Computers and Electronics in Agriculture 175 (2020) 105532

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Adapting smartphone app used in water testing, for soil nutrient analysis

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ARTICLE INFO

Keywords:
Smartphones
Test strips
Soil analysis
Fertilizer recommendations
Reflectometer

ABSTRACT

Smartphone technology has now penetrated every aspect of modern life. At such high rates of access and utilization, there is today much potential for the development of smartphones as high-performing tools in a number of industries. Traditionally, smartphones have been used as e.g. point-of-care testing devices in developing countries; now a similar approach can be extended to agriculture. This paper assesses the viability of utilizing smartphones in soil analysis. An Android-based smartphone application, in conjunction with commercially available Quantofix® test strips, was employed to analyze 92 soil samples collected across Indonesia. The soils tested encompassed a wide range of different textures (with 13%, 60% and 25% of samples constituting sandy, loamy and clayey soils, respectively), soil organic matter contents (range: 0.8–19.7%) and nutrient concentrations (range for plant-available N: 0.1–137.4 mg kg^{-1} and P: 1.2 to 64.2 mg kg^{-1}; on dry soil basis). The app utilizes the smartphone as a portable reflectometer, which relates the color of test strips to the concentration of particular nutrients present in the soil medium. Three mobile devices currently available on the market, representing low, mid- and high-end products, were used to test the application. The results obtained via the smartphone were compared against standard methods for determination of extractable nitrate-N and exchangeable phosphorus (Olsen-P) under laboratory conditions. The smartphone-mediated soil analysis was found to have a high degree of agreement with standard methods for nitrate-N determination (87% of samples with nitrate-N differed by less than 10 mg kg^{-1} from the standard method for the high-end smartphone) but not for phosphorus determination where chemical interferences to test strip colour development were noted. All three mobile devices were shown to be effective as portable reflectometers. However, color perception was found to differ amongst the devices, resulting in a consistent bias between the high-end phone and the remaining appliances. Whereas, it is essential to consider the inter-smartphone variability in readings and environmental factors such as temperature prior to the smartphone-mediated soil analysis, the smartphone-test strip combination might be employed as acceptable screening tool for soil nutrient concentration assessment to enhance crop outcomes, increasing yield, and preventing over-application of inputs, reducing consequent financial and environmental impact. Further enhancements can test the applicability of smartphone-mediated soil analysis in field conditions.

1. Introduction

Single- and multi-nutrient inorganic fertilizers have been a key force in driving large-scale productivity of the agricultural sector for over seventy years. Inputs of mineral fertilizer in post-industrial and industrialized nations have been steadily increasing to accommodate rising world demand for food (Coelli and Rao, 2005), bio-fuels (Hein and Leemans, 2012), sustainable intensification of agriculture, and high-yielding crop varieties characterized by high nutrient requirement (Robertson and Swinton, 2005). Such a high degree of reliance on mineral fertilizers calls for site-specific nutrient management, which results in higher efficiency of crop production and minimizes costs to the farmers whilst reducing the risk to the environment brought about by over-fertilization.

Laboratory measurement of nutrient concentration in the soil has been widely adopted as a means to achieve a satisfactory balance between inputs and outputs of plant-available nutrients. However, laboratory analyses can be resource-intensive and costly (Du and Zhou, 2009). The process is also time-sensitive with a relatively short window of opportunity for nutrient measurement around the period when the crops are sown, which can be used to establish the quantity of nutrients immediately available to crops and the mineralization potential over the growing-season (Myers, 1984). Attempts have been made to address the shortcomings of laboratory method by developing rapid, in-field

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https://doi.org/10.1016/j.compag.2020.105532
Received 1 October 2019; Received in revised form 30 March 2020; Accepted 25 May 2020
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assays for nutrient analysis, particularly, soil nitrate (Schepers and Raun, 2008).

Jemison and Fox (1988) evaluated the use of Merckquant nitrate test strips and used a Nitracheck hand-held reflectometer to measure nitrate concentration in diluted stalk tissue of corn (*Zea mays L.*) and soil. The results obtained correlated well with standard laboratory methods (R^2 of 0.87 and 0.98, respectively) and were shown to display a high degree of consistency over a 10-day measurement period (coefficient of variation ranged from 22.4 to 9.5% for the test strips and less than 3.5% for the reflectometer). Wetselaar et al. (1998) compared soil nitrate content measured with the Merckquant test strips and a Nitracheck reflectometer with two standard laboratory methods: steam distillation and the auto-analyzer hydrazine reduction method. The results were highly correlated, having an R^2 of 0.97 for steam distillation and an R^2 of 0.96 for the auto-analyzer. However, difficulties associated with assessing soil moisture in the field, the impact of extractants' chemical composition, and the temperature-dependency of the strips were highlighted as posing a barrier to their continued use (Wetselaar et al., 1998).

Schmidhalter (2005) proposed a set of correction factors to account for the effect of temperature on the test strip readings, addressing an overestimation of the nitrate content at higher temperatures, the opposite being true for lower temperatures. The limited impact of a short shaking time (approx. 5 min) on nitrate extraction was also noted (Schmidhalter, 2005). Similar studies (Aguilera et al., 2014; Hartz et al., 2000; Sims et al., 1995) employed battery-operated, hand-held instruments, i.e. Nitracheck and Cardy Meter, that were initially optimized for nitrate analysis of plant sap, but were adapted for soil analysis to minimize human error associated with visual colorimetric analysis. They recognized soil colloids and coloring as factors which might negatively impact color strip readings as a result of the interference with the reflected light from the test strip, however, the test strip/reflectometer system was shown to outperform other sensors developed for field use (Sims et al., 1995).

Test strips have been recommended as a reasonably precise and affordable tool, which can be employed in site-specific nutrient management in the US (Hartz et al., 2000), Germany (Schmidhalter, 2005) and Spain (Thompson et al., 2009). Furthermore, colorimetric kits have been employed successfully in a number of industrialized countries around the world (Nyi and Varughese, 2017). As the advantages of quick on-farm, in-field soil tests have been fully recognized, the method can be further improved by introducing modern technology into the analytical process to ensure a consistency of outcome. Smartphones, in particular, offer a unique combination of sensors, which might be employed in a similar capacity to reflectometers. Application of smartphones as color-readers have already been explored in agriculture (Han et al., 2016; Intaravanne and Sumriddetchkajorn, 2015; Vesali et al., 2015) and other fields, including medicine (Yetisen et al., 2014).

This work aimed to investigate: (1) if a smartphone, in conjunction with Quantofix® test strips, and optimized for nitrate and phosphate detection, can be employed in soil analysis, (2) to what degree a smartphone can be used as a hand-held reflectometer, and (3) the practical limits, within which a smartphone/test strip system can operate. The choice of location to implement this work was in Indonesia, the exercise being to assess the feasibility of this approach to assist small holder horticultural farmers in planning their nutrient management.

2. Methodology

2.1. Preparation of NO_3^- and PO_4^{3-} standards and measurement of temperature effects

Standards were prepared in accordance with standard operating procedures for chromatography developed by Cranfield University, UK. A set of 1000 ppm stock solutions were prepared for nitrate using 6.068 g of oven-dry $NaNO_3$ (Sigma-Aldrich, CAS number: 7631-99-4) diluted to 1000 mL and 1 mL of 1000 µg of P (Fisher Scientific, Catalogue number: J829805) diluted to 1000 mL. The stock solutions were then further diluted with distilled water to concentrations stipulated by the test strip manufacturer. The standards were measured in daylight and brightly lit conditions.

An additional short experiment was conducted to measure the impact of temperature on the speed of the reaction taking place on the reactive pad. The experiment was conducted in a temperature- and humidity-controlled plant growth chamber at Cranfield University. The humidity was set at 70% and the temperatures investigated comprising: 15, 20, 25, 30, 35 °C. Nitrate and phosphate standards were prepared freshly on the day of analysis and were allowed to reach the temperature of the room. Solution temperature was measured with a laboratory approved thermometer to confirm it matched the ambient temperature of the plant-growth chamber. Five strips were used subsequently to measure each standard solution for nitrate and phosphate at every temperature setting.

2.2. Soil samples

Soil samples were collected across Sumatra and East and Central Java between January 2017 and March 2018 as part of a country-wide soil mapping effort by Bogor University, Indonesia. Akvo.org, a non-profit developer of low-cost environmental testing methods, facilitated transport of a portion of the samples to Cranfield University to undergo soil nutrient testing with smartphone mediated soil analysis. Soil analysis conducted at Cranfield University concerned the measurement of the proportion of nitrate-N and P, recorded by standard method vs smartphone-mediated method and not the representative assessment of the nutrient status of the collection site. Utilization of soil samples collected across a large spatial scale ensured that soils with a range of properties were represented in the testing process. Characteristics of samples (N = 56) used in calibration of Akvo Caddisfly are summarized in Table 1.

2.3. Soil analytical methods

Available nitrate-N concentration was measured in field-moist and air-dried soil. Field-moist samples were sieved through 5.6 mm sieve and stored in the fridge (at 4 °C) prior to analysis. Nitrate-N was extracted with 2 M potassium chloride (KCl) for 2 hrs ± 10 min on a side-to-side shaker (300 min^{-1}, 21° C) at a soil-to-solution ratio of 1:5 (Keeney and Nelson, 1982). The filtrate was stored in the fridge overnight at 4 °C before 15 mL of filtrate (3 mL of extract diluted to 15 mL with distilled water) was pipetted into cuvettes and analyzed via the automated colorimetric method (Cd reduction column). Subsequently, soil samples were air-dried at 35 °C and sieved through a 2 mm sieve to remove stones, plant remains, and plastic constituents, following the method outlined by Vandendriessche et al. (2011). Available nitrate-N analysis in air-dried soil took place as per the above. Olsen-P was extracted with 0.5 M sodium hydrogen carbonate solution (pH = 8.5) for 30 ± 1 min on a side-to-side shaker (300 min-1, 20 °C) at a soil-to-solution ratio of 1:20 (Olsen et al., 1954). The solutions were analyzed colorimetrically via the molybdate blue–ascorbic acid colorimetric method (Murphy and Riley, 1962).

Table 1
Soil characteristics of 56 soil samples used for calibration of Akvo Caddisfly.

	NO_3^--N	P	K	OM	pH	Regional lithology
Min	0.0	0.2	20.2	0.8	4.9	Alluvium (recent volcanic),
Max	216.1	75.6	660.6	19.7	8.3	Limestone, Basalt
Average	33.7	11.8	159.7	6.8	6.5	

2.4. Soil smartphone-mediated analysis

Soil pre-treatment matched the preparation of soil samples prior to the standard laboratory method. Fifty milliliters of distilled water were used to extract 10 g of field-moist and air-dried soil for available nitrate-N measurement. Distilled water was used as extractant because it does not interfere with color development of the reactive pad of the test strip, as opposed to concentrated extractants such as 2 M KCl, 0.2MKCl or M1. Investigation of test strip – soil extractant interferences are described in Golicz et al., 2020. The samples were left on a mechanical side-to-side shaker for 5 min. The smartphone-mediated soil test is expected to be a field method, thus the time on the shaker was limited to 5 min because it was considered representative of the time and effort likely to be exerted in field conditions. The extractant-soil solution was transferred from a 250 mL polypropylene bottle into a 50 mL bottle through a funnel with Whatman #4 filter paper. Filtering was considered to be completed when ¾ of the bottle was filled with liquid. The Quantofix® (reference number: 913 51) nitrate strips (range: 0–100 mgL^{-1} of NO_3^{-}) were used for available nitrate-N analysis. Test strip analysis followed the manufacturer's instructions, which involved dipping the strip in the filtrate for one second and waiting a further 60 s for the color to develop.

Three smartphone models (Galaxy S8, OnePlus3 and Galaxy Tab 2) were used for strip testing, representing a spectrum of device costs. The mobile devices had the Akvo Caddisfly (Beta ver. 10.0) software app installed and running before the strip was submerged in the filtrate. Each phone was placed on a tripod at (h = 18 cm) and had the color correction card, which accompanies the Akvo Caddisfly app (Fig. 1A), fitted directly underneath its camera opening. The strip was removed from the solution and placed on the black area of the color correction card with the color pad facing upwards and directed towards the left side of the color correction card (Fig. 1B). The strip-specific option was selected within the app and the picture of the strip was taken after 60 s of waiting time.

Table 2
Hand texturing followed the field method described by Ilaco (1985). The soil texture types were grouped into three broad classes to simplify field-based analysis for smartphone-mediated phosphate analysis.

Soil texture class	Definition	Sample mass [g]
Sandy soil	Sandy soils include sand and loamy sand	2 ± 0.05
Loamy soil	Loamy soils include sandy loam and loam	5 ± 0.05
Clayey soils	Clayey soils include heavy loam, light loam and clay	15 ± 0.05

During preliminary testing, sandy soils were shown to have very high P content comparatively to clayey soil. Thus, for soil P analysis, sample weight was adjusted to account for the soil texture type. Soil texture was assessed via hand texturing (Ilaco, 1985) and the requisite amount of soil (Table 2) was placed into a 250 mL polypropylene bottle.

Fifty milliliters of freshly prepared Mehlich-1 solution (0.05 N HCl and 0.025 N H_2SO_4) was dispensed into the bottle. Mehlich-1 was selected as extractant as it sped up the filtration process (particularly, for clayey soils) and it (1) was not found to interfere with color development of test strip's reactive pad at low P concentrations (both Olsen-P and Bray 1 were found to be interfering agents), (2) is not acutely toxic like Bray 1 and thus, might be used in field conditions, and (3) does not have short expiration date like Olsen-P. Shaking time (on a mechanical side-to-side shaker) was set at 5 min. The extractant-soil solution was transferred from 250 mL polypropylene bottle into a 50 mL bottle through a funnel with Whatman #4V filter paper. The Quantofix® (reference number: 913 20) phosphate strips (range: 0–100 mgL^{-1} of PO_4^{3-}) were used for available P analysis. Test strip analysis followed the manufacturer's instructions, which involved (1) taking 5 mL of the aliquot and placing it in a tube provided by the manufacturer as part of the phosphate analytical kit, (2) mixing it with 5 drops of solution #1

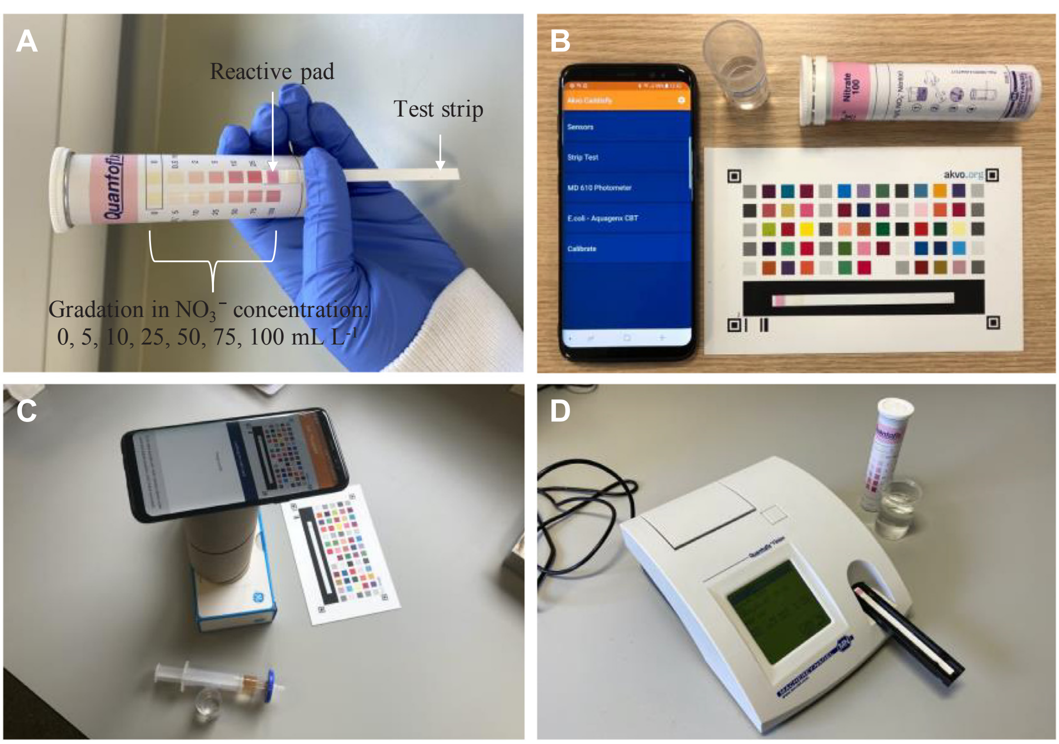

Fig. 1. A–D. Discerning colors of the reactive pad poses issues in terms on inter-rater agreement and repeatability due to gradation range and the semi-quantitative nature of test strips (A). Akvo Caddisfly set-up during the laboratory works (B), the app together with the calibration card and nitrate-sensitive test strip (C) and a Quantofix commercially available reflectometer (D). The calibration card was manufactured and provided by Akvo. Smartphones models used included: Samsung Galaxy S8 (pictured), OnePlus 3, Samsung Galaxy Tab 2. The devices were kept at the same height (approx. 18 cm), within 10 cm of each other. The main source of natural light was provided by a window facing the workstation.

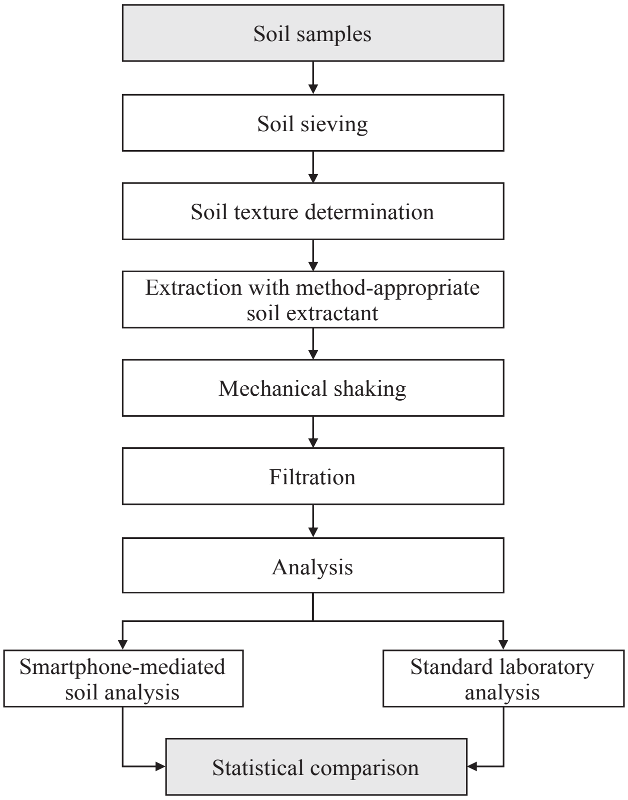

Fig. 2. Summary of the methods. Soil pre-treatment involved soil sieving and air-drying. Smartphone based soil analysis was carried out via Akvo Caddisfly app (beta ver. 10) installed on three smartphone models i.e. OnePlus 3 (OP3), Samsung Galaxy S8 (S8) and Samsung Galaxy Tab 2 (SGT2). The reference values were obtained via well-established standard methods of nitrate-N and phosphorus analysis. M1 refers to Mehlich 1 solution.

(provided by the manufacturer), (3) dipping the strip for 15 s in the mixture, (4) placing the strip in a second plastic tube filled with six drops of solution #2 (both provided by the manufacturer) for further 15 s, and (5) placing the strip on top of the color correction card and waiting for 60 s for the color to develop before taking an image of the reactive part of the strip with Akvo Caddisfly. Akvo Caddisfly has embedded within it both reference color and the reaction time corresponding to different strip types. The results were recorded and compared statistically (Fig. 2).

2.5. Calibration equations and statistical analysis

Akvo Caddisfly was not calibrated in a way that allowed direct comparison with the standard colorimetric method as opposed to results obtained with Quantofix Relax reflectometer. Therefore, a set of 56 samples was used to develop a calibration equation, which was derived from a linear regression recorded for standard colorimetric method vs. Akvo Caddisfly results obtained with a Galaxy S8 mobile phone (Fig. 3). The calibration was conducted in the laboratory, in a well-lit room with a constant temperature of 21.5 °C. The correlation coefficients were $R^2 = 0.95$ and $R^2 = 0.65$ for nitrate and phosphate, respectively. Attempt at development of calibration equation for phosphate analysis revealed the test strips to be prone to multiple chemical interferences, especially in sandy soils.

Bland-Altman (B-A) plots (Bland & Altman, 1986; Bland & Altman, 2003) were then employed to investigate the degree of agreement between standard laboratory and smartphone-mediated methods of nutrient analysis for a set of 92 samples, which did not include the calibration set., and the variation in readings between different smartphone models, and commercial level test strip reader (Quantofix® Relax Test Strip Reader). The B-A analysis involves constructing a scatter plot, in which the difference between the paired measurements is plotted on the y-axis, and the mean of the measures of two methods on the x-axis. The mean difference refers to the bias between two methods and is represented as a central horizontal line on the plot. Two additional lines are derived from the standard deviation (SD) of differences between paired measurements and represent 95% limits of agreement (mean bias ± 1.96 SD). Analysis were carried out in R Studio (ver. 1.1.447) and the blandr package (ver. 0.5.1).

3. Results

3.1. Comparison with the commercial grade test strip reader

The Quantofix® Relax reflectometer was successfully employed to measure the concentrations of standard stock solutions for nitrate (Fig. 4A) and phosphate (Fig. 4B). The readings obtained with the Quantofix® Relax were found to be nearly three times as high as those obtained with Akvo Caddisfly for nitrate, and four times as high as those obtained with Akvo Caddisfly for phosphate. The nitrate concentration was found to be more likely to be overestimated at lower concentrations (< 50 mL L^{-1}), in contrast to the trend noted for the smartphone-mediated soil analysis.

The relative standard error (RSE) between readings (N = 5) were found to be higher for smartphones than for the commercial grade reflectometer for both nitrate and phosphate, and the standard deviations were found to increase alongside the concentration gradient. The RSEs recorded for readings obtained via the commercial reflectometer constituted between 4.6% and 14.6% (from 0.5 to 13 mL L^{-1}; range: 5 to 100 mL L^{-1}) of the estimated value for NO_3^- and 4.3% to 9.2% (0 to 9 mL L^{-1}; range; from 3 to 80 mL L^{-1}) for PO_4^{3-}. The uncertainty associated with readings obtained via Akvo Caddisfly with the Samsung Galaxy S8 constituted between 4.6% and 17.5% (from 0.5 to 7.7 mL L^{-1}) of the estimated values for nitrate and 2.3% to 21.2% (0.1 to 5.5 mL L^{-1}) for phosphate.

The Akvo Caddisfly app was found to be sensitive to light conditions – readings were higher in bright artificial light than those in daylight. However, the difference was not statistically significant for the nitrate (ANOVA ($F_{(1,69)}$ = 2.59, p = 0.11) and phosphate (ANOVA ($F_{(1,35)}$ = 0.07, p = 0.79) readings. In bright light, phosphate test strips were reflecting light off the reactive pad, requiring multiple attempts at analysis.

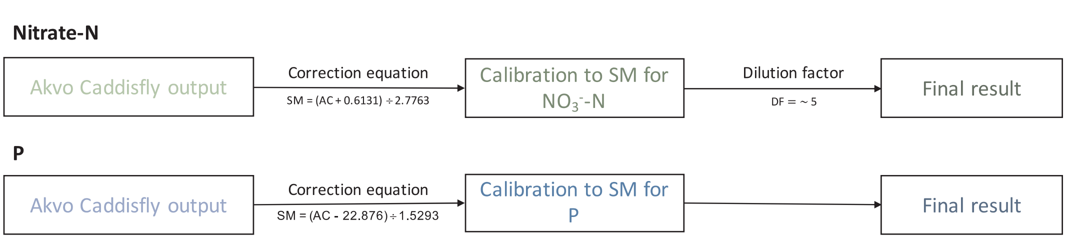

Fig. 3. Transformation follows the standard regression equation where SM – standard method and AC – Akvo Caddisfly. The results require a multiplication by a dilution factor of 5 for the extractable nitrate-N test.

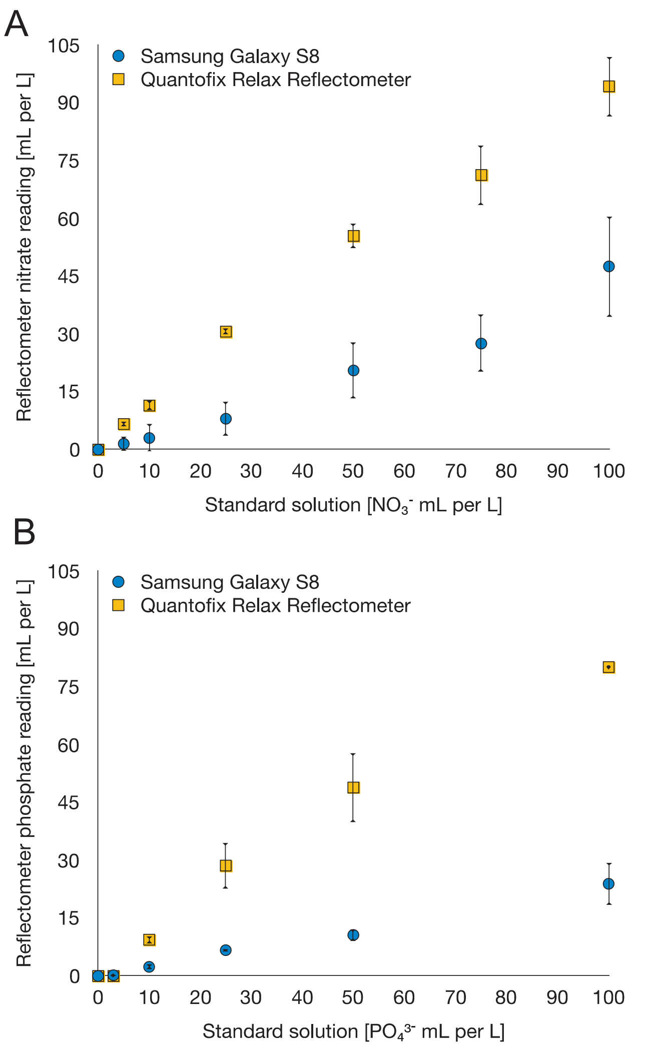

Fig. 4. A-B. Concentration of standard stock solutions (mean ± SD) for nitrate (A) and phosphate (B) as measured with Quantofix® Relax reflectometer (■) and Samsung Galaxy S8 with Akvo Caddisfly (●).

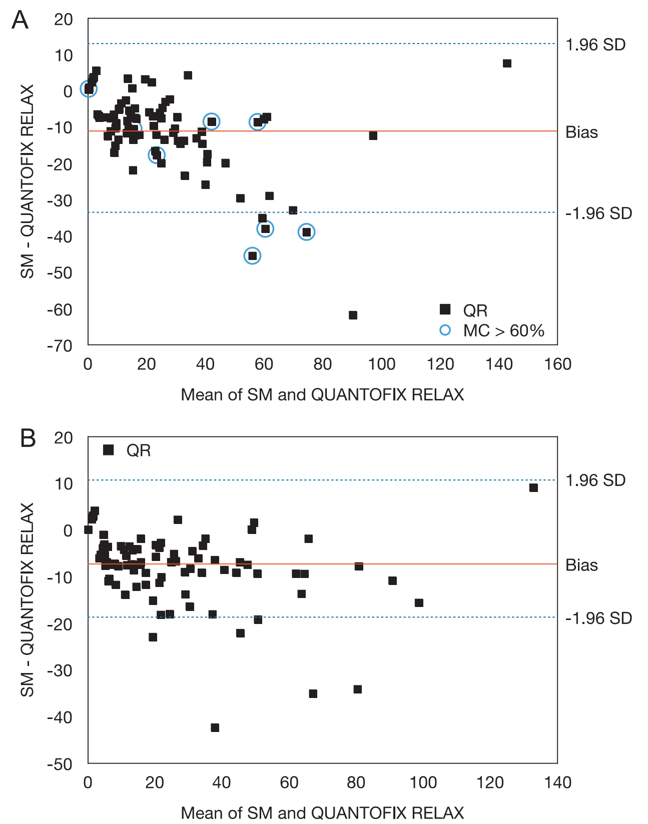

Fig. 5. A-B. Plots of the paired-differences for the automatic colorimetric method and Quantofix Relax for nitrate-N determination of field-moist (A) and air-dried (B) soil samples (N = 92). Blue circles represent samples with moisture content > 60%. The dashed lines represent the error tolerances defined as ± 1.96 SD. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Agreement with standard laboratory methods

3.2.1. Nitrate analysis

The results obtained via Quantofix® Relax and nitrate sensitive test-strips showed a good agreement with the standard method for nitrate-N determination for dry (mean bias: −3.96, CI: −2.44 to −5.48; U LoA = 10.52, CI: 7.91 to 13.12, L LoA = -18.45, CI: −21.05 to −15.84; SD = 7.39; N = 91) and field-moist soil (mean bias: −10.27 CI: −12.67 to −7.86; U LoA = 12.51, CI: 8.39 to 16.64, L LoA = −33.05, CI: −37.18 to −28.92; SD = 11.62; N = 91). The use of field-moist soil was shown to be more likely to result in over-estimation of nitrate-N concentration when soil moisture content was > 60% (Fig. 5A-B).

The mean bias between the standard method for nitrate analysis and Akvo Caddisfly for the high-end smartphone (S8) was 1.85 (95% confidence interval for the bias: 0.47–3.25) for dry soil samples analyzed with auto-analyzer using the cadmium reduction colorimetric method (Table 2). The absolute errors ranged from −11.22 (CI: −13.59 to −8.85) for the Lower Limit of Agreement to 14.92 (CI: 12.55 to 17.29) for the Upper Limit of Agreement. Overestimation of soil N concentration was found to be more likely for field-moist soils, with error greater than ± 10 ppm being recorded for 12% (OP3), 13% (S8) and 10% (SGT2) of samples. On dry soil, 11% (OP3), 18% (S8), and 9% (SGT2) of samples had their concentration assessed as more than ± 10 ppm of the standard method (see Table S2 for detailed breakdown of Bland-Altman analysis) (See Fig. 6).

3.2.2. Phosphate analysis

Olsen-P concentration of the samples investigated ranged from 0 to 64.2 mg kg^{-1}. During smartphone-mediated soil testing, prevalent chemical interferences to color development of the test strip pad were noted. Chemical interferences were exhibited either through no color change (the reactive pad remined pearly white) or very intense green–blue color at low soil Olsen-P concentrations. Multiple samples, primarily of sandy texture consistently showed elevated P concentrations even when the sample weight was reduced to 2 g. Those outliers could not be easily discerned by eye until after the comparison with standard method was conducted and thus, test strip technology was considered inadequate for soil testing purposes.

3.3. Inter-smartphone variability

The differences in readings were not evenly distributed for S8 vs OP3 and SGT2, and they increased with concentration (Fig. 7A-B). The errors observed were highest for the S8 and OP3 paired differences comparison (Lower LoA range: −7.91 to −6.07; Upper LoA range: 2.29–4.14) and lowest for OP3 and SGT2 (Lower LoA range: −4.37 to −3.01; Upper LoA range: 3.18 to 4.54). Overall, the high-end smartphone was shown to provide results consistently lower than the mid- and low-end devices with OP3 and SGT2 displaying converging results.

The inter-smartphone variability in readings for phosphate was established to be approximately three times higher than that for nitrate, reaching up to 20 ppm for the selected electronic devices (Table 3).

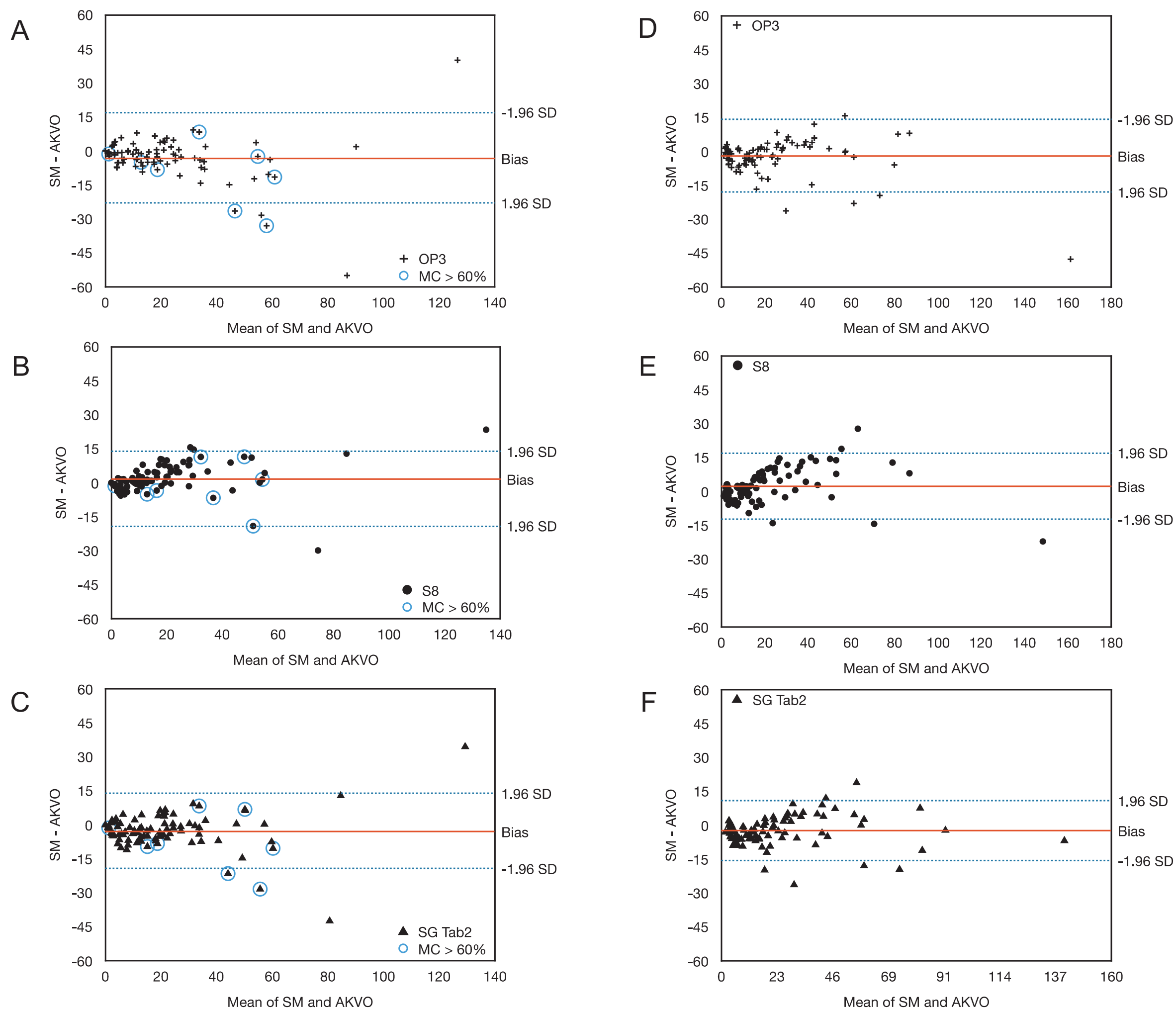

Fig. 6. A–F. Plots of the paired-differences for the automatic colorimetric method; and Akvo Caddisfly installed on OnePlus 3 (A, D), Samsung Galaxy S8 (B, E), Samsung Galaxy Tab 2 (C, F) for nitrate-N determination of field-moist (A-C) and air-dried (D-F) soil samples. The dashed lines represent the error tolerances defined as ± 1.96 SD.

Similarly, for nitrate readings, the Samsung devices were characterized by a higher degree of agreement between each other (mean bias: −0.41) than between OP3 (mean bias: −4.20 vs −3.23 for S8 and SGT2, respectively).

3.4. Practical application of smartphone-mediated soil analysis

Ten soil test values, selected at random from the pool of results presented in Section 3.2.1, were scaled up from mg kg^{-1} to kg ha^{-1} (assumed bulk density: 1.2; soil sample depth: 15 cm) and compared against fertilizer recommendations for three vegetables frequently grown in Indonesia i.e. mung bean (*Vigna radiata*), tomato (*Solanum lycopersicum*) and mustard green (*Brassica juncea*). The smartphone-mediated soil test was shown to be a useful tool in discerning when addition of fertilizer is unnecessary i.e. its accuracy was equal to 93% (Table 4). The differences in fertilizer recommendations derived from results provided by the standard method and smartphone-mediated method ranged from 2.8 kg ha^{-1} to −46.8 kg ha^{-1} with recommendations becoming less accurate at higher soil nitrate-N concentration.

4. Discussion

4.1. Comparison between a commercial grade reflectometer and a smartphone-as-reflectometer

There was a difference in magnitude between readings obtained via Quantofix® Relax and Akvo Caddisfly, with the readings obtained via Akvo Caddisfly being approximately three times lower than the readings obtained via Quantofix® Relax. It is hypothesized that the difference is partially a result of the ambient temperature at which the app was calibrated. This was tested in a temperature-controlled plant growth chamber at Cranfield University, where test strips were shown to display consistently elevated quantities of nitrate and phosphate at temperatures higher than 19.5 °C (See Supplementary material for detailed breakdown of temperature effect on test strip readings). Whereas, the incorporation of calibration curve into the application is of benefit as it decreases the reliance on standard stock solutions, which were shown to be too expensive and difficult to procure in rural settings in similar study (Aguilera et al., 2014), it is crucial to consider ambient temperature during the calibration stage of the app development process. Furthermore, calibration of the application at temperatures higher than those recommended by test strip manufacturers results in employing test strips to measure concentrations of solutions above their maximum capacity. For example, where stock solution is equal to 100 mL L^{-1} of NO_3^-; Akvo Caddisfly reads 42.5 ± 7.7 mL, at room

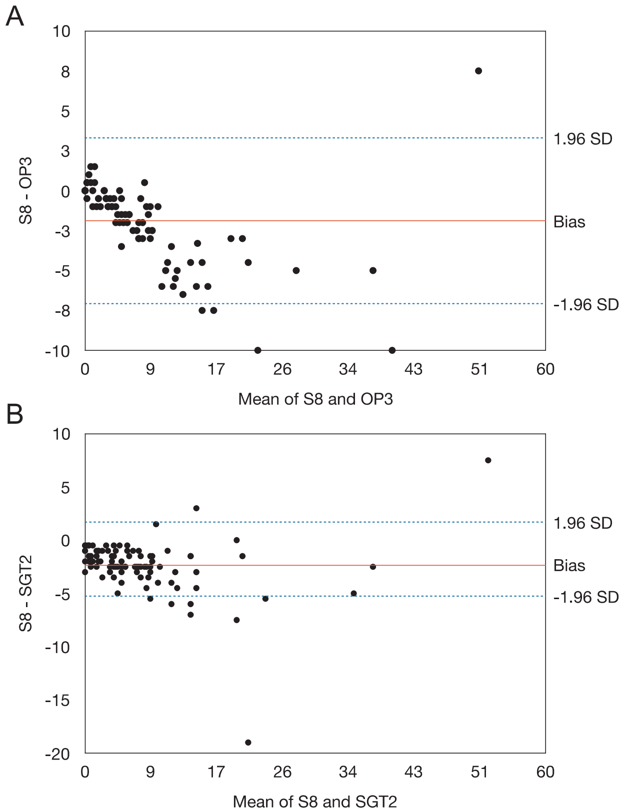

Fig. 7. A-B. Plots of the paired-differences of the reference measurement, i.e. Samsung Galaxy S8 output, minus outputs for (A) mid-range smartphone One Plus 3, and (B) low-range tablet Samsung Galaxy Tab 2. The dashed lines represent the error tolerances.

Table 3
Bland-Altman analysis including the bias (mean difference) and the limits of agreement together with 95% confidence intervals and standard errors for Android-operated devices compared against Samsung Galaxy S8.

Nutrient	Parameter	N	Estimate	95% CI	SE
NO_3^-	**S8 vs OP3**				
	Mean difference	93	−1.88	−2.42 to −1.34	2.60
	95% Lower LoA		−6.99	−7.91 to −6.07	
	95% Upper LoA		3.22	2.29 to 4.14	
	S8 vs SGT2				
	Mean difference	93	−1.80	−2.16 to −1.44	−1.80
	95% Lower LoA		−5.22	−5.83 to 2.23	
	95% Upper LoA		1.62	1.00 to 2.23	
	OP3 vs SGT2				
	Mean difference	93	0.08	−0.31 to 0.48	1.92
	95% Lower LoA		−3.70	−4.37 to −3.01	
	95% Upper LoA		3.86	3.18 to 4.54	
PO_4^{3-}	**S8 vs OP3**				
	Mean difference	90	−2.79	−4.21 to −1.36	6.79
	95% Lower LoA		−16.10	−18.54 to −13.66	
	95% Upper LoA		10.53	8.08 to 12.67	
	S8 vs SGT2				
	Mean difference	90	0.73	−1.43 to 2.89	10.31
	95% Lower LoA		−19.48	–23.18 to −15.77	
	95% Upper LoA		20.93	17.23 to 24.64	
	OnePlus 3 vs SGT2				
	Mean difference	90	3.51	1.43 to 5.60	9.94
	95% Lower LoA		−15.98	−19.55 to −12.41	
	95% Upper LoA		23.01	19.43 to 26.58	

temperature equal to 20.5 °C. Theoretically, the app can measure up to 200 mL L^{-1} of NO_3^-, however, the test strips was optimized for a maximum concentration of 100 mL L^{-1} of NO_3^-. This optimal concentration should not be exceeded as it could then lead to unstable and less reliable readings and might be a contributing factor to higher coefficients of variance recorded for smartphones as opposed to the Quantofix® Relax reflectometer.

4.2. Agreement with standard methods

Mobile devices in conjunction with test strips, as analyzed via Akvo Caddisfly, were applied in testing for nitrate-N present in the soil solution. The deviation from the standard method after transformation was equivalent to ± 16.7 mg kg^{-1} for Samsung Galaxy S8, and 20.0 and 16.5 mg kg^{-1} for One Plus 3 and Samsung Galaxy Tab2, respectively, for field-moist soil. For air-dried soil; the average deviation from the standard method was equivalent to ± 16.2 mg kg^{-1} (OP3), ± 16.7 mg kg^{-1} (S8) and ± 13.3 mg kg^{-1} (SGT2). These differences were higher than the difference expected between subsamples measured with the same segmented auto-analyzer during a single run of the equipment that might range from −3.8 to 10.4 mg kg^{-1}, or −11.7 to 31.2 kg ha^{-1} (Golicz et al., 2019), however, they were consistent with results reported by other test strip studies (Golicz et al., 2020). Thus, the smartphone - test strip combination provides a viable and cheap screening tool, which is of particular use in resource poor environments, where access to commercial soil laboratories is limited.

The limited success in phosphorus determination via Akvo Caddisfly was due to test strips being subject to color interferences, and difficulties with P extraction caused by weak extractant and limited extraction time. Interferences to color development in test strips developed for phosphate assessment have been previously reported by Maggini et al. (2010) who recorded frequent overestimation (approx. 5-fold) of orthophosphate values determined with field test kits comparative to ion chromatography. Similarly, Quantofix® PO_4^{-3} test strips were found to be prone to interferences resulting in a high number of outliers, the source of which cannot be easily discerned in field conditions, thus posing significant risks of an erroneous analytical result. No reliable predictor of interferences was recorded during this study and thus even arbitrary division of the result into ‘High’, ‘Medium’ and ‘Low’ could be misleading for a subset of interference-prone soils. Furthermore, in the absence of mechanical shakers, extraction time depends on the user’s physical ability as highly concentrated extractants such as CH_3COONa were shown to negatively impact to the color development of the test strip’s reactive pad and have to be avoided (Golicz et al., 2020). As phosphorus is solid bound (Adesanwo et al., 2013); it is less likely to be made labile during a field extraction and thus, the P in soil solution will constitute a relatively small pool. This results in reduced capacity to compare results obtained via test strips to the existing standard analytical methods.

Smartphone and test strip-mediated soil test is not proposed as a replacement for accepted soil testing methods. The tool is optimized for field use and is capable of providing screening for nitrate (but not phosphate) concentration present in the soil media within minutes of sample preparation. In situations where blanket fertilizer recommendations are the only option available to small-holder farmers (Rware et al., 2016), even limited soil nutrient information can be helpful in development of prescriptive and corrective strategies to address the crop fertilizer N needs whilst minimizing the risk of over-fertilization. Colorimetric methods are already being employed in developing countries in soil analysis (Nyi and Varughese, 2017) and increasingly in plant analysis (Singh et al., 2011; Swarbreck et al., 2019) and application of smartphones instead of commercial test strip readers greatly reduces the costs of testing whilst reducing the potential for human error in color detection. Due to the incorporation of the calibration curve within the app, any need for additional reagents, which are difficult to procure in rural settings (Aguilera et al., 2014) is eliminated. A further advantage of adopting the smart phone approach is that a future iteration of the app might also include some extension advice contingent on the results, combining a testing function with a

Table 4
Ten randomly selected test results were scaled up to kg per and compared against fertilizer recommendations for mung bean, tomato and mustard green. Fertilizer recommendations based on FAO (2005). Red values indicate soils where Nitrate-N quantity is sufficient for crop growth.

	Nitrate-N in kg × ha^{-1}							
			Mung bean	Tomato	Mustard green			
Test	SM	AC	SM	AC	SM	AC	SM	AC
1	125.7	135.9	−95.7	−105.9	−5.7	−15.9	−15.7	−25.9
2	178.3	268.0	−148.3	−238	−58.3	−148	−68.3	−158
3	43.8	54.2	−13.8	−24.2	76.2	65.8	66.2	55.8
4	96.1	72.4	−66.1	−42.4	23.9	47.6	13.9	37.6
5	8.3	11.1	21.7	18.9	111.7	108.9	101.7	98.9
6	142.1	115.5	−112.1	−85.5	−22.1	4.5	−32.1	−5.5
7	108.6	61.8	−78.6	−31.8	11.4	58.2	1.4	48.2
8	56.0	43.0	−26	−13	64.0	77.0	54.0	67.0
9	94.9	71.9	−64.9	−41.9	25.1	48.1	15.1	38.1
10	1.3	4.4	28.7	25.6	118.7	115.6	108.7	105.6

decision support capability and that it might be combined with other available smartphone-mediated tools developed to improve fertilizer management e.g. BaiKhao (Intaravanne and Sumriddetchkajorn, 2015).

4.3. The effects of smartphones' camera quality on the test results

Akvo.org recommended Samsung Galaxy S8 for testing and overall, color perception was shown to differ between smartphone models, which has a notable impact on the accuracy of the results. In order for the absolute errors to remain low (within limits of agreement established for the nitrate-N analysis), there needs to be a set of correction equations developed for different smartphone models, which is likely to be impractical in the applications anticipated e.g. small landowners in developing countries. Furthermore, establishing correction equations for multiple devices is impractical due to the extensive range of smartphone models available on the market, time and resource intensiveness and the associated costs. This issue can be mitigated by calibrating each phone separately prior to the analysis by utilizing the color card provided by Quantofix on the back of each box of paper strips. This approach has been successfully trialed by Yetisen et al. (2014) where no significant difference was noted between the results obtained via an iPhone 5 (with an inbuilt 8 Mega Pixel camera) and a Samsung I5500 Galaxy 5 with (with a 2 MP camera).

The difference in color perception between devices was particularly pronounced during available soil P testing. In additive color models, which are employed in smartphones and tablets smartphone's camera quality and light conditions are of paramount importance (Rosi et al., 2016) and if not corrected for with an appropriate algorithm, they will have an impact on the accuracy, precision and replicability. Future studies involving the use of smartphones as spectrophotometers should test and account for the inter-model variability, if present.

4.4. Implications for future practice

The maximum difference of ± 16.7 mg per kg of field-moist soil, i.e. the approximate deviation from the real value recorded for Samsung Galaxy S8, appears to be acceptable for a field method of nitrate-N determination. However, it is important to consider the spatial scale for which the results are likely to be applied. Fertilizer recommendations require scaling up of the results to the field level i.e. from mg per kg to kg per ha. Thus, the larger the field, the more pronounced the deviation between results obtained via the smartphone mediated soil analysis and the standard laboratory method. This issue can be partially mitigated by carrying out multiple tests across different parts of the field, especially if the results are at the end of the spectrum for a given fertility class to increase precision of the tool. The accuracy of the smartphone-mediated soil analysis might be improved by (1) incorporating test strips with higher concentrations of nitrate-N analysis as the differences between standard method and smartphone-mediated method increase at higher soil nutrient concentration and (2) improvements to the color detection algorithm that would reduce or eliminate differences in color perception between smartphone models.

Finally, it is important to note that the test strips, alongside similar 'quick' field test kits, were developed in Europe and the US and are likely to have been validated against Western methods of elemental analysis. Wet-chemistry methods of soil analysis differ within and between countries (Jordan-Meille et al., 2012) and thus, results obtained via test strips might not be equivalent to results of soil analyses employed in other parts of the world. In situations, where fertilizer recommendations are based on soil tests that do not correspond to standard protocols recommended for use in the UK, the smartphone-mediated soil testing might prove of lesser practical use. For example, the British fertilizer application advisory uses laboratory-derived extractable nitrate-N results, however, the preferred fertilizer advisory for tropical countries proposed by the Food and Agriculture Organization (Roy et al., 2007) utilizes total N. Those analytical methods are not directly comparable and other 'quick' tests should be considered in such circumstances. To date, very little research exists that compares soil analytical methods prevalent in the Northern Hemisphere and the tropics and those differences must be considered in future field test kit development.

4.5. Conclusions

Smartphone-mediated soil analysis provides an affordable screening tool, which offers the potential to measure soil nitrate-N concentration but not soil P concentration. Employing a smartphone in place of a reflectometer is cost-effective and, as a method, likely to reach a greater number of end-users, especially in developing countries. However, it is essential that future attempts at smartphone and test-strip mediated soil analysis consider both the limitations of test strip technology i.e. demonstrated by phosphate test strips, which should not be used in the context of soil science due to chemical interferences, and smartphone technology i.e. demonstrated by differences in color perception by three smartphone models investigated in this study. Smartphone technology offers exciting opportunities for low-cost decision-support tool development in agriculture, which should be capitalized upon in the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors wish to acknowledge Akvo.org for facilitating funds for testing out Akvo Caddisfly. The first author is grateful for the assistance provided by the laboratory staff at Bogor Agricultural University. This work was supported by the UK Natural Environment Research Council [NERC Ref: NE/M009009/1]. Data underlying this study will be made accessible through Cranfield University's repository at 10.17862/cranfield.rd.9328814.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compag.2020.105532.

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