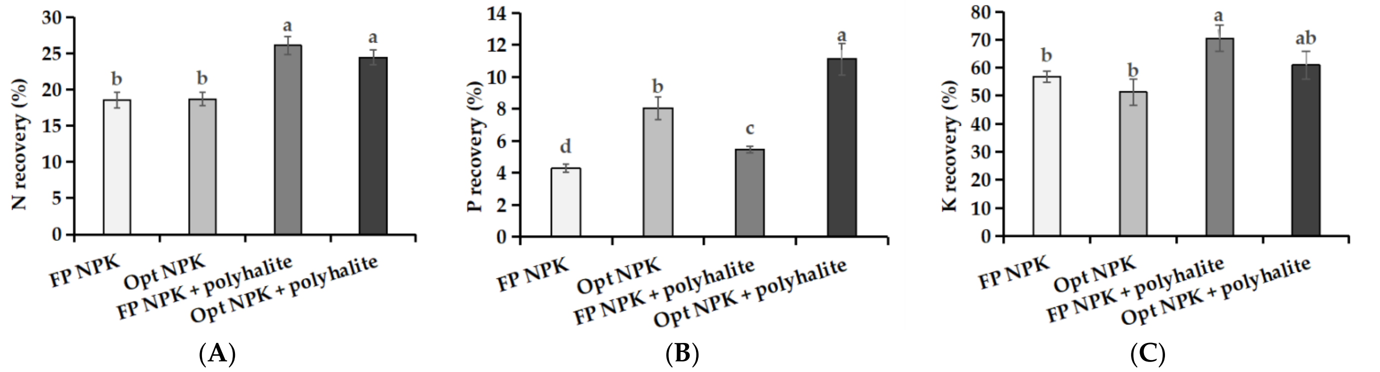

Figure 5. Effects of optimized NPK fertilizer ratio and supplemental polyhalite on nutrient recovery (**A**–**C**) in wax gourd. Different letters indicate statistical differences between treatments ($p < 0.05$).

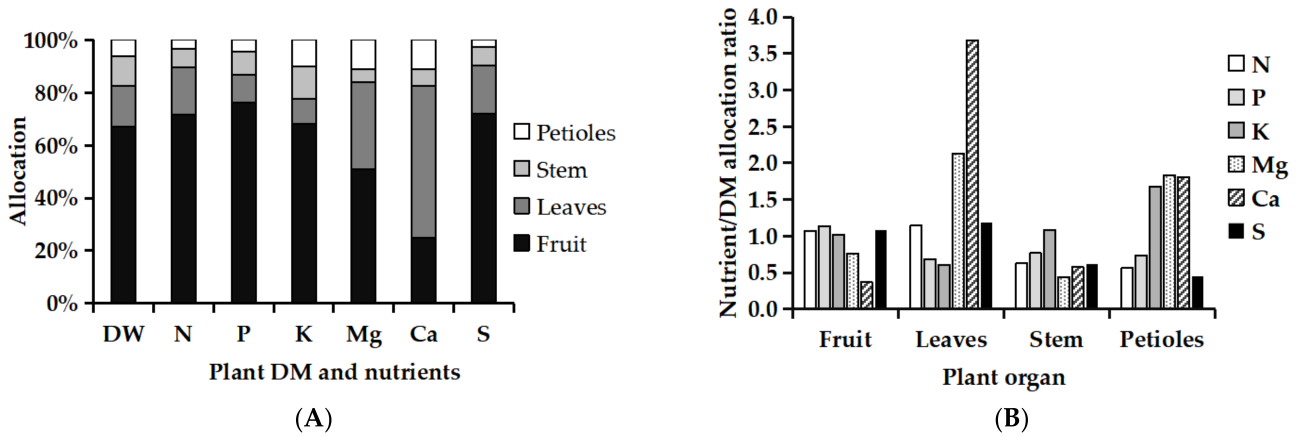

Figure 6. Dry matter and nutrient allocation among plant organs in wax gourd. Mean allocation rates (**A**); nutrient/dry matter allocation ratio in fruit, leaves, stem, and petioles of wax gourd (**B**).

The ratio between nutrient allocation and dry matter allocation to specific plant organs may indicate particular nutritive requirements or demands (Figure 6B). Thus, N, P, K, and S demands by wax gourd fruit correspond with that for overall dry matter, indicating that fruit retained an ordinary sink type for these nutrients. Nevertheless, fruit retained obviously weaker demands for Mg and Ca. Wax gourd leaves, in contrast, retained extraordinarily high demands for Mg and Ca, regular demands for N and S, and weaker demands for P and K. The stem has weak demand for most of the nutrients, excluding K. Wax gourd petioles retained strong demands for K, Mg, and Ca, and weak demands for N, P, and S (Figure 6B).

Nitrogen allocation among plant organs was hardly affected by optimized NPK ratio nor by polyhalite application (Figure 7). Optimized NPK ratio, and to some extent polyhalite application, shifted P from fruit and petioles to leaves and stems. Polyhalite application slightly increased K allocation into leaves, stem, and petioles at the expense of fruit. Both fertilizer treatments shifted Mg from fruit mainly to leaves, and to a lesser extent to stem and petioles. Calcium allocation to leaves and petioles slightly increased in response to modified NPK ratio, whereas polyhalite tended to reduce Ca flow to petioles. Polyhalite shifted S from fruit to leaves, stem, and petioles, while modified NPK ratio promoted S allocation to stem and petioles (Figure 7).

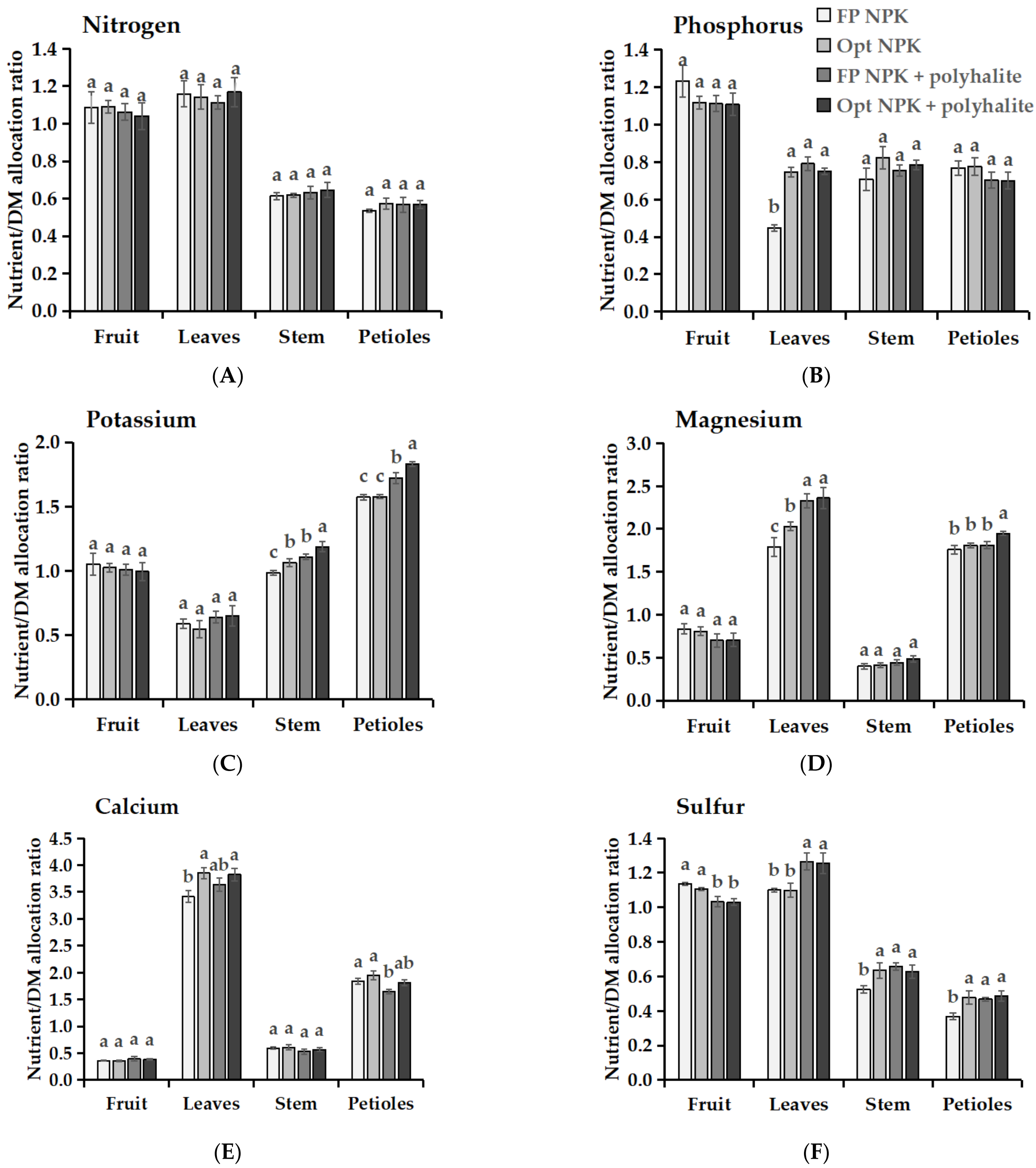

Figure 7. Effects of optimized NPK fertilizer ratio and supplementary polyhalite on the ratio between nutrient allocation and dry matter allocation to the main aboveground organs of wax gourd plants. Different letters indicate statistical differences between treatments ($p < 0.05$).

Ratios between cations such as K/Ca, K/Mg or (K+Mg)/Ca in certain plant organs might have metabolic and physiological significances. The rates of each ratio substantially differ between fruit, leaves, stem, and petioles (Table 4), Thus, K/Ca in wax gourd fruit was as high as 7–10, compared to very low value in leaves (about 0.5), and to moderate values in stem and petioles, about 5.8 and 2.8, respectively. Very similar patterns and values were observed for (K+Mg)/Ca (Table 4). Potassium/Mg was extremely high, 36–46, in the stem, about 22 in fruit, 15 in petioles, and only 4–6 in leaves (Table 4).

Table 4. Effects of optimized NPK fertilizer ratio and supplemental polyhalite on three cation ratios: K/Ca, K/Mg, and (K+Mg)/Ca, in main aboveground organs of wax gourd plants. Means followed by different letters differ significantly within an organ for each cation ratio ($p < 0.05$).

Organ	Treatment	Cation Ratio		
		K/Ca	K/Mg	(K+Mg)/Ca
Fruit	FP NPK	9.86 a	21.7 a	10.3 a
	Opt NPK	9.70 a	22.4 a	10.1 a
	FP NPK + polyhalite	7.00 b	20.9 a	7.3 b
	Opt NPK + polyhalite	7.34 b	21.7 a	7.7 b
Leaves	FP NPK	0.58 a	5.65 a	0.69 a
	Opt NPK	0.48 b	4.75 b	0.58 b
	FP NPK + polyhalite	0.48 b	3.98 c	0.60 b
	Opt NPK + polyhalite	0.48 b	4.24 bc	0.59 b
Stem	FP NPK	5.65 b	42.4 a	5.78 b
	Opt NPK	5.87 a	45.5 a	6.00 a
	FP NPK + polyhalite	5.69 b	36.4 b	5.84 b
	Opt NPK + polyhalite	5.90 a	37.7 b	6.06 a
Petioles	FP NPK	2.90 a	15.4 a	3.09 a
	Opt NPK	2.72 a	15.4 a	2.89 b
	FP NPK + polyhalite	2.84 a	13.8 b	3.05 a
	Opt NPK + polyhalite	2.86 a	14.5 a	3.06 a

Interestingly, polyhalite application significantly reduced K/Ca and (K+Mg)/Ca ratios in wax gourd fruit, as well as K/Mg ratio in leaves and stem (Table 4). Modified NPK ratio slightly reduced all three cation ratios in leaves.

4. Discussion

Vegetable crop production in China has experienced significant progress in recent decades. Improved fertilizer practices, namely systematic NPK application, can be especially credited to this progress. Nevertheless, substantial yield gaps still occur, and concerns grow relating to negative environmental consequences of excessive fertilizer application [20,27,61]. Several studies highlight that further improvement and optimization of fertilizer practices seem necessary [25,26,62,63]. In the present study, two different approaches were tested, separately and combined, aiming to evaluate yield and quality, and to make wax gourd production more efficient: 1. optimization of NPK ratio; 2. application of supplementary nutrients—Mg, Ca, and S—using polyhalite.

The first approach, optimization of NPK ratio, was examined through the reduction in P application rate by half, modifying NPK ratio from 15:15:15 to 16:8:18 (Table 2). The influence of this approach on wax gourd performance was quite poor or marginal. It did not affect the total dry matter production and yield, but slightly reduced chlorophyll degradation in the fruit peel (Figure 2), as well as faintly enhancing dry matter allocation to fruit (Figure 3F). The main advantage gained through modified NPK ratio was a considerable enhancement of the agricultural efficiency of P application, indicated by P recovery (Figure 5B). However, this was a direct outcome of the absolute irresponsiveness of P uptake to the change in NPK ratio (Figure 4B). Reduced P rate, as applied in the modified NPK ratio, also enhanced the allocation of P, Mg, and Ca to the leaves (Figure 7). These results clearly indicate that the currently recommended P application rate for wax gourd is much higher than required. Furthermore, N and P recovery rates were very low, 18 and 4%, respectively; however, the common N and P application rates easily supported the higher production and yield rates obtained by supplementary polyhalite application (Figures 1 and 3). Moreover, the optimum NPK ratio requirements significantly change according to the crop developmental stage [14,15,20–22]. Additionally, due to inadequate information regarding wax gourd nutrient requirements, the results of the present study call for further fine-tuning of the optimum NPK ratio for this crop, focusing on minimizing

N and P application rates, and on accurate adjustment of NPK application ratio to crop developmental stages.

The use of supplementary polyhalite had remarkable effects on most of the crop performance parameters. It enhanced total aboveground dry matter production (Figure 3), increased fruit yield (Figure 1), and improved produce quality (Figure 2 and Table 3). Interestingly, polyhalite enhanced internal fruit ripening parameters related to sugar accumulation and organic acids degradation. However, simultaneously, it maintained higher fruit firmness (Table 3) and decelerated chlorophyll degradation pathways in the fruit peel (Figure 2C). These effects resulted in a quite rare but desired combination of improved palatability with prolonged shelf life. The results highlight the significance of nutrients provided by polyhalite, including Mg, Ca, and S, as well as possible interactions they may have with NPK that altogether improve wax gourd crop performance.

The significant increase in the foliar biomass in response to supplementary polyhalite, 30–40% (Figure 3B), is fundamental to any further improvement of crop performance. Adequate leaf area is the engine of dry matter production and a prerequisite to the fruit yield increment obtained later on (Figures 1 and 3E). Uptake of all nutrients increased in response to supplementary polyhalite (Figure 4), as an anticipated consequence of the rise in total crop dry biomass (Figure 3A). While polyhalite enriched the soil with remarkable amounts of S (Table 2), no direct significant impact of this nutrient on uptake, allocation, or fruit yield and quality could be observed in the present case. However, the well-known synergism between N and S in protein metabolism [45,47,64,65] might have contributed to the improvement in crop performance. In contrast, Mg and Ca were the only nutrients that increased their uptake/growth ratio (Figure 4G), indicating a possible deficiency in these nutrients in the first place. Magnesium and Ca were found to be allocated predominantly to leaves, at much higher level than the proportion of leaves in crop biomass (Figure 6). Magnesium is central in every chlorophyll molecule and therefore essential to photosynthesis, carbon assimilation, and hence, to dry matter production [12,24]. This nutrient is also responsible for enzyme activation in numerous metabolic pathways [12], promotes phloem loading and carbon transport and allocation to sink organs [21,24,33]. Furthermore, optimum plant Mg status enhances crop tolerance to abiotic stresses [35]. Thus, along with the particular increase in uptake/growth ratio of Mg (but not of Ca) in leaves (Figure 7) in response to polyhalite, the vital role of Mg in leaf function and plant growth and development is clearly demonstrated.

Similarly to Mg, Ca uptake by wax gourd crop increased in response to supplementary polyhalite (Figure 4E), and relatively, even beyond polyhalite contribution to the increment in crop dry matter production (Figure 4G). Calcium is essential for a broad spectrum of plant growth and functions that can be classified as structural or regulatory [12]. Reasonably, the increased Ca availability must have contributed to the general improvement in crop performance in the present study. However, Ca role in fruit quality requires special attention. This nutrient is known to facilitate developmental and stress response signaling, stabilize membranes, influence water relations and modify cell wall properties through cross-linking of de-esterified pectins, thus having significant impacts on the development, physical traits and disease susceptibility of fruit [41]. It appears, therefore, that in spite of the relatively small proportion of Ca allocation to fruit (Figure 6), it made a major contribution to the improved fruit quality with supplementary polyhalite (Table 3 and Figure 2).

Polyhalite contribution to K status, and consequently to crop performance, is difficult to evaluate in the present study. Potassium uptake increased with the application of polyhalite but to a lesser rate when compared to the rise in total dry matter (Figure 4C,G), which may indicate surplus K nutrition. In contrast, K recovery increase (Figure 5C) may be due to the slower release rate of nutrients from polyhalite [53]. High K availability is particularly important during the late stages of fruit development, towards ripening [51], in accordance with the role of K in carbohydrate transport and accumulation [16,17]. Interestingly, polyhalite enhanced K allocation particularly to petioles (Figure 7), which retained a relatively strong sink for K, Mg, and Ca (Figure 6), pointing to their special role governing carbohydrate translocation in cucurbitaceae [66].

Nutrient concentration ratios such as K/Ca and (K+Mg)/Ca, rather than individual nutrient concentration, may provide accurate fruit quality indicators, in addition to total soluble solids and titratable acidity [39]. Towards fruit ripening, excessive K/Ca ratio negatively affects membrane selectivity and cell wall integrity [67] and hence reduces produce shelf life [42]. In apples, a negative correlation occurred between high K/Ca and fruit firmness at harvest [68]. Additionally, high fruit K/Ca was associated with increased incidence of undesirable texture and fruit diseases [69] (Sharples, 1985). Additionally, high (K+Mg)/Ca ratio was associated with high titratable acidity in fruit juice [36,70]. Although polyhalite application increased the uptake of all three nutrients (Figure 4), Ca allocation to fruit was sufficiently high to produce significantly lower K/Ca and (K+Mg)/Ca ratios that might have been responsible for the higher fruit quality traits (firmness and sugar/acids ratio) obtained with polyhalite (Table 3).

The interaction between K and Mg is complex [37,39]. Both nutrients are essential in carbohydrate metabolism and transport [71]; however, antagonistic effects between K and Mg might occur under high K/Mg ratios [37]. In the present study, polyhalite supply did not affect K/Mg in fruit, but simultaneously, this ratio declined significantly in leaves and stem (Table 4). This situation might have intensified phloem loading in source leaves, as well as further sugar accumulation in fruit (Table 3). It appears, therefore, that polyhalite contribution to wax gourd Mg and Ca uptake was greater than some antagonistic effects that may have arisen from the excess K uptake.

5. Conclusions

Two crop nutrition options were examined in the present study, separately and combined, aiming at enhancing wax gourd fruit yield and quality, while reducing negative environmental consequences of fertilizer management. The first option, which focused on optimization of the NPK ratio, demonstrated that a significant reduction in P application rate had no effect on fruit yield or quality. The second option, enriching the soil with polyhalite as a source of Mg, Ca, and S, and supplementary K at a slower release rate, gave rise to enhanced crop performance, and to significant improvement of fruit yield and quality. Combining the two options creates a balanced and precise crop nutrition strategy that offers improved yield and quality, increased nutrient use efficiency, and reduced risks of nutrient pollution. Nevertheless, plenty of space remains for studies of further adjustments to NPK application management, focusing on reduced rates, optimized ratio, and accurate timing of application for each nutrient. The commodity value of wax gourd is mainly determined by yield and appearance quality. Fruit shape not only affects the yield, but also is an important basis for the classification and grading of wax gourd. In the future work, we will continue to study the physiological mechanism of nutrition regulation on fruit quality, to provides the theory basis for improving the quality of shape.

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