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Too little, too imbalanced: Nutrient supply in smallholder oil palm fields in Indonesia

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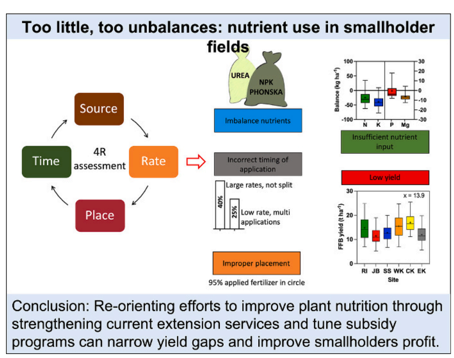
HIGHLIGHTS

- Despite Indonesia is a major consumer of fertilizers, widespread nutrient deficiencies have been reported across independent smallholder oil palm fields.
- We diagnosed nutrient management in 977 independent smallholder oil palm fields in terms of rate, source, placement, and split of fertilizer.
- We found that nutrient input was insufficient and imbalanced to achieve high yields.
- Most farmers did not follow recommended practices on placement of fertilizer and splits.
- Improving nutrient management in smallholder fields will require technical assistance and mechanisms to facilitate farmers access to proper fertilizer sources.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Smallholders account for *ca.* 40% of oil palm area in Indonesia but average yield remains low. Despite higher overall fertilizer use in Indonesia compared with other Southeast Asian countries, poor plant nutrition has been identified as a major factor explaining yield gaps in smallholder oil palm fields and little is known about the underlying management drivers.
OBJECTIVE: To assess nutrient management in smallholder fields and identify entry points to narrow the existing yield gap *via* improved plant nutrition.
METHODS: We assessed nutrient balances and gaps for nitrogen (N), phosphorous (P), potassium (K), and magnesium (Mg) and inter-relationships between fertilizer use, leaf nutrient concentration, and yield, using data collected from 977 smallholder fields in Indonesia over two years.
RESULTS AND CONCLUSIONS: There was a positive relationship between yield and nutrient rates, especially for potassium (K). Only half of the fields received fertilizer and average nutrient rates in fertilized fields represented 45% (N), 83% (P), 28% (K), and 25% (Mg) of the associated removal with harvested yield. Applied fertilizer was generally rich in N and P, but poor in K and Mg, leading to nutrient imbalances. Additionally, farmers did not follow appropriate practices on fertilizer placement and splits. Improving current fertilizer supply and management is needed to increase smallholder yields and profit.
SIGNIFICANCE: Current agricultural and research programs will benefit from re-orienting efforts to improve nutrient management in oil palm as a pathway to narrow yield gaps in smallholder fields, which, in turn, requires strengthening extension services to fill in knowledge gaps and tune subsidy programs to facilitate farmer access to fertilizer sources more suited to the crop.

1. Introduction

Oil palm (*Elaeis guineensis*) is the most important source of vegetable oil in the world. Global crude palm oil (CPO) production reached 73 million metric tons (MMT), representing 40% of global vegetable oil production (USDA, 2020–2021). Palm oil demand is projected to increase another 15–20% over the next 10 years (OECD/FAO, 2022). Indonesia is the largest oil palm producing country, accounting for 60% of global CPO production (USDA, 2022). About 40% of oil palm area in Indonesia is managed by smallholder farmers, which, in turn, account for 34% of annual CPO production, while the rest is managed by large plantations (Directorate General of Estate Crops, 2021). There are two types of smallholders in Indonesia: (i) 'plasma' smallholders, who are tied to a large plantation and receive financial support, supervision, and training, and (ii) independent smallholders, who are not tied to a large plantation and account for *ca.* two thirds of the total smallholder oil palm area (Manggabarani, 2009; Pahan, 2012; Molenaar et al., 2013; Jelsma et al., 2019). Average yield in independent smallholder fields is low, representing only 42% of the attainable yield (Monzon et al., 2023, this issue). Hence, an opportunity exists for Indonesia to increase CPO output by closing the large yield gap that exists in independent smallholder fields, which, in turn, can alleviate pressure to expand plantation areas into fragile ecosystems such as forests and peatlands (Molenaar et al., 2013; Woittiez et al., 2017; Monzon et al., 2021).

Indonesia is one of the largest users of mineral fertilizers in Southeast Asia (FAOSTAT, 2022a; IFASTAT, 2023). As a consequence of a combination of relatively low fertilizer prices due to subsidy programs and a well-organized fertilizer distribution and supply chain, nutrient rates are relatively high in smallholders' rice and maize fields (Ludemann et al., 2022; Rizzo et al., 2023). Indeed, Indonesia spends *ca.* 2 billion USD annually on fertilizer subsidy programs to facilitate smallholders' access to nutrients (Kemenkeu, 2021; Ministry of Agriculture, 2022). However, at present, smallholder oil palm farmers are not included within the subsidy scheme, and only received support from replanting programs supported by the government to facilitate access to certified planting material and fertilizer during the establishment of new plantations but not thereafter (Nurfatriani et al., 2019). A recent study by Sugianto et al. (2023), this issue, has found widespread nutrient deficiencies across independent smallholder oil palm fields in Indonesia. In this study, nearly 90% of the fields exhibited potassium (K) deficiencies, whereas nitrogen (N) and phosphorous (P) deficiencies were evident in nearly half and two thirds of the fields, respectively. This finding is of particular importance considering the large exploitable yield gap in smallholder fields and the relationship that exists between on-farm net profit and yield (Monzon et al., 2021, 2023, this issue). Thus, if the current poor plant nutrition status of smallholder fields in Indonesia can be improved through better nutrient management, it could lead to increases in productivity and profit for farmers, also benefiting local communities and the country as a whole.

High oil palm yields have large nutrient requirements. As a reference, a well-managed oil palm plantation that produces 30 t ha^{-1} of fresh fruit bunches (FFB) per year, removes *ca.* 95 kg nitrogen (N), 12 kg phosphorous (P), 117 kg potassium (K), and 17 kg magnesium (Mg) per hectare with the harvested FFB (Lim et al., 2018). Indigenous soil nutrient supply, internal recycling *via* pruned fronds, and inputs from rainfall do not provide sufficient nutrients to sustain high yields (Ng et al., 1999). For example, yield is low without regular nutrient inputs, not exceeding 10 t FFB ha^{-1} in long-term nutrient-omission plots (Sidhu et al., 2004; Prabowo et al., 2006; Sidhu et al., 2009, 2014; Lee et al., 2019). Besides lower yield and its impact on farmer income, there is a progressive loss of soil quality when nutrient removal exceeds inputs over the long term (Van Noordwijk and Cadisch, 2002; Woittiez et al., 2018; Sundram et al., 2019). Hence, relatively large nutrient inputs are required to achieve high and profitable oil palm yields while preserving the long-term sustainability of the soil. Besides nutrient rates, fertilizer management in relation to source, placement, and number of splits has an important role at determining nutrient losses and thus the amount of nutrients that is ultimately absorbed by the crop (Kee et al., 2005; Tiemann et al., 2018). We are not aware of studies in oil palm aiming to benchmark current fertilizer use against that required to achieve the site-specific attainable yield, as determined by weather and soil (Rhebergen, 2012; Hoffmann et al., 2014), and assess farmer fertilizer management in terms of placement and number of splits. Such assessment would be useful to identify entry points to improve nutrient management and orient national agricultural research and development (AR&D) programs and policy accordingly.

Here we assessed the management drivers for poor plant nutrition in smallholder oil palm fields using data on yield and applied nutrients collected from a total of 977 fields located across six oil palm producing areas in Indonesia over two years (2020−2021). We assessed how current nutrient rate compares with site-specific plant nutrient requirements and diagnosed nutrient management in terms of sources, placement, and splits. Finally, we discussed implications of our results for AR&D programs and policy.

2. Materials and methods

2.1. Description of study area and data collection

We focused on independent smallholder fields located in mineral soils in Indonesia. Our study sites were located in six provinces in Indonesia: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), Central Kalimantan (CK), and East Kalimantan (EK) (Fig. 1). Hereafter, sites are referred to using the name of the province where they are located. Site selection was based upon availability of local partners to collect the data. Overall, selected sites were representative of climate-soil domains that account for 87% of the oil palm area in mineral soils in Indonesia (Agus et al., 2023, this issue). At each site, we selected 200 oil palm fields for our study. All fields were under the first cycle of oil palm cultivation and we only considered fields with oil palm during the productive phase and before the usual replanting age (25 years), with palm age ranging between 6 and 22 years across fields. We did not include fields with intercropping in their oil palm field, and home gardens (<0.1 ha). Each field was mapped with GPS devices and drone imagery and associated field size area was calculated (average: 1.2 to 2.1 ha across sites). Detailed description of the biophysical, management, and socio-economic background database of the sites is provided elsewhere (Monzon et al., 2023, this issue).

Data used for this study were collected *via* a farmer diary. Briefly, farmers kept daily records on harvested FFB and price, and the rate, cost, and type of applied fertilizer. Harvested FFB and rate of fertilizer were reported on a per-field basis. We also requested farmers to submit photos of the fertilizer bags to facilitate identification of the fertilizer source and associated nutrient concentration. To ensure data accuracy, we implemented rigorous quality control measures to identify and correct any erroneous data entries, including typos and outliers. For this purpose, we established protocols that defined acceptable ranges for data entries associated with each variable. Local partners collected the farmer dairy data monthly and re-checked them as needed when records were missing and/or suspicious. The farmer data were collected from Jan 1, 2020 to Dec 31, 2021. Average national FFB yield and fertilizer prices during the 2020–2021 period were comparable to long-term averages calculated over the past 10 years (2012−2021) (Ashari et al., 2021; FAOSTAT, 2022b).

After removing fields with incomplete data records and/or suspicious data, as detected through our quality control, we have a total of 977 fields available for the analysis, with number of fields ranging from 121 (EK) to 194 fields (CK) across sites. Reported fertilizer use and harvested FFB, together with field size and nutrient concentration associated with each fertilizer source, were used to estimate annual nutrient rate and yield for each field in each year (2020 and 2021). For our analysis, we focused on nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg) as these are the most common fertilizer nutrient inputs in oil palm and those for which deficiencies have been reported in the literature (Sugianto et al., 2023). We did not include fields receiving empty fruit bunches (EFB), manure, or compost application given uncertainty in associated rates and nutrient concentration and the small number of fields receiving organic fertilizer inputs (3% of total fields). For our analysis, we averaged data on actual FFB yield and fertilizer use over the two years (2020 and 2021) for each field to minimize the impact of episodic reporting errors and/or transitory changes in management practices. All yields reported here were expressed as t of FFB, while nutrient-related variables (*i.e.*, rate, balance, gap, removal) were expressed as elemental nutrients, both on a per-ha and annual basis.

2.2. Computation of partial nutrient balance

For descriptive purposes, we first categorized fertilizers into two main sources: straight fertilizers (*i.e.*, those containing just one nutrient) and compound fertilizers (*i.e.*, those containing more than one nutrient). Straight fertilizers included urea, muriate of potash (MOP), dolomite, single superphosphate (SP-36), and triple superphosphate (TSP). Compound fertilizers included N, P, and K (locally referred to as 'phonska') and other NPK formulations with relatively higher K and Mg concentration (hereafter referred to as NPK+). We calculated the frequency of fields receiving each fertilizer type, and associated price range was calculated using inter-quartile ranges (IQR) to remove outliers.

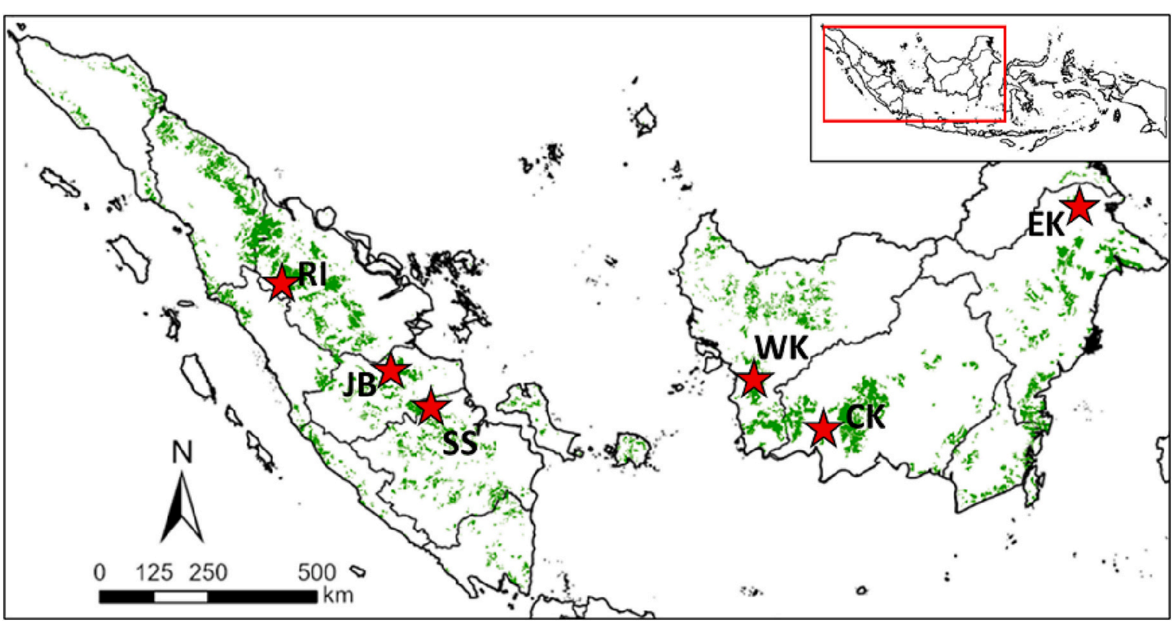

Fig. 1. Location of the study sites in Indonesia. Sites are referred to using the name of the province where they are located: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), Central Kalimantan (CK), and East Kalimantan (EK). Red stars indicate site location while green area shows oil palm area in mineral soils (Ministry of Agriculture, 2012; Harris et al., 2015). Inset shows area of interest within Indonesia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As a first step to assess nutrient inputs in relation to plant nutrient requirement, we computed partial nutrient balances for each field and nutrient as follows:

$$\mathrm{Balance} = N_F - NR_{FFB} \quad (1)$$

where N_F is the rate of nutrient applied with fertilizer, and NR_{FFB} is the crop nutrient removal with harvested FFB. Estimation of NR_{FFB} was based on yield and expected nutrient removal per t of FFB following FFB nutrient contents reported by Lim et al. (2018): 3.15 kg N, 0.40 kg P, 3.89 kg K, and 0.57 kg Mg per t FFB. We are not aware of direct comparisons of nutrient content between tenera and dura palm type in the published literature. Thus, we assumed the same nutrient content for both palm types. Following Tiemann et al. (2018), our approach to estimate nutrient balances assumed that (i) nutrient losses (*e.g.*, leaching, volatilization, runoff) equal nutrient inputs from rainfall, atmospheric deposition, and other sources, and (ii) indigenous soil nutrients will be recycled *via* pruned fronds and root decay. For the calculation of the nutrient balance, we did not consider nutrient immobilization in trunk as much of these nutrients will eventually return to the soil once fields are replanted (Goh and Härdter, 2003; Tao et al., 2018).

To evaluate the degree of balance among nutrients in the applied fertilizer, in relation to plant nutrient requirements, we computed the ratio between N, P, and K inputs (N:P, N:K, and P:K). Subsequently, these values were compared against "balanced" ratios derived from measured FFB removal in well-managed plantations reported by Lim et al. (2018): 7.9 (N:P), 0.8 (N:K), and 0.1 (P:K). For comparison purposes, an optimal range for balanced nutrition was set as ±20% of the balanced ratios. Hence, we assumed that a field would receive imbalanced nutrient supply when deviating from the balanced ratio by >20% and calculated the frequency of fields exhibiting balanced and imbalanced fertilizer nutrient inputs.

For each of the main fertilizer sources (*e.g.*, urea, NPK, MOP), we determined the frequency of fields receiving a given fertilizer *via* a single dose *versus* those where fertilizer was split into several applications. To do so, we defined a 'split application' as one in which the same type of fertilizer was applied more than once in each of the study years. Following Goh and Härdter (2003), we used 2 kg palm^{-1} as a threshold to distinguish between high and low fertilizer applications, except for urea, for which we assumed 1 kg palm^{-1} because smaller urea applications are preferable to reduce N volatilization losses. We computed the frequency of fields with (i) high nutrient rates but without split application and (ii) low nutrient rates with split application either once or more times within a year. Finally, we categorized each field based on whether each type of fertilizer was applied in the palm circle only, frond heaps only, or both to assess to which extent smallholders follow recommended practices on fertilizer placement. Fertilizer should be applied on the spread fronds (below which the 'feeding roots' are located), except for urea, which should be applied inside the palm circle to maximize fertilizer-soil contact and avoid high volatilization losses (Rankine and Fairhurst, 1998).

2.3. Calculation of nutrient gaps in smallholder fields

Partial nutrient balances give a first estimate of the degree of nutrient limitations. However, a zero-nutrient balance does not consider the nutrient uptake requirement associated to the attainable yield (Yatt) as determined by climate and soil. Therefore, a zero-nutrient balance alone should not be used as a benchmark to assess the degree of nutrient limitations, especially in a context of low yields and nutrient inputs. Furthermore, the partial nutrient balances in Section 2.2 do not account for nutrients immobilized in annual trunk growth, which should be considered for estimating nutrient fertilizer requirements (Tao et al., 2018). To benchmark current nutrient input in smallholder fields, against the nutrient required to meet plant requirements, we calculated the nutrient gap for each field as follows:

$$\mathrm{Gap} = NF_{YATT} - N_F \quad (2)$$

where NF_{YATT} is the nutrient fertilizer requirement associated with the attainable yield (Yatt). A zero gap was assumed in fields where $N_F > NF_{YATT}$. Similar to the calculation of partial nutrient balances, our approach to estimate nutrient gaps assumed that indigenous soil nutrients will be recycled *via* pruned fronds and root decay. Hence, the NF_{YATT} was estimated following a reposition criteria that includes both the nutrients in harvested FFB as well as those immobilized in annual trunk growth, considering the field-specific Yatt as determined by climate, soil, and palm age (Ng et al., 1968; Lim et al., 2018). The Yatt was estimated as 70% of the simulated yield potential estimated for each field by Monzon et al. (2023) using a well-validated crop simulation model coupled with local weather and soil data, assuming optimal nutrient and management practices and considering the field-specific palm age. We note that 70% of the yield potential is a reasonable yield goal for farmers who have reasonable access to markets, inputs, and extension services (Hoffmann et al., 2017; Monzon et al., 2021, 2023, this issue). Subsequently, the Yatt was used to estimate NF_{YATT} based on the relationship between removed nutrients in FFB plus immobilized nutrients in trunk growth *versus* FFB yield (Supplementary Fig. 1). This relationship was derived from measurements across a subset of 60 fields located at the same sites during the same period, with FFB yield ranging from 5 to 35 t ha^{-1} (Sugianto et al., 2022). Palm age ranged from 9 to 20 years across these fields, which was comparable to the range in palm age observed across the 977 fields analyzed in the present study. For each of the 60 fields, annual nutrient removal with FFB was estimated based on measured yield and average nutrient content in FFB reported by Lim et al. (2018). In turn, nutrient immobilization in annual trunk growth was determined based on (i) analysis of trunk nutrient concentration through tissue analysis (Tao et al., 2018), and (ii) annual changes in trunk biomass estimated using allometric measurements (Tao et al., 2017; Prabowo et al., 2023). Trunk values vary with age (Ng et al., 1968; Gray, 1969; Siang et al., 2022) but major changes occur in plantations younger than ours. Indeed, our data showed that trunk values were strongly related to FFB yield rather than palm age (Supplementary Fig. 2). Therefore, we ignore palm age in computing nutrient immobilized in trunk.

2.4. Impact of nutrient fertilizer inputs on smallholder yields and plant nutrient status

We assessed relationships between nutrient inputs and yield using linear regression analysis. Additionally, we fitted a boundary function using quantile regression for the 95th percentiles (Koenker and Basset, 1978) using the "quantreg" package in R (Koenker, 2017). Farmer yield was expressed as a percentage of Yatt (%Yatt) to account for differences in palm age and site-specific climate-soil conditions. Considering the long period for yield determination in oil palm (39 months), current yield does not necessarily depend on current nutrient inputs but rather on applied fertilizer over the past two to three years (Oberthür et al., 2015, 2017). Hence, an implicit assumption of our analysis was that fields with higher nutrient inputs during our study period were also the ones receiving higher nutrient inputs in previous years, which is a reasonable assumption considering the strong correlation we found in yield and nutrient inputs in 2021 *versus* 2020 across fields ($p < 0.01$). Finally, we also assessed the relationship between leaf nutrient concentration and nutrient inputs for the same group of 977 smallholder fields. Details on measurement of leaf nutrient status are provided elsewhere (Sugianto et al., 2023, this issue).

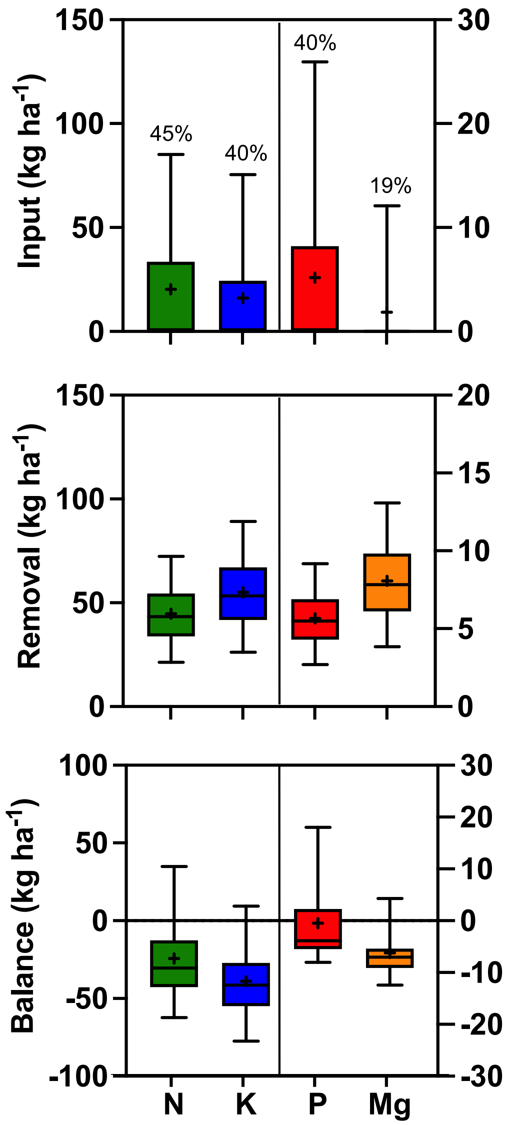

Fig. 2. Box plots for annual nutrient input (top), nutrient removal with fresh fruit bunches (middle), and partial nutrient balance (bottom) for nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg) based on pooled data collected from 977 smallholder fields across six sites in Indonesia over two years (2020–2021). Left Y-axis corresponds to N and K and right Y-axis to P and Mg. Percentage values in upper panels show frequency of fields receiving fertilizer input. Boxes represent 25th and 75th percentiles and bars show 10th and 90th percentiles. Horizontal lines and crosses within boxes are the median and mean, respectively.

3. Results

3.1. Nutrient management in smallholder fields

Nutrient input was extremely low in smallholder fields. For example, about half of the fields did not receive any N, P, K or Mg fertilizer input, and nutrient rates were low in fields receiving fertilizer (Fig. 2). Considering all (fertilized and unfertilized) fields, annual nutrient rates averaged 20, 5, 15, and 2 kg ha^{-1} for N, P, K, and Mg, respectively. There was variation in nutrient rates among sites, which was explained to some extent by differences in fertilizer price (Pearson $r = -0.30$, $p < 0.01$), with JB and CK showing the lowest and highest frequency of fertilized fields, respectively (Supplementary Fig. 3). We found a high correlation between N, P, and K inputs ($r > 0.60$, $p < 0.01$), indicating that most farmers used compound fertilizers containing the three nutrients. Indeed, the most common fertilizer source was NPK-Phonska, which was less expensive than other fertilizers (Table 1). In contrast, only 10% of fields received application of sources rich in K (*e.g.*, MOP and NPK+), which were comparably more expensive.

Table 1
Sources of fertilizer in smallholder oil palm fields, average price (and associated inter-quartile range), and frequency of fields receiving each fertilizer source based on the pooled data collected from smallholder fields across six sites in Indonesia.

Fertilizer type	Formulation[a] (N:P:K:Mg)	Fertilizer price (US$ kg^{-1} product)	Applied fields (%)
Straight fertilizers			
Urea[b]	46:0:0:0	0.31 (0.21–0.40)	20
MOP	0:0:50:0	0.35 (0.23–0.43)	9
Dolomite	0:0:0:11	0.09 (0.06–0.09)	7
SP-36[b]	0:16:0:0	0.24 (0.20–0.26)	3
TSP	0:20:0:0	0.39 (0.31–0.42)	3
Compound fertilizers			
NPK-Phonska[b]	15:7:12:0	0.24 (0.21–0.24)	23
NPK+	13:3:22:2	0.45 (0.41–0.50)	10
NPK-HC	16:7:13:0	0.56 (0.44–0.65)	5

[a] Elemental nutrient concentration.
[b] Subsidized fertilizers for a number of food crops, not including oil palm (Ministry of Agriculture, 2020; Kemenkeu, 2021). MOP: muriate of potash; TSP: triple superphosphate; SP-36: single superphosphate; NPK+: NPK formulation with higher K and Mg, NPK-HC: NPK formulation with slightly higher N and K.

Average (2020–2021) yield across the six sites was 13.9 t ha^{-1}, ranging from 11.4 t ha^{-1} in JB and EK to 17 t ha^{-1} in CK (Supplementary Fig. 4). Average yield was 19% below national average yield of 17 t ha^{-1} (FAOSTAT, 2011–2020), and well below the attainable yield of 33.4 t ha^{-1} estimated for independent smallholders by Monzon et al. (2023). About 20% of the fields produced <10 t ha^{-1} and even the upper range of yields at each site was well below the attainable yield. Average yield was relatively high in CK, where frequency of fertilized fields and average fertilizer rates were highest, and low in JB and EK where fertilizer use was little, and rates were low (Supplementary Fig. 3). Due to low yields, NR_{FFB} was also modest, averaging 44 kg N ha^{-1}, 6 kg P ha^{-1}, 54 kg K ha^{-1}, and 8 kg Mg ha^{-1} (Fig. 2). Still, nutrient balances were negative because nutrient rates were smaller than NR_{FFB}, suggesting soil nutrient mining. In the case of N and K, fertilizer nutrient inputs represented only 45% and 28% of NR_{FFB}, leading to large negative nutrient balances (−24 and −39 kg ha^{-1}, respectively). This was also the case for Mg inputs, representing 25% of NR_{FFB}, but magnitude of Mg deficit (−6 kg ha^{-1}) was smaller than that for N and K given the lower Mg removal. In contrast to other nutrients, average P balance was near zero, with P inputs exceeding NR_{FFB} in *ca.* one third of the fields.

Current nutrient inputs were imbalanced in relation to plant nutrient requirements (Fig. 3). For example, farmers applied comparably more N than K (68% of fields), while proportionally more P is applied compared to N or K (70% of fields). This pattern was related to greater use of N- and P-rich fertilizer sources, such as NPK-Phonska and urea (Table 1). In connection to this point, the diagonal of dots in Fig. 3 correspond to fields receiving only NPK-Phonska (23% of fields), while those aligning along the horizontal axis in Fig. 3a applied only urea (10% of fields), in all cases leading to large nutrient imbalances. Only 11% of the fields exhibited balanced ratios for K:N and P:K, 6% for P:N, and just two fields for the three nutrients. Farmer yields were influenced by nutrient imbalances. For example, yield was 15% higher in fields with balanced K:N ratio compared with their counterparts with low K:N ratio ($p < 0.01$), although it is difficult to discern whether this difference was driven by a favorable K:N ratio, higher K fertilizer, or both.

Applied fertilizer was not split in 40% of fields receiving relatively large rates of compound and/or straight fertilizer. On the other hand, applied fertilizer was split in 25% of the fields where nutrient rate was

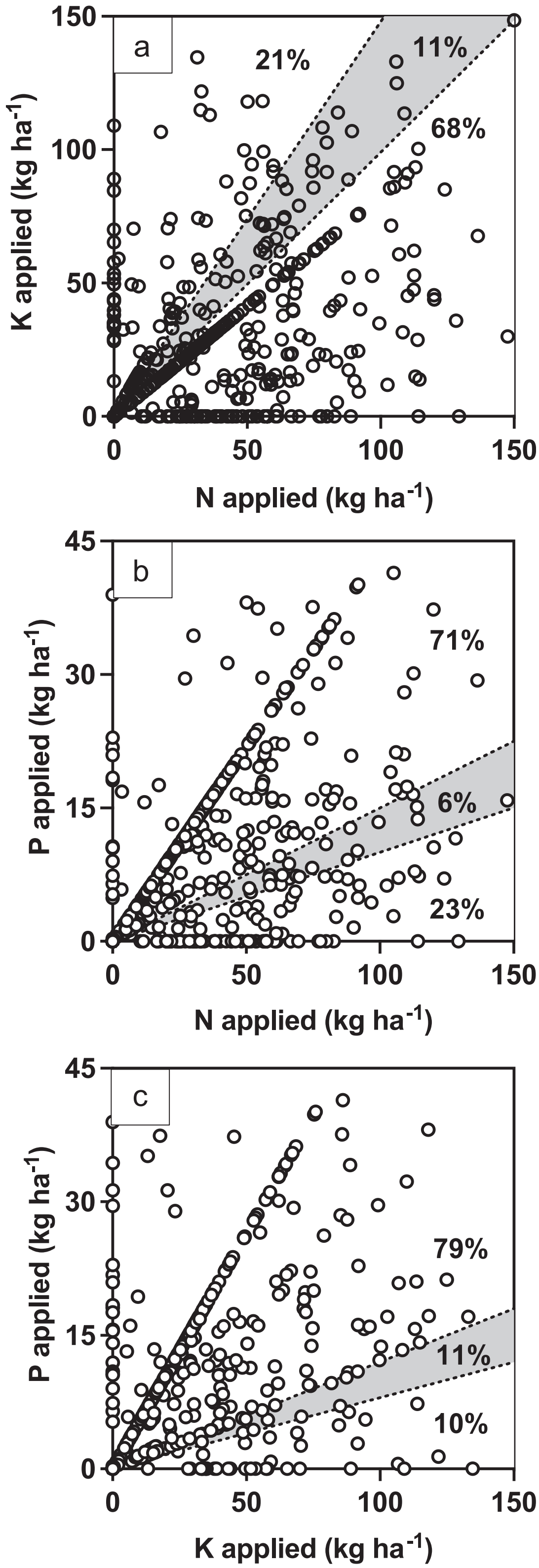

Fig. 3. Assessment of nutrient input ratios for nitrogen (N), phosphorous (P), and potassium (K) based on data collected from smallholder fields in Indonesia. Each data point corresponds to the average for a farmer field over two years (2020–2021). Shadow bands represents the balanced ratio range for each pair of nutrients. Fields falling outside bands are imbalanced for one nutrient in relation to the other. Also shown are frequencies of fields falling above, within, and below the balanced range.

low. We note that our thresholds to decide when (or not) to split fertilizers were relatively conservative. Using higher thresholds to decide when splitting was needed (*e.g.*, 1.5 kg palm^{-1} for urea and 3.5 kg palm^{-1} for other sources) would have led to a smaller frequency of fields where the fertilizer should have been split but also a higher number of fields where split was not needed. In relation to fertilizer placement, nearly all farmers applied fertilizer in the palm circle regardless of fertilizer type, except for 10% of farmers applying compound NPK fertilizer on the stacked fronds as recommended.

3.2. Nutrient gaps in smallholder oil palm fields

High FFB yields have large nutrient requirements. Hence, applying nutrient solely to replace those removed through FFB are not sufficient to achieve and sustain high yields over the long-term, while avoiding depletion of soil nutrient stocks. Across sites, the annual NF_{YATT} averaged 150 kg N, 19 kg P, 195 kg K, and 23 kg Mg per ha (Fig. 4). Nutrient requirement was larger in WK compared with other sites due to higher Yatt associated with plantations that are at the yield peak (Supplementary Fig. 4), highlighting the importance of benchmarking current nutrient use in relation to NF_{YATT} rather than a fixed yield target. Across sites, average NF_{YATT} were 8×, 13×, and 12× larger than current N, K, and Mg fertilizer rates, respectively, and 4× higher in the case of P. Annual nutrient gap averaged 130 kg N, 14 kg P, 180 kg K, and 21 kg Mg per ha, and large nutrient gaps were consistent across all nutrient-site combinations (Supplementary Table 1). While N and K rates were well below NF_{YATT} in all fields, some fields exhibited P and Mg above NF_{YATT} (9% and 3% of fields, respectively); these cases were associated with large applications of NPK-Phonska and dolomite, respectively (Fig. 4).

3.3. Impact of fertilizer use on smallholder yields and plant nutrient status

We found statistically significant positive relationships ($p < 0.05$) between yield, expressed as percentage of Yatt (%Yatt), and nutrient inputs (Fig. 5). Correlations were stronger when data were pooled across sites, compared with those performed separately for each site, as it extended range of yields and nutrient inputs. Still, there was large variation in %Yatt at any given level of nutrient inputs and it was remarkable the large variation in %Yatt without fertilizer applications, probably reflecting variation in applied fertilizer in previous years and/ variation in indigenous soil nutrient supply. Correlations between yield and K inputs were stronger and more stable across sites than for other nutrients. In contrast, correlations between yield and Mg inputs were the weakest among the four nutrients. Consistent with these findings, we also found statistically significant relationships between leaf nutrient concentration and fertilizer inputs for N, P, and K ($p<0.01$) but not for Mg ($p = 0.24$).

4. Discussion

Increased use of fertilizer, together with use of improved plant varieties and adoption of pest control measures, sustained large increases in rice and maize yields in Indonesia since the onset of the Green Revolution in the mid-1960s (FAOSTAT, 2022b). At present, average rice and maize yields represent 77 and 63% of the attainable yields, respectively (Rizzo et al., 2023). In contrast, independent oil palm smallholders still wait for their Green Revolution. Our study shows that current nutrient use in independent smallholder oil palm fields is insufficient and imbalanced due to a combination of small nutrient inputs (only half of the fields received fertilizer) together with a preference for using fertilizers that are rich in N and P, but poor in K and Mg (Figs. 2-3, Table 1). To sustain higher yields in smallholder fields, fertilizer use must increase for all nutrients, and proportionally more in the case of K for a balanced nutrition that matches plant nutrient requirements. A knowledge gap is also apparent among smallholders in relation to fertilizer management in their fields. For example, most

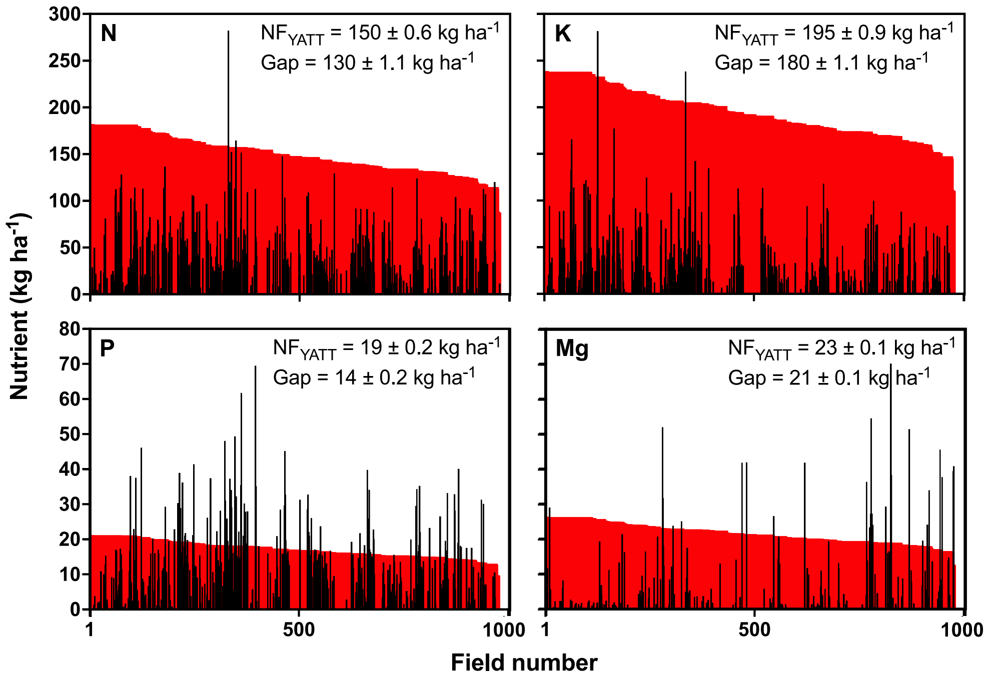

Fig. 4. Nutrient fertilizer requirement associated with the attainable yield (NF$_{YATT}$) for nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg) across 977 smallholder fields in Indonesia. Red bars show the 2-year (2020–2021) average NF$_{YATT}$ for a given field while black bars represent the actual applied nutrient; the difference between red and black bars is the nutrient gap. Fields were sorted from largest to smallest NF$_{YATT}$. Also shown are the average NF$_{YATT}$ and nutrient gap (±standard errors). For calculation of nutrient gaps, no gap was assumed in those fields in which actual applied nutrient exceeded NF$_{YATT}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

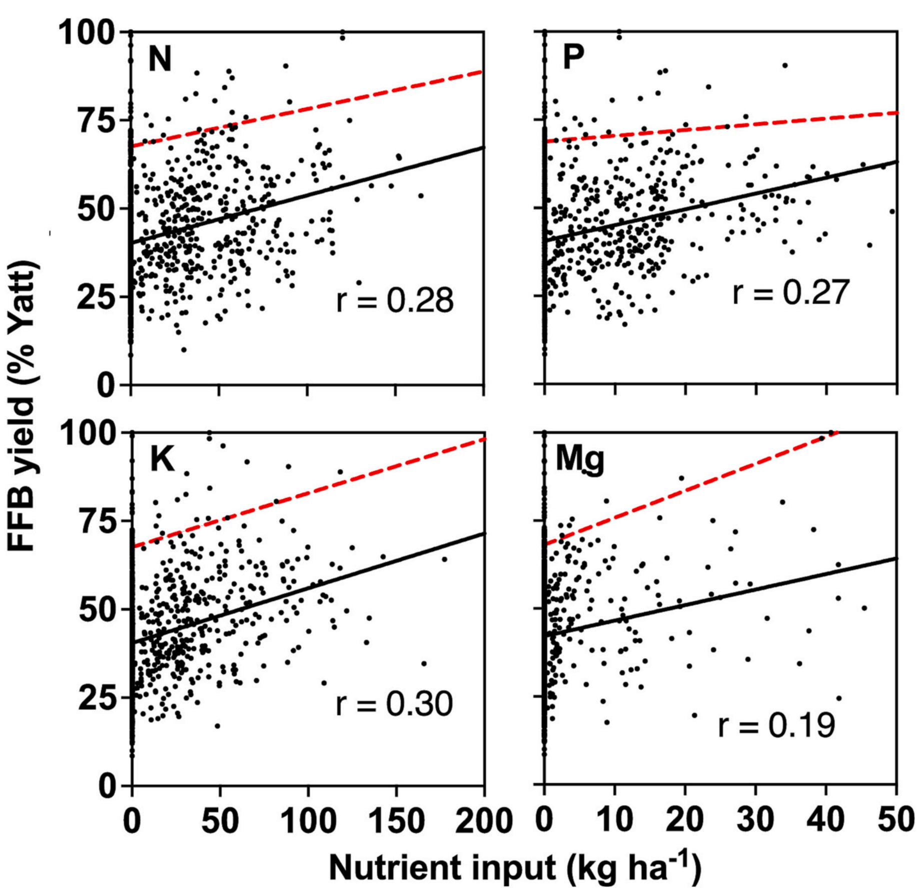

Fig. 5. Relationships between annual fresh fruit bunches (FFB) yield (expressed as a percentage of attainable yield), and nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg) nutrient rates based on data collected from 977 smallholder fields in Indonesia. Each data points represents the 2-year average yield and nutrient rate for a given field. Also shown are the Pearson's correlation coefficients (r). Associations between FFB yield and nutrient rates were all statistically significant ($p < 0.01$). Fitted linear regression models are shown with black solid lines; dashed red lines represent the boundary functions fitted using quantile regression (95th percentile).

smallholders in our study did not follow well-known recommendations on fertilizer placement and splits. This is not surprising considering that a baseline survey among the same farmers indicated that only one third of the farmers received training on fertilizer use at least once in their lives. Given the magnitude of nutrient imbalances found in our study, we suggest that increasing nutrient supply in balanced ratios should be a priority in any program that aims to increase productivity in smallholders oil palm fields, with a parallel effort to ensure proper placement and split of fertilizer once higher fertilizer rates are applied. Likewise, besides poor plant nutrition, other factors such as inappropriate harvest, pruning, and weed management have been identified as constraints to oil palm yield in smallholder fields (Euler et al., 2016; Woittiez et al., 2017; Monzon et al., 2023, this issue). The influence of these other factors is illustrated by the large variation in yield for a given level of nutrient application (Fig. 5). Hence, efforts to promote greater fertilizer use in smallholder fields must also include the needed technical assistance and training to ensure not only proper fertilizer management but also good crop management and field upkeep in order to maximize plant nutrient uptake while minimizing environmental losses.

A question is how to foster higher and balanced nutrient use in smallholder fields while being sensitive to their financial constraints and lack of access to technical information. Fertilizers are expensive for smallholders as shown by their preference for cheaper fertilizers (Table 1). At present, current replanting programs by the government provides organized independent smallholders with support to use certified planting material and fertilizer for the establishment phase of new oil palm plantations, but for the years thereafter smallholders need to ensure the access to fertilizer by themselves (Nurfatriani et al., 2019). Hence, if the desire is to increase smallholders' yields, it can be considered to include oil palm as a crop in the national fertilizer subsidy program and offer a subsidized fertilizer with a suitable nutrient content ratio for oil palm (*e.g.*, NPK+). At the local level, some form of micro-credit scheme to help smallholders buy fertilizers would also be helpful. Another option is to strengthen the relationship between independent smallholders and mills, similar as for plasma farmers. Independent smallholders could be engaged in plasma-like schemes, where they receive financial and technical assistance from large plantations to apply proper nutrient and crop management practices, in return for delivering their FFB exclusively to their mills. New drivers towards such relations are the Roundtable on Sustainable Palm Oil (RSPO) and Indonesia Sustainable Palm Oil (ISPO) certification schemes and the need for traceability as expressed by importing countries (Leegwater and van Duijin, 2012; Dharmawan et al., 2021). We note, however, that several constraints exist for joining such schemes, such as land titling and lack of collective action (Jelsma et al., 2017; de Vos et al., 2023). Indeed, only one third of smallholders are currently engaged in plasma-like schemes and their proportion is decreasing over time. Hence, it would be prudent to consider this option (*i.e.*, plasma-like schemes) as a possible longer-term solution and, in the meantime, develop AR&D programs and policy that explicitly aims to improve *now* the current nutrient supply in independent smallholder fields.

A pragmatic approach to remove current N, P, and K limitations is to use a nutrient replacement approach to replenish the nutrients that are removed *via* FFB, also accounting for those immobilized in the trunk, as done here to estimate nutrient fertilizer requirements. However, while our estimated nutrient fertilizer requirements to achieve the attainable yield (150 kg N, 19 kg P, and 195 kg K per ha) are comparable to those applied in large plantations in Indonesia (Monzon et al., 2021), they are several times higher than in independent smallholders' fields (Fig. 4). Given financial constrains to purchase fertilizer, the yield target for smallholders can instead be set based on current FFB yield (or average regional yield if the field yield is too low) and then gradually increased as the crop benefits from the improved nutrient supply and plant nutrition. A more aggressive approach for farmers who can afford larger quantities of fertilizer would be to target the yield of nearby large plantations or 'best' smallholders' fields located in comparable climate-soil conditions (Agus et al., 2023, this issue). The nutrient balance approach followed here is particularly suitable for N, P and K. In the case of Mg, deficiencies are less frequent compared with N, P, and K (Sugianto et al., 2023, this issue) and responses to Mg fertilizer tend to be smaller and less consistent (Caliman et al., 2001; Prabowo et al., 2023). Hence, Mg can be prioritized for fields where deficiencies are apparent (as determined through visual symptoms or leaf tissue analysis) and years with favorable FFB: fertilizer price ratio. A similar approach can be used for boron (B), which has also been found to be deficient in a high frequency of smallholder fields (Sugianto et al., 2023, this issue). Such approach (*i.e.*, application of N, P, and K fertilizer based on site-specific yield targets complemented with Mg and B as needed) is expected to deliver quick and large increases in yield (Caliman et al., 2001; Sugianto et al., 2022). While higher nutrient use increases production costs, gross profit is likely to increase more than proportionally, ultimately improving net profit as shown by Monzon et al. (2023) and Sugianto et al. (2022). Considering that income derived from oil palm cultivation accounts for half of the annual household income, and the large number of independent smallholder households across the country (*ca.* 1.5 million), increasing current yield *via* better plant nutrition could have a huge positive economic impact for smallholders and associated rural communities.

There may also be potential to combine use of synthetic fertilizer with organic sources such as EFB, manure, and compost. Indeed, EFB application is a common practice in large oil palm plantations where it helps recover a large fraction of the nutrients removed with the harvested FFB. However, this is not a common practice in smallholder fields due to competition with large plantations for EFB, and high transportation costs (Molenaar et al., 2010; Jelsma et al., 2019). Hence, in the foreseeable future, use of synthetic fertilizer will have to play a key role to remove the current nutrient gap in smallholder fields. In connection to this point, it would be relevant to estimate the additional fertilizer consumption at national level associated with a scenario of yield improvement across the entire independent smallholder area in mineral soils in Indonesia (*ca.* 3 M ha). For this exercise, we assumed that closing half of the exploitable yield gap through improved plant nutrition and other management practices is a reasonable short-term target, which is supported by empirical evidence from on-going field trials (Sugianto et al., 2022). In this scenario, average yield would increase from 13.9 t ha^{-1} to 23.7 t ha^{-1}, increasing national FFB production by 30 MMT, which is equivalent to 6 MMT CPO (+12% from current level). Achieving this yield improvement will require 5×, 2×, and 9× higher rates of N, P, and K fertilizer, respectively, as estimated using our nutrient replacement approach. At national level, the annual nutrient fertilizer consumption would increase by 267, 22, and 373 thousand tons for N, P, and K, respectively, representing a + 11% (N), +2% (P) and + 20% (K) increase in fertilizer consumption for all crops relative to current levels (IFASTAT, 2023).

5. Conclusions

Fertilizer use is insufficient and imbalanced in independent smallholder fields and fertilizer management is poor in relation to place and split of applications. Higher rates of fertilizer application are needed to achieve higher yield. Closing the current yield gap will require substantial increase in nutrient use, especially for K, and access to technical information. These changes will require re-orientation of current AR&D programs so that improved plant nutrition becomes a pillar in efforts to increase smallholder productivity, with emphasis on using fertilizer sources that better match oil palm nutrient requirements. Complementing strong extension services and policy to ensure access to proper fertilizer sources can have a massive impact at increasing smallholder yields and profit and increase the associated return to investment on A&R programs. Results from this study have been shared with stakeholders through a Fertilizer Roundtable held in Jakarta in January 2023. The associated final document with the consensus points is available at: https://rccc.ui.ac.id/wp-content/uploads/2023/03/Jakarta-Roundtable-Points-of-Consensus-final_bilingual_29Mar23.pdf

Declaration of Competing Interest

The authors declare no conflict of interest. The paper contents have not been previously published nor are under consideration for publication elsewhere. All co-authors have contributed to the paper and have agreed to be listed as co-authors.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103729.

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