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An analysis of in-field soil testing and mapping for improving fertiliser decision-making in vegetable production in Kenya and Ghana

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Abstract

In-field soil testing and soil mapping can contribute to addressing the challenge of poor soil fertility and limited fertiliser application across sub-Saharan Africa. Semi-quantitative colorimetric methods such as paper test strips, are frequently employed in soil nutrient assessment across developing countries, especially in South-East Asia. This research investigated the accuracy of nutrient-sensitive paper strips and smartphone, which was re-purposed to act as a reflectometer, to assess soil nitrate-N, and different methods for mapping soil fertility to identify areas of land that are suitable for human waste derived fertilisers (HWDF) application. The study entailed testing soil samples across 42 different farms in Kenya and Ghana and compared it to laboratory results in-country. It was found that paper strips were capable of assessing available nitrate-N concentration present in the soil within ± 20 kg ha^{-1} of the standard method for 86% of the farms. Paper strips were less effective in Ghana as they had been calibrated for a method that was not used by local laboratories. Paper strips were not effective for HWDF samples, where chemical interferences and concentration of different forms of nitrates were too high, resulting in overestimation of readings and thus negatively affecting any associated nutrient management advice. Soil mapping has the potential to use open-source data to inform farmers through mobile technology. For soil mapping two methods were deployed which includes targeting organic matter deficient areas and stakeholder led mapping, with the latter shown to be more effective in identifying areas for HWDF application.

Keywords

Horticulture; Precision Agriculture; Mobile Technology; Soil Testing; sub-Saharan Africa; Soil Mapping; biosolids; sewage sludge

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1 Introduction

Agriculture in Sub-Saharan Africa faces abundant challenges, among others low crop yields estimated at 1.5t ha^{-1} for cereals compared to a global average of 3.5t ha^{-1} (FAO 2015). This is primarily due to the sector's dependence on variable rainfall (Chauvin *et al*. 2012) and low application rates of mineral fertilisers, with Ghana and Kenya applying 23.8 and 28.6 kg ha^{-1} to arable land, respectively, compared with the global average of 137.6kg ha^{-1} (World Bank 2018). Focusing specifically on Nitrogen, Ghana and Kenya apply 3.91 kg ha^{-1} and 15.56 kg ha^{-1}, respectively, compared with a global average of 69.8 kg ha^{-1} (FAO 2020).

Limited access to mineral fertilisers in Sub-Saharan Africa is often a matter of expense (Tittonell *et al.*, 2008). Previous studies (Diener et al. 2014, Murray et al. 2011) have identified resource recovery (in the form of fertiliser) as a financial driver towards operating faecal sludge treatment in Sub-Saharan Africa. Considering the inherent nutrient value of human excreta and its potential for Human Waste Derived Fertiliser (HWDF) (Guzha *et al*. 2005; Korentajer 1991; Mallory *et al.* 2020; Moya *et al*. 2017), the use of treated faecal sludge in agriculture could contribute to food security while simultaneously improving sanitation.

The positive effects of HWDF on crop development are well-documented (Guzha *et al*. 2005; Mnkeni and Austin 2009; Moya *et al*. 2017). However, there are constraints around HWDF usage, which include health risks arising from poor waste treatment practices (Cofie *et al*. 2005), and unwillingness to use fertilisers from human-waste caused by prevailing social perceptions (Cofie *et al.* 2010; Mariwah and Drangert, 2011; Dalton *et al.* 2014). The lack of knowledge on how to apply HWDF, has been identified as another important constraint to usage (Mallory *et al*. 2019). This is also exacerbated by the inherent variation of nutrients in HWDF.

In-field test kits can be utilised to fill the gaps in HWDF nutrient profile evaluation. Semi-quantitative colorimetric methods for nutrient assessment are favoured in many developing countries, especially in South-East Asia (Nyi *et al.*, 2017). The most prominent example of those approaches are paper test strips. Paper test strips consist of a long plastic strip equipped with a reactive zone that changes colour in response to a specific target analyte within a sample. These, in conjunction with reflectometers that quantify the reactive zone's colour, have been successfully applied in soil testing across the USA (Jemison and Fox, 1988), Germany (Schmidhalter, 2005) and Australia (Wetselaar, Smith and Angus, 1998). However, concerns regarding agreement between paper strips and conventional methods of nutrient analysis have been recently highlighted (Golicz, Hallett and Sakrabani, 2020). In this study, nitrate-sensitive paper strips were used alongside Akvo Caddisfly – a smartphone app that temporarily turns the phone into a portable reflectometer, to understand how useful the tool is as a method for assisting farmers in using HWDF.

Building upon the ability to use appropriate technology to obtain improved information about soil in-field conditions, there is an increasing amount of literature using geospatial datasets to provide information about soil or climate conditions to assist farmers in the decision-making processes (Hallett *et al*. 2017; Hengl *et al*. 2017; Wadsworth *et al*. 2018). For example, Kenya Crops and Fertilizer App, shown in Figure 1 uses soil grids data from International Soil Reference and Information Centre (ISRIC) and the farm management handbook of

Kenya (FAO, 2006) provides soil information and crop recommendations across the country, based on the methods by Hengel *et al* (2017). However, this service offers soil data at very coarse resolution (250m x 250m grids), neglecting micro-variations and real plot values when providing recommendations. Furthermore, the app lacks features for assisting with fertiliser planning. By adapting existing decision support tools for fertiliser application and combining them with innovative testing methods to assess nutrient levels in soils, it is possible that the two technologies could work in tandem to provide information to farmers in how to apply inputs and HWDF to increase yields.

Figure 1. Screenshots of Kenya Crops and Fertilizer App (Google 2017).

This research aims to investigate the efficacy of in-field paper strip method and soil mapping as decision support technology to assist farmers in using HWDF efficiently to increase agricultural productivity, but also to look at how it can enable wider use of HWDF and demand for treated human waste to encourage improved sanitation. The research focused on Ghana and Kenya where there are already companies producing treated commercial HWDF.

2 Methods

2.1 Targeted farmers and crops and sampling method for soil testing

Fieldwork was conducted in Kenya between July and October 2018, and in Ghana between October 2018 and December 2018. In Kenya, the farmers using HWDF were growing horticultural crops including tomatoes (*Solanum lycopersicum*) and watermelons (*Citrullus lanatus*) as these provided a return on investment in using HWDF. Twenty farms were visited across four counties i.e. Embu, Kirinyaga, Machakos and Tharaka-Nithi, that were served by the HWDF sales hub located in Embu, shown in Figure 2A. The farms ranged from 5-50 acres (2-20.2ha) in size. These counties are all in close proximity to Mount Kenya, the highest mountain in the country, which acts as a water tower for much of the surrounding areas (Kenya Water Towers Agency, 2020). It is the source of the Tana and Ewaso Ng'iro rivers which means there are many streams that act as a source for irrigation schemes. This combined with the relative proximity to the major market of Nairobi makes it a viable area for vegetable growth and HWDF sales in the other direction.

Table 1. Characteristics of Research Areas

Characteristics	Kenya Sample Areas	Ghana Sample Areas
Latitude and Longitude of closest city	0.5388° S, 37.4596° E	5.6037° N 0.187° W
Main Crops	Tomatoes and Watermelons	Tomatoes and Okra
Reasons for Case Selection	Proximity to Nairobi, irrigation schemes and water sources. Historic use of HWDF	Proximity to Accra, irrigation schemes and designated extension officers

In Ghana, the farmers using HWDF were based in two irrigation schemes, Tuba and Klagon, located 40 and 50km from Accra, respectively, as shown in Figure 2B. As part of the irrigation schemes there are extension officers responsible for the area, providing a potential way for provision of soil testing and advice. Combined with the proximity to the major market of Accra it makes the site viable for both vegetable growth and HWDF sales. The farmers paid a yearly fee for farmland, irrigation and extension service. The farmers grew a variety of vegetables depending on season, with tomatoes and okra (*Abelmoschus esculentus*) being the most common. The average farm area was 3 acres (1.2ha).

Sampling rates for both case studies were chosen based on three factors:

- Financial resources for testing of samples in conventional laboratory to provide benchmark comparison;
- Constraints on transporting samples from farm to laboratory whilst keeping samples cold;

- Availability of land at post-harvest stage of farming cycle.

In Kenya, transport distances meant that multiple sites surrounding a central point in Embu were visited in a week which reduced the number of samples that could be transported back to Nairobi whilst keeping samples fresh in a cooler box. Almost every farmer interviewed had an area of land that was post-harvest land. A sampling rate of a 5-point W was taken on every 0.5 acre (0.2ha) of land available. This led to 19 W-shape samples being taken totalling 95 samples.

In Ghana, transport distances were less so farms could be visited and sampled on the same day and soil samples returned to Accra, meaning the capacity for sampling per farm was higher. However, there were fewer plots at post-harvest stage available. For this reason, an increased sampling rate of 3 5-point W's was taken on every 0.5 acre (0.2ha) of land available. This led to 24 W-shaped samples taken totalling 120 samples.

Figure 2A-B. Sampling locations in Kenya (A) and Ghana (B). In Kenya, 19 farms were sampled across four counties, Embu, Machakos, Kirinyaga and Tharaka-Nithi. In Ghana, 24 sites were sampled in Tuba and Klagon, located within Accra Municipality.

2.2 Soil and HWDF testing protocol

Samples were taken to a depth of 15cm using a trowel at 5 points in a W-shape across a hectare of land, as shown in Figure 3. Selected plots were prepared for sowing with no fertiliser (or HWDF) applied prior to the upcoming crop growing season as the goal was to measure soil residual nitrate-N. This is to assess the secondary benefit of additional Nitrogen that results from consistent use of HWDF in farms and the potential value that could be gained by reducing fertiliser use accordingly. Samples were collected and extracted with the same method. The protocol was as follows:

- Weigh 10g of sample;
- Measure 50ml of water and add to sample;
- Shake mixture for 5 minutes;
- Filter through medium grade filter paper;
- Dip paper strip into filtrate and take reading using Akvo Caddisfly app.

HWDFs were measured with the same method. HWDF was sampled in piles as it had matured. Five scoops of HWDF from each pile was sampled and mixed together to obtain one composite sample and the same procedure was carried out to obtain three replicates. Instead of 10g of sample, 1g of HWDF was extracted due to the extremely high concentration of nitrate. When the filtrate concentration exceeded paper strip maximum (i.e. 100mg L^{-1}), a dilution was performed.

Figure 3. Step-by-step protocol of in-field soil sampling, extraction and analysis.

Filtrate testing was conducted using the Quantofix paper strips (manufacturer: Machery-Negel, product reference: 913 51) and Akvo Caddisfly app (Heijstek, 2017; Akvo, 2020), which acted as a portable reflectometer i.e. a test-strip colour reader, following the method developed by Golicz et al. (2020). Akvo Caddisfly requires a calibration card to adjust colour development in the paper strip during the reaction time (for 60 seconds) and then uses a phone's camera to quantify the amount of available nitrate based on the colour intensity of the reactive pad. After field-testing, equivalent number of soil and HWDF samples was sent to laboratories in Kenya and Ghana to undergo soil analysis for nitrate-N with conventional laboratory methods.

In Kenya, the local method for available nitrate-N assessment involved sample extraction with 2M KCl and subsequent analysis with segmented flow auto-analyser (MAFF, 1986). In Ghana, the method involved sample extraction with NaOH and subsequent analysis with spectrophotometer (Motsara and Roy 2008). A sub-set of samples collected in Ghana was re-analysed at Cranfield University after fieldwork concluded. The method employed at Cranfield University involved soil extraction with 2M KCl and analysis with segmented flow autoanalyzer, following British Standards based on the method by Keeney and Nelson (1982).

2.3 Spatial modelling of HWDF application

Two approaches to identifying suitable HWDF landbank were identified in consultation with stakeholders and the literature, as summarised in Figure 4. These are listed below:

1. Targeting HWDF application to raise soil organic matter content to a minimum threshold level and applying different constraints based on factors such as transport, as has been done for application of biosolids for phosphates in the UK (Wadsworth *et al*. 2018)
2. Targeting HWDF application to areas that are near waterbodies and irrigation schemes, which constitutes the main criteria of horticulture farmers who are the main clients of HWDF producers

In Scenario 1, the key criterion for identifying suitable landbank to apply HWDF was to map spatial distribution of soil organic matter content. This recognises the primary role and selling point of HWDF is the increased soil fertility, and the second benefit of additional available nitrate-N can be assessed with the paper strip method. Data on soil organic carbon content was adapted from Hengel *et al* (2017). Total organic matter content is calculated from the available dataset of organic carbon by applying the Van Bemmelen ratio of organic carbon to organic matter content of 0.58 (Iglesias Jiménez and Pérez García 1992). A target minimum threshold of 3% soil organic matter content was set based upon recommendations about minimum organic carbon requirements (Adoyele and Omotoso 2008; Patrick *et al.* 2013). The requirements for reaching 3% soil organic matter content were calculated based on an assumed bulk density of 1.1g cm^{-3} and a soil depth of 0.10m.

Having calculated the initial requirements for organic matter application across Kenya and Ghana, four constraints for application were selected as with Wadsworth *et al*. 2018. The following constraints, which could be modelled using available data, were identified:

- **Transport:** Road network datasets from OpenStreetMap were used to create service layers, identifying areas within 100km of sources of HWDF. In Kenya, Nairobi (i.e. central production site of HWDF) and Embu (i.e. distribution centre to transport HWDF to farmers) were used. In Ghana, the production site for HWDF was used. The map of recommended organic matter was clipped to service areas representing these transport constraints.
- **Rainfall in a growing period:** Data from Tamsat was used across 5 months, representing a crop growing period. This was totalled for both countries and scored based upon whether an area was statistically in the upper or lower half of rainfall. The map was constrained to areas in the upper half of rainfall to target areas of higher rainfall.
- **Protected areas:** National parks were used as a constraint. In Kenya, protected areas were available through open access data from UNOSAT (ICPAC 2017). This data was visually confirmed against maps of known national parks and verified as accurate. In Ghana, it was verified that there were no national parks within 100km of the site in Accra, so this was not modelled as a constraint.
- **Sand content:** Data from ISRIC was used to delineate areas with sandy soils (> 40% of sand) as soils with lower clay content are likely to require more regular applications of HWDF to maintain levels of organic matter (Hengl *et al*. 2017).

Scenario 2 is based on the methodology used by HWDF-producers and farmers when locating land and recommending application rates. The principal criterion was to identify farmers who irrigate and grow high-value crops and are as such more likely to invest in HWDF. Proximity buffers were used to map areas within 1km of water bodies that have landcover designated for agriculture, as per Sentinel data. Data from OpenStreetMap was found to be unreliable in identifying rivers so STRM data was used for cross-referencing. The presence of rivers was verified by checking their proximity to OpenStreetMap rivers to ensure that the STRM method covered all known waterbodies. For newly mapped rivers, the dataset was limited to stream order, a measure of how upstream or downstream in a catchment a river line is, and visually checked against satellite data and NDVI to ensure accuracy. Application rates are then set at a uniform 2.5t/ha as recommended by the HWDF producer for tomatoes (Farm Star, 2019)

Figure 4. Summary of methods applied to formulate maps for identification of HWDF landbanks, for Scenario 1 and Scenario 2.

2.4 Statistical analysis and fertiliser input calculations

To analyse the results comparing paper strip and conventional laboratory testing of soil nitrate-N, a Bland-Altman (B-A) approach was employed. In B-A analysis, plots display the difference between two methods against the mean results of the two methods (Bland and Altman 2003). This is a statistical approach suitable for comparing two measurement techniques that should give the same result.

To calculate fertiliser inputs, each 5-point W sample area was given a FARM ID and the average soil nitrate-N content was calculated from laboratory and paper strip results for the area. The average soil residual NO_3^--N was converted from mg kg^{-1} to kg ha^{-1} (with soil depth of 0.15m and assumed bulk density of 1.1g cm^{-3}). The soil NO_3^--N was subtracted from standard baseline recommendations for tomato (*Solanum lycopersicum*) in Kenya (200kg ha^{-1}; de Putter 2009) and Ghana (96kg ha^{-1}; Ghana Ministry of Agriculture, 2019) to calculate a targeted N application plan.

3 Results

3.1 Background soil information

Background soil information is summarised in Table 2. In Kenya, 96% of the sampled soils had soil organic matter (SOM) content of over 3%. Soil pH was weakly acidic to neutral with 26% of samples having a pH > 6. In Ghana, 86% of the soil samples had SOM lower than 3% with average pH of 6.0. The soil has a broad classification as Ferralsol and Ferric Acrisols for Kenya and Ghana, respectively.

Table 2. Summary of soil information relevant to agronomic purposes. N – number of samples, MC – moisture content, % OM – percent of organic matter, % C – percent carbon.

	Kenya				Ghana			
	N	pH	MC	% OM	N	pH	% C	% OM
Average	48	6.8	3.6	9.4	108	7.5	1.6	2.8
Min	48	5.8	0.8	2.8	108	6.0	0.08	0.1
Max	48	8.0	9.3	25.1	108	8.8	11.7	20.2
STDV	48	0.5	2.2	4.5	108	0.6	2.6	4.5
Soil type	Rhodic Ferralsol, Lixic Ferralsol				Ferric Acrisols, Chrmoic Vertisol			

3.2 Comparison of available nitrate-N in soil and HWDF from paper strip method and conventional laboratory methods

Figure 5A-C shows B-A plots comparing results of conventional and paper strip analysis of soil NO_3^--N. For samples collected in Kenya, there is a good agreement between the paper strip readings and the conventional laboratory results with 83% of readings being within ± 8 mg kg^{-1} (13.2 kg ha^{-1}) of the standard method, as shown in Figure 5A. The mean bias between methods was 0.43 (95% CI: -1.31 to 2.17) with absolute errors ranging from -8.03 (CI: -6.29 to -9.77) for the Lower Limit of Agreement to 8.88 (CI: 6.49 to 9.97) for the Upper Limit of Agreement (SD = 4.23).

For samples collected in Ghana, the agreement between the methods is poor. The error is skewed and shown to be increasing with concentration. The paper strip method overestimated soil nitrate-N, compared to conventional method, as shown in Figure 5B. The mean bias between methods was -10.62 (CI: -6.04 to -15.20) with absolute errors ranging from -35.94 (CI: -31.36 to -40.52) for the Lower Limit of Agreement to 14.71 (CI: 10.13 to 19.29) for the Upper Limit of Agreement (SD = 12.66).

The same trend was recorded for comparison between laboratory analysis conducted in Ghana and the UK, as shown in Figure 5C. The mean bias between methods was -4.37 (CI: 0.45 to -9.19) with absolute errors ranging from -23.22 (CI: -18.40 to -28.04) for the Lower Limit of Agreement to 14.73 (CI: 9.91 to 19.55) for the Upper Limit of Agreement (SD = 9.42). This error distribution is indicative of a systematic error in measurement i.e. a consistent difference between methods, rather than a random error.

Figure 5A-C. Bland-Altman analysis of soil testing methods comparing (A) Kenyan Lab and Paper Strip Methods (N = 68), (B) Ghanaian Lab and Paper Strip Methods (N = 88), and (C) Ghanaian Lab and UK Lab (N = 44). All measurements given in mg kg^{-1} of NO_3^--N. The dashed lines represent the error tolerances defined as ± 1.96 SD.

Nitrate testing was conducted for HWDF samples from Kenya and Ghana. Paper strips provided an unreliable measure of NO_3^--N content of HWDF with absolute errors between the laboratory method and the paper strip method ranging from 6 to 330 mg kg^{-1} of NO_3^--N with paper strips overestimating HWDF nitrate-N content. Nitrite interference was recorded for 12% of samples.

3.3 Predicted N level and N supply demand

Soil nitrate-N content was found to be low across the investigated farms. According to the conventional soil test results, 74% of arable soils in Kenya had NO_3^--N content lower than 20 kg ha^{-1}. In Ghana, over 90% of farms had soil nitrate-N content < 20 kg ha^{-1}. In Kenya, the paper strips predicted the required nitrate-N to within ± 10 kg ha^{-1} of the laboratory results for 90% farms and within ± 25kg ha^{-1} for all farms, as shown in Figure 6A.

In Ghana, the paper strip predicted the nitrate-N content to within ± 10 kg ha^{-1} for 57% of the farms and within ± 25kg ha^{-1} of the laboratory results for 18 out of 23 farms (78%), as shown in Figure 6B. At Farms 4, 5, 6, 22 and 23, paper strips overestimated available nitrate-N by an average of 48.6 kg ha^{-1}.

Figure 6A-B. Soil nitrate-N content on farms in (A) Kenya and (B) Ghana based on laboratory in-field testing (Mean ± SE). The red line represents recommended N fertiliser rate for tomato crop as per local guidelines for Kenya and Ghana.

3.4 Mapping of nutrients and HWDF recommendations for Kenya and Ghana

Using existing spatial datasets for soil quality indicators and yield responses together with other available geospatial information designed to aid agricultural decision making, shown in Table 3, maps of suitable areas and levels of application of nutrients and HWDF were formulated for Kenya and Ghana.

Table 3. Table of input data for mapping with justification and sources.

Data Source Required	Justification	Sources

Soil Texture	Have a large influence on possible yields and crops and identifies need for organic matter application	WOSSAC Hengl *et al.* 2017 Kenyan Government Agro-Economical Zones Batjes and Gicheru, 2004
Nutrients and pH	Have a large influence on possible yields and crops	Hengl *et al.* 2017 Tests and sampling in fieldwork
Climate	Helps plan seasonality of different crops	Tamsat
Road Maps	Helps map access from sources of inputs to households using support tools	OpenStreetMap
Sources of inputs (fertilisers/HWDF)	Enables mapping of resources for decision support	Interviews and mapping

In Scenario 1 HWDF application was required to increase SOM to reach the minimum threshold value (equal to 3%) across Kenya and Ghana. The quantity of organic matter to be added to improve soil quality was modelled according to two scenarios, as shown in Figure 7A-D. In Kenya, SOM in the areas surrounding Embu was above 3% with no need for HWDF application to reach the minimum threshold (Figure 7A). The HWDF hotspots requiring heavy applications of organic matter were located on the East and South-East of Embu (Figure 7A). In Ghana, the areas surveyed were below 3% OM content and were identified as landbanks for HWDF (Figure 7B). The models corresponded to fieldwork results, shown in Table 2.

In Scenario 2, suitable areas for HWDF application were identified based on proximity to water bodies, transport networks and if the land was existing farm area. Application rates were then set according to recommendations from HWDF producers. In Embu, this method was able to identify farming areas that are served by the tributaries of water flowing from Mount Kenya (Figure 7C) and lakes. This had a stronger correlation with the identified farms then targeting to increase SOM to reach 3% (Figure 7A). In Ghana, for scenario 2, the proximity to water and transport network was effective at identifying and locating irrigation projects and suitable farm area.

Figure 7A-D. Maps of soil application for Scenario 1 (A - Kenya and B - Ghana) and Scenario 2 (C - Kenya and D - Ghana).

4 Discussion

4.1 Accuracy and application of in-field soil paper strip method in Sub-Saharan Africa

Paper strips were successfully applied in soil analysis in Kenya and, to a lesser extent, in Ghana. In Kenya, the difference between methods is similar to that found with the methods of soil analysis currently used for advisory purposes i.e. the difference between sub-samples analysed during a single run of segmented flow autoanalyzer was estimated at ± 10 mg kg^{-1} (Golicz *et al.*, 2019). Those results are consistent with other paper strip studies,

where the deviation from standard method can range between 19.9 mg kg^{-1} and −55.7 mg kg^{-1} (Golicz, Hallett and Sakrabani, 2020). To be able to inform better decisions about soil fertility and crop growth, paper strips would only provide part of a wider range of information support that is needed in the capacity as a screening tool. It is still promising to demonstrate a relatively inexpensive simple method of assessing nitrate-N, one of the major components, but further research into other methods of in-field testing is needed.

The amount of time that passed between in-field testing and conventional laboratory analysis is expected to have influenced the quality of comparison between the methods. Soil nitrogen concentration is highly variable - in lightly textured soils, there can be a 20.2% deviation from day 1 to day 2 for refrigerated samples (Vandendriessche et al. 2011). This means, the time between using the paper strip and the time taken for laboratories to conduct the comparison test is expected to have contributed to the variation recorded.

In contrast, local laboratories in Ghana employed soil analytical methods that corresponded to neither paper strips nor European standard methods. In soil sciences, the choice of extractant, varied testing methodologies and equipment, and their impact on soil test results are well documented (Pittman *et al.*, 2005; Sikora, F. J. Howe, P. S. Hill, L. E. Reid, D. C. Harover, 2005; Gikonyo *et al.*, 2010; Omran, 2017) with large variations existing within the same country e.g. between Scottish and English laboratories (Walker and Edwards, 2010). This has implications for applicability of in-field test kits developed in Europe and North America as they are calibrated to methods that are not necessarily available or rarely employed globally.

Regardless of the difference in methodologies, the paper strips were effective, with exception of 5 farms, in determining that the investigated soils were low in nitrate-N content, which could encourage farmers to invest in mineral and HWDF-derived fertilisers. Low fertility soils are the most responsive to fertiliser treatment (Tittonell *et al.*, 2008), and so fertiliser applications in these areas are likely to result in high return on investment with limited inputs (Aune, Coulibaly and Giller, 2017). Chemical interferences with colour development and high ambient temperature are likely to have contributed to overestimation of soil nitrate-N content on 5 Ghanaian farms. Nitrate-sensitive test strips employed in the context of soil science are not expected to yield false positive results due to chemical interferences (Wetselaar, Smith and Angus, 1998). This warrants further investigation.

Paper strips were unsuccessful in testing HWDF samples, potentially as a result of the HWDF samples requiring a fiftyfold dilution prior to analysis, with further dilutions conducted as required. Accuracy and precision of analyte measurement are negatively affected by serial dilutions (Ellison and Williams 2012), particularly if these are conducted in the field, where there is no access to equipment necessary to produce precise measurements. Furthermore, colorimetric paper strips can be prone to chemical interferences (Jemison and Fox, 1988) where the concentration of interfering compounds exceeds the quantity specified by paper strip manufacturer. Maggini et al. (2010) investigated a range of quick test kits developed for nitrate, ammonium and phosphate assessment and found that interferences from foreign substances resulted in severe distortions to the final result. Paper strips

remain ill-suited to analysis of HWDF samples unless they are redesigned to account for high concentrations of analyte and associated chemical interferences.

4.2 Practical considerations of soil and HWDF testing protocol

There were several practical considerations that constrained the use of paper strip test as an in-field soil testing method in Sub-Saharan Africa. Major considerations involved: filtration, time, wind speed, and temperature. Other issues were light, phone battery/brightness, and transport.

In Kenya, filtration was made difficult due to the heavy texture and the red colour of investigated soils. High speed filter paper i.e. 4V Whatman paper (pore size: 25µm), allowed clay particles to pass through, giving the filtrate a reddish hue. Thus, the measurement of nitrate, which is based on the reactive pad turning red, was not possible. Machery-Nagel MN 616 filter paper (pore size: 4-12µm) replaced 4V Whatman paper in later stages of fieldwork, which made protocol possible but slower.

Time was another practical consideration reducing viability of the in-field soil testing method. Soil sampling, extraction and filtration with medium speed filter paper for three W's, or 15 samples, took a few hours, limiting the number of farms that could be reached in a day for a soil testing service. Reduction in time requirement can be achieved by utilising a coagulating soil extractant such as 0.01M KCl, which has limited negative effect on the test strip colour development (Golicz et al. 2020) or a syringe filter.

Wind speeds in the field made measuring the soil out for extraction difficult. The wind would often blow the sample around the scale which would cause the measured weight to fluctuate making it hard to consistently measure out 10g. Finally, no record of temperature was taken during soil testing and thus, a single temperature correction factor i.e. 0.9 for Kenya (assumed T at sampling = 23°C) and 0.8 for Ghana (assumed T at sampling = 27°C) was utilised. Golicz et al. 2020 details the impact of temperature on the reaction speed of two types of test strips – it is expected that the results obtained could be improved by incorporating correction factors (e.g. proposed by Schmidhalter, 2005, Golicz et al., 2019) to account for temperature effects, for each measurement.

4.3 Soil mapping

For soil mapping methods, open-source data and WOSSAC resources were used to build a base map of soil, climate and transport information across Ghana and Kenya. This built upon existing examples of mapping being used to assist in decisions around land use and biosolids applications (Hallett *et al.*, 2017; Wadsworth, Hallett and Sakrabani, 2018; Truckell *et al.*, 2019). These datasets were used to identify landbank for HWDF in two different scenarios, bringing soil up to a minimum quality threshold, and using HWDF-producer criteria to target farmers who irrigate. The approaches to mapping have been used for targeting phosphates from biosolids in the UK previously (Wadsworth *et al*. 2018). One of the major differences in this context is the availability of data that can inform mapping approaches. This is particularly worth considering when looking at the potential of soil mapping in sub-Saharan Africa in general as Kenya and Ghana are wealthier countries with more adoption of mobile technology (GSMA, 2018). Another consideration is that the mapped demands of organic matter much

exceed HWDF production in the study countries (World Bank, 2019), so a more specific approach may be needed to best use limited resources. The current organisation producing HWDF generates 500t of HWDF in a year, which would only be sufficient for 18ha of land area most in need in scenario 1 or 200ha of land in scenario 2. Whilst capacity could hugely expand as sanitation coverage increases, HWDF is limited in terms of improving OM at a national level currently.

Decision support tools have been developed in Malaysia investigating at the use of palm oil residue, which integrated soil criteria, transport constraints and environmental conditions (Truckell *et al.*, 2019). A major difference was that transport constraints were much more limited, only limiting within 4km of production whilst HWDF in Kenya and Ghana was transported up to 100km. This shows the need for mapping to be led by the local constraints. In the context of palm residues in Malaysia the transport cost is a large determinant so mapping using transport links is a key exploration. Whereas in the context of this paper transport distances are much more flexible meaning that other criteria become more important in finding land for HWDF. This highlights the need for stakeholder led mapping in designing appropriate decision tools.

This mapping has demonstrated the potential for resources to be used to identify regions of interest based on specific criteria which could help planning for horticulture at a regional level. A limitation of the method to consider is the uncertainty about the data around soil parameters used, and the temporal nature of the data and how much soil qualities change over time particularly in intensive short-season horticulture settings. For this reason, it was found that stakeholder led mapping of identifying irrigation areas was more effective than using less certain datasets. This highlights the need for end-users of data to be participants in the process of mapping to ensure that criteria used are relevant.

5 Conclusion

This paper assessed the potential of two technologies to assist the process of agriculture and horticulture in Sub-Saharan Africa, particularly with a view to enabling wider use of HWDF: in-field soil testing beginning with a paper strip-based mobile application for nitrate readings, and soil mapping for regional identification of areas of soil organic matter deficiency. Paper strip methods for soil testing were found to be reasonably reliable for assessing available nitrate-N in the soil, though issues of temperature and local laboratory methods need to be accounted for. For soil mapping, openly available datasets were capable of identifying landbank, but not with regular enough updates to account for the changes in horticultural land. Without more regular satellite data, stakeholder mapping that engages farmers is more successful at identifying suitable landbank for HWDF.

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Conflict of interests

The authors declare no conflict of interests.

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