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First things first: Widespread nutrient deficiencies limit yields in smallholder oil palm fields

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HIGHLIGHTS

- A focus on improved plant nutrition is needed to increase smallholder oil palm yields.
- We assessed palm nutrients status with a sampling methodology explicitly developed for smallholder oil palm fields.
- Many fields were deficient in potassium (88%), nitrogen (65%), boron (65%), phosphorous (52%), and magnesium (34%).
- Improved nutrition offers the opportunity to increase smallholder yields by 47%, equivalent to *ca.* 1.2 t oil ha^{-1}.
- Oil production can be increased on existing plantations *via* improved nutrition, without need to clear new land for planting.

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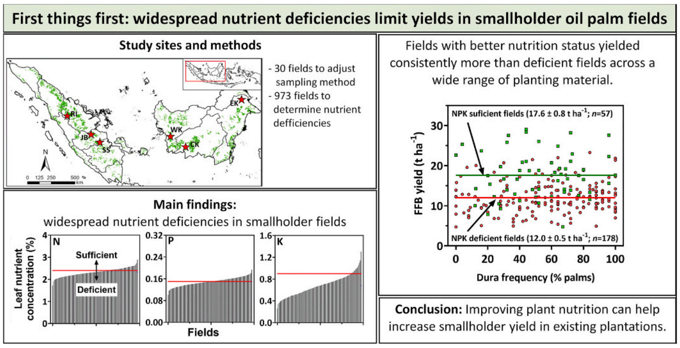
GRAPHICAL ABSTRACT



Fields with better nutrition status yielded consistently more than deficient fields across a wide range of planting material.

Conclusion: Improving plant nutrition can help increase smallholder yield in existing plantations.

ABSTRACT

CONTEXT: Indonesia is the most important oil palm producing country. Nearly 40% of planted area is managed by smallholders, with yields well below the potential. Efforts to increase productivity have focused on the source of planting material, with little attention paid to plant nutrition.

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Nutrients
Smallholders
Yield
Planting material

OBJECTIVE: To assess the degree to which current productivity in smallholder oil palm fields is limited by nutrients in scenarios with distinct sources of planting material.

METHODS: We collected detailed data on leaf nutrient concentration from 30 fields to derive minimum sampling size needed to diagnose nutrient status. Subsequently, we collected data on yield and palm type from 973 smallholder fields to assess the importance of nutrient status and planting material in the determination of yield.

RESULTS AND CONCLUSIONS: Potassium (K) deficiency was widespread (88% of fields) and often severe. Nearly two thirds of fields were also deficient for nitrogen (N) and boron (B), half were phosphorous (P) deficient, and one third were magnesium (Mg) deficient. Nutrient imbalances, especially between K and N, were also common. Fields with sufficient N, P, and K levels yielded 47% more (equivalent to 1.2 t oil ha^{-1}) than deficient fields across the entire range of planting materials. We conclude that improved plant nutrition increases fresh fruit yields in smallholder fields irrespective of the source of planting material. The advantage of certified planting material is reflected in the higher oil extraction rates.

SIGNIFICANCE: Increased smallholder oil palm yields on existing plantations through improved plant nutrition offers the opportunity to improve smallholder profits and livelihoods, whilst at the same time increasing total oil production without bringing new areas into cultivation.

1. Introduction

Oil palm is the main global source of vegetable oil in the world, accounting for *ca.* 40% of global production. Indonesia, the main palm oil producing country with *ca.* 15 M ha planted in 2020 (BPS, 2021), produces 59% of global palm oil (USDA, 2022). Large plantations account for *ca.* 60% of oil palm area in Indonesia. The remaining 40% of the area is managed by smallholders. Some of these smallholders (*ca.* one third) are bound to sell their fruit to the core plantation which provides them with financial and technical assistance ("plasma" smallholders), whilst others (*ca.* two third), hereafter referred to as 'independent smallholders', establish their own plantations and get no technical assistance directly from the core plantation (Molenaar et al., 2013; Jelsma and Schonevelg, 2016). In contrast to large plantations, where field size ranges from 25 to 40 ha, independent smallholder fields are small, typically ranging between 1.2 and 2.1 ha (Monzon et al., 2023, this issue). Despite the small field size, the income of *ca.* 2.6 million households depends directly on revenue from selling fresh fruit bunches (FFB) (Directorate General of Estate Crops, 2020). The average yield in independent smallholder fields is 13.9 t ha^{-1}; this yield level represents 42% of the attainable yield and is considered low (Monzon et al., 2023, this issue). Hence, identification and correction of causes for the yield gap, defined as the difference between actual and attainable yield, could not only improve farmers' livelihoods but also increase total oil production on existing planted area, without need to clear new land for cultivation (Monzon et al., 2021).

Current efforts to improve the FFB yield of independent smallholders focus on promoting replanting fields with certified planting material (Molenaar et al., 2013; Zen et al., 2005; Coordinating Ministry for Economic Affairs, 2023; Indonesian Oil Palm Association, 2023). In Indonesia, certified planting material has a high frequency (>98%) of tenera palm type (SNI, 2015). In contrast, non-certified planting material typically exhibits a higher frequency of dura palms. Oil extraction rate (OER) is generally greater in tenera palms, with OER decreasing 0.35–0.50 percentual points per 10% increase in dura frequency (Donough et al., 1993; Ho et al., 1996; Oberthür et al., 2012). Certified planting material has been massively adopted by large plantations whereas independent smallholders typically use non-certified planting material (Molenaar et al., 2013; De Vos et al., 2021; Monzon et al., 2023, this issue). Adopting certified planting material is only possible at planting time or replanting, which usually occurs when plantations reach *ca.* 25 years. Hence, ways to rapidly increase yield of existing smallholder plantations *via* improved agronomic practices are vital for increased current smallholder yields and income (Woittiez et al., 2018a; Rhebergen et al., 2019, De Vos et al., 2021; Monzon et al., 2023, this issue).

Adequate plant nutrition is essential to reach attainable yields in mature oil palm plantations (Goh et al., 1994*;* Goh et al., 2003; Foster, 2003; Sidhu et al., 2001). Inadequate plant nutrition has been postulated as a major cause of low productivity in smallholder fields (Woittiez et al., 2018a; Jelsma et al., 2019). Furthermore, according to Monzon et al., 2023 (this issue), closing yield gaps through yield-improving technologies also leads to higher farmer net profit. Hence, if plant nutrition can be improved through better use of fertilizers, it can provide a cost-effective, fast approach to increase smallholders yield and profit from the 4 million ha of palm they manage. Moreover, local communities and mills will also perceive benefits leading to a large positive economic impact at the country level. We hypothesized that an evaluation of plant nutrition on existing smallholders' plantations could rapidly provide guidelines on the expected FFB and oil yield increases from improved nutrient management.

Suitable diagnostic tools are required to evaluate the nutrient status of smallholder fields. We have not been able to find any guidelines that were established specifically to determine the nutrient status of smallholder oil palm fields. The standard diagnostic for nutrient deficiencies in oil palm measures leaf nutrient concentration of a standard reference frond (Chapman and Gray, 1949; Broeshart, 1955; Smilde and Chapas, 1963), and compares the concentration of each nutrient with a range of previously established critical values (Von Uexküll and Fairhurst, 1991). Reliable data on the nutrient status, based on leaf nutrient content of leaves, is extremely scarce in independent smallholder fields over the oil palm producing areas in Indonesia. For a robust diagnosis of the status of a field, several palms need to be sampled per field. Available recommendations on sample size for leaf nutrient were developed from fertilizer experiments and uniformity trials performed in large, commercial plantations or in research centers (Chapman and Gray, 1949; Broeshart, 1955; Smilde and Chapas, 1963; Smilde and Leyritz, 1965; Ward, 1966; Ng and Walters, 1969; Poon et al., 1970). For example, Ward (1966) indicated that sampling 1% of the palm population provides adequate precision to determine leaf N, P, and K concentration for a 30-ha field. Following this recommendation, many large plantations use a fixed grid sampling scheme to sample 1% of total palms per field. Unfortunately, these guidelines are not appropriate for smallholder fields, with much smaller size (*ca.* 2 ha) and potentially greater heterogeneity than that found in large plantations due to use of non-certified planting material and poor seedling selection. For example, application of the sampling protocol developed for large plantations to a typical smallholder field of 2 ha would sample only one or two palms per field.

There is a dearth of knowledge in relation to the degree and severity of nutrient limitations in smallholder oil palm fields and its impact on yield. Here, robust guidelines for determination of nutrient status in smallholder fields were used to diagnose nutrient status of palms across 973 smallholder fields located across the oil palm producing area in Indonesia. From this diagnosis, the relationship between yield and plant nutrient status was appraised for fields with a range of dura frequencies. Implications for agronomists and agricultural research and development (AR&D) programs are then discussed. Management drivers explaining the nutrient deficiencies reported here are assessed in a separate study

(Lim et al., 2023, this issue).

2. Materials and methods

2.1. Study sites

Our study focused on six sites located within the oil palm producing area in Sumatra and Kalimantan islands in Indonesia (Fig. 1, Table 1). The sites correspond with climate-soil domains that account for 87% of current oil palm area in Indonesia (Agus et al., 2023, this issue). Sites were selected based upon availability of local partners to collect the data and included only independent smallholder fields with mineral soils (Monzon et al., 2023, this issue). We excluded fields where oil palm was intercropped with other crops (*e.g.*, banana, cassava, *etc.*), home gardens (<0.1 ha), and immature (< 3 years) or very old plantations (> 25 years). Following these criteria, we selected 200 independent smallholders at each site, totaling 1200 farmers across sites. We only considered the largest field for each farmer (average: 2 ha). After quality control (see below), a total of 973 fields were used for the analysis. The data generated from these fields was used to determine the extent of nutrient limitations and their impact on smallholder fresh fruit bunch yield. An additional 30 fields at all sites (except for East Kalimantan (EK) were selected for the detailed sampling size analysis. In both cases, fields were sampled between January and October 2021 and the mean sampling time was 16 days per site. Description of weather, soil, and management at each site is provided elsewhere (Monzon et al., 2023, this issue).

2.2. Minimum sample size to determine nutrient status in smallholder fields

We measured leaf nutrient concentration for individual palms in independent smallholder fields at five production regions located across Sumatra and Kalimantan islands in Indonesia (Fig. 1). For simplicity, we referred to each site using the name of the associated province: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), and Central Kalimantan (CK). We sampled six independent smallholder fields per site; hence, a total of 30 fields were used to determine an adequate sample size for leaf sampling per field (Table 1). The fields were selected to portray the observed range in nutrient status based on preliminary leaf nutrient concentration data collected in the previous year. The fields were also selected to provide a good representation of the variation in field size, palm age, soil properties, FFB yield, and dura frequency in the five sites (Tables S1-S2).

Table 1
Description of databases used in the present study to assess nutrient status in smallholder oil palm fields in Indonesia.

Objective	Sites (and field per site)	Sampled palms per field	Leaf nutrient sampling	Other measured variables
Determine sample size needed to assess nutrient status	5[a] (6)	20	An individual sample per sampled palm	none
Evaluate extent of nutrient deficiencies across fields	6 (120–194)	10	Composited sample from 10 palms per field	FFB yield, dura frequency

[a] All sites but East Kalimantan.

In each selected field, 20 palms located along a two-row harvesting path were selected for this study, totaling 600 palms (Table 1). Contiguous palms and field edges were avoided (Fig. 2a). We also excluded abnormal palms (*e.g.*, infertile) and those severely affected by diseases (*e.g.*, Ganoderma). Following Rhebergen et al. (2018), we sampled frond #17 in each selected palm, collecting the leaflets located within the middle portion of the frond (Fig. 2b, c). A total of 30 leaflets were sampled from each frond, with 15 leaflets collected from each side of the rachis. We note that this is more than the usual six leaflets per frond because we needed to ensure that there was enough plant material from each palm for the chemical analysis. Leaflets were gently wiped with a soft towel (previously immersed in distilled water) to remove dust. The mid-ribs of the leaflets were removed, and the remaining lamina was cut into small pieces (*ca.* 1–1.5 cm), oven-dried, and packed and labelled separately for each individual palm. Samples were sent to the Asian Agri (AA) laboratory in North Sumatra (https://www.asianagri.com) to determine nitrogen (N) by Kjeldahl titrimetry, phosphorus (P) and boron (B) by spectrophotometry, potassium (K) by flame

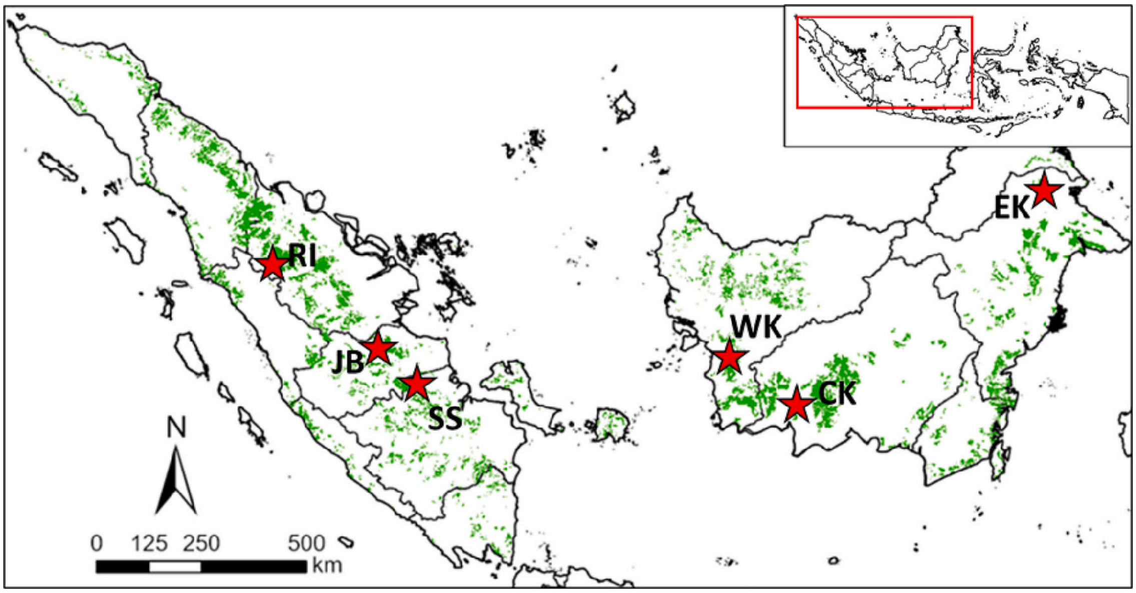

Fig. 1. Map showing the location of the six study sites in Indonesia: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), Central Kalimantan (CK), and East Kalimantan (EK). Inset shows the study area within Indonesia. Green area shows oil palm area in mineral soils (Ministry of Agriculture, 2012; Harris et al., 2015). See Table 1 for description of data collected at each site. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

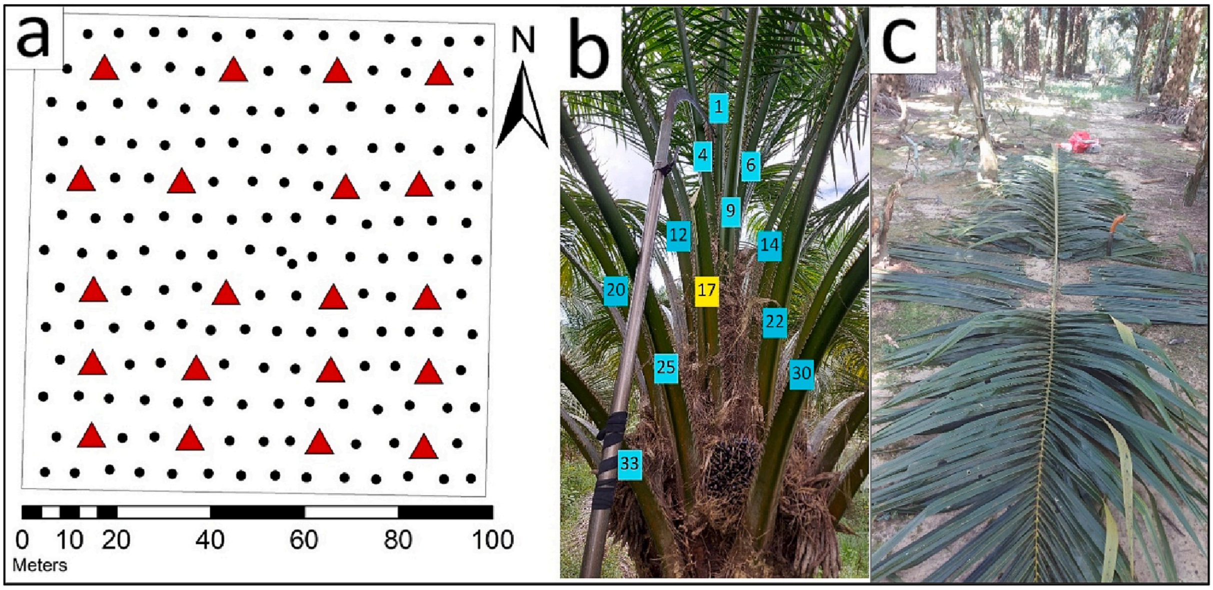

Fig. 2. (a) Map showing an example of the 20 sampled palms (triangles) in one of the selected fields. (b, c) Pictures showing the frond #17 being sampled and collection of associated leaflets.

photometry, and magnesium (Mg) and calcium (Ca) by atomic absorption spectrophotometry. The AA laboratory is actively participating in WEPAL (Wageningen Evaluating Programs for Analytical Laboratories, International plant-analytical exchange IPE, 2022) for objectively evaluating the performance of the laboratory by cross-comparison with those of other laboratories at regular time intervals. Based on the latest report, the *Z*-score for the AA laboratory is 0.35 (N), -0.08 (P), -0.25 (K), -0.88 (Mg), 0.95 (Ca) and 0.14 (B), indicating a high accuracy on their tests.

We followed two approaches to estimate the minimum number of palms needed for a robust estimation of nutrient concentration: *power analysis* and *bootstrapping*. Power analysis was performed as described by Desu and Raghavarao (1990) using the sample mean and standard deviation derived for each field based on the measured values from individual palms for each variable, assuming normality in the data distribution. *Bootstrapping* uses computer intensive resampling to make inferences rather than assuming a parametric form for the data distribution. A bootstrap sample is formed by selecting samples from a given statistical dataset by random resampling with replacement, which means that any sample may occur no times, one time, or many times in each bootstrap sample (Simpson and Mayer-Hasselwander, 1985). For each nutrient (N, P, K, Mg, Ca, and B), we estimated the average value using different numbers of palms (n, from 1 to 20 palms) with 200 subsets of palms of size n re-sampled from the 20 oil palms. The resulting range gives an indication of uncertainty due to field-to-field variability for each variable. Following both approaches (*i.e.*, power analysis and bootstrapping), we estimated the minimum number of palms needed to achieve different levels of precision (5%, 10%, and 15%) based on a 95% confidence interval. Palm-to-palm variation in leaf nutrient concentration was quantified for each field and each nutrient using the coefficient of variation (CV, %).

2.3. *Assessing nutrient deficiencies in independent smallholder fields*

We diagnosed nutrient status in 973 smallholder fields in the five sites previously described (*i.e.*, RI, JB, SS, WK, and CK) and we included an additional site in East Kalimantan (EK) (Table 1, Fig. 1). Samples from total of 182 (RI), 162 (JB), 147 (SS), 168 (WK), 194 (CK), and 120 fields (EK) were collected. The 30 fields that were used to derive the guidelines on sample size were not included in this assessment. Sample size was determined based on the results from our previous analysis, following a similar approach to select the palms to be sampled in each field. From each palm, we collected six leaflets from frond #17 following the approach described in Section 2.2 and a single composite sample for each field was prepared to determine leaf nutrient concentration on a field basis. Comparison of actual nutrient concentration *versus* the lower level of the sufficiency range reported in the literature (Von Uexküll and Fairhurst, 1991), was used to establish the frequency of deficient fields for each site and nutrient. In the case of K and Mg, it has been suggested that expressing these cations as percentage of the total leaf cations (TLC) provide a more accurate representation of their status (Foster and Chang, 1977; Foster et al., 1988). In our case, TLC-K and TLC-Mg were highly correlated with K and Mg concentrations ($r^2 > 0.90$, $p < 0.001$) leading to identical findings and interpretations. For simplicity, we only showed the results for leaf K and Mg concentrations without any correction by TLC. Finally, we evaluated ratios between nutrients as suggested by Ng (2002) and Goh and Härdter (2003). Balanced N:K and P:K ratios were estimated as the quotients between the lower end of the optimum range of leaf concentration reported for each nutrient (Von Uexküll and Fairhurst, 1991), the balanced N:P ratio was derived from the leaf N concentration following the equation reported by Ollagnier and Ochs (1981). Subsequently the nutrient ratios derived from each field were compared with the balanced ratios, considering nutrients to be balanced for a given combination of nutrients when the associated ratio was within ±25% from the balanced ratio.

2.4. *Assessing relationships between nutrient status and yield as influenced by dura frequency*

Data on FFB yield were collected over two years (2020−2021) in the same fields that were sampled across the six sites. Quality control measures were implemented to detect erroneous yield data entries and outliers. For example, yields exceeded 35 t FFB ha^{-1} in a few fields, which, after field validation, were found to be associated with FFB pooling across adjacent fields. In other cases, yield was extremely low ($<$3 t FFB ha^{-1}) and/or average harvest interval was too long ($>$45 days) because fields were quasi-abandoned and/or subjected to prolonged flooding. These fields were excluded from the database. For all our analyses, we used the average annual FFB yield calculated as the average over the two years (2020-2021). Detailed description of database and quality control is provided elsewhere (Monzon et al., 2023, this issue). In the case of planting material, qualified personnel from the Indonesian

Oil Palm Research Institute (PPKS) checked the frequency of dura palms in each field based on a sub-sample of 25 palms selected to portray the field variability. As a first approach to assess the link between FFB yield and plant nutrition, taking into account dura frequency, we performed a multiple regression analysis including FFB yield (dependent variable) and leaf nutrient concentration, dura frequency, and their interactions (independent variables). Quadratic terms were not significant ($p > 0.10$) and thus excluded from the model. Analysis of variance (ANOVA) was used to test the statistically significance of each term using F tests. Given the lack of a formal experimental design underpinning our database, we used sequential type-I sum of squares for our multiple-regression analysis. To further assess relationships between FFB yield and leaf nutrient concentration and planting material background, we created two groups of fields based on their measured leaf nutrient status: NPK-sufficient (*i.e.*, fields sufficient for *all* three nutrients) and NPK-deficient (*i.e.*, fields deficient for *all* three nutrients). The FFB yields were plotted against dura frequency and linear-regression analysis was used to evaluate the overall regression and differences between sufficient and deficient fields over the range of dura frequency. Finally, to account for the influence of dura frequency on OER, we calculated oil yield for each field based on FFB yield and frequency of each palm type, assuming an average (OER) of 18% for dura and 24% for tenera palms. These values were derived from our own measurement of OER in 446 individual palms performed across a subset of 31 fields between Aug 2022 and Feb 2023 following the method proposed by Hasibuan et al. (2013) and Hasibuan and Nuryanto (2015). Our average OER for dura and tenera are consistent with those reported in the literature (Donough et al., 1993; Ho et al., 1996; Oberthür et al., 2012).

3. Results

3.1. Minimum sampling size for estimation of leaf nutrient concentration

Our subset of 30 fields portrayed a wide range of leaf nutrient concentration values (Fig. S1). Palm-to-palm variation in nutrient concentration, quantified using the average CV across fields, was relatively low for N (6%) and P (7%), intermediate for Ca (16%), B (17%), and K (19%), and high for Mg (28%) (Fig. S1). The two approaches (*i.e.*, power analysis and bootstrapping) used to estimate the minimum sampling size delivered similar results (Fig. 3). Considering 10% as a reasonable level of precision, our analysis showed that three palms per field were sufficient to estimate N and P concentration at field level, which was consistent with the small palm-to-palm CV observed for these nutrients. However, a larger sample size would be needed for other nutrients to achieve a similar level of precision. Assuming that 15% is still a reasonable level of precision, 10 palms per field were generally sufficient for robust estimation of K, Ca, and B in smallholder fields. In contrast, the required sampling size was larger for Mg, in some cases requiring up to 30 palms to reach a precision level of 15%.

3.2. Extent and type of nutrient deficiencies across smallholder fields

Extensive sampling was performed across six sites spread out across the Indonesian archipelago, including a total of 973 smallholder fields. In each field, 10 palms were sampled, and leaf nutrient concentration was determined from a composite sample collected from each field. Comparison of the nutrient concentration in each field *versus* the sufficiency ranges reported in the literature allowed us to determine the extent and severity of nutrient deficiencies across smallholder fields (Fig. 4). Leaf nutrient concentration varied across sites and across fields within each site. In the case of N and P, leaf nutrient concentration was relatively stable across sites and fields (average CVs = 8% and 10%). In contrast, other nutrients (K, Mg, Ca, and B) exhibited larger spatial variation (average CVs = 27%, 31%, 22%, and 28%, respectively).

Deficient nutrient levels were found in a large proportion of smallholder fields (Fig. 4; Fig. S2). The K deficiency was widespread (88% of fields), while N and P were deficient in *ca.* two thirds of the fields. Deficiencies of these nutrients were more frequent and severe in JB and less

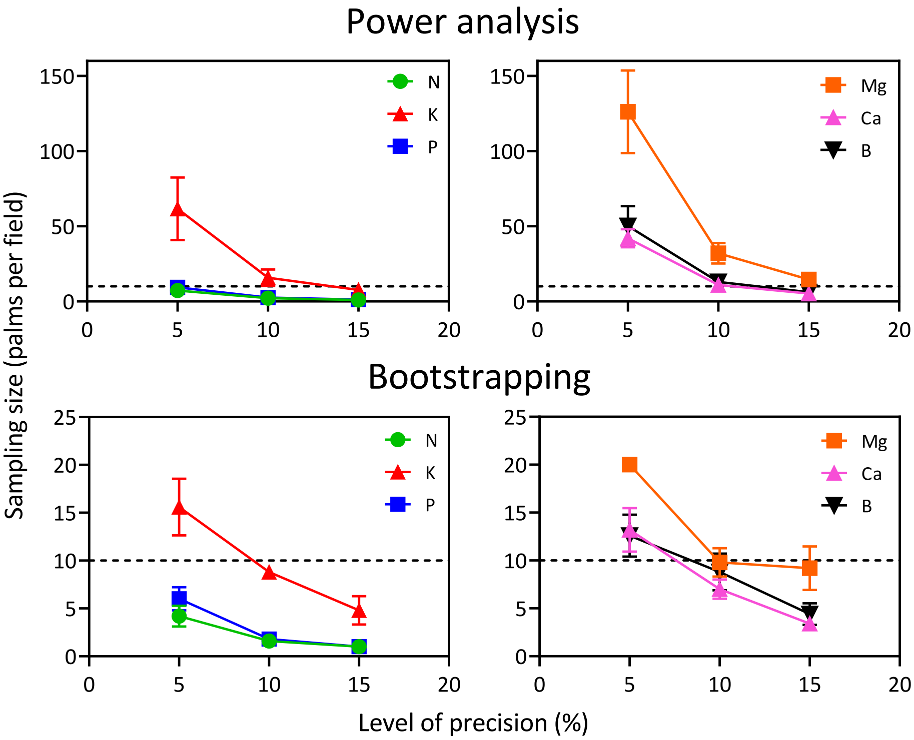

Fig. 3. Sampling size for estimation of nutrient concentration for different levels of precision (5%, 10%, and 15%) as determined using power analysis (upper panels) and bootstrapping (lower panels) for each nutrient: nitrogen (N), phosphorous (P), potassium (K), magnesium (Mg), calcium (Ca), and boron (B). Values are averages (± standard deviation) across all 30 sampled fields. Dasheline, in all panels, shows a sampling size of 10 palms.

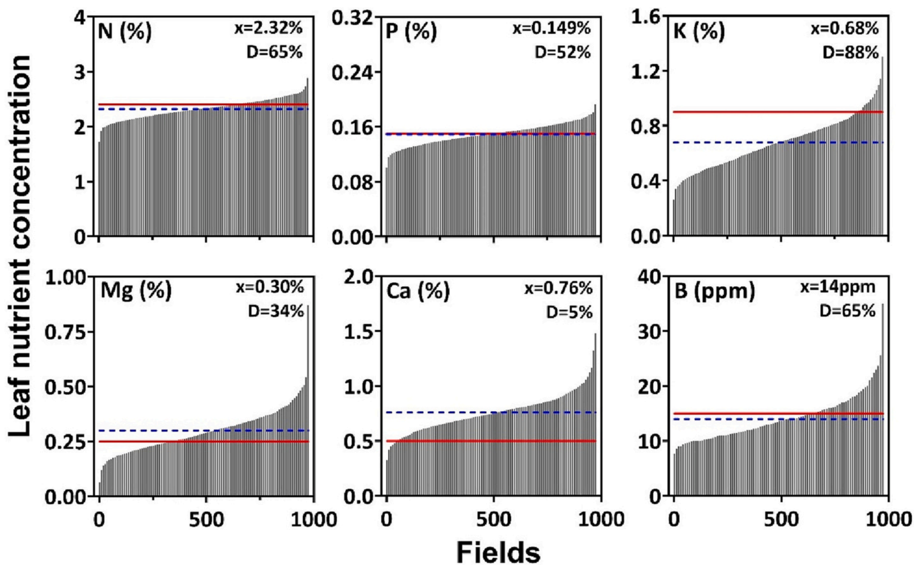

Fig. 4. Leaf nitrogen (N), phosphorous (P), potassium (K), magnesium (Mg), calcium (Ca), and boron (B) concentration based on data collected from 973 smallholder fields in Indonesia. Each bar corresponds to a farmer field; the fields are sorted from lowest to highest nutrient concentration. Horizontal lines indicate average nutrient concentration (dashed blue) and the lower end of the sufficiency level for each nutrient (solid red) as reported by Von Uexküll and Fairhurst (1991). Also shown are means (x) and percentage of deficient fields (D). Extremely low and high leaf nutrition concentrations shown for a few fields should be taken with caution as they probably reflect human error in sample collection and/or processing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

frequent in CK. Also, B and Mg deficiencies were apparent in about half and one third of the fields, respectively, especially in RI and JB (B) and CK (Mg). In contrast, Ca deficiency was rare and, indeed, values well above the sufficiency threshold in a large proportion of fields, especially in WK, CK, and RI. There were large deviations from the balanced nutrient ratios, especially in the case of K (Fig. 5). While 58% of the fields had a balanced N:P ratio (*i.e.*, within ±25% from the balanced ratio derived from the literature), only 22% and 20% of the fields had balanced N:K and P:K ratios. When nutrients were sufficient *and* in balanced ratios, yields were consistently greater.

3.3. *Effect of leaf nutrients status on FFB yield as influenced by dura frequency*

A multiple regression model including N, P, K, dura frequency, and their interactions, explained close to 20% of observed variation in yield ($p < 0.01$). Statistically significant ($p < 0.05$) positive effects of leaf N, P, and K concentration, and P × K and N × P × K interactions, on FFB yield were detected (Table 2). In contrast, dura frequency and interactions with nutrients had no statistically significant effect on FFB yield, although the analysis suggested a possible dura × P interaction ($p = 0.06$).

We further investigated the influence of nutrient status and dura contamination on yield by comparing NPK-deficient fields *versus*

Table 2
Multiple-regression analysis for annual FFB yield (t ha^{-1}). Independent variables included leaf nitrogen (N), phosphorous (P), and potassium (K) concentration (in %), dura frequency (D, %), and their interactions.

Source of variation	d.f.	Coefficient (±s.e.)	SS	*F*-test	*p*-value
Intercept	15	2.46(±16.44)			
N	1	0.74(±8.07)	547	28	<0.001
P	1	124.3(±94)	2489	126	<0.001
K	1	4.58(±20.43)	624	32	<0.001
D	1	0.02(±0.21)	0.30	0.02	0.90
N × P	1	−32.59(±40.12)	4.4	0.22	0.64
N × K	1	−10.1(±10.62)	59	3.0	0.09
P × K	1	32.51(±47.96)	123	6.2	0.01
D × N	1	0.05(±0.11)	1.4	0.07	0.79
D × P	1	−0.38(±0.48)	71	3.6	0.06
D × K	1	−0.19(±0.3)	5.0	0.25	0.61
N × P × K	1	51.78(±30.75)	74	3.7	0.05
D × N × P	1	−0.27(±0.3)	8.3	0.42	0.52
D × N × K	1	0.06(±0.15)	5.7	0.29	0.59
D × P × K	1	0.73(±0.48)	46	2.30	0.12
D × N × P × K	1	−0.12(±0.38)	1.8	0.09	0.76
Error	957		18,939		
Total	972		22,997		

d.f.: degrees of freedom; s.e.: standard error, SS: type-I sum of squares.

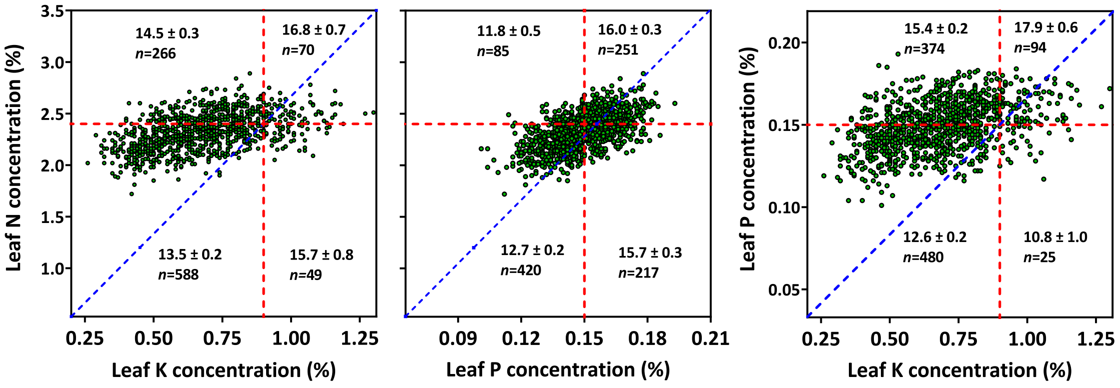

Fig. 5. Comparison between leaf nitrogen (N), phosphorous (P), and potassium (K) concentration based on data collected from 973 smallholder fields. Red dashed lines show the lower end of the sufficiency range for each nutrient. Average yield (± standard error) and number of fields (n) are shown for each quadrant. Also shown are the balanced ratios for each combination of nutrients with the blue dashed lines (see Material and Methods). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

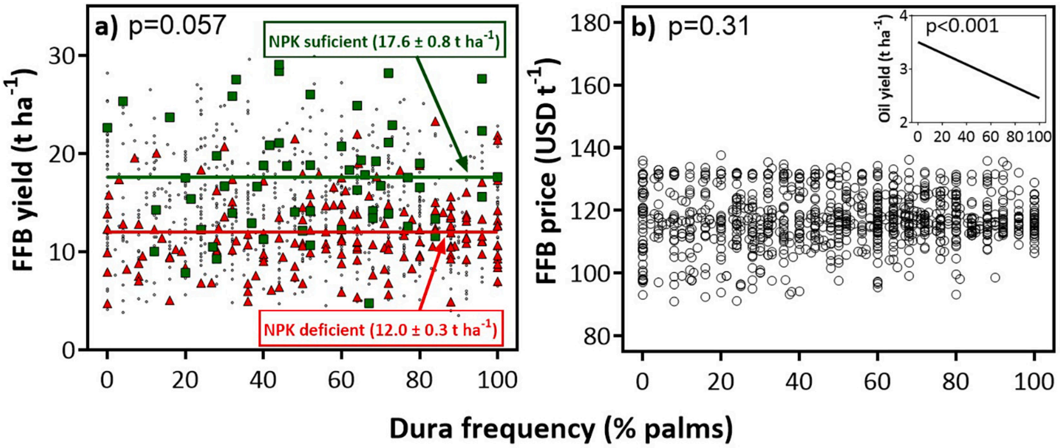

Fig. 6. Influence of dura frequency on (a) fresh fruit bunch (FFB) yield and (b) FFB price received by farmers based on data collected from 973 smallholder fields. Statistical significance of the linear regression model fitted to the pooled data is shown. Red triangles and green squares in (a) show fields categorized into deficient and sufficient ($n = 178$ and 57, respectively), according to their leaf nitrogen (N), phosphorous (P), and potassium (K) concentration; horizontal lines and values indicate means (± standard error) for each group. Inset in (b) shows oil yield as a function of dura frequency. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sufficient fields across the range of dura frequency (Fig. 6a). On average, NPK-sufficient fields yielded 5.6 t FFB ha^{-1} (+47%) more than NPK deficient fields ($p < 0.001$). The yield difference between the two groups of fields was consistent over the entire range of dura frequency, as indicated by the lack of statistical significance for the interaction term ($p = 0.17$). Only fields sufficient in N, P, and K yielded >25 t ha^{-1}, with some approaching 30 t ha^{-1}, while most NPK-deficient fields (82%) yielded <15 t ha^{-1}. The magnitude of fresh fruit yield change due to dura frequency was relatively small, with FFB yield decreasing by 7% as dura frequency went from zero to 100% ($p = 0.057$). However, our measurements of OER for a subset of fields showed that OER is greater in tenera than in dura palms (Fig. 7), and consequently oil yield is likely to be greater as dura frequency decreases. When we accounted for the impact of dura frequency on OER, the oil yield decreased by 30% as dura frequency increased from 0 to 100% ($p < 0.001$) (Fig. 6b, inset). Despite these differences in oil yields, the price received by farmers remained stable over the range of dura frequencies (Fig. 6b).

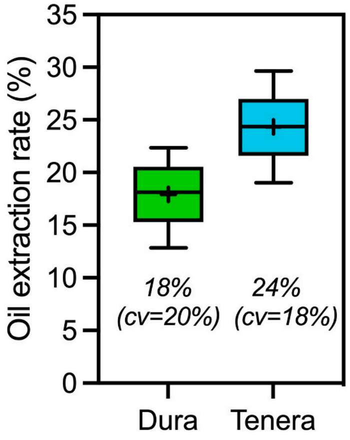

Fig. 7. Box plots for oil extraction rates (OER) measured in individual dura (n=235) and tenera palms (n=211) across a subset of 31 smallholder fields located in Riau, Jambi, South Sumatra, West Kalimantan, and Central Kalimantan. Upper and lower boundaries of boxes indicate 75th and 25th percentile, respectively. Vertical bars indicate 5th and 95th percentile values. Horizontal lines and crosses within boxes are the median and mean, respectively. Also shown are the mean and the coefficient of variation (cv, in %) for each palm type.

4. Discussion

To our knowledge, this is the first time that a detailed and extensive leaf sampling scheme, explicitly developed for smallholders, has been used to diagnose nutrient deficiencies in smallholder fields (Table 1). Recent studies that included leaf analysis to diagnose nutrient status in smallholder oil palm fields in Indonesia (Woittiez et al., 2018b; Jelsma et al., 2019) and Ghana (Rhebergen et al., 2018; Rhebergen et al., 2020) used arbitrary sample sizes. For example, Woittiez et al. (2018b) sampled smallholder fields to determine leaf nutrient concentration at two study sites: at one site, they selected three palms per field "*randomly*" avoiding "*sick*" or "*unrepresentative*" palms, while, at the second site, they selected four palms "*in the four corners of the field, three palms away from the edge*". Jelsma et al. (2019) sampled "*a minimum of four non-randomly selected palms*" per field "*at least two rows away from the road and preferably at least five palms away from other sampled palms*", avoiding palms with any "visual abnormalities". In Ghana, Rhebergen et al. (2019, 2020) selected "*every fifth palm in every fifth row to provide a sampling density of 3–6% at each trial plot (5–9 palms per ha)*" to "*produce sufficient leaf sample material for each treatment plot*".

Ten palms per field provided a reasonable compromise between precision and labor, providing an average precision level of 3% (N), 4% (P), 10% (K), 14% (Mg), 8% (Ca), and 9% (B) as calculated *via* power analysis (Fig. 3). This sampling size is higher than in previous studies diagnosing nutrient deficiencies in smallholder oil palm fields in Indonesia (Woittiez et al., 2018a; Jelsma et al., 2019). We also found that palm-to-palm variation in nutrient concentration was low-to-intermediate for N, P, K, Ca, and B, but comparably higher for Mg, confirming results of previous studies in large plantations (Ng and Walters, 1969; Smilde and Leyritz, 1965). This similarity suggests that palm-to-palm variation in smallholder fields is not necessarily higher than that in large plantations and that the trends for greater variability in some nutrients is similar in both circumstances, smallholders and larger plantations. Thus, we conclude that 10 palms per field is sufficient for robust diagnosis of nutrient deficiencies in smallholder fields. In our study, sampling size guidelines were derived from fields ranging in size from 0.6 to 2.2 ha. The sampling size depends on the desirable level of accuracy and the expected spatial variation. Hence, sample size would not be expected to be greater for larger smallholder fields unless the spatial variation is larger. However, as the spatial variation is unknown *a priori* in most cases, ten palms may not be sufficient to portray the spatial variation in larger fields. Hence, we suggest, it would be prudent to increase the sampling size in larger fields (>10 ha) to allow for greater accuracy, where a reasonable compromise would be to follow the recommendation of sampling 1% of the palm population made for large plantations (Ward, 1966; Ng and Walters, 1969). Sampling time also influences the nutrient content of leaves. In oil palm, it is recommended to collect leaf samples around the same time of the year to avoid the confounding effect of seasonal changes in nutrient contents (Foster and Chang, 1977; Martineau et al., 1969; Foster, 2003). In our study, it took around 16 days to complete the sampling at each site, both for the sampling size study as well as for assessing the extent of nutrient limitations (Table 1). As one can imagine, it was logistically impossible to sample all sites at the same time. However, seasonal fluctuations in nutrient concentrations reported in previous studies (Foster and Chang, 1977; Martineau et al., 1969; Ng and Thamboo, 1969; Foster, 2003) are small when compared to the wide range of concentrations between fields in this study (Fig. 4). Hence, seasonal fluctuations were deemed unlikely to affect the overall results and conclusions from the study.

Oil palm FFB yield was significantly associated with leaf nutrient concentration (Figs. 5 and 6; Table 2). This finding confirms the conclusion from previous local studies based on a small number of fields (Woittiez et al., 2018b; Jelsma et al., 2019) that nutrient deficiency is a major yield constraint in independent smallholder oil palm fields in Indonesia. Most fields were deficient in K and a large proportion were also deficient in N, P, Mg, and B. The concentration of leaf N, P, K, and Mg in many samples was well below those reported in treatments receiving adequate nutrient amounts to reach or exceed yields of 30 t ha^{-1} indicating that deficiencies are both common and severe (Sidhu et al., 2001, 2009, 2014; Prabowo et al., 2006; Lee et al., 2019). Severe K deficiencies are most prevalent, with many fields with less than half the level considered to be sufficient (Fig. 5). Indeed, many K leaf nutrient concentrations are comparable to or even lower than those reported in long-term fertilizer-omission trials in Indonesia and elsewhere (Sidhu et al., 2001, 2009, 2014; Prabowo et al., 2006; Lee et al., 2019). On the other hand, high leaf Ca concentration (>1%) was found on 8% of fields: this is likely due to the smallholder practice of applying dolomite (Lim et al., 2023, this issue). However, we note that Ca excess can interfere with K and Mg absorption and exacerbate the deficiencies of these nutrients (Xie et al., 2021; Von Uexküll and Fairhurst, 1991). We could not find statistically significant relationships between soil parameters (nutrient concentration, pH, soil organic matter) and leaf nutrient concentration, indicating that soil variables should not be used to diagnose nutrient deficiencies in oil palm.

The large number of fields that are distant from the balanced nutrient ratios suggests a high frequency of fields with nutrient imbalance (Fig. 5). However, care is needed in interpreting this lack of nutrient balance. A point close to the blue line in Fig. 5 in the lower left quadrant might suggest a good nutrient balance, however the plants would clearly be deficient in both the nutrients in question. The optimum point for yield is likely to be close to the intersection of the dotted red lines, with all points in the upper right quadrant deficient in neither of the two nutrients. Foster (2003) points out that in commercial practice only the most deficient nutrients can be accurately diagnosed from leaf nutrient levels as the levels of all the other nutrients are distorted. We suggest that, while nutrient ratios may have value when only one nutrient is deficient, they should be treated with care when one or more of the other nutrients are deficient. Nevertheless, the frequent cases of extreme K deficiency, when compared with the much smaller range of nutrient values for N and P (Fig. 4), in conjunction with the many points in the lower left quadrants (Fig. 5), indicates that not only is nutrient deficiency common on smallholder fields, but also that there is a lack of balance in the nutrient supply. The large number of points well to the left of the dotted red line in the case of K concentration is indicative of a generalized imbalance in nutrient supply with insufficient use of K fertilizers, as documented by Lim et al., 2023 (this issue).

Inadequate nutrient management was identified as the most important single factor contributing to the large yield gap on smallholders' fields (Monzon et al., 2023, this issue). Our survey data which diagnoses nutrient deficiency in individual fields, and shows relationships between deficiencies with yield, validates the conclusion that nutrient management is critical to closing yield gaps. We estimated here that improving the nutrient supply to achieve nutrient sufficiency on currently nutrient deficient fields would increase the yields of deficient fields by 47%, equivalent to 5.6 t FFB ha^{-1} (Fig. 6a). This increase is equivalent to 1.2 t ha^{-1} of crude palm oil (CPO) and has the potential to massively impact productivity and return to investment on millions of hectares of oil palm managed by independent smallholders. Although we focus here on nutrient deficiencies, there are many other management factors besides nutrients (*e.g.*, harvest, pruning, weed management) that have been identified as yield constrains (Monzon et al., 2023, this issue). Hence, the estimate of yield gain due to improved plant nutrition is conservative as it would likely be larger if complemented by improved overall management. Indeed, the yields of many NPK-sufficient fields were similar to those of deficient fields (<15 t ha^{-1}), probably reflecting the incidence of other yield constraints. Although fresh fruit yield and the response to nutrients was similar for high and low dura frequencies, the oil yields are greater with low dura frequency due to the positive effect on the oil extraction rate (OER) and thus oil yield (Fig. 6b, Fig. 7). Hence, improved plant nutrition has the potential to increase oil yield during the current plantation cycle and amplify the positive impact of certified planting material with low dura frequency when fields are replanted. For example, with the average FFB yield in NPK-sufficient fields in our study, we estimate that a reduction of dura frequency from 50%, which is commonly found in smallholder fields (Monzon et al., 2023, this issue), to close to zero would increase the average oil yield by 0.6 t CPO ha^{-1}, from 3.7 to 4.3 t ha^{-1}. We note that this estimate is based on actual OER measurements performed for a subset of fields (Fig. 7). In contrast, the absolute impact of adopting planting material with low dura frequency would be smaller in a context of nutrient deficiencies. In the case of NPK-deficient fields, the increase in oil yield would be 0.4 t CPO ha^{-1}, from 2.5 to 2.9 t ha^{-1}.

Current efforts to increase smallholder yield heavily focus on a replanting program promoting use of certified planting material with low dura frequency. Over the long term, there are evident advantages to the Indonesian oil palm industry of reducing the dura contamination from the current high levels we observed. However, this advantage is not picked up by the independent smallholder as the industry does not measure oil yield at the field level and the price received by farmers does not depend on the dura frequency (Fig. 6b). Hence, farmers managing fields with lower dura frequency do not capture the economic benefit associated with higher OER and, thus, will have little incentive to use certified planting material when fields are replanted. To be paid according to OER, farmers would need to produce sufficient volume and collectively sell directly to a mill which would grade their feedstock and pay accordingly (Molenaar et al., 2013). However, the industry does not, at present, measure oil yield at the field level and farmers sell FFB to the mill through intermediaries. Hence, improving traceability and OER measurement seem key factors to incentivize adoption of certified material in smallholder fields. Over the shorter term, given the extent and severity of nutrient deficiencies, improved fertilization (see Lim et al., 2023, this issue) offers the opportunity to increase the FFB yield over the range of dura frequencies. This will complement the programs directed to reducing dura frequency and planting of improved planting material with greater total oil yield. Such an approach would further increase the impact of replanting programs and help smallholders to increase both FFB and oil yields on existing and newly replanted plantations, improving farmer profit and providing Indonesia with a pathway to increase CPO production on existing plantation area, avoiding further conversion of fragile ecosystems for oil palm cultivation.

5. Conclusions

Following criteria for sampling size that were explicitly developed for smallholders, we identified widespread nutrient deficiencies across independent smallholder fields in Indonesia, with N and P deficiencies common and severe K deficiency prevalent across fields. The FFB yield of fields that were sufficient for N, P, and K were 47% greater (equivalent to about 1.2 t CPO ha^{-1}) than the yields in deficient fields. Dura frequency did not influence relationships between FFB yield and nutrient status. We conclude that better plant nutrition has the potential to rapidly improve yield of existing plantations and complement the impact of better planting material on oil yield when fields are replanted. Such an approach would improve farmer livelihood and simultaneously increase palm oil production on existing plantation area.

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.2023.103709.

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