Agronomy for Sustainable Development (2022) 42: 13
https://doi.org/10.1007/s13593-022-00753-z

META-ANALYSIS

The use of oil palm empty fruit bunches as a soil amendment to improve growth and yield of crops. A meta-analysis

Michael Osei Adu[1] · **Kofi Atia**[2] · **Emmanuel Arthur**[3] · **Paul Agu Asare**[1] · **Peter Bilson Obour**[4] · **Eric Oppong Danso**[5] · **Kwame Agyei Frimpong**[2] · **Kwabena Azure Sanleri**[1] · **Samuel Asare-Larbi**[1] · **Richmond Adjei**[2] · **George Mensah**[2] · **Mathias Neumann Andersen**[3]

Accepted: 6 January 2022

Abstract

Oil palm plantations worldwide generate vast amounts of empty fruit bunches (EFB), often disposed of as waste and left to undergo natural decomposition or incinerated, contributing to greenhouse gas emissions. However, EFB could be used as soil conditioner to improve soil properties and increase crop yields. We conducted a meta-analysis to synthesize evidence of the effect of soil amendment by different forms of EFB on crop growth and yield and how other factors moderate performance. The meta-analysis included 19 studies on the growth and yield of crops grown on EFB-amended and unamended soils. Applying EFB as mulch, biochar, or compost to soil led to a 49.2% increase in crop growth and yield compared to unamended soils. When EFB were co-applied with a second material such as mineral fertilizers, crop growth and yield was increased by 16.4% compared to unamended soils. The growth and yield advantages were affected by the location of the experiment, soil texture, or the form of EFB applied. Compared to unamended soils, crops grown on soils amended with pyrolyzed EFB, raw EFB, composted, and ash EFB recorded growth and yield increase by ~78.4%, 33.8%, 30.9%, and 21.0%, respectively. Overall, amending soil with EFB is likely to increase crop yield. Still, the benefits must be clarified by a benefit-cost analysis based on the ratio of yield advantages from its usage to the cost of accessing or using the product by farmers.

Keywords Empty oil palm fruit bunches · *Elaeis guineensis* · Crop growth · Crop yield · Soil amendment · Soil conservation · Climate resilience

1 Introduction

Climate change is projected to modify the world's soil resources (e.g., Brevik 2013). In highly weathered tropical soils in sub-Saharan Africa (SSA), the predicted increases in temperatures may negatively impact soil-forming processes (Bazzaz and Sombroek 1996) and soils' role in providing vital ecosystem services. Given that the population of SSA is projected to quadruple by the end of the century (Gerland et al. 2014), food insecurity could become the biggest challenge in the region (Zuberi and Thomas 2012). The adverse impacts of climate change on crop production are expected to exacerbate in the future, putting pressure on an already vulnerable society. Therefore, SSA countries should adopt integrated and sustainable crop production practices that are climate change resilient and efficient in resource use.

In crop production, climate change resilience and sustainable use of arable soils could be realized through several

✉ Michael Osei Adu
michael.adu@ucc.edu.gh

[1] Department of Crop Science, School of Agriculture, College of Agriculture and Natural Sciences, University of Cape Coast, Cape Coast, Ghana

[2] Department of Soil Science, School of Agriculture, College of Agriculture and Natural Sciences, University of Cape Coast, Cape Coast, Ghana

[3] Department of Agroecology, Faculty of Technical Sciences, Aarhus University, Tjele, Denmark

[4] Department of Geography and Resource Development, University of Ghana, Legon, Accra, Ghana

[5] Forest and Horticultural Crops Research Centre, School of Agriculture, University of Ghana, Legon, Accra, Ghana

processes. For example, applying organic amendments to replenish soil nutrients has been suggested for resource-poor farmers (Oppong Danso et al. 2015; Anyaoha et al. 2018). The application of organic amendments can increase soil organic matter, improve soil fertility, and ameliorate degraded soils (Rickson et al. 2015). Particularly for resource-poor regions, the use of locally available bio-wastes such as empty oil palm fruit bunches (EFBs) to improve soil water and nutrient retention is suggested to be among the most sustainable options for soil conservation and improvement in soil fertility (Ortiz et al. 1992; Sung et al. 2010; Moradi et al. 2015). Empty oil palm fruit bunches are the biomass that remains after the fresh oil palm fruits have been removed from the fruit bunch. Palm oil plantations, globally, produce vast amounts of EFB, which often are disposed of as waste where it undergoes natural decomposition or through burning to increase greenhouse gas emissions such as methane and carbon dioxide, respectively. Empty oil palm fruit bunches constitute one-third of the dry biomass generated from crude palm oil production. Yearly, close to 99 million metric tons of EFB are produced globally (Geng, 2013). Oil palm plantations in Ghana produce approximately 390 t of EFB daily (Richard Nwiah, personal communication). These enormous masses of EFB could be incorporated into the soil, thereby mitigating emissions emanating from its decomposition or incineration.

Several studies have reported on the use of EFB, applied raw (organic mulch), pyrolyzed, or composted before application to soils (Fig. 1) (Anyaoha et al. 2018). As a mulch, EFBs primarily enhance soil water retention. When applied in the composted form or as biochar, EFBs improved soil water and nutrient content (Ahmad Dani 2018), possibly due to the losses of C from the anaerobic respiration involved in composting or the pyrolysis involved in biochar preparation (Fig. 1). EFBs may be a cheap organic fertilizer (Lim et al. 2015) because they can improve soil organic carbon (SOC) and other soil chemical properties such as pH and exchangeable K (Bakar et al. 2011; Zaharah and Lim 2000). Yet, data supporting the fertilizer value of EFBs and their effects on crop yield is patchy and scarce. Some reviews (e.g., Kong et al. 2014; Anyaoha et al. 2018) have evaluated the potential of EFB as a soil amendment to improve soil fertility and increase yield. However, these reviews did not account for potential moderators or variables that may influence the role of EFB in soils. The previous reviews have also been narrative and might be subjective and irreproducible. Moreover, the data on the use of EFB as a soil amendment in these reviews have been either fragmented or anecdotal, suggesting the need for a pooled quantitative synthesis of the evidence.

To fully implement a large-scale application of EFB as a soil conditioner and exploit the potential agronomic benefits, its effect on crop growth and yield must be quantified. To justify a recommendation, there is a need to quantify the impact of EFB application on crop growth and yield, vis-à-vis unamended soils. A pooled quantitative study will allow reasonable and reliable generalizations for broader utilization of EFB in crop production and elucidate how some moderators, e.g., soil, crop, and environmental factors, can enhance or reduce the fertilizer value of EFBs. Therefore, a meta-analysis was conducted to examine the performance of EFBs applications on crop growth and yield and how the performance is moderated by factors such as the location of experiments, crop type, soil textural class, and form or type of EFB applied. Further, the meta-analysis highlights critical prospects and challenges of using EFB as a soil amendment for agricultural production, particularly in smallholder farming systems.

2 Methods

2.1 Data collection

We conducted a systematic literature search to collect growth and or yield measurements from publications that had reported side-by-side comparisons of no EFB (control group) and EFB amended (experimental group). A title search was done in Scopus and Google Scholar using combinations of the following search terms: efb OR "empty fruit bunch" OR "oil palm empty fruit bunch" AND "plant growth" OR "crop growth" OR yield. Included studies reported growth and or yield data on individual crop species grown in soil with EFB treatment and an unamended control. A study was also included if it reported an additional treatment where EFB was combined with other amendments such as farmyard manure (FYM) or mineral fertilizer. The reported data must originate from primary research and should not have been already included in another paper to avoid multiple counting. Besides, growth or yield observations should be reported for both the unamended and EFB experimental groups. Also, the reported mean (X), sample size (N), and a measure of dispersion (standard error (SE), standard deviation (SD), or 95% confidence interval (CI), not necessarily mandatory) should be present as numerical or graphical data, or it should be possible to estimate from the reported data. In studies where SD or SE was not available, SD was reassigned as 10% of the mean and the effect of this assumption on the results was assessed by sensitivity analyses (Adu et al. 2018, 2019). Non-independent observations were accounted for as described in Supplementary Methods 1.

2.2 Computing effect sizes and aggregating dependent effect sizes

We computed effect sizes and aggregated dependent effect sizes (see Supplementary Methods 2) and performed two types of analysis. We firstly performed a meta-analysis including data of multiple variables (effect sizes) from the same

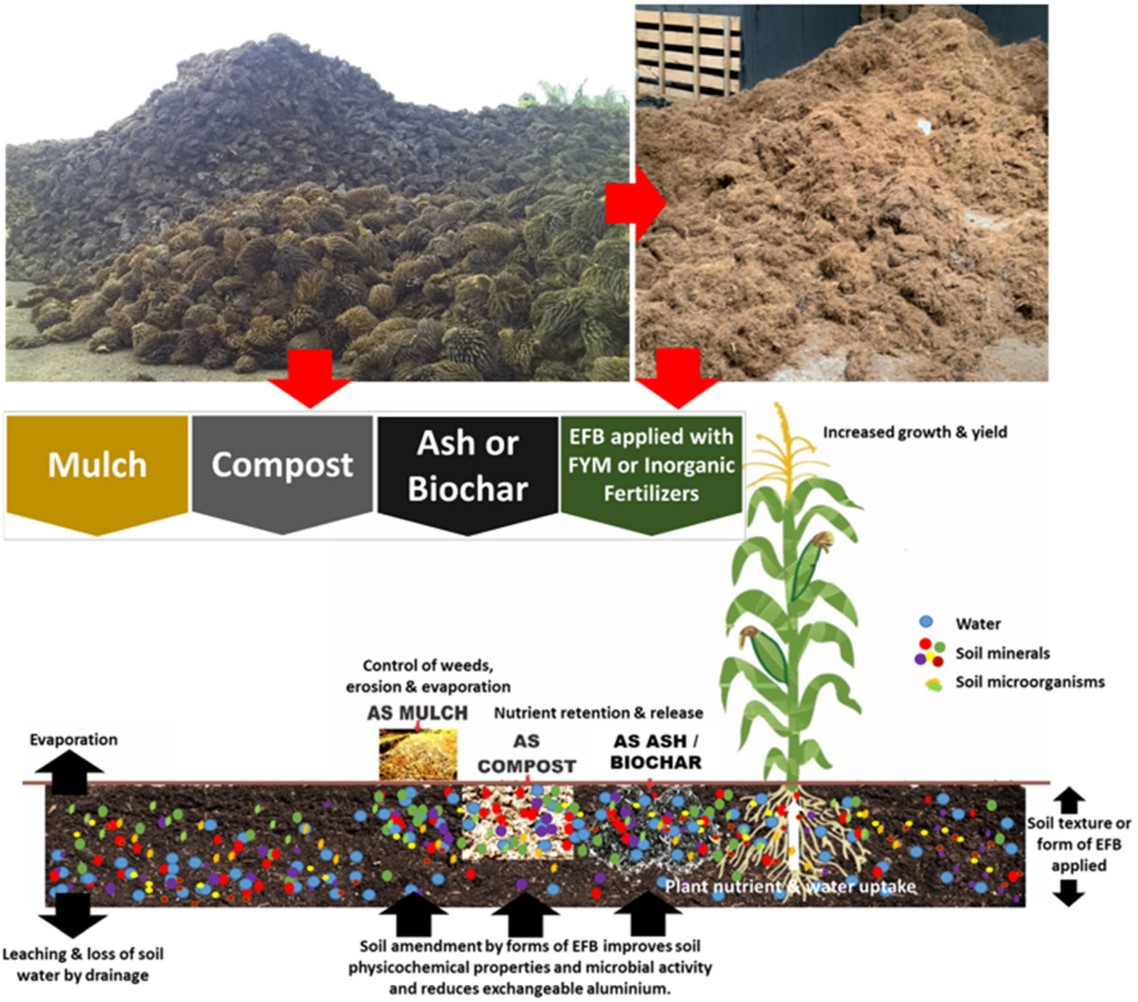

Fig. 1 Stockpile of empty oil palm fruit bunches (EFBs; top-left panel) that have been shredded (top-right panel) processed for soil conditioning. Empty oil palm fruit bunches are applied in several forms (bottom panel) as a soil conditioner. They could contribute to soil water conservation, nutrient cycling, enhancement of soil physicochemical properties, and plant-microbe interactions to influence crop growth, development, and yield. Still, these effects could be moderated by soil textural class and or the form in which the EFB was applied. FYM farmyard manure.

sample (i.e., where the same plant provided data for the different outcomes such as plant height and shoot dry weight). We used this non-aggregated dataset for moderator or subgroup analyses. Subsequently, in studies where several outcomes were presented for different plant traits, we aggregated all these outcomes to produce a single effect size per a study, using the Borenstein, Hedges, Higgins, and Rothstein (BHHR) univariate procedure (Del Re 2015). The BHHR accounts for the correlation among within-study effect sizes. Due to the non-availability of between-measure correlations within the studies, we inputted the within-study correlation between effect sizes at $r = 0.5$. Subsequently, we performed sensitivity analyses for $r = 0.3$ to $r = 0.7$. The BHHR procedure is implemented in the MAd package (Del Re and Hoyt 2014) of the R Project for Statistical Computing (R Core Team 2019).

A summary effect and heterogeneity of the summary effect were subsequently estimated. In the case of heterogeneity between studies, moderator analysis was performed via meta-regression to explain the heterogeneity therein. The log response ratio (R) (Eq. 1), computed as the ratio of the natural logarithm of means of the unamended and experimental group, was used. The R and attendant log standard error (SE) were subsequently back-transformed (i.e., $R = e^{\ln R}$) for ease in interpretation. For each variable, an $R>1$ indicated that the amendment of EFB to soil increased the metric of interest, while $R <1$ showed a decrease compared to the control. A random-effects model was used to determine the overall effect of EFB on the aggregated effect size from each study using the mareg function (Mad package) conducted in R Project for Statistical Computing (R Core Team 2019). The restricted maximum likelihood method (REML) was used to estimate the between-study variance. The mean effect size was considered significantly different from zero if its confidence interval did not include zero (Koricheva et al. 2013).

$$\ln R = \ln\left(\frac{Y_1}{Y_2}\right) = \ln Y_1 - \ln Y_2 \qquad (1)$$

where Y_1 and Y_2 are the mean of the EFB experimental and unamended groups, respectively. The variance of ln$R$ is given by Eq. 2:

$$v_{\ln R} = \frac{s_1^2}{N_1 Y_1^2} + \frac{s_2^2}{N_2 Y_2^2} \qquad (2)$$

where N_1 and N_2 are the sample size of the experimental group and the unamended group, respectively, and s_1 and s_2 are the standard deviations of the experimental group and the unamended group, respectively (Rosenberg et al. 2013). Moderator, publication bias, and sensitivity analyses are described in Supplementary Methods 3 and 4, respectively.

2.3 Data analyses

Statistical analyses were conducted in OpenMEE (Wallace et al. 2017) and metafor (Viechtbauer 2010), and Microsoft Excel 2016 was used to produce the forest plots.

3 Results and discussion

3.1 Overview of included studies, publication bias, between-study variability, and sensitivity analysis

Based on the exclusion criteria used in the literature screening, 19 studies were included in the meta-analysis. The studies generated 99 effect sizes (Supplementary Figure S1) consisting of eight greenhouse experiments conducted in three countries and 11 field experiments conducted in four countries in Asia and Africa. Most data came from Malaysia (Supplementary Figure S2a; Supplementary data: Table S1). The included studies span 15 years, with the earliest published in 2004 and the latest in 2019. The years 2010, 2016, and 2017 contributed the largest outcomes to the analysis (Supplementary Figure S2b). The majority of the studies were conducted on cereals, mainly on maize (*Zea mays* L.) (Supplementary Figure S2c), and most studies measured shoot-related parameters (Supplementary Figure S2d). Six of the included studies had additional treatments where some additives, such as FYM, were mixed with EFB and co-applied (Supplementary data: Table S2). The measurement of growth or yield is often based on multiple metrics. For example, growth could be estimated as increased cell numbers, tissue volumes, plant height, stem or root diameter, shoot or root fresh weight or dry weight, and leaf numbers, area, or weight. Similarly, in addition to the yield measurement itself, there are multiple yield components, including the number of panicles per unit land area, the number of spikelets per panicle, the percentage of filled spikelets, and 1000-grain weight measured. This was typical of many of the included studies in the present analysis, and each provided an estimate of the efficacy of EFB application. However, the number of effect sizes reported from individual studies was unequal, ranging from 1 to 18.

Funnel plots produced for both the non-aggregated ($k = 99$; Fig. 2a) and the aggregated ($k = 19$; Fig. 2b) datasets indicated a weak tendency for smaller sample sizes to be associated with stronger negative effects. For both datasets, the funnel plots were near symmetrical (Fig. 2 a and b), and trim and fill analysis indicated that no studies were missing to the side of the overall mean. Rosenberg's fail-safe number computed for the non-aggregated dataset was 120629, a value remarkably greater than the threshold of 505 ($5 \times n + 10$) needed to consider the mean effect size robust. Thus, a relatively larger number of unpublished studies would be required to change statistically significant effects observed in this analysis.

Variation in study outcomes between studies was overly large with I^2 values of >90%. Thus, the large dispersions in the summary effect are probably explained by study-level covariates. Differences in experimental approaches, environmental variables, and variations between studies could explain the observed high heterogeneities. Besides, many additional study characteristics could moderate the efficiency of EFB as a soil conditioner. Soil factors such as organic carbon, bulk density, soil moisture content, EC, and soil microbiological properties, among others, could ultimately affect the soil's buffering capacity and therefore could have a moderating role in the efficiency of EFBs as a soil conditioner. These potential moderators were, however, hardly reported in the included studies. This could be one of the reasons for the overly large values of I^2 obtained even after moderator analyses and meta-regressions. Indeed, large I^2 values reduce the predictive value of meta-analyses (Melsen et al. 2014), but I^2 are also substantially biased when the number of studies is small. For example, for a few studies with no true heterogeneity, the I^2 can overestimate heterogeneity by an average of 12 percentage points (von Hippel, 2015). The large degree of uncertainty in our observed estimates of the I^2 could be attributed to low statistical power due to the inclusion of a small number of studies in the meta-analysis (Ioannidis et al. 2007). The sensitivity analysis suggested that effect sizes for studies that had initially been reported measures of dispersion were comparable to those for which these measures had to be estimated (Supplementary Figure S3). Similarly, a sensitivity analysis conducted using various correlation values (r = 0.3 to r = 0.7) suggested no, or at best, very insignificant qualitative or quantitative changes in the trends compared to that obtained with our chosen r-value of 0.5 (Supplementary Figure S3).

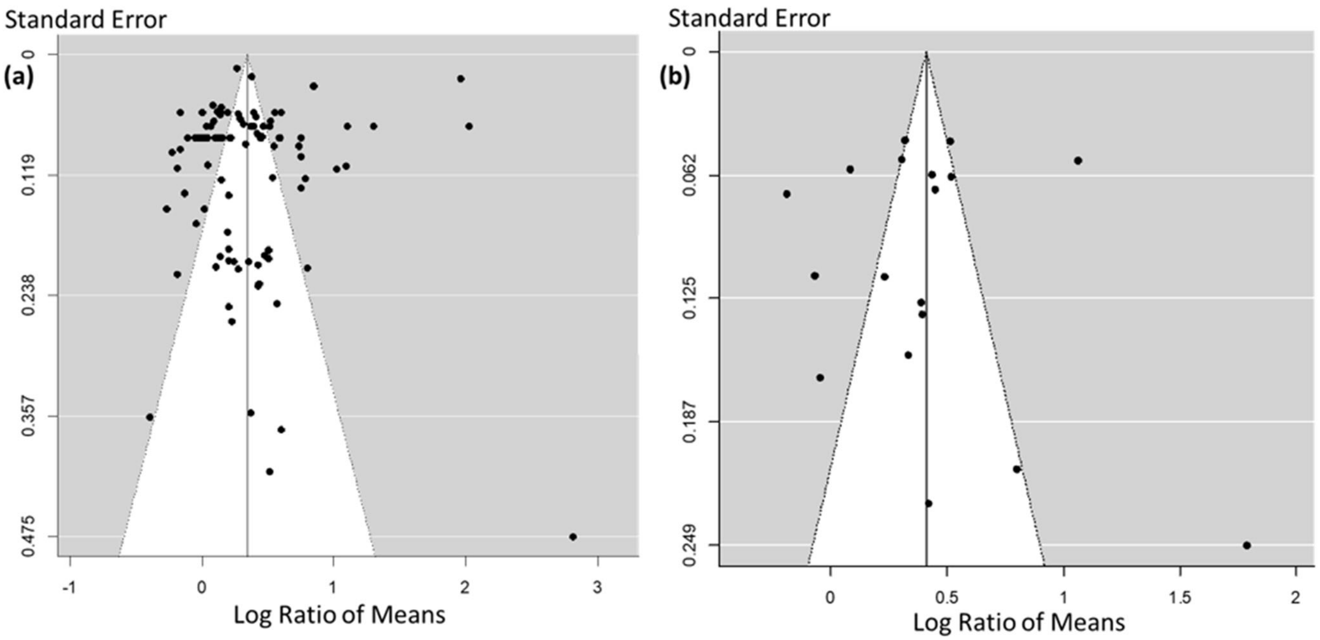

Fig. 2 Funnel plots of average effect sizes (log ratio of means) for (**a**) non-aggregated dataset (*k*=99) and (**b**) aggregated dataset (*k*=19), which compared growth and yield between empty fruit bunches-amended soils and non-amended soils; the *X*-axis shows the effect size log ratio of means and the *Y*-axis presents the inverse standard error of the effect size as a precision index. No effect size was estimated missing on the right side of the overall mean from trim and fill analysis.

3.2 Growth and yield response of soils amended with EFB

The application of EFB to soils led to approximately 49.2% increase in crop growth and yield compared to unamended soils (ln$R$ = 0.40; 95% CI of 0.22–0.58; $p < 0.001$; Fig. 3a). The I^2 = 96.0% (93.1%, 98.5%) indicated that there is a large degree of between-study heterogeneity. The present results suggest that EFBs could be an important resource for tropical agriculture, possibly organic fertilizer. If EFBs are incorporated into the soil with a second material, the growth and yield advantage of EFB plus additives over unamended soil increased by 24.5%, however, not statistically significant (ln$R$ = 0.22; 95% CI = −0.002 to 0.439; $p = 0.052$; $k = 6$; Fig. 3b). Again, the I^2 = 91.1% (76.6%, 98.3%) indicated a considerable degree of between-study heterogeneity. From Fig. 3 a and b, the yield advantage from the application of EFB appears to be lower when additives are added to the EFB and co-applied. In the present work, however, we only compared EFBs with unamended soil and separation of effects

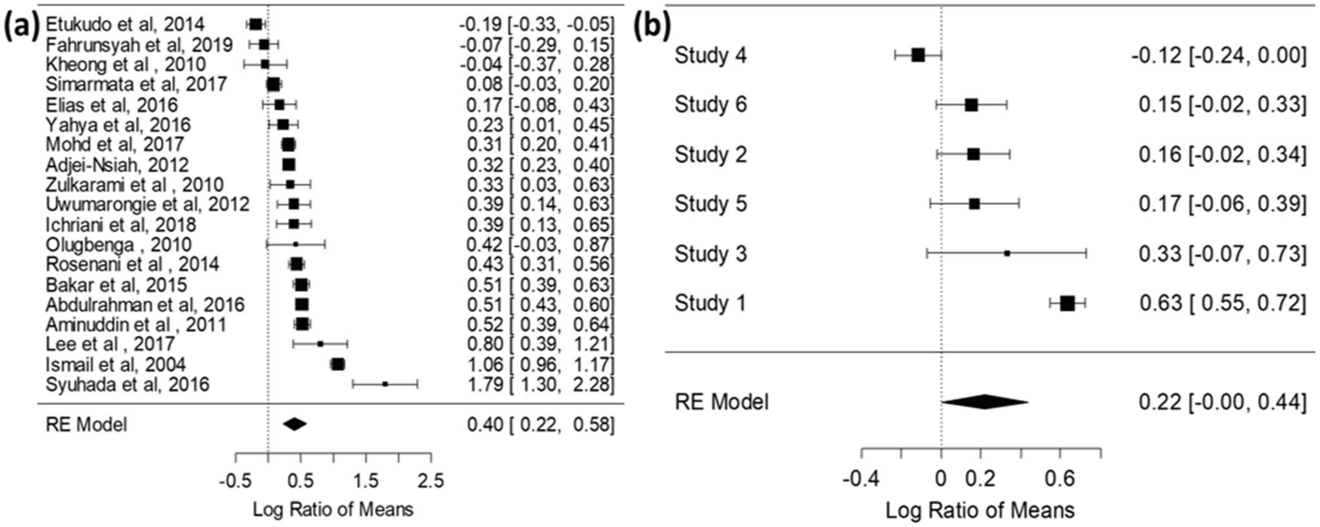

Fig. 3 Effect of empty fruit bunch amendment, with no additive (a; *k*=19) and with additives (b; *k*=6), on growth and yield of crop plants. The error bar indicates the 95% confidence interval (CI), and the dotted vertical line (effect size = 0) indicates no effect. Effect size is considered statistically significant if the 95% CI does not overlap the zero line.

involving EFB or additives alone or their combination was not assessed. Therefore, we cannot assign yield effects to EFB and additives until these effects are known. It is also important to note the fewer studies and outcomes in our analyses and the attendant large confidence intervals. The reports of Pangaribuan et al. (2017), Ghazali et al. (2018), and Fahrunsyah et al. (2019) suggest that when combined with additives, EFBs have a better effect.

Regardless of the EFB form applied, it primarily holds onto and releases nutrients either through decomposition or mineralization due to decreasing C:N ratio (Fig. 1) (Lim and Zaharah 2000; Caliman et al. 2001). It has been reported that the plant nutrient value of EFB (0.158% N, 0.08% P, 0.70% K, and 0.08% Mg) is high enough to return to the soil and serve as an economically cost-effective option of fertilization (Nithedpattarapong et al. 1996). Caliman et al. (2001) assessed the fertilizing value of EFB from an application of 60 t ha^{-1} of EFB. They noted that the initial content was 2.60, 0.725, 6.80, and 1.250 kg/palm for equivalent urea, triple superphosphate (TSP), muriate of potash (MOP), and magnesium sulfate, respectively. The average weekly equivalent fertilizer released within the first month was 0.11, 0.04, 0.87, and 0.06 kg/palm for urea, TSP, MOP, and $MgSO_4$. The average monthly equivalent fertilizer released from the 2nd to the 11th month were 0.22, 0.09, 1.10, and 0.15 kg/palm for urea, TSP, MOP, and $MgSO_4$, respectively. Potassium was the primary content of EFB, with almost the entire K in EFB released to the soil within 3 months after application (Caliman et al. 2001). These dynamics might be critical in adjusting the rate and frequency of EFB applications in cropping systems.

Notably, the potential nutrient inputs of EFB to the soil are affected by how the EFB is treated before application. For example, composting of EFB before its application results in a reduction in the C:N ratios (Thambirajah et al. 1995). Microbial decomposition of the plant material leads to an overall loss of cellulose and carbon and an increase in nitrogen content, microbial protein, and humic substances during the compositing of EFB (Thambirajah et al. 1995). Also, where EFB is charred into biochar, the pyrolysis temperature is a critical determinant of the physicochemical properties of EFB-biochar. The porosity, ash content, electrical conductivity (EC), and pH of EFB increase with pyrolysis temperature, but cation exchange capacity (CEC), and C and N contents decrease with increasing pyrolysis temperature (Claoston et al. 2014). EFB amendments likely improve crop growth and yield by enhancing soil physical and chemical properties, suppressing weeds and controlling erosion (Chiew and Rahman 2002; Bakar et al. 2011; Moradi et al. 2012; Carron et al. 2015; Budianta et al. 2018; Anyaoha et al. 2018).

3.3 Moderator and meta-regression analysis

Employing the original dataset of $k = 99$, analysis of moderators and, subsequently, meta-regression was conducted to determine the study characteristics that might account for dispersions in the summary effect. The log ratio of means was significantly positive for experiments conducted under greenhouse and field conditions. The difference in growth or yield of greenhouse and field-grown plants was significant, suggesting that the effect of EFB on crop growth or yield might be affected by the location of experiments ($Q_B = 6.09$; $df = 1$; $p = 0.0136$; $I^2 = 96.97\%$, Fig. 4a). We found approximately 68.0% difference between the growth and yield of crops grown under greenhouse and in field conditions, even when both receive the same EFB application. This observation is consistent with Krug and Fink (1988). They measured growth parameters such as relative growth rate (RGR) and net assimilation rate (NAR) of radish in growth chambers, greenhouses, and open fields and found that RGR and NAR from the open field were the lowest. Lower yield and growth for the field compared to greenhouse experiments is probably due to the tendency of extreme and uncontrollable conditions to occur under open field conditions compared to under greenhouse conditions where most of the growth conditions are controlled. Nevertheless, decisions on EFBs in crop production should ideally be based on data generated under field conditions.

Although the effect sizes differed from zero for all crops except for tubers (Fig. 4b), the meta-regression analysis showed that improvement in crop growth or yield under EFB application is not affected by the type of crops ($Q_B= 9.34$; $df = 5$; $p = 0.0962$; $I^2= 97.05\%$;). The crop growth and yield enhancement under the EFB application are not affected by the part of the plant used as the metric in the included studies ($Q_B= 4.56$; $df = 4$; $p = 0.335$; $I^2 = 96.8$; Fig. 4c). Compared to similar plant parts from plants grown on non-amended soil, the log ratios of means for grains, leaves, roots, shoots, and total plant biomass were 0.276, 0.391, 0.271, 0.283 and 0.501, respectively (Fig. 4c).

The effect size of growth and yield was positive and significantly different from zero, irrespective of the form in which EFB was applied (Fig. 4d). Subgroup analysis showed that EFB applied as biochar, mulch, compost, or ash led to approximately 78.4%, 33.8%, 30.9%, and 21.0% increase in growth and yields, respectively, compared with crops grown on the unamended soils. The meta-regression analysis also showed that there are significant differences among effect sizes for the various forms of EFB ($Q_B = 12.6$; $df = 3$; $p = 0.005$; $I^2= 96.84\%$; Fig. 4d). Compared with yield from other forms of EFB amendments, the growth or yield was higher when amended with EFB biochar than the unamended soils and other forms of EFBs.

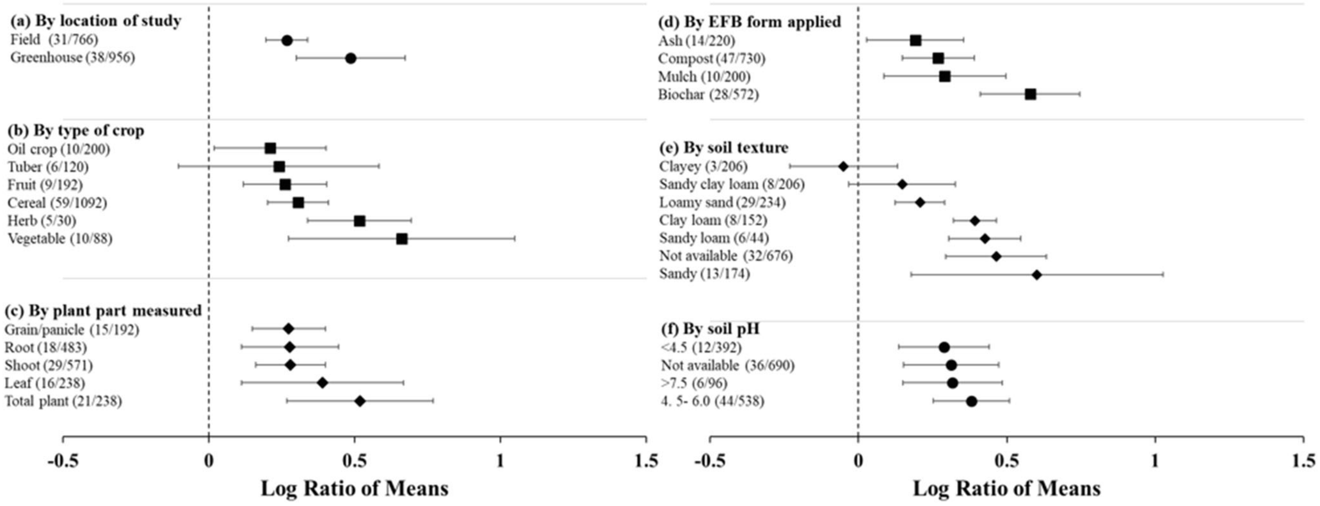

Figure 4 Influence of study location (**a**), type of crop (**b**), part of the crop measured (**c**), EFB form applied (**d**), soil texture (**e**), and soil pH (**f**), on effect sizes of growth or yield of crop plants under EFB application. The error bar indicates the 95% confidence interval (CI) and the broken vertical line (effect size = 0) indicates no effect. Effect size is considered statistically significant if the 95% CI does not overlap the zero line. The number of study outcomes and total sample size included in each category is displayed in parentheses.

In terms of the effects of EFBs amendment on soil properties, when applied as biochar, EFB can significantly change the pore size distribution by altering the mesopores to micropores ratio (Edeh and Mašek, 2021). The application of EFB biochar to coarse-textured soil increased the soil's surface area, which in turn increases soil water retention (Moradi et al. 2015; Blanco-Canqui 2017; Atkinson 2018; Razzaghi et al. 2020) and nutrient retention (Oppong Danso et al. 2019; Mukherjee and Lal 2013; Abdulrazzaq et al. 2014). The relatively higher crop growth and yield caused by EFB biochar are probably related to improved soil water retention and enhanced phosphorus uptake through increased pH of acidic soils (Awodun et al. 2007; Oppong Danso et al. 2019; Obour et al. 2019; Chintala et al. 2014).

Carron et al. (2015) reported that the contribution of raw decomposing EFB to soil N, P, K, Mg, Ca, and organic C lasted for only 1 month and decreased afterwards. Thus, EFB decomposes and briefly contributes N, P, K, and Mg when used as mulch for plant uptake. The application of EFB compost to soil also led to an increased soil pH 60 days after application (Caliman et al. 2001). EFBs have a low initial N content of less than 2%, with high lignin and polyphenol content. Therefore, to avoid the possible N immobilization during decomposition, when EFB is applied as a mulch, it should ideally be supplemented with a mineral N fertilizer (Zaharah and Lim 2000). Given that there could be some diminishing returns when EFBs are applied with additives, it would be critical to probe further the dynamics underlying the application of EFBs with mineral or organic fertilizers.

The use of EFB in crop production could also be considered climate-smart and sustainable (Aljuboori 2013; Suresh 2013). Co-composting of EFB with palm oil mill effluent, for example, can reduce up to 76% of greenhouse gas (GHG) emission by reducing the methane gas emitted from uncontrolled dumping of EFB and the replacement of the use of mineral fertilizers as soil amendments (Krishnan et al. 2017). In general, fresh EFB is about 50% carbon, but this decreases during decomposition (Zaharah and Lim 2000). If applied as biochar or compost, EFB mitigates GHGs via soil carbon (C) sequestration of external C inputs. Conversely, there is complete N-immobilization during the decomposition of EFBs. Zaharah and Lim (2000) investigated the decomposition and nutrient release from EFB components with and without N fertilizers in a 9-month experiment. They reported that the N content of EFB increased by an average of 54% for the EFB stalk, spikelet, and mixture over the initial N content of these EFB parts. Thus, the C:N ratio of EFB decreases with time, facilitating mineralization of N.

Overall, EFBs impact on plant growth and yield is affected by the soil types (Q_B = 15.2; df = 6; p = 0.0185; I^2= 96.7%; Fig. 4e). When crops are grown on EFB amended soils, growth and or yield increased over unamended soils is in the order of sand (0.566), sandy loam (0.411), clay loam (0.384), loamy sand (0.207), sandy clay loam (0.118), and clay (−0.065) soils (Fig. 3e). Thus, the present meta-analysis suggests that plants cultivated on coarser textured soils amended with EFB do relatively better than plants cultivated on EFB-amended finer-textured soils. This is probably because coarse-textured soils are more responsive to organic amendments (Tester 1990). This could also be due to the law of diminishing returns because the responses here were calculated as a percentage increase. For example, applying N to soil with a low mineral N content might lead to a higher percentage yield increase than the yield obtained from the soil with an inherently higher mineral N content when the same rate of N is applied. Even so, the effect of the EFB amendment on crop growth and yield was inconsistent. The inconsistent results between and within soil types point to the need for more studies to conclusively establish the effect of EFB amendment on crop growth and yield across different soil textures. The meta-analysis showed that plant growth and yield after EFB amendment was not significantly affected by soil pH ($QB = 0.663$; $df = 4$; $p = 0.956$; $I^2 = 97.28\%$; Fig. 4f).

4 Conclusions and perspectives

Using renewable by-products such as EFB for crop production in a carbon-constrained future economy will become imperative. Meta-analysis of the literature showed that (i) EFB effects on crop growth and yield were more pronounced under greenhouse conditions compared to field-grown crops; (ii) due to the lignocellulosic nature of EFB, its conversion to biochar and application to soil led to larger effects on crop growth and yield than when applied as a mulch, ash, or compost; (iii) crops grown on EFB-amended soil showed significantly higher growth and yield than crops grown on unamended soil; and (iv) the impact of EFBs on crop production was more pronounced on coarse-textured soils typically characterized by low organic matter, increased leaching of nutrients, and erosion. Consequently, to optimize the use of EFBs in crop production, a better knowledge of the dynamics of its mineralization and the release of mineral nutrients, depending on soil and environmental conditions, is critical. For the targeted application of the EFBs, routine soil testing is required for smallholder farmers who typically practice blanket soil amendments without recourse to initial soil testing results.

The findings from this meta-analysis suggest that EFBs can offer an economical route to sustainable agriculture in SSA and other regions where there is limited use of mineral fertilizers to improve soil properties for crop production. However, the cost versus benefits of using EFBs as soil conditioners, including the cost of transforming EFB into biochar or compost, must be assessed to determine cost-effectiveness and sustainability. This is because there are several alternative uses of EFB, such as fuel for small-scale industries and food processing companies, which might contribute to the cost of EFB and compete for the resource.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13593-022-00753-z.

Acknowledgements We thank Pr Jonathan P. Tetteh of the School of Agriculture, University of Cape Coast, Ghana, for internal review and advice on the manuscript. We are also grateful to Mr Amegbor Richard for his assistance in providing some graphics for the manuscript.

Authors' contributions Conceptualization, M.O.A., K.A., and P.A.A.; methodology, M.O.A, K.A., K.A.S., S.A.-L., R.A, and G.M.; analysis, M.O.A, E.A., P.A.A., P.B.O., and E.O.D.; writing (original draft), M.O.A., E.A. P.B.O., and E.O.D.; writing (review and editing), M.O.A., K.A., P.A.A, E.A., P.B.O., E.O.D., K.A.F, and M.N.A.; funding acquisition, M.O.A., K.A., P.A.A, E.A., P.B.O., E.O.D., K.A.F, and M.N.A.; supervision, M.N.A.

Funding This research was funded by the Ministry of Foreign Affairs of Denmark through the project "Building vegetable farmers resilience to climate change," DFC project no: 19-04-AU.

Data availability All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Code availability Not applicable

Declarations

Consent to participate Not applicable

Consent for publication Not applicable

Conflict of interests The authors declare no competing interests.

References

Abdulrazzaq H, Jol H, Husni A, Abu-Bakr R (2014) Biochar from empty fruit bunches, wood, and rice husks: effects on soil physical properties and growth of sweet corn on acidic soil. J Agric Sci 7:p192. https://doi.org/10.5539/jas.v7n1p192

Adu MO, Yawson DO, Abano EE, Asare PA, Armah FA, Opoku EK (2019) Does water-saving irrigation improve the quality of fruits and vegetables? Evidence from a meta-analysis. Irrig Sci 37:669–690. https://doi.org/10.1007/s00271-019-00646-2

Adu MO, Yawson DO, Armah FA, Asare PA, Frimpong KA (2018) Meta-analysis of crop yields of full, deficit, and partial root-zone drying irrigation. Agric Water Manag 197:79–90. https://doi.org/10.1016/j.agwat.2017.11.019

Ahmad Dani MS (2018) An evaluation of empty fruit bunch (EFB) biochar and EFB compost as growing media for oil palm seedling. Dissertation, Universiti Teknologi MARA, Melaka, Faculty of Plantation and Agrotechnology

Aljuboori AHR (2013) Oil palm biomass residue in Malaysia: availability and sustainability. Int J Biomass Renew 2:18–18

Anyaoha KE, Sakrabani R, Patchigolla K, Mouazen AM (2018) Critical evaluation of oil palm fresh fruit bunch solid wastes as soil amendments: prospects and challenges. Resour Conserv Recycl 136:399–409. https://doi.org/10.1016/j.resconrec.2018.04.022

Atkinson CJ (2018) How good is the evidence that soil applied biochar improves water holding capacity? Soil Use Manag 34:177–186. https://doi.org/10.1111/sum.12413

Awodun MA, Ojeniyi SO, Adeboye A, Odedina SA (2007) Effect of oil palm bunch refuse ash on soil and plant nutrient composition and yield of maize. Am-Eurasian J Sustain Agric 1:50–54

Bakar AR, Darus SZ, Kulaseharan S, Jamaluddin N (2011) Effects of ten year application of empty fruit bunches in an oil palm plantation on soil chemical properties. Nutr Cycl Agroecosystems 89:341–349. https://doi.org/10.1007/s10705-010-9398-9

Bazzaz FA, Sombroek WG eds (1996) Global climate change and agricultural production. Direct and indirect effects of changing hydrological, pedological and plant physiological processes. Wiley for FAO

Blanco-Canqui H (2017) Biochar and soil physical properties. Soil Sci Soc Am J 81:687–711. https://doi.org/10.2136/sssaj2017.01.0017

Brevik EC (2013) The potential impact of climate change on soil properties and processes and corresponding influence on food security. Agriculture 3(3):398–417. https://doi.org/10.3390/agriculture3030398

Budianta D, Wiralaga AYA, Lestari W (2018) Changes in some soil chemical properties of Ultisol applied by mulch from empty fruit bunches in an oil palm plantation. J Trop Soils 15:111–118. https://doi.org/10.5400/jts.2010.v15i2.111-118

Caliman J-P, Martha B, Salètes S (2001) Dynamics of nutrient release from empty fruit bunches in field conditions and soil characteristics changes. In: Cut.-Edge Technol. Sustain. Compet. Agric. Conf. Proc. 2001 PIPOC Int. Palm Oil Congr. 20 - 22 August 2001 Mutiara Kuala Lumpur Malays. http://agritrop.cirad.fr/525566/. Accessed 11 Jul 2020

Carron MP, Pierrat M, Snoeck D, Villenave C, Ribeyre F, Suhardi, Marichal R, Caliman JP (2015) Temporal variability in soil quality after organic residue application in mature oil palm plantations. Soil Res 53:205–215. https://doi.org/10.1071/SR14249

Chiew LK, Rahman ZA (2002) The effects oil palm empty fruit bunches on oil palm nutrition and yield, and soil chemical properties. J Oil Palm Res 14:1–9

Chintala R, Mollinedo J, Schumacher TE, Malo DD, Julson JL (2014) Effect of biochar on chemical properties of acidic soil. Arch Agron Soil Sci 60:393–404. https://doi.org/10.1080/03650340.2013.789870

Claoston N, Samsuri AW, Ahmad Husni MH, Mohd Amran MS (2014) Effects of pyrolysis temperature on the physicochemical properties of empty fruit bunch and rice husk biochars. Waste Manag Res 32(4):331–339. https://doi.org/10.1177/0734242X14525822

Danso EO, Abenney-Mickson S, Sabi EB et al (2015) Effect of different fertilization and irrigation methods on nitrogen uptake, intercepted radiation and yield of okra (*Abelmoschus esculentum* L.) grown in the Keta Sand Spit of Southeast Ghana. Agric Water Manag 147:34–42. https://doi.org/10.1016/j.agwat.2014.07.029

Danso EO, Yakubu A, Darrah YO, Arthur E, Manevski K, Sabi EB, Abenney-Mickson S, Ofori K, Plauborg F, Andersen MN (2019) Impact of rice straw biochar and irrigation on maize yield, intercepted radiation and water productivity in a tropical sandy clay loam. Field Crops Res 243:107628

Del Re AC (2015) A practical tutorial on conducting meta-analysis in R. Quant Methods Psychol 11:37–50. https://doi.org/10.20982/tqmp.11.1.p037

Del Re AC, Hoyt TW (2014) “MAd: Meta-analysis with mean differences.” R package version 0.8–2. URL http://cran.r-project.org/web/packages/MAd

Edeh IG, Mašek O (2021) The role of biochar particle size and hydrophobicity in improving soil hydraulic properties. Eur. J. Soil Sci. https://doi.org/10.1111/ejss.13138

Fahrunsyah F, Kusuma Z, Prasetya B, Handayanto E (2019) Utilization of coal fly ash and oil palm empty fruit bunch compost to improve uptake of soil phosphorus and yield of maize grown on an ultisol. J. Ecol Eng 20:36–43. https://doi.org/10.12911/22998993/108635

Geng A (2013) Conversion of oil palm empty fruit bunch to biofuels. In: Liquid, gaseous and solid biofuels. InTech Open Access Publisher, London, pp 479–490

Gerland P, Raftery AE, Ševcíková H et al (2014) World population stabilization unlikely this century. Science 346:234–237. https://doi.org/10.1126/science.1257469

Ghazali MR, Shahrum SA, SAbd M et al (2018) Application of empty fruit bunches (EFB) and cow manure (CM) compost as planting medium on the growth and yield of chilli (*Capsicum annum*) treated with different fertilizer. Int J ChemTech Res 11:135–141. https://doi.org/10.20902/IJCTR.2018.111017

Ioannidis JPA, Patsopoulos NA, Evangelou E (2007) Uncertainty in heterogeneity estimates in meta-analyses. BMJ 335:914–916. https://doi.org/10.1136/bmj.39343.408449.80

Kong S-H, Loh S-K, Bachmann RT, Rahim SA, Salimon J (2014) Biochar from oil palm biomass: a review of its potential and challenges. Renew Sustain Energy Rev 39:729–739. https://doi.org/10.1016/j.rser.2014.07.107

Koricheva J, Gurevitch J, Mengersen K (eds) (2013) Handbook of meta-analysis in ecology and evolution. Princeton University Press

Krishnan Y, Bong CPC, Azman NF, Zakaria Z, Othman N’A, Abdullah N, Ho CS, Lee CT, Hansen SB, Hara H (2017) Co-composting of palm empty fruit bunch and palm oil mill effluent: microbial diversity and potential mitigation of greenhouse gas emission. J Clean Prod 146:94–100. https://doi.org/10.1016/j.jclepro.2016.08.118

Krug H, Fink M (1988) Transferability of plant reaction parameters to climate - growth chambers, greenhouses, field. Acta Hortic 248:401–408. https://doi.org/10.17660/ActaHortic.1989.248.50

Lim KC, Zaharah AR (2000) Decomposition and N & K release by oil palm empty fruit bunches applied under mature palms. J Oil Palm Res 12:55–62

Lim PN, Wu TY, Clarke C, Daud NN (2015) A potential bioconversion of empty fruit bunches into organic fertilizer using *Eudrilus eugeniae*. Int J Environ Sci Technol 12:2533–2544. https://doi.org/10.1007/s13762-014-0648-2

Melsen WG, Bootsma MC, Rovers MM, Bonten MJ (2014) The effects of clinical and statistical heterogeneity on the predictive values of results from meta-analyses. Clin Microbiol Infection 20(2):123–129. https://doi.org/10.1111/1469-0691.12494

Moradi A, Sung CTB, Joo GK et al (2012) Evaluation of four soil conservation practices in a non-terraced oil palm plantation. Agron J 104:1727–1740. https://doi.org/10.2134/agronj2012.0120

Moradi A, Teh Boon Sung C, Goh KJ, Husni Mohd Hanif A, Fauziah Ishak C et al (2015) Effect of four soil and water conservation practices on soil physical processes in a non-terraced oil palm plantation. Soil Tillage Res 145:62–71. https://doi.org/10.1016/j.still.2014.08.005

Mukherjee A, Lal R (2013) Biochar impacts on soil physical properties and greenhouse gas emissions. Agronomy 3:313–339. https://doi.org/10.3390/agronomy3020313

Nithedpattarapong S, Srikul S, Korawis C (1996). Application of empty fruit bunch of oil palm as a source of plant nutrients in oil palm plantation. Warasan Wichakan Kaset.

Obour PB, Danso EO, Yakubu A, Abenney-Mickson S, Sabi EB, Darrah YK, Arthur E. (2019) Water retention, air exchange and pore structure characteristics after three years of rice straw biochar application to an Acrisol. Soil Sci Soc Am J 83(6):1664–71

Ortiz R, Villalobos E, Fernández O (1992) Mulch and fertilizer effect on soil nutrient content, water conservation and oil palm growth. ASD Oil Palm Pap 6:1–11

Pangaribuan DH, Nurmauli N, Sengadji SF (2017) The effect of enriched compost and nitrogen fertilizer on the growth and yield of sweet corn (*Zea mays* L.). Acta Hortic 387–392. 10.17660/ActaHortic.2017.1152.52

R Core Team (2019) R: The R Project for Statistical Computing. In: R Found. Stat. Comput. Vienna Austria URL HttpswwwR-Proj. https://www.r-project.org/. Accessed 12 Jul 2020

Razzaghi F, Obour PB, Arthur E (2020) Does biochar improve soil water retention? A systematic review and meta-analysis. Geoderma 361:114055. https://doi.org/10.1016/j.geoderma.2019.114055

Rickson RJ, Deeks LK, Graves A (2015) Input constraints to food production: the impact of soil degradation. Food Secur 7:351–364. https://doi.org/10.1007/s12571-015-0437-x

Rosenberg MS, Rothstein HR, Gurevitch J (2013) Effect sizes: conventional choices and calculations. In: Handbook of Meta-analysis in Ecology and Evolution. Princeton University Press, pp. 61–71

Sung S, GohKah J, Kamarudin KN (2010) Physical changes to oil palm empty fruit bunches (EFB) and EFB mat (Ecomat) during their decomposition in the field. Pertanika J Trop Agric Sci 33:33–44

Suresh K (2013) Adaptation and mitigation strategies for climate-resilient oil palm. In: Singh HCP, Rao NKS, Shivashankar KS (eds) Climate-Resilient Horticulture: Adaptation and Mitigation Strategies. Springer, India, pp 199–211

Tester CF (1990) Organic amendment effects on physical and chemical properties of a sandy soil. Soil Sci Soc Am J 54:827–831. https://doi.org/10.2136/sssaj1990.03615995005400030035x

Thambirajah JJ, Zulkali MD, Hashim MA (1995) Microbiological and biochemical changes during the composting of oil palm empty-fruit-bunches. Effect of nitrogen supplementation on the substrate. Bioresour. Technol. 52(2):133–144. https://doi.org/10.1016/0960-8524(95)00008-3

Viechtbauer W (2010) Conducting meta-analyses in R with the metafor Package. J Stat Softw 36:1–48. https://doi.org/10.18637/jss.v036.i03

von Hippel PT (2015) The heterogeneity statistic I^2 can be biased in small meta-analyses. BMC Med Res Methodol 15(1):1–8. https://doi.org/10.1186/s12874-015-0024-z

Wallace BC, Lajeunesse MJ, Dietz G, Dahabreh IJ, Trikalinos TA, Schmid CH, Gurevitch J (2017) OpenMEE: intuitive, open-source software for meta-analysis in ecology and evolutionary biology. Methods Ecol Evol 8:941–947. https://doi.org/10.1111/2041-210X.12708

Zaharah AR, Lim KC (2000) Oil palm empty fruit bunch as a source of nutrients. Malays J Soil Sci 4:51–66

Zuberi T, Thomas KJA (2012) Demographic projections, the environment and food security in sub-Saharan Africa. Regional bureau for Africa, United Nations working group, 22

References of the meta-analysis

Abdulrahman DK, Othman R, Saud HM (2016) Effects of empty fruit bunch biochar and nitrogen-fixing bacteria on soil properties and growth of sweet corn. Malaysian J. Soil Sci 20:177–194

Adjei-Nsiah S (2012, 2012) Response of maize (*Zea mays* L.) to different rates of palm bunch ash application in the semi-deciduous forest agro-ecological zone of Ghana. Appl Environ Soil Sci (870948):5. https://doi.org/10.1155/2012/870948

Aminuddin M, Affendy H, Azmy M, Amizi MA, Assis K, Tamer AT (2011) Effect of organic fertilizers application to the growth of *Orthosiphon stamineus* Benth. intercropped with *Hevea brasiliensis* Willd. and Durio zibethinus Murr. Int J Agric Res. 6(2):180–187

Bakar RA, Razak ZA, Ahmad SH, Seh-Bardan BJ, Tsong LC, Meng CP (2015) Influence of oil palm empty fruit bunch biochar on floodwater pH and yield components of rice cultivated on acid sulphate soil under rice intensification practices. Plant Prod Sci. 18(4):491–500. https://doi.org/10.1626/pps.18.491

Elias A, Mutalib SA, Mustapha WA (2016) Effect of empty fruit bunch to the accumulated plant height, mass of fresh and dry weight of tomato plant treated with organic and inorganic fertilizer. In: AIP Conference Proceedings 2016 Nov 17 (Vol. 1784, No. 1, p. 030041). AIP Publishing LLC. https://doi.org/10.1063/1.4966779

Etukudo MM, Roberts E. MI, Omeje FI (2014) Early seedling growth and development response of *Zea mays*. L. to extract from palm bunch ash (PBAE) *Elaeis Guineensis*. Jacq Int J Recent Sci Res 5:1307-10.

Fahrunsyah F, Kusuma Z, Prasetya B, Handayanto E (2019b) Utilization of coal fly ash and oil palm empty fruit bunch compost to improve the uptake of soil phosphorus and yield of maize grown on Ultisol. J Ecol Eng. 20(6):36–43. https://doi.org/10.12911/22998993/108635

Ichriani GI, Nuraini Y, Handayanto E (2018) Formulation of biochar-compost and phosphate solubilizing fungi from oil palm empty fruit bunch to improve growth of maize in an Ultisol of Central Kalimantan. J Ecol Eng. 19(6, 45):–55. https://doi.org/10.12911/22998993/92891

Ismail MR, Sze LY, Poulus P, Ibrahim H (2004) The use of empty oil palm fruit bunch (EFB) compost as additive in coconut dust soilless system for vegetable crop production. In: International Symposium on Growing Media and Hydroponics 644 2001 Sep 8 (pp. 193-198).

Kheong LV, Rahman ZA, Musa MH, Hussein A (2010) Nutrient absorption by oil palm primary roots as affected by empty fruit bunch application. J Oil Palm Res. 22:711–720

Lee SC, Rosenani AB, Ishak CF, Idris A, Abdul Rahim K, Meyer-Aurich A (2017) 15N-labelled fertilizer recovery by maize (*Zea mays* L.) and leaching of nutrients as influenced by oil palm empty fruit bunch biochar in a mini-lysimeter under controlled tropical environment. Arch Agron Soil Sci. 63(12):1711–1724. https://doi.org/10.1080/03650340.2017.1303574

Mohd RI, Saud HM, Habib SH, Kausar H, Maleque MA, Hakim MA (2017) Efficacy evaluation of empty palm oil fruit bunch compost in improving soil characteristics, plant growth and disease suppression of tomato plants under tropical acid soil. J Environ Biol. 38(1):123

Rosenani AB, Ahmad SH, Nurul Adila S (2014) Biochar as a soil amendment to improve crop yield and soil carbon sequestration. In: International Symposium on Organic Matter Management and Compost Use in Horticulture 1018 2011 Apr 7 (pp. 203-209).

Simarmata M, Barchia MF, Simatupang SN (2017) Prospect for growing sorghum (*Sorghum bicolor* L. Moench) at marginal dry land in coastal area retrieved with organic soil amendments. Asian J Crop Sci. 9(4):118–124

Syuhada AB, Shamshuddin J, Fauziah CI, Rosenani AB, Arifin A (2016) Biochar as soil amendment: Impact on chemical properties and corn nutrient uptake in a Podzol. Can. J. Soil Sci. 96(4):400–412. https://doi.org/10.1139/cjss-2015-0044

Uwumarongie-Ilori EG, Sulaiman-Ilobu BB, Ederion O, Imogie A, Imoisi BO, Garuba N, Ugbah M (2012) Vegetative growth performance of oil palm (*Elaeis guineensis*) seedlings in response to inorganic and organic fertilizers. Greener J Agric Sci 2:26–30

Yahya MY, Haya BB, Tajarudin NK (2016) Storage root nutrient and yield enhancement in sweet potato variety vitato using empty fruit bunch compost and hexaconazole. Asian J Crop Sci. 8(3):87–95

Zaharah AR, Lim KC (2000) Oil palm empty fruit bunch as a source of nutrients. Malaysian J Soil Sci. 4:51–66

Zulkarami B, Ashrafuzzaman M, Razi IM (2010) Morpho-physiological growth, yield and fruit quality of rock melon as affected by growing media and electrical conductivity. J Food Agric Environ. 8(1):249–252