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Pomelo Green Production on Acidic Soil: Reduce Traditional Fertilizers, but Do Not Ignore Magnesium

Xiaohui Chen[1,2,3†], *Xiaojun Yan*[1†], *Muhammad Atif Muneer*[1], *Xuefan Weng*[4], *Yuanyang Cai*[5], *Changcheng Ma*[1], *You Liu*[1], *Siwen Zhang*[1], *Weiqiang Zhang*[1], *Wenhao Yang*[1], *Liangquan Wu*[1*], *Shungui Zhou*[3] and *Fusuo Zhang*[1,2]

[1] *International Magnesium Institute, College of Resources and Environment, Fujian Agriculture and Forestry University, Fuzhou, China,* [2] *Key Laboratory of Plant-Soil Interactions, Ministry of Education, College of Resources and Environmental Sciences, National Academy of Agriculture Green Development, China Agricultural University, Beijing, China,* [3] *Fujian Provincial Key Laboratory of Soil Environmental Health and Regulation, College of Resources and Environment, Fujian Agriculture and Forestry University, Fuzhou, China,* [4] *College of Economics, Fujian Agriculture and Forestry University, Fuzhou, China,* [5] *College of Plant and Science, Jilin University, Changchun, China*

Orchards in acid soils are at risk of magnesium (Mg) deficiency which negatively affects the plant growth, yield, and quality. However, the impacts of Mg supplementation on fruit yield, quality, and environmental and economic benefits have only been rarely addressed. We conducted 15 pomelo (*Citrus grandis* L.) orchard trials in South China to assess more efficient integrated nutrient management (INM) practices, including local farmer fertilization practices (FP; average application rate of nitrogen, phosphorus, and potassium were 1,075 kg N ha^{-1}, 826 kg P_2O_5 ha^{-1}, and 948 kg K_2O ha^{-1}, respectively), optimum fertilization practice (OPT; average application rate of nitrogen, phosphorus, and potassium were 550 kg N ha^{-1}, 295 kg P_2O_5 ha^{-1}, and 498 kg K_2O ha^{-1}, respectively) and optimum fertilization supplemented with Mg (OPT+Mg; average application rate of Mg was 196 kg MgO ha^{-1}). The results showed that the yield, total soluble solid-to-titratable acidity ratio, and economic benefits under OPT practice were not significantly different from those of FP, while those of OPT+Mg were significantly higher than those of FP, by 8.76, 8.79, and 15.00%, respectively, while titratable acidity contents were significantly lower by 7.35%. In addition, compared with those from FP, the energy inputs and greenhouse gas (GHG) emissions from OPT were 31.00 and 26.48% lower, and those from OPT+Mg were 26.71 and 23.40% lower, respectively. Compared with those of OPT, the marginal efficiency of energy, GHG emissions, and capital of Mg under OPT+Mg were reduced by 62.30, 44.19, and 21.07%, respectively. Overall, adopting OPT+Mg for pomelo production could further enhance yield, fruit quality, and economic benefits while reducing the environmental burdens.

Keywords: magnesium fertilizer, yield, energy balance, greenhouse gas emission, economic benefit

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Shaghef Ejaz,
Bahauddin Zakariya
University, Pakistan

Reviewed by:
Muhammad Qayyum,
Bahauddin Zakariya
University, Pakistan
Zhao Xiao Hu,
Huazhong Agricultural
University, China

Correspondence:
Liangquan Wu
liangquan01@163.com

†These authors have contributed equally to this work and share first authorship

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KEY POINTS

- Agronomic-environmental-economic indicators of pomelo production are evaluated.
- Integrated nutrient management (INM) practices can increase fruit yield and quality.
- INM practices reduced energy inputs by 23–27% and GHG emissions by 27–31%.
- INM practices increased the economic efficiency of energy inputs and GHG emissions.
- Magnesium helps to obtain more and better products with lower environmental costs.

INTRODUCTION

Excessive nitrogen (N), phosphorus (P), and potassium (K) fertilizer application in agricultural production has caused severe negative environmental impacts, such as soil acidification (Guo et al., 2010), eutrophication (Conley et al., 2009; Huang et al., 2017), decreased air and water quality (Liu et al., 2013), and global warming (Paerl and Scott, 2010; Steffen et al., 2015). Integrated nutrient management (INM), therefore, is urgently required for the sustainability of higher crop production while improving the soil health and environmental safety (Verma et al., 2010; Yu et al., 2017), which has also been proven to be achievable and highly successful (Chen et al., 2014; Cui et al., 2018). Currently, INM practices are applied to major cereal crops (Nath et al., 2011; Jiao et al., 2018) and greenhouse vegetables (Yang et al., 2016; Wang et al., 2021). However, little is known about the effects of INM in orchard systems. Therefore, it is imperative to address the issues and challenges related to nutrient management in fruit production systems to overcome the problems of poor yield and quality.

Pomelo (*Citrus grandis* L.) is the third major type of citrus in production after mandarin (*Citrus reticulata* L.) and oranges (*Citrus sinensis* L.) (Li et al., 2015). Pinghe County is a key area of pomelo cultivation in China (Wei et al., 2020). However, excessive fertilization has caused various problems in pomelo orchard, such as sharp declines in fruit and soil quality and with a high product carbon footprint in recent years (Zhang et al., 2003; Li et al., 2015; Guo et al., 2019; Chen et al., 2020). Large amounts of N, P, and K fertilizer are applied in this region, but soil magnesium (Mg) deficiency is typically ignored. In contrast, Mg deficiency frequently occurs in orchards (Wallace, 1940; Diao et al., 2013) and can affect yield (Li et al., 2015; Dechen et al., 2016). However, the impacts of Mg on yield and quality improvement in agricultural products have been overlooked (Yan and Hou, 2018; Guo et al., 2020). Recently, a meta-analysis of data from 99 field studies revealed that Mg application could increase crop yield by ∼8.5% (Wang et al., 2020). Therefore, INM for citrus production must address the management of macro-elements and secondary macronutrients such as Mg during crop production system (Hien et al., 2017).

In China, energy consumption and greenhouse gas (GHG) emissions caused by agriculture account for approximately 6 and 17% of the national total energy consumption and GHG emissions, respectively (Dong et al., 2008; Lin and Fei, 2015). More agricultural production will lead to greater energy consumption and carbon emissions (Koondhar et al., 2020). Generally, fertilizer is considered an important factor influencing energy consumption and GHG emissions in different agricultural crop production systems (Moradi et al., 2018; Baran et al., 2020; Khanali et al., 2021). Whereas, reducing fertilizer application is known to reduce energy inputs and GHG emissions (Chen et al., 2020), but it remains unclear whether adding Mg fertilizer with reduced fertilizer inputs would further amplify this efficiency or not?

Overall, in addition to on-farm evaluations of fruit products and economic benefits, understanding and quantifying the environmental costs of fruit production under different nutrient management systems may provide additional information to help identify greener and more efficient INM strategies (Wang et al., 2018). Therefore, this study aims to demonstrate a suitable fertilization strategy for the sustainable production of pomelo in terms of yield, fruit quality, energy inputs, GHG emissions, and economic benefits and to provide a reference for highly intensive and potentially Mg-deficient citrus production worldwide.

MATERIALS AND METHODS

Study Area

The study area is located in Pinghe County (24°02′-24°35′ N, 116°54′-117°31′ E, and 10–1,545 m above sea level), Zhangzhou city, Fujian Province, Southeast China (**Figure 1**). It is characterized by a subtropical oceanic monsoon climate with an annual average temperature of 17.5–21.3°C. The annual precipitation is approximately 1,600–2,000 mm. The soil types in this study area are ferralsols, classified as red soils in the Chinese soil classification (Smith, 2014). Low-elevation mountains and hills are the main landforms in Pinghe County; these landforms are distributed mostly in the valleys and intermountain regions of the Huashanxi Basin, accounting for 91.5% of the total area (www.pinghe.gov.cn).

Field Experimental Design

Fifteen pomelo orchards trials in total were conducted during 2017–2020 in Pinghe County (**Figure 1**) to explore the effects of reduced chemical fertilizers input and their integrated use with Mg fertilizer on the yield, quality, energy balance, GHG emissions, and economic benefits of pomelo production during the entire production and packing process. Urea, superphosphate, potassium sulfate, and magnesium sulfate were used as the sources of N, P_2O_5, K_2O, and MgO in fertilizer, respectively, and were applied to pomelo orchards in each growing season (**Figure 2**). The tested nutrient management practices included local farmer practices (FP; in 10 orchards with 95 trees) as the control and INM strategies, namely, an optimum NPK treatment (OPT; in 13 orchards with 105 trees) and the optimum NPK treatment with magnesium (OPT+Mg; in 13 orchards with 105 trees), as the experimental treatments. The fertilizer application rates for the OPT strategies were determined by agronomist recommendations based on the target yield and the soil fertility level, which varied from field to field (Obreza and Morgan, 2008; Li et al., 2019). The mean fertilizer application rates for N, P_2O_5, K_2O, and MgO have been shown in **Figure 2**. Except for the differences in fertilizer use, all management methods applied to the orchards were the same. The detailed information about the fertilizer usage and other material (energy) inputs are shown in **Supplementary Table 1**. Titratable acid (TA) was determined by the titration method (Jiang et al., 2004), and the total soluble solid (TSS) concentration was measured by a hand-held Brix meter (Japan, PAL-1). The soil physical and chemical properties of the experimental sites have been shown in **Supplementary Table 2**.

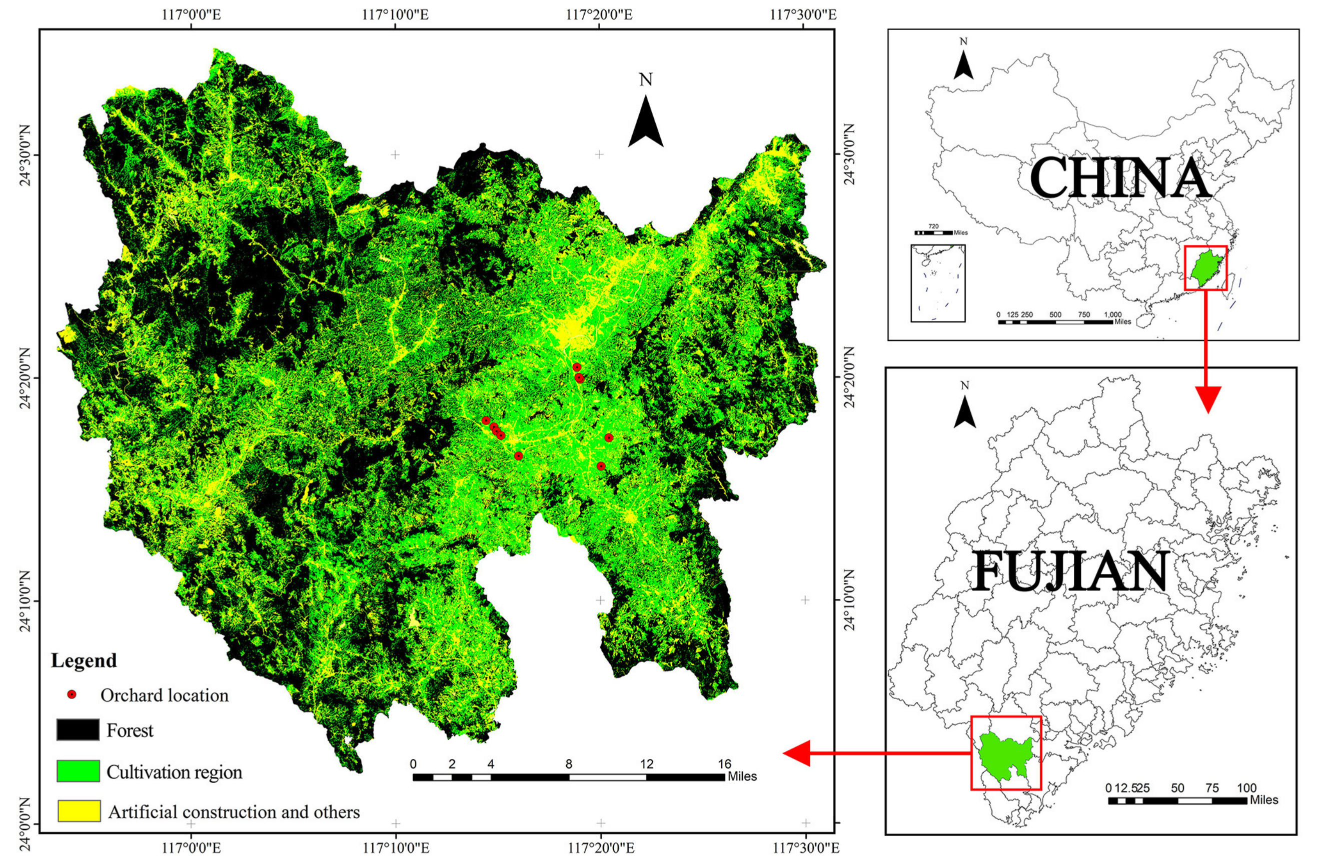

FIGURE 1 | Geographical distribution of field experimental sites within Pinghe County, China, in 2017–2020.

System Boundaries and Functional Units

The system boundaries included the pomelo production upstream stage, the planting stage, and the postharvest stage (**Figure 3**). The upstream stage included all inputs used in pomelo production, such as chemical fertilizers, farmyard manure, pesticides, paper bags (for fruit bagging), diesel fuel, and human labor (considered only as an energy flow). The postharvest stage included electricity, packing bags, and human labor (considered only an energy flow). The energy output in the planting stage was highly dependent on the pomelo harvest, and the GHG emissions (in carbon dioxide equivalents; CO_2 eq) from the planting stage included direct nitrous oxide (N_2O), indirect N_2O (ammonia (NH_3) emissions, and nitrate (NO_3^-) runoff and leaching), and methane (CH_4) (IPCC, 2019; Chen et al., 2020). The functional units for pomelo production were one ton (t) of fresh product and one hectare (ha) of orchard area.

Energy and GHG Emission Quantification

The energy inputs, energy outputs, and net energy outputs of pomelo production were estimated using the following equations (Equations 1–3). The energy input per unit area (ha) was calculated as the sum of the partial energy equivalent of each input used in GJ ha^{-1} (GJ = 10^9 J).

$$\text{Energy Input (GJ ha}^{-1}\text{)} = \sum (I_I \times EE_i) \tag{1}$$

$$\text{Energy Output} = \text{Yield} \times EE_{pomelo} \tag{2}$$

$$\text{Net Energy Output} = \text{Energy Output} - \text{Energy Input} \tag{3}$$

Where I represent the kind of input, I_i is the amount of the ith input, EE_i is the energy equivalent of the ith input, and EE_{pomelo} represents the energy equivalent of the pomelo output.

The GHG emissions (t CO_2 eq ha^{-1}) were calculated using the following equations (Equations 4–9). The upstream GHG emissions per unit area (ha) were calculated as the sum of the partial CO_2 emissions of each input used in pomelo production. The GHG emissions in the planting stage were estimated as described in Chen et al. (2020). The postharvest GHG emissions per unit area (ha) were calculated as the sum of the partial CO_2 emissions from each input used in the pomelo

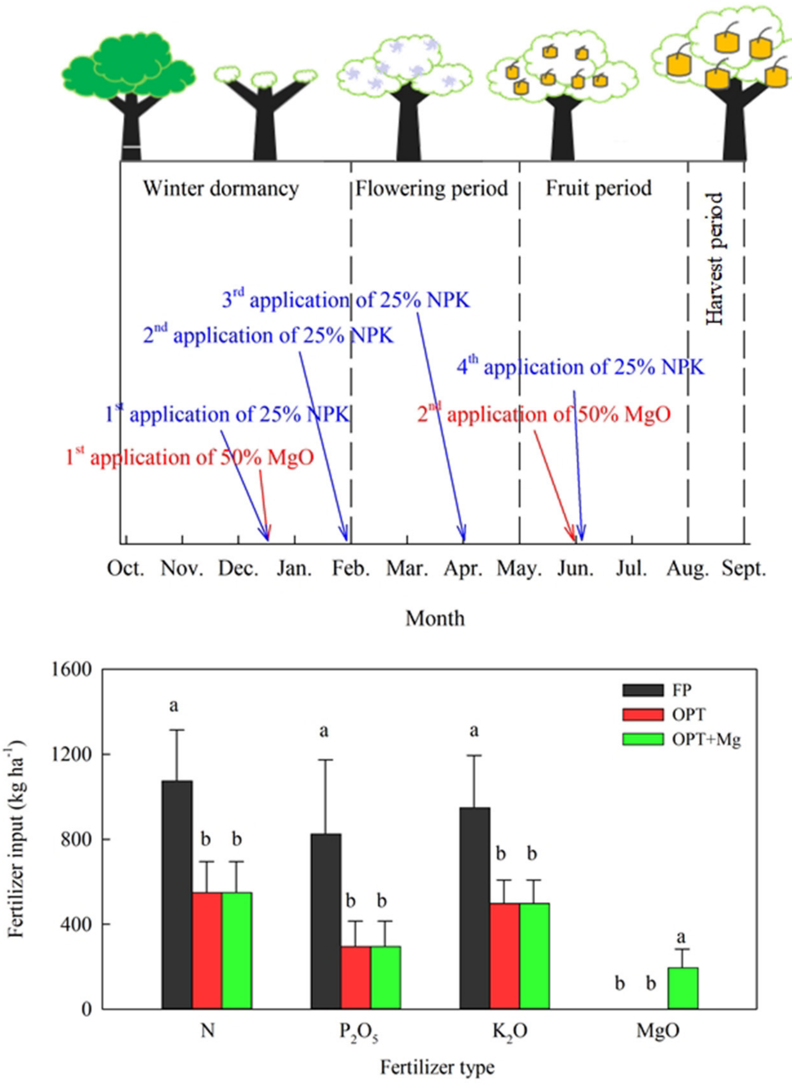

FIGURE 2 | Chemical fertilizer application time and amount in the different treatments of pomelo production. The black error bars in the figure indicate the overall standard deviations (SDs). Different letters above histogram bars indicate statistically significant differences at $P < 0.05$.

postharvest stage.

$$\begin{aligned}\text{GHG Emissions} &= \text{GHG}_{\text{upstream}} + \text{GHG}_{\text{plant}} \\ &\quad + GHG_{\text{postharvest}}\end{aligned} \tag{4}$$

$$\text{GHG}_{\text{upstream}} = \sum (\text{Ij} \times \text{EFj}) \tag{5}$$

$$\begin{aligned}\text{GHG}_{\text{plant}} &= \text{GHG Emission}_{\text{N2O}} \\ &\quad + GHG\ Emission_{\text{CH4}}\end{aligned} \tag{6}$$

$$\begin{aligned}\text{GHG Emission}_{\text{N2O}} &= \{C_N \times (1.2\% + 10.8\% \times 0.01 + 10.0\% \\ &\quad \times 0.0075) + M_N \times (0.6\% + 29.3\% \times 0.01)\} \\ &\quad \times \frac{44}{28} \times 265\end{aligned} \tag{7}$$

$$\text{GHG Emission}_{\text{CH4}} = M_C \times 0.20\% \times \frac{16}{12} \times 28 \tag{8}$$

$$\text{GHG}_{\text{postharvest}} = \sum (I_k \times EF_k) \tag{9}$$

Where j represents the type of upstream input; I_j is the amount of the jth input; EF_j is the emission coefficient of the jth input; C_N and M_N are the quantities of N in chemical fertilizer and farmyard manure applied during the annual production season, respectively; M_C represents the total carbon input from manure application; 1.20% (Xie et al., 2014), 10.80% (Ge et al., 2011), and 10.00% (Qian et al., 2012; Ventura et al., 2013) are the scaling factors for N_2O, NH_3, and NO_3^- emissions or runoff and leaching from chemical N fertilizer application; 0.60% and 29.30% represent the scaling factors for N_2O and NH_3 emissions from farmyard manure application (Zhang et al., 2017); 0.01

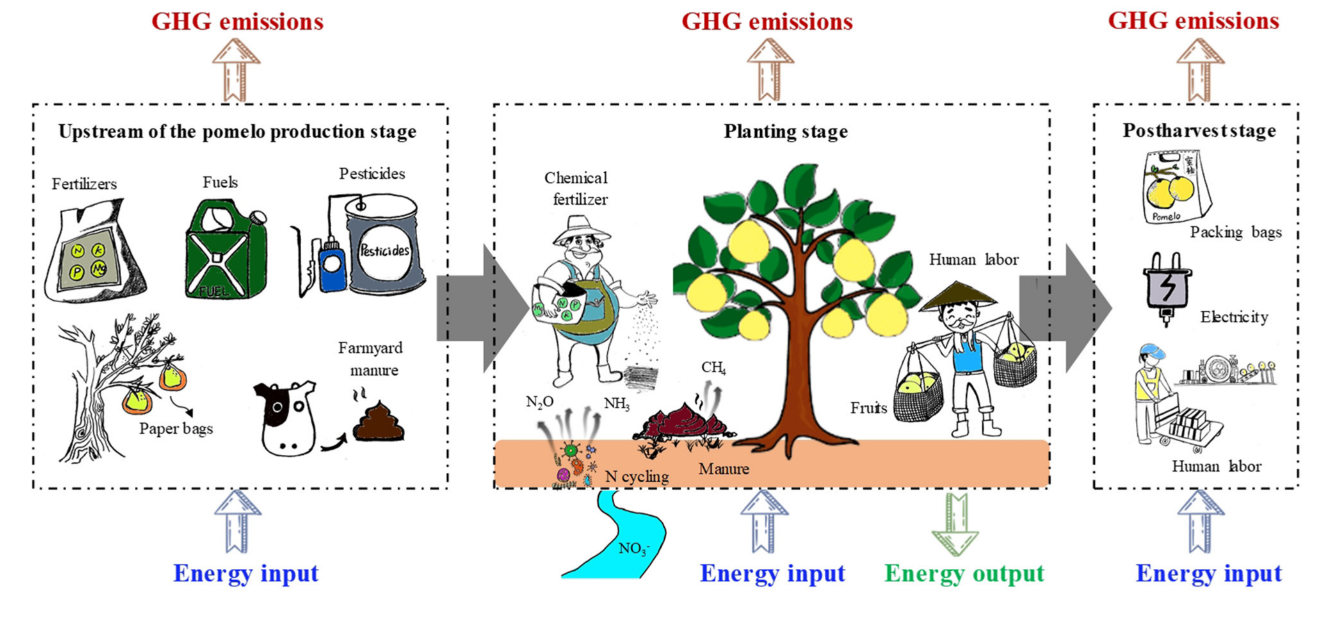

FIGURE 3 | The system boundaries of pomelo production.

and 0.0075 are the conversion coefficients of NH_3 volatilization and NO_3^- runoff and leaching, respectively, in N_2O equivalents (Eggleston et al., 2006); 44/28 is the molecular conversion factor of N_2 to N_2O; 265 is the global warming potential of N_2O for a 100-year period (Change, 2014); 0.20% is the CH_4 emission coefficient of farmyard manure applied in the field (Wan et al., 2014); 16/12 is the molecular conversion factor of C to CH_4; 28 is the global warming potential of CH_4 for a 100-year period (Change, 2014); k represents the type of postharvest input; I_k is the amount of the kth input; and EF_k is the emission coefficient of the kth input. All energy equivalents and CO_2 emission coefficients used are listed in **Table 1**.

The environmental cost efficiency was calculated with Equation (10). To measure the benefits of Mg fertilization, three indicators were set up and modeled on the concept of marginal benefit in economics (Slemrod and Yitzhaki, 2001): marginal energy efficiency, marginal GHG emission efficiency, and marginal capital efficiency (Equation 11). These three indicators represent the energy input cost, GHG emission cost, and capital investment cost of the increased yield due to Mg fertilization.

$$\text{Environmental cost efficiency} = \frac{U'}{\text{Yield}} \qquad (10)$$

$$\text{Marginal efficiency} = \frac{U'_{\text{OPT+Mg}} - U'_{\text{OPT}}}{\text{Yield}_{\text{OPT+Mg}} - \text{Yield}_{\text{OPT}}} \qquad (11)$$

where U refers to energy input (GJ), GHG emissions (t CO_2 eq), and capital investment (million CNY, only for marginal efficiency calculation).

Data Analysis

Data processing and visualization were performed using Microsoft Office Excel 2019, ArcGIS 10.2, and Easy Paint Tool SAI 1.2.0. Note that nearest-neighbor interpolation in the curve fitting tool of MATLAB R2019b was used to make the contour map of energy input, GHG emissions, and economic benefits. All statistical analyses were conducted using SPSS 21.0. One-way analysis of variance (ANOVA) and least significant difference (LSD) tests were used to detect the differences among different nutrient managements. The levels of significance were defined at $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***).

RESULTS

Yield and Quality

The different fertilization treatments significantly affected the pomelo yield and fruit quality (**Table 2**). The yield under OPT was not significantly different from that under FP, but OPT+Mg resulted in 8.76% higher yield than FP. The number of hanging fruits was the decisive factor in this significant difference. Compared with FP, OPT, and OPT+Mg did not affect the edible rate and TSS concentration, while OPT+Mg treatment significantly reduced the TA concentration by 7.35% and increased the TSS/TA by 8.79%.

Energy Balance

The energy input was highest under FP (176.29 GJ ha^{-1}), while inputs of 129.60 and 135.04 GJ ha^{-1} were required for OPT and OPT+Mg, respectively (**Figure 4A**). Chemical fertilizer and paper bags were the major sources of energy input in all fertilization treatments (**Figure 4B**). The average chemical fertilizer and paper bag energy inputs of FP,

TABLE 1 | Energy equivalents and greenhouse gas (GHG) emission coefficients in agricultural production.

Inputs and outputs (unit)	Energy equivalents (MJ unit^{-1})	Emission coefficient (kg CO_2 eq kg^{-1})
Inputs		
Human labor (h)	1.96 (Mobtaker et al., 2012)	–
Nitrogen (kg)	66.14 (Esengun et al., 2007)	8.30 (Zhang et al., 2013)
Phosphorus (kg)	12.44 (Unakitan et al., 2010)	2.33 (Chen et al., 2015)
Potassium (kg)	11.12 (Mobtaker et al., 2010)	0.66 (Chen et al., 2015)
Magnesium (kg)	6.70 (Mihov and Tringovska, 2010)	3.80 (Luong et al., 2018)
Farmyard manure (kg)	0.30 (Bojaca and Schrevens, 2010)	0.20 (Li J. Z. et al., 2016)
Pesticides (kg)	199.00 (Ozkan et al., 2004)	18.0 (Yang et al., 2014)
Diesel fuel (L)	56.31 (Unakitan et al., 2010)	2.76 (Dyer and Desjardins, 2003)
Paper bags (kg)	46.60 (Liu et al., 2010)	1.54 (Chen and Qiu, 2014)
Electricity (kWh)	12.0 (Khoshnevisan et al., 2013)	0.61 (Khoshnevisan et al., 2013)
Packing bags (kg)	90.0 (Heidari and Omid, 2011)	22.72 (Wang et al., 2017)
Output		
Pomelo (kg)	1.90 (Ozkan et al., 2004)	–

TABLE 2 | Pomelo yield and fruit quality under the different fertilization treatments (Mean ± SD).

Treatment	Pomelo yield (t ha^{-1})	Individual fruit weight (kg)	Number of fruits per tree	Edible rate (%)	TSS concentration (%)	TA concentration (%)	TSS/TA ratio
FP	50.12 ± 13.21 b	1.34 ± 0.18 ab	45.64 ± 11.25 b	73.30 ± 6.29 a	10.85 ± 0.78 a	0.68 ± 0.11 a	16.39 ± 2.58 b
OPT	49.05 ± 11.42 b	1.30 ± 0.13 b	46.53 ± 10.54 ab	72.41 ± 6.07 a	10.86 ± 0.98 a	0.66 ± 0.12 ab	16.93 ± 3.58 ab
OPT+Mg	54.51 ± 14.79 a	1.36 ± 0.17 a	49.11 ± 11.62 a	71.51 ± 7.31 a	10.89 ± 0.92 a	0.63 ± 0.11 b	17.83 ± 3.46 a

The edible rate is equal to the percentage of fruit weight accounted for by the pulp. TSS and TA refer to total soluble solids and titratable acidity, respectively. Different letters indicate statistically significant differences at $P < 0.05$.

OPT, and OPT+Mg accounted for 51.92 and 19.44%, 35.28 and 26.38%, and 34.89 and 27.66% of their total energy inputs, respectively.

Compared with the FP treatment, the OPT and OPT+Mg treatments significantly reduced the energy inputs of the upstream and planting stages, while no significant difference was recorded between these treatments (**Figure 4C**). The highest energy output for the postharvest stage was observed in OPT+Mg, but no significant difference was found between FP and OPT. In addition, the net energy outputs of OPT (−36.40 GJ ha^{-1}) and OPT+Mg (−31.46 GJ ha^{-1}) were also significantly different from that of FP (−81.07 GJ ha^{-1}). The average energy efficiency values (**Figure 4D**) were 2.74 GJ t^{-1} under OPT and 2.62 GJ t^{-1} under OPT+Mg, which were significantly lower than that under FP (3.67 GJ t^{-1}).

GHG Emissions

The GHG emissions from both OPT (18.99 t CO_2 eq ha^{-1}) and OPT+Mg (20.17 t CO_2 eq ha^{-1}) treatments were significantly lower than that from FP (27.52 t CO_2 eq ha^{-1}), and there was no significant difference between OPT and OPT+Mg (**Figure 5A**). The application of chemical fertilizer had the highest impact on the total GHG emissions, accounting for 63.90, 45.69, and 46.59% of emissions under FP, OPT, and OPT+Mg, respectively (**Figures 5A,B**). Packing bags were the second major source of GHG emissions, accounting for 22.43, 32.86, and 32.64%, and other emission sources accounted for 13.67, 21.45, and 20.77% of emissions from FP, OPT, and OPT+Mg, respectively.

The GHG emissions from the upstream and planting stages under both OPT (12.48 t CO_2 eq ha^{-1}) and OPT+Mg (13.29 t CO_2 eq ha^{-1}) were significantly lower than those under FP (21.01 t CO_2 eq ha^{-1}), while there were no significant differences between OPT and OPT+Mg (**Figure 5C**). The GHG emissions from the postharvest stage were not significantly different among the three treatments. In this study, the GHG emission efficiency from FP was 0.58 t CO_2 eq t^{-1}, which was significantly higher than those from OPT and OPT+Mg (by 40.80 and 43.17%, respectively) (**Figure 5D**).

Economic Benefits

The economic costs of FP were significantly higher than those of OPT and OPT+Mg (by 13.49 and 4.97%, respectively), and the cost of OPT was significantly lower than that of OPT+Mg (**Figure 6A**). Human labor had the highest impact and represented 49.52, 55.02, and 53.57% of the total costs of FP, OPT, and OPT+Mg, respectively (**Figures 6A,B**). Compared with FP, the proportion of chemical fertilizer costs in OPT and OPT+Mg decreased from 21.56% to 11.39–14.52%. In addition, pesticides (accounting for 12.58–13.73% of costs) and paper bags (accounting for 11.01–12.56% of costs) were also important sources of economic costs.

The costs from the upstream stage to the planting stage of FP were significantly different from those of OPT and

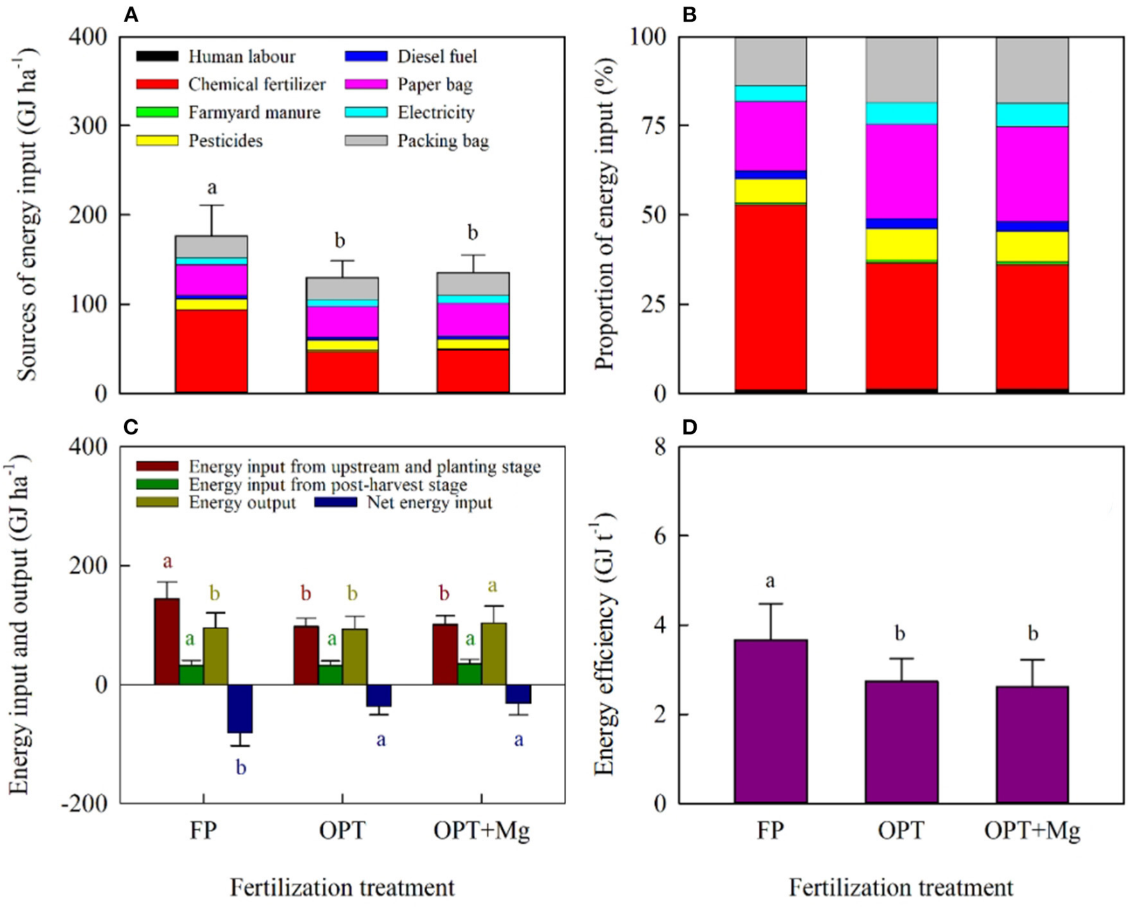

FIGURE 4 | Different sources **(A)** and proportions **(B)** of energy input, energy input and output **(C)**, and energy efficiency **(D)** under different fertilization treatments in pomelo production. The black error bars in the figure indicate the standard deviation (SDs). Different letters above histogram bars with the same color indicate statistically significant differences at $P < 0.05$.

OPT+Mg, while the highest costs in the postharvest stage were observed under the OPT+Mg treatment. The income of OPT+Mg was significantly higher than that of FP and OPT, by 10.46 and 10.80%, respectively (**Figure 6C**). The economic benefit of OPT+Mg (0.23 million CNY ha^{-1}) was significantly higher than that of FP (0.20 million CNY ha^{-1}) and OPT (0.21 million CNY ha^{-1}). The income-to-cost ratio was 4.62 under OPT and 4.72 under OPT+Mg, both significantly higher than that under FP (4.09) (**Figure 6D**).

Coupled Analysis of Yield, Energy Input, and GHG Emissions

Compared with FP, OPT and OPT+Mg resulted in the same yield with lower energy inputs and GHG emissions (**Figures 7A,B**). Although there was no significant linear relationship between economic benefit and GHG emissions or energy input (**Figures 7C,D**), the contour map of yield-energy input-GHG emissions clearly shows that OPT+Mg is better than OPT and FP and that OPT+Mg provided the highest economic benefits with the lowest energy inputs and GHG emissions (**Figure 8**).

DISCUSSION

Integrated nutrient management (INM) is a feasible way to receive future economic and environmental benefits from agricultural production (Chen et al., 2014; Zhang et al., 2016; Cui et al., 2018). Our results suggest that Mg management during INM practices is integral to promoting green, high-quality development in agricultural systems.

Strengthening Mg and Optimizing NPK to Further Increase Yield

To achieve a high yield, smallholders in China often depend on using large amounts of external inputs (especially high levels of N, P, and K fertilizers) (Zhang Q. et al., 2020). Empirical evidence has shown that when fruit yield nears the theoretically highest level, the yield responses to additional N, P, and K fertilizer application become almost nil (Zhang

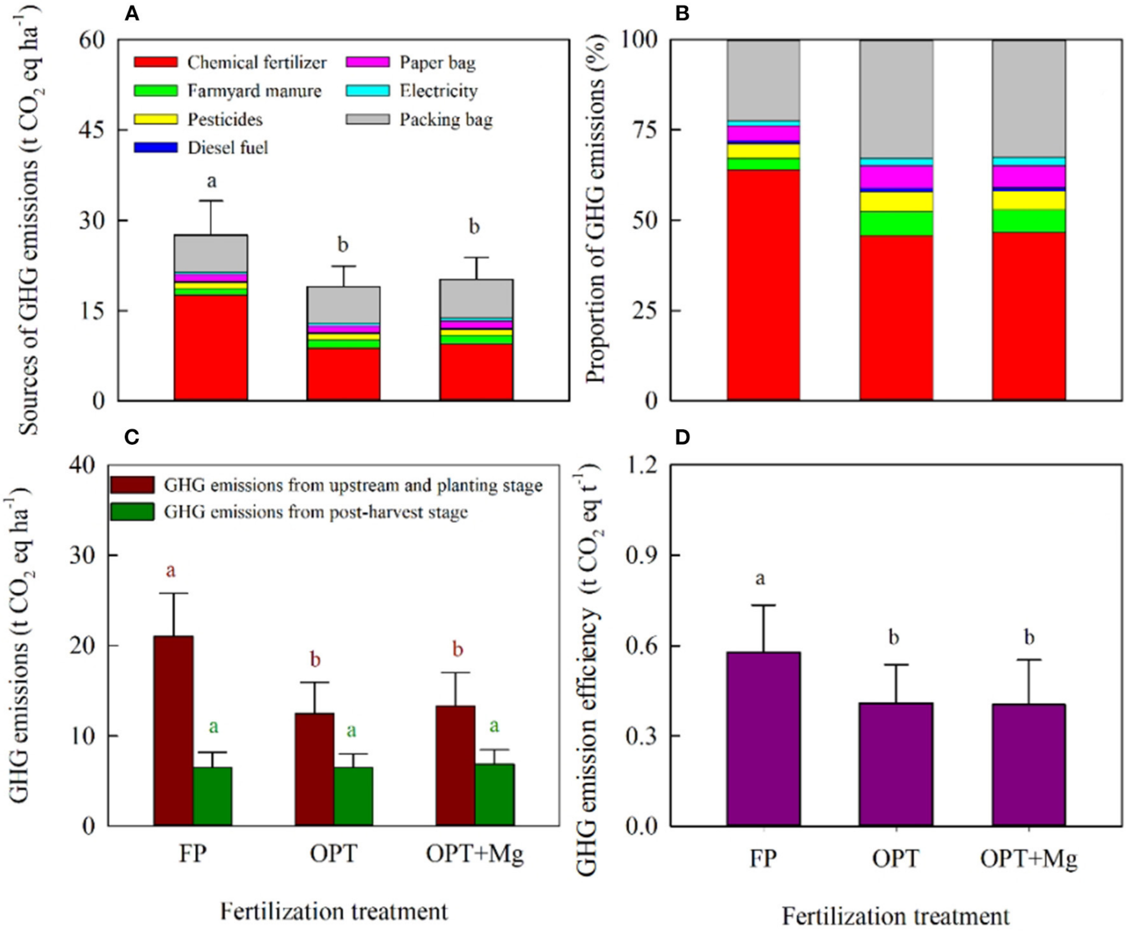

FIGURE 5 | Different sources **(A)** and proportions **(B)** of greenhouse gas (GHG) emissions, GHG emissions from different stages **(C)**, and GHG emissions efficiency **(D)** under different fertilization treatments in pomelo production. The black error bars in the figure indicate the standard deviations (SDs). Different letters above histogram bars with the same pattern indicate statistically significant differences at $P < 0.05$.

et al., 2012; Ahmed et al., 2017), while the secondary macronutrient element, such as Mg has become the key factors responsible for further increases in fruit yield, especially in areas where soil Mg is deficient (Wang et al., 2020).

According to Li et al. (2019), the recommended rates of N, P_2O_5, and K_2O fertilizer application to produce one ton of citrus fruit are 10.4, 5.2, and 8.2 kg on average, respectively. However, these values in Pinghe County were 21.45 (N), 16.48 (P_2O_5), and 18.92 (K_2O) kg on average in conventional practices (**Figure 2**). It indicates that in Pinghe County, farmer knowledge about the nutrient management needed to meet pomelo nutrient requirements is very limited (Li Q. et al., 2016; Chen et al., 2020). The current study showed that the traditional fertilizer application rate could be reduced by nearly 53% (49, 47, and 64% for N, P_2O_5, and K_2O, respectively) on average without significantly reducing the pomelo yield (**Table 2**). Therefore, this fertilizer reduction measure proved effective for pomelo production in Pinghe County. This strategy has also been proven effective for apple orchards in China (Wang et al., 2016).

As an essential nutrient for plant growth, Mg is involved in physiological and biochemical processes such as chlorophyll synthesis, photosynthesis, and enzyme activation (Cakmak and Yazici, 2010; Chen et al., 2018; Tian et al., 2021). Mg is also involved in carbohydrate transport from source-to-sink organs; hence, the excess carbohydrate accumulation in leaves rather than transported to fruit and grain results from Mg deficiency (Farhat et al., 2016; Tian et al., 2021). Therefore, an adequate amount of Mg is particularly required during the period of reproductive growth (Römheld and Kirkby, 2009). Various studies have shown that higher Mg concentration enhances the plant resistance to various environmental stresses such as light, heat, and drought (Cakmak, 2013; Gransee and Führs, 2013; Mengutay et al., 2013). Moreover, Mg deficiency also interferes with N metabolism, which has important implications for crop production and the environment (Grzebisz, 2013; Zhang et al., 2021). Therefore, Mg deficiency would affect plant development

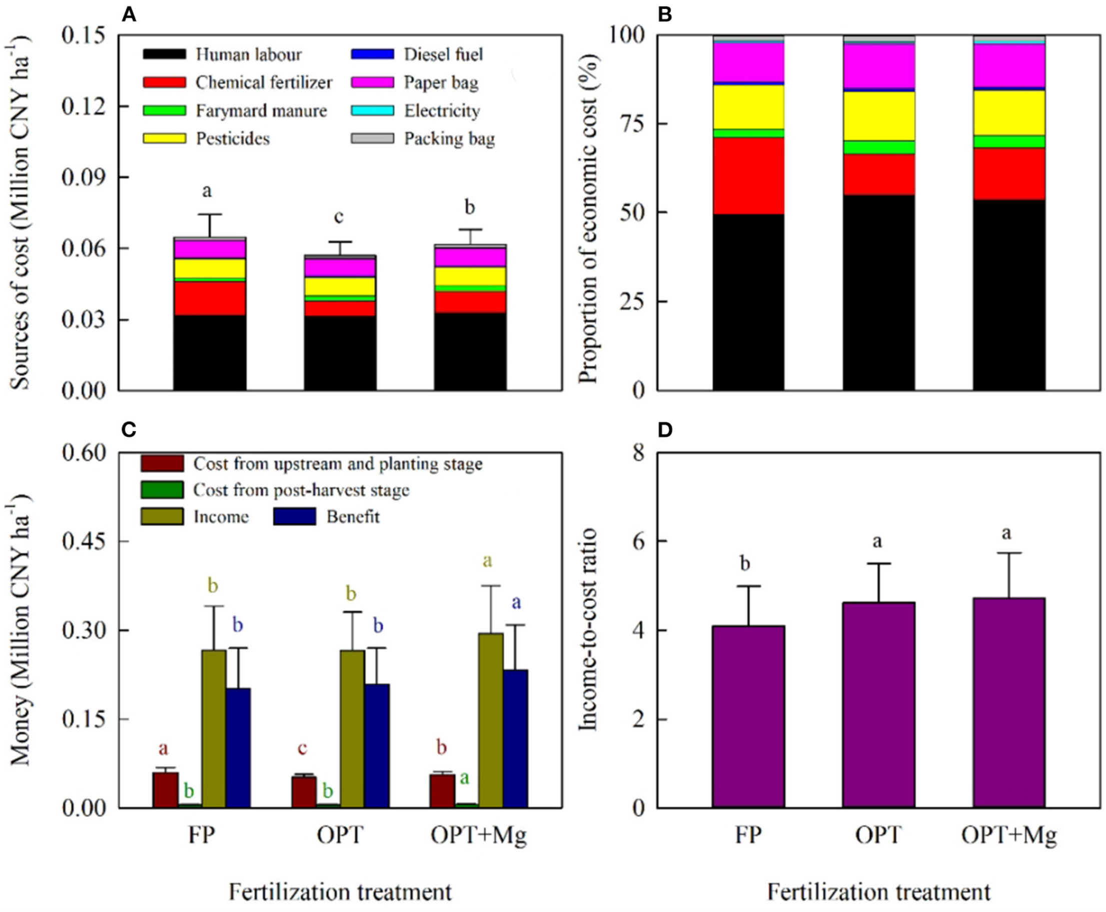

FIGURE 6 | Different sources **(A)** and proportions of economic costs **(B)**, costs and income **(C)**, and income-to-cost ratio **(D)** under different fertilization treatments in pomelo production. The black error bars in the figure indicate the overall standard deviations (SDs). Different letters above histogram bars indicate statistically significant differences at $P < 0.05$.

and the formation of yield and quality. However, despite this recognition, the role of Mg in crop nutrition management has not received much attention compared to other major nutrients (Cakmak and Yazici, 2010; Guo et al., 2016).

Mg uptake by plants can be low due to competition from other cations, including potassium (K^+), ammonium (NH_4^+), and aluminum (Al^{3+}), especially in acidic soils that are low in Mg (Gransee and Führs, 2013). The soil survey results showed that the soil pH of all 44 samples from pomelo orchards in Pinghe County ranged from 3.5 to 4.9, which is lower than the optimum range of 5.0–6.5 for pomelo growth (Guo et al., 2019). Previous research showed that the improvement of crop production by Mg in acidic soils was three times greater than that in calcareous soils (Wang et al., 2020). Despite the importance of Mg, few farmers have considered its role in pomelo production. Therefore, the positive response of pomelo yield to fertilizer reduction and Mg fertilizer addition is not surprising (**Table 2**; **Figure 7**). Although the yield under OPT was not significantly different from that under FP, OPT+Mg resulted in an 8.77% higher yield than FP (**Table 2**). Many other orchard experiments also revealed that Mg enhances the yield and quality of pear (Fawzi et al., 2010), vine grapes (Zlámalová et al., 2015), wax gourd (Zhang B. et al., 2020), and pepper (Lu et al., 2021). In short, to facilitate the sustainable and green development of agriculture in Mg-deficient regions, it is necessary to strengthen cooperation among governments, enterprises, and institutions to guide farmers (Zhang et al., 2016) to use the Mg fertilizer scientifically while reducing the application of N, P and K fertilizers.

Environmental Cost Efficiency

The energy inputs and GHG emissions of OPT and OPT+Mg were significantly lower than those of FP (**Figures 4A, 5A**) and were influenced mostly by chemical fertilizer (**Figures 4B, 5B**). Therefore, reducing fertilizer application is important for improving energy and GHG efficiency in pomelo production. These findings are consistent with existing reports that energy inputs and GHG emissions can be reduced substantially under advanced INM practices (Chen et al., 2014; Wu and Ma, 2015; Sarkar et al., 2018; Fathi et al., 2020). Although OPT+Mg slightly

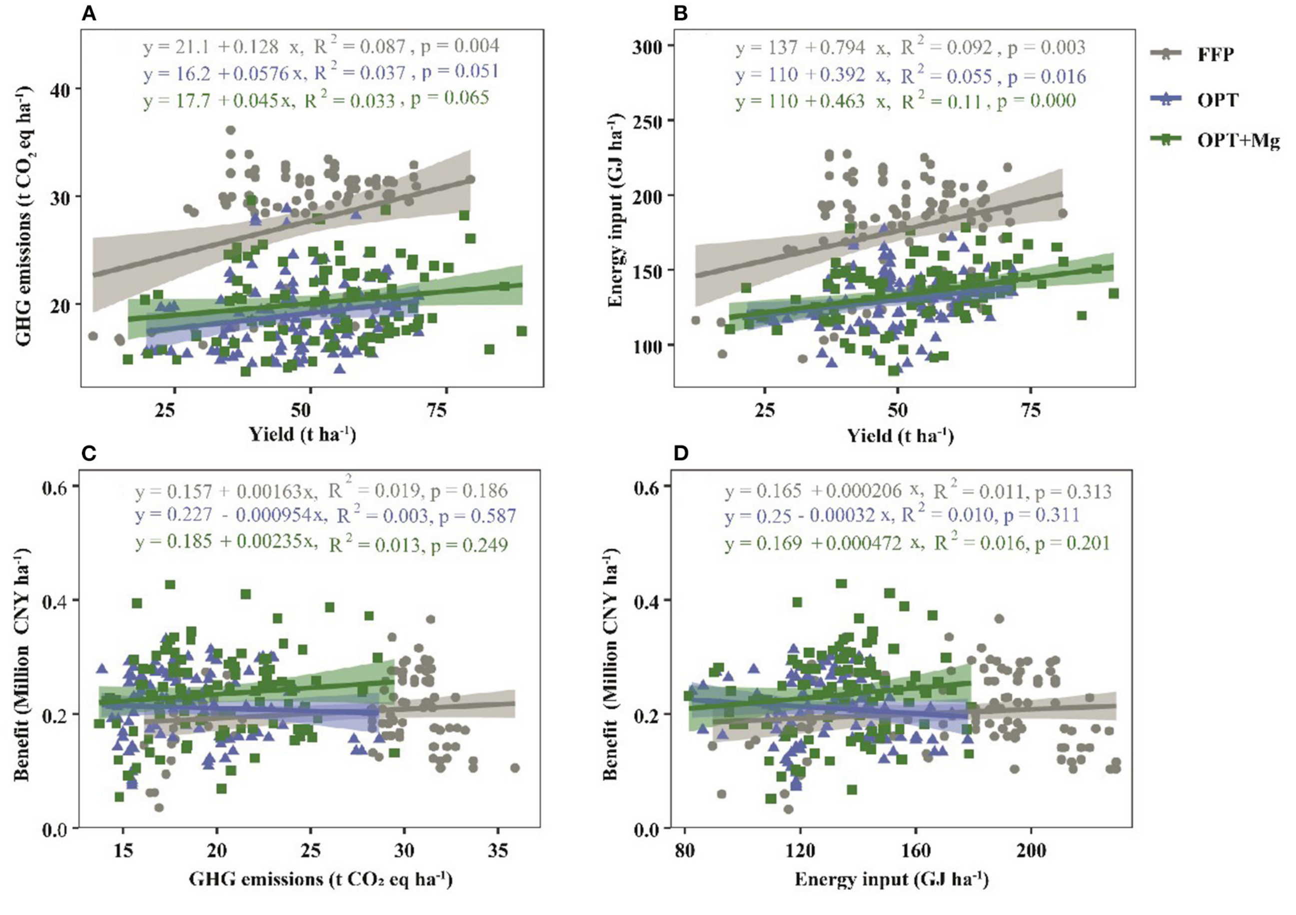

FIGURE 7 | Linear relationship between yield and GHG emissions **(A)**, yield and energy input **(B)**, GHG emissions and benefit **(C)**, energy input and benefit **(D)**. The different colors of the scattered dots, lines, shadows, and formulas represent the different fertilizer treatments. The shaded areas represent the 95% confidence intervals.

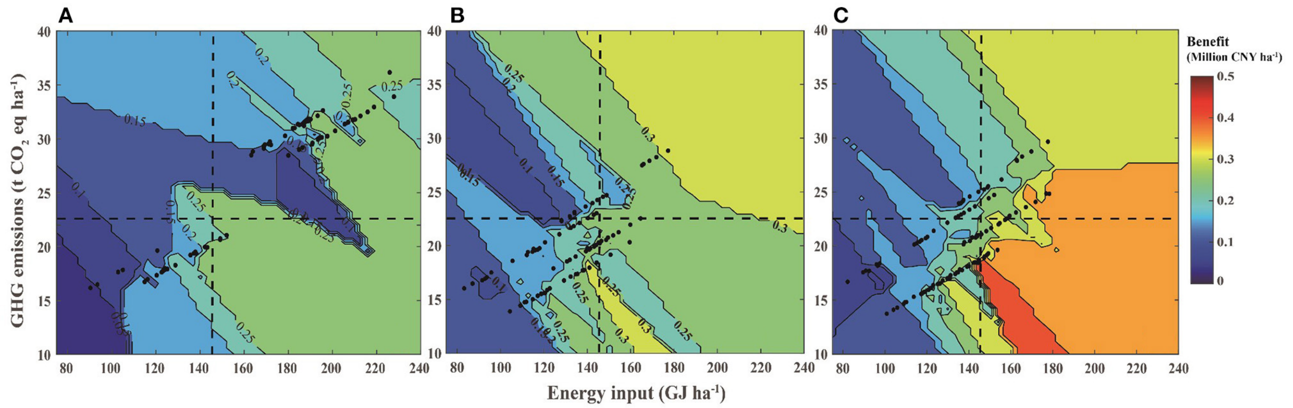

FIGURE 8 | Contour maps of energy inputs, GHG emissions, and economic benefits in different fertilizer treatments. **(A–C)** represent FP, OPT, and OPT+Mg, respectively. The dotted lines represent the average values of energy input and GHG emissions. The black dots represent the three-dimensional coordinates of the original data points, and the different numbers on the contour lines indicate the economic benefit values.

increased the energy inputs and GHG emissions in pomelo production by 4.20 and 6.21% (**Figures 4A**, **5A**), respectively, the pomelo yield was significantly higher (by 11.14%) than that under OPT (**Table 2**). Indeed, the potential of Mg to

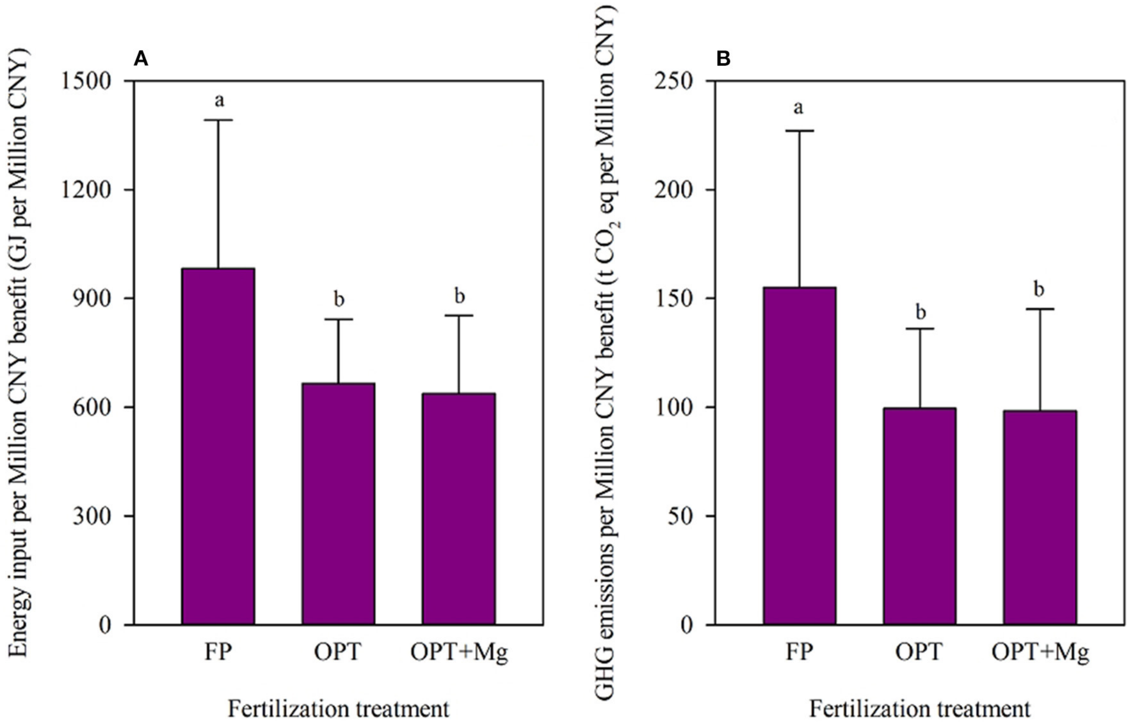

FIGURE 9 | Energy input **(A)** and GHG emissions **(B)** per million CNY of economic benefit under different fertilization treatments. The black error bars in the figure indicate the standard deviations (SDs). Different letters on the histogram bars indicate statistically significant differences at $P < 0.05$.

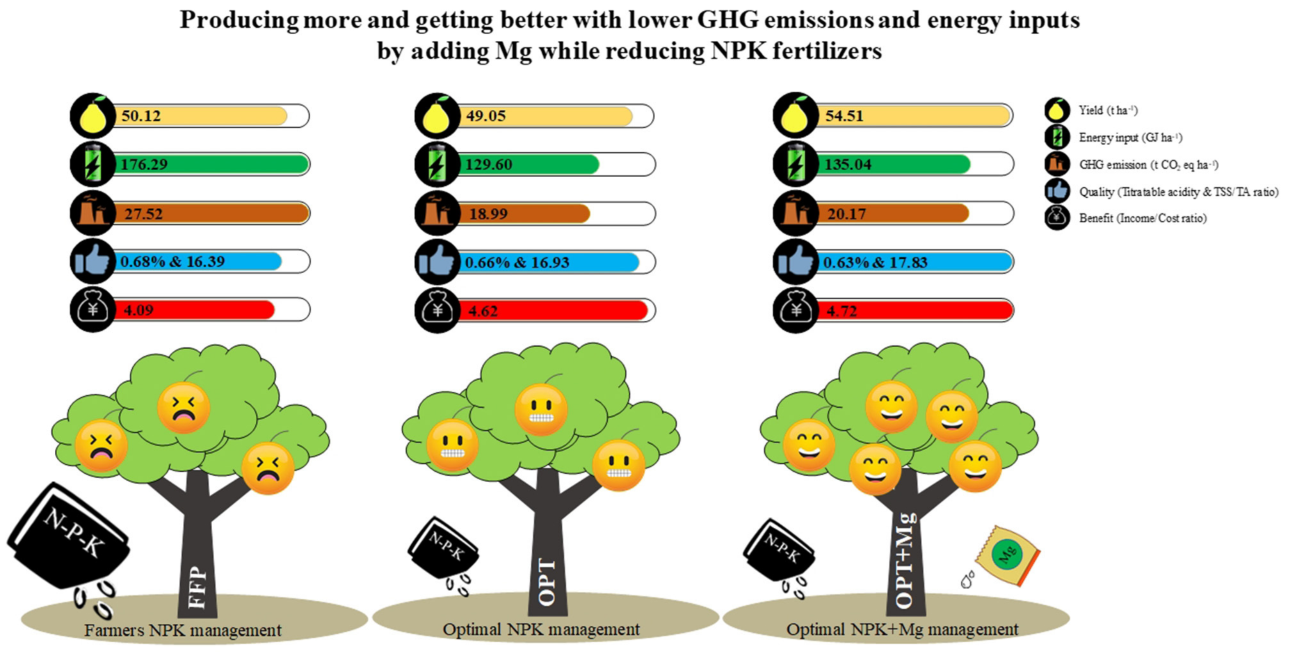

FIGURE 10 | Graphical conclusion.

increase the economic benefits of agricultural production cannot be neglected. Compared with FP, the economic benefits of OPT and OPT+Mg were 3.40 and 15.33% higher, respectively, because of cost savings and income increments (**Figure 6A**). Mg application can also improve economic efficiency in other systems, such as maize and tea gardens (Jat et al., 2018; Huang et al., 2020).

Further analysis revealed that adding Mg fertilizer can provide higher economic benefits with lower environmental costs (**Figure 8**). In addition, compared with that in OPT, the marginal efficiency of energy, GHG emissions and capital of Mg in OPT+Mg were reduced by 62.30, 44.19 and 21.07%, respectively (**Table 2**; **Figures 3–5**). INM practices can increase the economic efficiency of energy inputs and GHG emissions (**Figure 9**). The average energy consumption values needed to obtain one unit of economic benefit were 665.26 and 637.09 GJ per million CNY under OPT and OPT+Mg, respectively, which were significantly lower than that under FP (982.05 GJ per million CNY). The GHG emissions needed to obtain one unit of economic benefit under FP, OPT, and OPT+Mg were 155.01, 99.40, and 98.27 t CO_2 eq per million CNY, respectively. Unfortunately, very little research has been conducted on the influences of Mg fertilizer application on energy and GHG emission efficiency in agroecosystems. Therefore, the present study provides strong evidence for promoting Mg application in agricultural production.

Outlook and Limitations

Although we quantitatively evaluated the effects of different nutrient management strategies on yield, quality, economic benefits, energy consumption, and GHG emissions in pomelo production, the present study had several limitations. First, carbon sequestration in orchard systems (Chen et al., 2020) was ignored at the research boundary because this was not the focus of the present study. This will introduce uncertainty because the capability for carbon sequestration in orchards depends on fruit tree age (Wu et al., 2012), vegetation, climate, and management practices (Liu et al., 2011). Second, due to data and method limitations, we used a set of commonly used empirical N_2O and NH_3 emission parameters and NO_3^- runoff and leaching rates. However, reactive N loss and N surplus have an exponential relationship rather than a linear relationship (Cui et al., 2013), and N_2O, NH_3, and NO_3^- losses from fertilizer application are greatly impacted by the application rate (Ge et al., 2011; Wang et al., 2019), especially in extremely overfertilized systems. Therefore, the GHG emissions in this study may be underestimated. Third, fertilization based on the "4 Rs" (right rate, right source, right time, and right place) is the critical nutrient management approach for sustaining crop productivity (Mikkelsen, 2011; Chen et al., 2020). The findings of this study showed that reducing NPK fertilizer application while adding Mg fertilizer resulted in higher yields and better fruit quality with lower environmental costs. However, the potential for fertilizer reduction and a scientifically determined appropriate Mg application rate has yet to be precisely determined.

CONCLUSION

Over fertilization with nitrogen (N), phosphorus (P), and potassium (K) in pursuit of higher economic benefits is very common in the fruit production system of China. In the present study, different nutrient management strategies for pomelo production were evaluated based on yield, fruit quality, energy balance, greenhouse gas (GHG) emissions, and economic benefits. The results suggested that reducing conventional N, P, and K fertilization by 53% is feasible. This reduction would increase the efficiency of energy input and GHG emissions in pomelo production systems. Moreover, adding magnesium (Mg) while reducing N, P, and K fertilizer application could further mitigate the environmental costs and enhance the yield, fruit quality, and economic benefits (**Figure 10**). Therefore, China's traditional intensive, high-input nutrient management practices in fruit systems urgently need to be changed. A key focus of the future green development of fruit production will be how to obtain the highest return with the lowest input, and Mg could prove to be a key component.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

XC: conceptualization, writing—original draft, writing-review and editing, formal analysis, and visualization. XY: conceptualization, investigation, writing—original draft, formal analysis, and visualization. MM: writing—review and editing. XW and CM: visualization. YC: formal analysis and visualization. YL, SZha, WZ, and WY: data collection. LW: conceptualization, resources, supervision, and funding acquisition. SZho: supervision. FZ: resources, supervision, and funding acquisition. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.948810/full#supplementary-material

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