CRANFIELD UNIVERSITY

Karolina K Golicz

Development of an in-field diagnostic tool for soil nutrient screening

School of Water, Energy and Environment

This thesis is submitted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy

PhD

Academic Year: 2017 – 2020

Supervisor: Dr Ruben Sakrabani

Associate supervisor: Professor Stephen Hallett

CRANFIELD UNIVERSITY

School of Water, Energy and Environment

PhD

Academic Year: 2017 – 2020

Karolina K Golicz

Development of an in-field diagnostic tool for soil nutrient screening

Supervisor: Dr Ruben Sakrabani

Associate supervisor: Professor Stephen Hallett

June 2020

This thesis is submitted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy

ABSTRACT

The use of external inputs in the form of inorganic fertilisers is rising across the world. Rapidly growing crops such as vegetables necessitate high fertiliser inputs, whilst remaining an attractive cash-crop option for farmers, especially smallholders in the developing countries. For vegetable farming to be sustainable, these inputs should be monitored so the crop nutrient use efficiency is high and the potential for under- and over-fertilisation is low.

Therefore, there is a need for the development of low-cost tools that can bring site-specific soil information to farmers who do not ordinarily have access to such knowledge. In recent years, smartphone technology has given rise to a number of advanced apps that aim to improve agronomic production, especially in the Southern Hemisphere. The work in this thesis centres around method development and appraisal for the application of a smartphone-mediated diagnostic tool for use in soil nutrient screening.

A smartphone application marketed as Akvo Caddisfly, used together with nutrient-sensitive test strips was repurposed for the analysis of soil samples. The app was used alongside selected test strip types and underwent rigorous laboratory testing to evaluate its suitability for soil analysis and to identify its strengths and weaknesses. The laboratory-based experiments allowed for the development of soil extraction, filtration and analysis methodologies, through the utilisation of variable soil samples obtained from Indonesia, an approach subsequently employed in field conditions in other study sites.

The field-based experiments were undertaken in the People's Republic of China, Ghana and Kenya, allowing for a critical appraisal of smartphone-mediated soil analysis as an effective tool for fertiliser recommendations in smallholder vegetable production. In China, where frequent overfertilisation of crops is the chief cause of soil acidification and heavy metal pollution as well as eutrophication of waterbodies and high N_2O emissions, smartphone-mediated soil analysis was employed successfully in identifying overfertilised plots. In contrast, in Sub-Saharan Africa, where soil Nitrogen content was low, smartphone-mediated soil analysis encouraged farmers to apply organic fertilisers to improve their yields.

Referencing the metadata, which was collected during laboratory and field-based experiments, a framework for designing and evaluating future in-field soil test kits was created. The data consisted of a collation of quantitative analyses and qualitative observations and these were synthesised into a step-by-step process that can be used at the test kit evaluation stage to reduce the time and costs associated with their development. Finally, a range of statistical approaches were employed to investigate the level of agreement between the in-field method and the accepted laboratory standard methods employed in agricultural soil analysis. They were described in detail to encourage their wider application in method comparison studies across environmental science.

KEYWORDS: Smartphone technology, test strips, in-field soil testing kits, soil analysis, method comparison studies, mobile environmental sensing, sustainable agricultural development

ACKNOWLEDGEMENTS

Thank you all who have contributed to the creation of this thesis –

You are the best!

Special thanks to my family (human and furry) who, upon realizing that being a pedantic perfectionist does not bode well for working with inherently variable soil systems, have showed extreme patience towards me for years –

Love you lots.

Many thanks to my supervisors Dr Ruben Sakrabani and Professor Stephen Hallett and funders including Akvo.org, Natural Environment Research Council, Newton Fund China, DREAM CDT as well as staff at Bogor University, exceptional young scientists [with Professor Genxing Pan at the forefront] of Nanjing Agricultural University and lovely people at the National Institute of Agricultural Botany.

This research would not be possible without you!

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY AND DEFINITION OF KEY TERMS

Akvo Foundation: A not-for-profit organisation with a goal of creating public domain internet and mobile software and sensors. AKVO is a partner organisation in the PhD project

Akvo Caddisfly App: A smartphone app developed in conjunction with a simple water and soil testing kit. The app records concentrations of different chemical compounds, stores geotagged information, and makes it available on-line

AC: Akvo Caddisfly app

Akvo Caddisfly Colour Correction Card: A multicoloured card necessary for calibration of the Akvo Caddisfly app and to control for illumination conditions

APP: Application

B-A analysis: Bland-Altman analysis

CF: Correction factor

Colorimetry: A technique used to determine the concentration of coloured compounds in a solution

CNY: Chinese Yuan

DAT: Digital Agricultural Technologies: innovation that enable farmers and agribusiness to increase their productivity, efficiency, and competitiveness, facilitate access to markets, improve nutritional outcomes and enhance resilience to climate change

Extractant: Chemical solution used to extract soil nutrients

FAO: Food and Agriculture Organisation of the United Nations

GIS: Geographic Information System

GPS: Global Positioning System

HWDF: Human waste derived fertiliser

ICT: Any device, tool or application that permits the exchange or collection of data through interaction or transmission

JMP 16: Statistical software produced by the Statistical Analysis System Institute

K: Potassium

KCl: Potassium chloride

MC: Moisture content

METHCOMP: Statistical package in R programming language used for analysis of method comparison studies

$NaHCO_3$: Sodium bicarbonate

N: Nitrogen

N_2O: Nitrous oxide

NO_3^-: Nitrate ion

NO_3-N: Nitrate Nitrogen ($NO_3^- * 0.226$)

NPK: Nitrogen Phosphorus Potassium

m-Agriculture: Mobile Agriculture, i.e. mobile technology supported agriculture

Olsen-P: Soil PO_4-P assessment method using 0.5M sodium bicarbonate ($NaHCO_3$) at pH of 8.5 as extractant

P: Phosphorus

PO_4^{3-}: Phosphate ion

PO_4^{-3}-P: Phosphate Phosphorus ($PO_4^{3-} * 0.3261$)

PPM: Parts per million [equivalent to mg per kg]

QR: Quantofix Relax i.e. a test strip reader developed by Quantofix

RGB values: Red, green and blue colour values in the RGB colour model

SM: Standard method [of soil analysis]

Smallholder: A small scale farmer, pastoralist, forest keeper or fisherman

Smallholding: A farm between 1ha and 10ha in size managed largely by a single-family unit

T: Temperature

Test strip I Paper strip: A white plastic strip containing white paper pads coated in reagents that develop a specific colour after exposure to a selected chemical compound

Chapter 1: Introduction

Summary: This chapter outlines the need for undertaking this research project and articulates research objectives formulated to meet the research aim. It highlights gaps in knowledge, which had been identified at the commencement of the project and provides a short history of mobile phones in agriculture as well as in-field tools employed in recent decades for rapid soil fertility assessment. It provides statement of contribution of the author and explains the thesis structure.

Highlights:

- Explanation of rationale for providing smallholders with in-field soil testing kits;
- Short history of mobile phones in environmental monitoring and soil science;
- Statement of the research aim and objectives formulated to meet the aim;
- Explanation of the thesis structure.

1.1 Overview

Open-field and greenhouse-based vegetable production systems necessitate high inputs of mineral fertilisers whilst being characterised by low nutrient recovery rates (Ju et al., 2007; Song et al., 2009; Thompson et al., 2009). Environmental risks associated with nutrient leaching, which can be as high as 139kg of Nitrogen ha^{-1} per growing season in greenhouse vegetables systems in subtropical China (Zhang et al., 2017), are a cause for concern. High greenhouse gas emissions resulting from N fertiliser production (Swarbreck et al., 2019), and contamination of aquifers (Rodrigo et al., 2007), surface water pollution (Willett et al., 2019) and severe soil acidification (Liang et al., 2013) resulting from mismanagement of fertiliser applications have all been identified as damaging to the ecosystem processes on which agricultural systems depend.

As fertiliser consumption rises across the world (FAO, 2015), there is a need for implementing agricultural management practices that improve and optimise mineral fertiliser use. There is a marked difference in approaches to reducing application rates to match crop demand across the developed and the developing nations; that derives from differences in the scale of operations. Developed countries, which favour high-input large-scale agriculture have access to resources such as national soil maps (Prager and McKee, 2014), soil laboratory testing (Lobry de Bruyn and Andrews 2016), agronomic advice (Cowlrick and Lester, 2000), and high-tech solutions, e.g. drones and robots (Singh et al., 2011), which are used to maximise efficiency. In contrast, the developing regions remain dependant on blanket fertiliser recommendations, which often ignore micro-scale differences in soil fertility profiles (Tittonell et al., 2008), limiting potential for optimal nutrient prescriptive-corrective management (Giller et al., 2004). Therefore, there is a continued need for low-cost, in-field tools that are accessible and can be utilised by farmers as decision support to assist site-specific nutrient management.

1.2 In-field soil test kits based on colorimetric principles

One of the first in-field soil testing kits made available was developed by the United States Department of Agriculture (USDA) in the early 1950s (Liebig et al., 1996). These involved qualitative and semi-quantitative colorimetric methods for assessment of soil health indicators, including soil colour, pH and N status. In the mid-70s, test strips, i.e. paper strips equipped with a reactive pad that changes colour when exposed to a specific chemical compound, were found to be particularly useful for on-farm application because they were affordable, simple to operate and provided results within a short period of time in contrast to laboratory tests, which commanded higher costs and time requirement.

Subsequently, test strips alongside commercial grade reflectometers, which increased precision of readings fourfold in comparison to visual methods of colour comparison (Schaefer, 1986), were adopted by the US extension service for measurement of macro-nutrient concentration, especially nitrate, in soil solution and plant sap (Jemison and Fox, 1988) and were later offered as a practical solution to farmers in Australia (Wetselaar et al., 1998), Germany (Schmidhalter, 2005) and Spain (Thompson et al., 2009). These colorimetric approaches to soil analysis were readily incorporated into rapid soil testing kits developed for remote areas in Thailand, Philippines, Indonesia and Myanmar as a way for 'soil doctors', i.e. agricultural extension workers, to provide soil fertility evaluation data to smallholders (Nyi et al., 2017; **Figure 1-1**).

Colorimetric assessments of plant available soil N, P and K in combination with country or region-specific crop nutrient demand look-up tables have been shown to provide effective nutrient recommendations (Chinabut, 2005; Attanandana et al., 2008; Chianu et al., 2012; FAO, 2020). By engaging smallholders and increasing their capacity to make informed decisions about what type of, when and how to apply mineral fertilisers, soil testing kits can provide benefits resulting from their use. However, the kits' design limitations manifest as:

- Difficulties with development and implementation of quality control;
- The ability to correlate with standard methods of soil analysis, rarely complemented with robust crop response data;
- Obscurity of the statistical methodologies employed for assessment of accuracy and precision;
- Dependence on subjective judgment of intensity of colour resulting in reduced accuracy and replicability issues when multiple-users are involved.

One of the ways in which to address these shortcomings involves incorporating modern technology, in the form of smartphones, into the soil kit testing process. Smartphones can act as affordable reflectometers, which improve precision and replicability of colour readings, whilst offering capacity for geotagging locations and keeping records for future use, as well as the integration of other extension advice.

Figure 1-1. In-field test kits employed in soil fertility assessment in South East Asia. The kits consist of qualitative and semi-quantitative colorimetric charts. The deeper the colour, the higher the quantity of the measured nutrient (from Nyi et al., 2017).

1.3 Smartphones in environmental monitoring and scope for use in soil science

Globally, there are over 4.8 billion mobile-phones with 3.5 billion of these constituting smartphones (Statista, 2020). The rapid increase in computing power of mobile devices, coupled with their low cost and greater accessibility, introduced them into more and more aspects of modern life, including healthcare (Bogoch et al., 2013; Oncescu et al., 2013; Ozcan 2014), education (Gikas and Grant, 2013; Libman and Huang, 2013), and environmental monitoring (Teacher et al., 2013; Aitkenhead et al., 2014).

Wildlife recording apps, which were adapted for crowd-sourcing sightings of invasive species constituted amongst the very first examples of utilising smartphones as powerful 'in-field' tools (Teacher et al., 2013). The water utility sector took smartphone technology a step further by designing dedicated hardware and software packages to conduct water testing. The first smartphone-mediated nitrite and pH determination method was detailed by Lopez-Ruiz et al. (2014), with Wang et al. (2015) developing the concept further and creating a portable platform for nitrate detection with the capacity for data sharing. Wei et al. (2014) designed an optical imaging system for mercury detection and tested it across California, whereas Levin et al. (2016) focused on fluoride monitoring throughout rural India. In environmental monitoring, smartphones are expected to match and eventually exceed the capacity of currently available field methods (Aitkenhead et al., 2014).

1.3.1 Smartphone-mediated measurement of soil properties

As with environmental monitoring, the number of mobile apps acting as agricultural decision support tools started increasing from 2013 onwards. The first app designed to support nutrient management planning was the Nitrogen Index

(Delgado et al., 2013). The Nitrogen Index constituted a USDA-approved software package, which assessed the risk of nitrogen loss resulting from farm-specific nutrient management practices. The software was adapted to the smartphone ecosystem, allowing for data input to be conducted away from the desktop computer and thus, providing a portable and effective tool for N management to farmers across the US.

Following Delgado et al. (2013), it has been quickly recognised that the smartphone's capacity for integration of sensors into data-collection process provides a unique platform which goes beyond taking a personal computer into the field for data entry purposes. At present, the most frequently utilised sensors are GPS and camera and these have been incorporated into specifically designed apps to analyse soil colour, carbon content, NPK (directly and indirectly via leaf spectroscopy), soil erosion rate as well as improving irrigation and spray coverage (**Table 1-1**).

1.3.2 Akvo Caddisfly app – Linking smartphone technology with colorimetric test strips to improve in-field soil testing kits

Akvo.org is a not-for-profit foundation with a core goal of creating public domain internet and mobile software and sensors for use, primarily, in water testing in developing countries. The organisation has created Akvo Caddisfly app, i.e. a smartphone app that records concentration of different chemical compounds via colorimetry, stores geotagged information, and makes it available on-line.

Akvo.org became a partner organisation in this PhD project in an attempt to expand its services to include soil testing. The app is calibrated for multiple commercially-available test strips, which can be applied in soil testing provided appropriate soil extraction and analysis methods are employed (**Figure 1-2**).

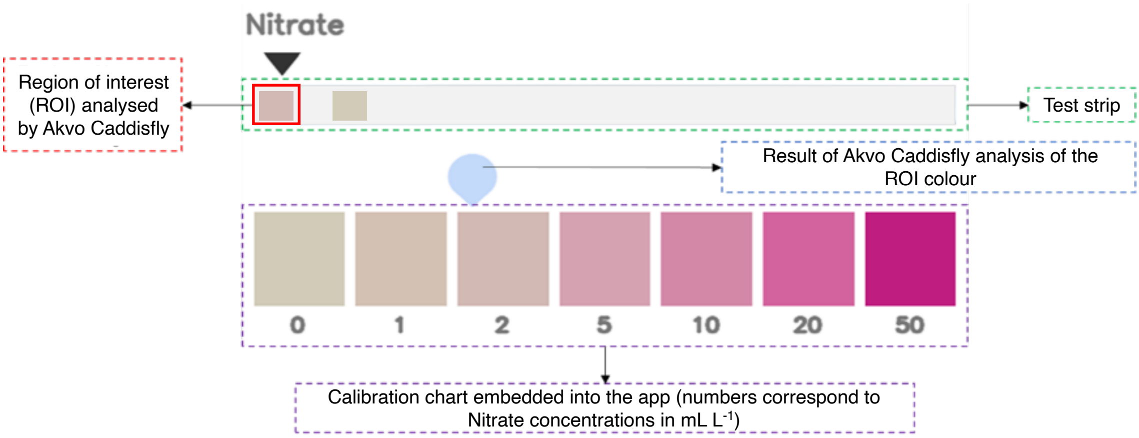


Figure 1-2. Example photo of the test strip analysis with Akvo Caddisfly. The region of interest (ROI) constitutes the reactive part of the test strip. The app is calibrated by expressing standard concentrations as RGB values [calibration curve], and; incorporating the reaction time.

Four test strips types incorporated into Akvo Caddisfly were deemed suitable for soil media testing:

- Quantofix (reference number: 913 51) nitrate strips (range: 0-100mg L^{-1} of NO_3^-);
- Quantofix (reference number: 913 20) phosphate strips (range: 0-100mg L^{-1} of PO_4^{3-});
- Quantofix (reference number: 913 15) ammonium strips (range: 0-400mg L^{-1} of NH_4^+); and,
- Merck KGaA® (reference number: 117985) potassium strips (range: 0-1500mg L^{-1} of K).

Nitrate and phosphate test strips had the highest agreement with standard solutions and thus, were considered the most reliable and appropriate for soil analysis. Further works confirmed nitrate test strips to be suitable for use in soil screening (**Chapters 3-6**) whereas phosphate test strips were prone to multiple chemical interferences (**Chapter 3**) and did not correlate to plant response (**Chapter 4**). In contrast, ammonium and potassium test strips were disregarded as potential tools for soil nutrient screening due to low agreement with standard solutions and high deviations between readings (**Chapter 6**).

Table 1-1 The summary of smartphone apps developed for soil testing. Apps marked in bold are available for download on Apple Store and Google Play Store. All apps reviewed underwent rigorous scientific testing. [1]**Gomez-Robledo et al. (2013) developed software only;** [2]**Colour correction / water sensitive cards required;** [3]**Worst case scenarios;** [4]**Calibration + validation data points;** [5]**Relative percentage difference**

Measured parameter	Standard methods	Smartphone apps	Sensor	Hardware add-on	Correlation with SM	Detection limit	Sample number	References
Soil colour	Visual inspection with Munsell colour chart, vis–NIR spectrometer	Soil Scanner	Camera, GPS	Yes[1]	4.0 ± 3.3 CIELAB units[3]	N/A	295	Stiglitz et al., 2017
		N/A	Camera	Yes[1]	R^2 = 90%	N/A	500	Han et al., 2016
		N/A	Camera	Yes[1]	3.7 ± 1.8 CIELAB units	N/A	60	Gómez-Robledo et al., 2013
Soil carbon	Loss on ignition	**SOCiT**	Camera	Yes[2]	R^2 = 80%	0% LOI	2614 + 32[4]	Aitkenhead et al., 2015
Indirect measurement of N, and NK deficiency	SPAD analyser, Kjeldahl tissue analysis	**BaiKhao**	Camera	Yes[2]	R^2 = 90%	-	80	Intaravanne and Sumriddetchkajorn 2015
		SmartSPAD	Camera	No	R^2 = 70%	-	480 + 60[4]	Vesali et al., 2015
N loss monitoring	Radioactive N	**The Nitrogen Index**	-	No	R^2 = 80%	-	-	Delgado et al., 2013
P content	Spectrophotometer method	Phosphorus analysis	Camera	Yes	R^2 = 99%	0mg P L^{-1}	10	Moonrungsee et al., 2015
		Phosphorus analysis	Camera	Yes	RPD[5] < 4%	1mg P L^{-1}	5	Campbell et al., 2015
Real time field irrigation	Field environmental sensors, Automatic /Remote control	**Cotton App**	GPS	No	N/A	N/A	N/A	Vellidis et al., 2016
		WISE	GPS	No	N/A	N/A	N/A	Bartlett et al., 2015
		Smartirrigation Turf	GPS	No	N/A	N/A	N/A	Migliaccio et al., 2015
Spray coverage	Manual counting of droplets	**SnapCard**	Camera, GPS	Yes**	N/A	N/A	132	Nansen et al., 2015

1.4 Research aims and objectives

The aim of this research is to formulate a methodology employing smartphones and test strips to analyse in-field soil nutrient content to establish appropriate fertiliser recommendations to optimise horticultural production whilst minimising environmental and economic risks arising from overfertilisation.

To achieve this, the following research objectives were adopted:

1. Development and evaluation of a smartphone-mediated colorimetric method to assess soil nutrient content, drawing from nationally-representative soil samples, collected from horticultural plots across Indonesia.
2. Identification and minimisation of analytical and calibration errors, associated with environmental conditions and technological challenges, in using the smartphones and test strip method, to improve the accuracy and precision of smartphone-mediated soil analysis.
3. Implementation and evaluation of a horticultural case study approach in selected developing nations to assess the performance of smartphone-mediated soil analysis.
4. Development of best-practices for the implementation of test strips in similar studies, through development of a step-by-step evaluation process, to better inform agricultural management practices, relating to enhancing agronomic yields and reducing risks.

1.4.1 Thesis structure

This thesis is presented in the same logical order as the research aims and objectives. A literature review has informed a review paper on the use of smartphones in sustainable mineral fertiliser management and advised subsequent laboratory work by providing information on previously identified concerns regarding the use of test strip and smartphones employed as reflectometers.

During the laboratory work, a method for soil extraction including appropriate extractants and soil to extractant ratio was finalised. Calibration equations were developed to allow for comparison and harmonisation between standard laboratory methods and smartphone-mediated soil analysis.

The laboratory work laid foundation for smartphone-mediated soil testing in People's Republic of China, Indonesia, Kenya and Ghana. The in-field testing resulted in fine-tuning of the methodology and identification of important environmental factors influencing the smartphone-mediated soil analysis. It has also highlighted potential issues of the transferability of the soil testing tools.

Finally, the metadata collected across laboratory and field work alongside data extracted from test strip-oriented literature has allowed for the development of a process designed to streamline testing of paper strips designated for soil analysis. This work has highlighted the importance of utilising appropriate statistical methodologies in method comparison studies. The links between the thesis chapters are summarised in **Figure 1-3**.

1.4.2 Disclosure and dissemination from this PhD thesis

At the submission of this thesis, three papers (**Chapters 3**, **4** and **6**) have been published in international peer-reviewed scientific journals and two further papers (**Chapter 2** and **5**) have been submitted for publication.

I am the first author of four chapters formatted as academic papers, and I am responsible for the literature review, data collection, statistical analysis and writing of all relevant sections.

Dr Ruben Sakrabani and Dr Stephen Hallett have contributed by acting as academic supervisors and have helped in the preparation and submission of published papers and paper manuscripts. Professor Genxing Pan contributed as editor of Chapter 4. Mr Joy Ghosh provided input regarding the Akvo Caddisfly software used to enhance discussion relating to colour detection in smartphones, described in **Chapter 3.**

Furthermore, I am a co-author of one chapter (**Chapter 5**) formatted as an academic paper, and am responsible for part of the literature review, data analysis relating to smartphone-mediated soil testing, write-up of a portion of the methods and discussion sections, as well as, editing and creation of figures.

Submitted papers:

Golicz K, Hallett SH, Sakrabani R (2020). Old problem, the Millennial Solution: Using mobile phone technologies for sustainable fertiliser management. Current Opinions in Environmental sustainability [**Chapter 2**]

Papers accepted for publication after minor revisions:

Mallory, A., Golicz, K., and Sakrabani, R. (2020). An analysis of in-field soil testing and mapping for improving fertiliser decision making in vegetable production in Kenya and Ghana. Soil Use and Management [**Chapter 5**]

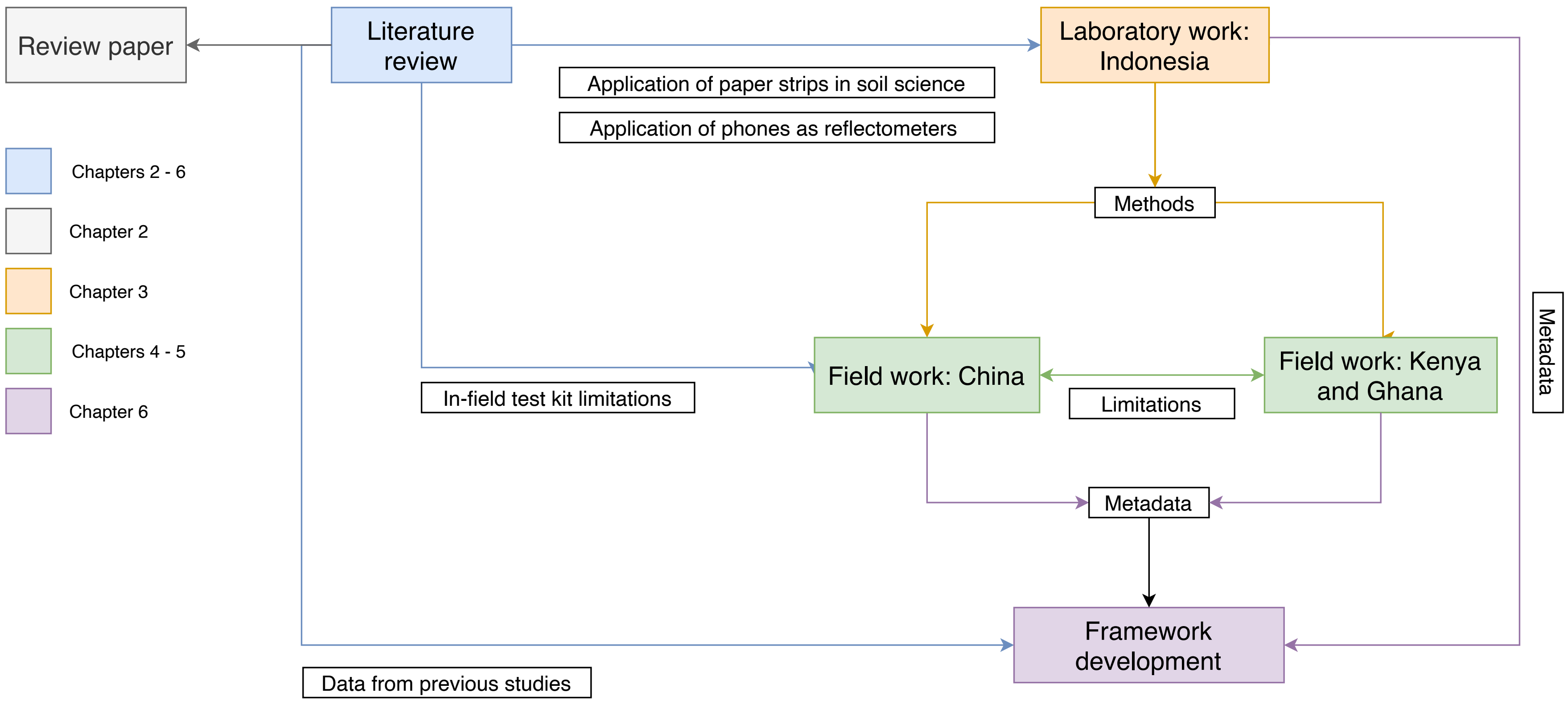


Figure 1-3. Overview of the thesis structure. Each chapter has a series of individual objectives which have been designed to satisfy the four individual objectives of the PhD thesis.

Published papers:

Golicz K, Hallett S, Sakrabani R, Ghosh J (2020) Adapting smartphone app used in water testing, for soil nutrient analysis. Comput Electron Agric 175:105532. doi: 10.1016/j.compag.2020.105532 [**Chapter 3**]

Golicz K, Hallett SH, Sakrabani R, Pan G (2019) The potential for using smartphones as portable soil nutrient analyzers on suburban farms in central East China. Sci Rep 9:1–10. doi: 10.1038/s41598-019-52702-8 [**Chapter 4**]

Golicz K, Hallett SH, Sakrabani R (2020) Novel procedure for testing of soil field test kits involving paper strips. Soil Use Manag 00:1–11. doi: 10.1111/sum.12582 [**Chapter 6**]

Additional outputs have been classified as Research Outreach [**p. 159**] and involve a visual guide developed for potential users of Akvo Caddisfly (currently employed by researchers in a life project in Madagascar and Pakistan funded by the Royal Academy of Engineering) and a short piece outlining the unrealised potential of smartphones in agriculture, written as a popular science piece and published in Landmark, i.e. an internal magazine of the UK National Institute for Agricultural Botany.

1.5 References

Aitkenhead MJ, Donnelly D, Coull MC, Hastings E (2014) Innovations in environmental monitoring using mobile phone technology – a review. Int J Interact Mob Technol 8:50–58

Aitkenhead MJ, Donnelly D, Sutherland L, et al (2015) Predicting Scottish topsoil organic matter content from colour and environmental factors. Eur J Soil Sci 66:112–120. doi: 10.1111/ejss.12199

Attanandana T, Verapattananirund P, Yost R (2008) Refining and disseminating site-specific nutrient management technology in Thailand. Agron Sustain Dev 28:291–297. doi: 10.1051/agro:2008006

Bartlett AC, Andales AA, Arabi M, Bauder TA (2015) A smartphone app to extend use of a cloud-based irrigation scheduling tool. Comput Electron Agric 111:127–130. doi: 10.1016/j.compag.2014.12.021

Bogoch II, Andrews JR, Speich B, et al (2013) Short report: Mobile phone microscopy for the diagnosis of soil-transmitted helminth infections: A proof-of-concept study. Am J Trop Med Hyg 88:626–629. doi: 10.4269/ajtmh.12-0742

Campbell ER, Warsko K, Davidson AM, Campbell WH (2015) Determination of phosphate in soil extracts in the field: A green chemistry enzymatic method. MethodsX 2:211–218. doi: 10.1016/j.mex.2015.04.003

Chianu JN, Chianu JN, Mairura F (2012) Mineral fertilisers in the farming systems of sub-Saharan Africa. A review. Agron Sustain Dev 32:545–566. doi: 10.1007/s13593-011-0050-0

Chinabut N (2005) The “Dr soils” program of the Land Development Department, Thailand. In: Management of Tropical Sandy Soils for Sustainable Agriculture. Khon Kaen, p 404

Cowlrick T, Lester D (2000) An agronomic quality system - Our experiences. Commun Soil Sci Plant Anal 31:1887–1894. doi: 10.1080/00103620009370545

Delgado JA, Kowalski K, Tebbe C (2013) The first Nitrogen Index app for mobile devices: Using portable technology for smart agricultural management. Comput Electron Agric 91:121–123. doi: 10.1016/j.compag.2012.12.008

FAO (2015) Statistical Pocketbook: World food and agriculture. Accessed from: http://www.fao.org/3/a-i4691e.pdf

FAO (2020) Manual for the implementation of the Soil Doctors Global Programme at the country level - A farmer-to-farmer training programme. Rome. Accessed from: http://www.fao.org/3/ca7492en/CA7492EN.pdf

Gikas J, Grant MM (2013) Mobile computing devices in higher education: Student perspectives on learning with cellphones, smartphones & social media. Internet High Educ 19:18–26. doi: 10.1016/j.iheduc.2013.06.002

Giller KE, Chalk P, Debermann A, et al (2004) Emerging technologies to increase effciency of use of fertiliser nitrogen. In: Mosier A, Syers JK, Freney JR (eds) Agriculture and the Nitrogen Cycle, 1st edn. Island Press, Washington, DC, pp 31–51

Gómez-Robledo L, López-Ruiz N, Melgosa M, et al (2013) Using the mobile phone as munsell soil-colour sensor: An experiment under controlled illumination conditions. Comput Electron Agric 99:200–208. doi: 10.1016/j.compag.2013.10.002

Han P, Dong D, Zhao X, et al (2016) A smartphone-based soil colour sensor: For soil type classification. Comput Electron Agric 123:232–241. doi: 10.1016/j.compag.2016.02.024

Intaravanne Y, Sumriddetchkajorn S (2015) Android-based rice leaf colour analyzer for estimating the needed amount of nitrogen fertiliser. Comput Electron Agric 116:228–233. doi: 10.1016/j.compag.2015.07.005

Jemison JM, Fox RH (1988) A quick-test procedure for soil and plant tissue nitrates using test strips and a hand-held reflectometer. Commun Soil Sci Plant Anal 19:1569–1582. doi: 10.1080/00103628809368035

Ju XT, Kou CL, Christie P, et al (2007) Changes in the soil environment from excessive application of fertilisers and manures to two contrasting intensive cropping systems on the North China Plain. Environ Pollut 145:497–506. doi: 10.1016/j.envpol.2006.04.017

Levin S, Krishnan S, Rajkumar S, et al (2016) Monitoring of fluoride in water samples using a smartphone. Sci Total Environ 551–552:101–107. doi: 10.1016/j.scitotenv.2016.01.156

Liang L., Zhao XY, Chen ZC, et al (2013) Excessive application of nitrogen and phosphorus fertilisers induces soil acidification and phosphorus enrichment during vegetable production in Yangtze River Delta, China. Soil Use Manag 29:161–168. doi: 10.1111/sum.12035

Libman D, Huang L (2013) Chemistry on the Go: Review of chemistry apps on smartphones. J Chem Educ 90:320–325. doi: 10.1021/ed300329e

Liebig MA, Doran JW, Gardner JC (1996) Evaluation of a field test kit for measuring selected soil quality indicators. Agron J 88:683–686

Lobry de Bruyn L, Andrews S (2016) Are Australian and United States Farmers Using Soil Information for Soil Health Management? Sustainability 8:304. doi: https://doi.org/10.3390/su8040304

Lopez-Ruiz N, Curto VF, Erenas MM, et al (2014) Smartphone-based simultaneous pH and nitrite colorimetric determination for paper microfluidic devices. Anal Chem 86:9554–9562. doi: 10.1021/ac5019205

Migliaccio KW, Morgan KT, Fraisse C, et al (2015) Performance evaluation of urban turf irrigation smartphone app. Comput Electron Agric. doi: 10.1016/j.compag.2015.08.015

Moonrungsee N, Pencharee S, Jakmunee J (2015) Colorimetric analyzer based on mobile phone camera for determination of available phosphorus in soil. Talanta 136:204–209. doi: 10.1016/j.talanta.2015.01.024

Nansen C, Ferguson JC, Moore J, et al (2015) Optimizing pesticide spray coverage using a novel web and smartphone tool, SnapCard. Agron Sustain Dev 35:1075–1085. doi: 10.1007/s13593-015-0309-y

Nyi T, Varughese P, bin Hj Bujang MI, et al (2017) ASEAN Guidelines on Soil and Nutrient Management. Bangkok

Oncescu V, O'Dell D, Erickson D (2013) Smartphone based health accessory for colorimetric detection of biomarkers in sweat and saliva. Lab Chip 13:3232. doi: 10.1039/c3lc50431j

Ozcan A (2014) Mobile Phones Democratize and Cultivate Next-Generation Imaging, Diagnostics and Measurement Tools. Lab Chip 14:3187–3194. doi: 10.1038/nmeth.2839.A

Prager K, McKee A (2014) Use and awareness of soil data and information among local authorities, farmers and estate managers. Aberdeen

Rodrigo MC, López D, Carazo N, Ramos C (2007) Nitrate sap and chlorophyll meters as nitrogen monitoring tools for artichoke grown in sand culture. Acta Hortic 747:519–522. doi: 10.17660/ActaHortic.2007.747.67

Schmidhalter U (2005) Development of a quick on-farm test to determine nitrate levels in soil. J Plant Nutr Soil Sci 168:432–438. doi: 10.1002/jpln.200520521

Schaefer, NL (1986) Evaluation of a hand held reflectometer for rapid quantitative determination of nitrate. Commun. Soil Sci. Plan. 17: 937–951

Singh B, Sharma RK, Jaspreet-Kaur, et al (2011) Assessment of the nitrogen management strategy using an optical sensor for irrigated wheat. Agron

Sustain Dev 31:589–603. doi: 10.1007/s13593-011-0005-5

Song XZ, Zhao CX, Wang XL, Li J (2009) Study of nitrate leaching and nitrogen fate under intensive vegetable production pattern in northern China. Comptes Rendus - Biol 332:385–392. doi: 10.1016/j.crvi.2008.11.005

Statista (2017) Number of mobile app downloads worldwide from 2009 to 2017 (in millions). https://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide/. Accessed 15 Jan 2018

Stiglitz R, Mikhailova E, Post C, et al (2017) Soil colour sensor data collection using a GPS-enabled smartphone application. Geoderma 269:108–11. doi: 10.1016/j.geoderma.2017.02.018

Swarbreck SM, Wang M, Wang Y, et al (2019) A Roadmap for Lowering Crop Nitrogen Requirement. Trends Plant Sci 24:892–904. doi: 10.1016/j.tplants.2019.06.006

Teacher AGF, Griffiths DJ, Hodgson DJ, Inger R (2013) Smartphones in ecology and evolution: A guide for the app-rehensive. Ecol Evol. doi: 10.1002/ece3.888

Thompson RB, Gallardo M, Joya M, et al (2009) Evaluation of rapid analysis systems for on-farm nitrate analysis in vegetable cropping. Spanish J Agric Res t. 7(1) p.:200–211

Tittonell P, Vanlauwe B, Corbeels M, Giller KE (2008) Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant Soil 313:19–37. doi: 10.1007/s11104-008-9676-3

Vellidis G, Liakos V, Andreis JH, et al (2016) Development and assessment of a smartphone application for irrigation scheduling in cotton. Comput Electron Agric 127:249–259. doi: 10.1016/j.compag.2016.06.021

Vesali F, Omid M, Kaleita A, Mobli H (2015) Development of an android app to estimate chlorophyll content of corn leaves based on contact imaging. Comput Electron Agric. doi: 10.1016/j.compag.2015.06.012

Vinet L, Zhedanov A (2010) A “missing” family of classical orthogonal polynomials. World Dev Rep 65:461–468. doi: 10.1088/1751-8113/44/8/085201

Wang X, Gartia MR, Jiang J, et al (2015) Audio jack based miniaturised mobile phone electrochemical sensing platform. Sensors Actuators, B Chem 209:677–685. doi: 10.1016/j.snb.2014.12.017

Wei Q, Nagi R, Sadeghi K, et al (2014) Detection and spatial mapping of mercury contamination in water samples using a smart-phone. ACS Nano 8:1121–1129. doi: 10.1021/nn406571t

Wetselaar R, Smith GD, Angus JF (1998) Field measurement of soil nitrate concentrations. Commun Soil Sci Plant Anal 29:729–739. doi: 10.1080/00103629809369980

Willett W, Rockström J, Loken B, et al (2019) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393:447–492. doi: 10.1016/S0140-6736(18)31788-4

Zhang B, Li Q, Cao J, et al (2017) Reducing nitrogen leaching in a subtropical vegetable system. Agric Ecosyst Environ 241:133–141. doi: 10.1016/j.agee.2017.03.006

Chapter 2: Old problem; the Millennial solution: Using mobile phone technologies for sustainable fertiliser management

Summary: This chapter outlines the current state of knowledge relating to the use of smartphone technology in sustainable mineral fertiliser management. A number of smartphone apps were reviewed with the focus on their applicability. This information was used to inform laboratory (Objective 1 and 2) and field work (Objective 3) efforts. Furthermore, a wider analysis of benefits and limitations associated with on-going implementation of Information and Communication Technology (ICT) in modern agriculture was conducted.

Highlights:

- Smartphones can be used as decision-support tools in improving mineral fertiliser management;
- Provision of technology is insufficient to ensure its uptake;
- More efforts need to be directed towards incorporation of social dimensions into the design process of current and future IC technologies.

Data access: No new data was generated during production of this work.

Publication: This chapter has been submitted to Current Opinions in Environmental Sustainability (Special Issues) as: *Golicz, K., Hallett, S., Sakrabani, R. (2020). Old problem, the Millennial Solution: Using mobile phone technologies for sustainable fertiliser management.*

2.1 Introduction

Mineral fertilisers (MF's) play an irreplaceable role in ensuring that the growing demand for food is met without jeopardising long-term soil fertility (Douglas, 2003; Oliver and Gregory, 2015). Greenhouse gas emissions associated with fertiliser production and continuous use (Snyder et al., 2009), as well as soil and water pollution resulting from over application and mismanagement of fertiliser (Ju et al., 2007), and soil degradation caused by lack of organic inputs (Stockdale et al., 2006) have all been recognised as posing serious threats to global food security.

Regardless, both developed and developing countries are set to increase their MF demand, predicted to reach 201.66 million tonnes by the end of 2020 (Tittonell et al., 2008; FAO, 2017a). Despite the fact that MF's have been available for over sixty years, their application is often detrimental to crop growth due to a limited access to critical soil and plant information (Yadav et al., 1997) and the resulting low nutrient use efficiency (Zhang et al., 2020). Lack of information, in combination with decreasing farmer participation in soil testing and farm planning (<30% of American and Australian farmers take part in such programmes at recommended frequencies; Lobry de Bruyn and Andrews 2016) give rise to concerns regarding the long-term sustainability of conventional agriculture. Thus, it is essential to enhance the availability and access to tools that allow for better MF management. These include e.g. fertiliser advisory service (Nyi et al., 2017), elementary models of plant-soil processes (Delgado et al., 2008), in-field (Liebig et al., 1996; Aguilera et al., 2014) and off-field (Sims et al., 1995, 2000) soil and plant matter testing.

Mobile technologies offer a wide range of potential ways to contribute to creation of such tools. Smartphones have been repurposed for use in farm management the moment they became affordable, and thus, available to the general public (Duncombe, 2012) and continue to play a compelling role as decision support tools (DSTs) (Pongnumkul et al., 2015; Eichler-Inwood and Dale, 2019). This review aims to investigate the increasing impact of mobile devices on agricultural decision making relating to sustainable use of MF's via phone-mediated soil-plant testing, farm level agronomic extension services, and assessment of economic viability of fertiliser application. It also highlights opportunities and challenges associated with these technologies.

2.1.1 Mobile technology in the era of Smart Agriculture

Starting with a 412MHz CPU and 128MB eDRAM in 2007 and transitioning today into powerful microcomputers with 64-bit multi-core processors supporting 4GB of RAM; and over 250GB of internal memory by 2019, smartphones demand little IT literacy and provide an easy and cost-effective means to access information at will via the Internet. In the early years of mobile technology adoption, the devices available gave rise to productivity-oriented software with weather monitoring, agricultural news, and record keeping, acting as a backbone of ‘mobile Agriculture’, or m-Agriculture (Costopoulou et al., 2016; Dehnen-Schmutz et al., 2016) (**Figure 2.1**).

However, as technology advanced, smartphone apps began to display a higher degree of sophistication and task-specificity to accommodate the growing needs of modern and information-intensive agriculture. From assessing potential Nitrogen losses in the west of the United States (Delgado et al., 2013) to connecting farmers in Ghana (Lomotey et al., 2018), and fine-tuning fertiliser recommendations in Thailand (Intaravanne and Sumriddetchkajorn, 2015), they showed potential at contributing to the development of a new generation of agriculture-oriented information technology architecture, where data is instantly received, recorded and either shared between interested parties or stored in the cloud for ease of recall or use.

Due to their capacity to collect and manage data both quickly and easily, mobile devices enable and promote the concept of smart farming, which builds on the concept of precision agriculture but is not confined solely to accounting for in-field variability. In smart farming, decision making that forms part of agricultural management is based on data, and therefore, becomes enhanced by contextual and situational awareness whilst remaining responsive to events taking place in real-time (Wolfert et al., 2017). This can bring substantial benefits to sustainable and integrated MF management as field-specific and geo-located information and agronomic knowledge become democratised through access to Information and Communication Technology (ICT) brought about by mobile devices.

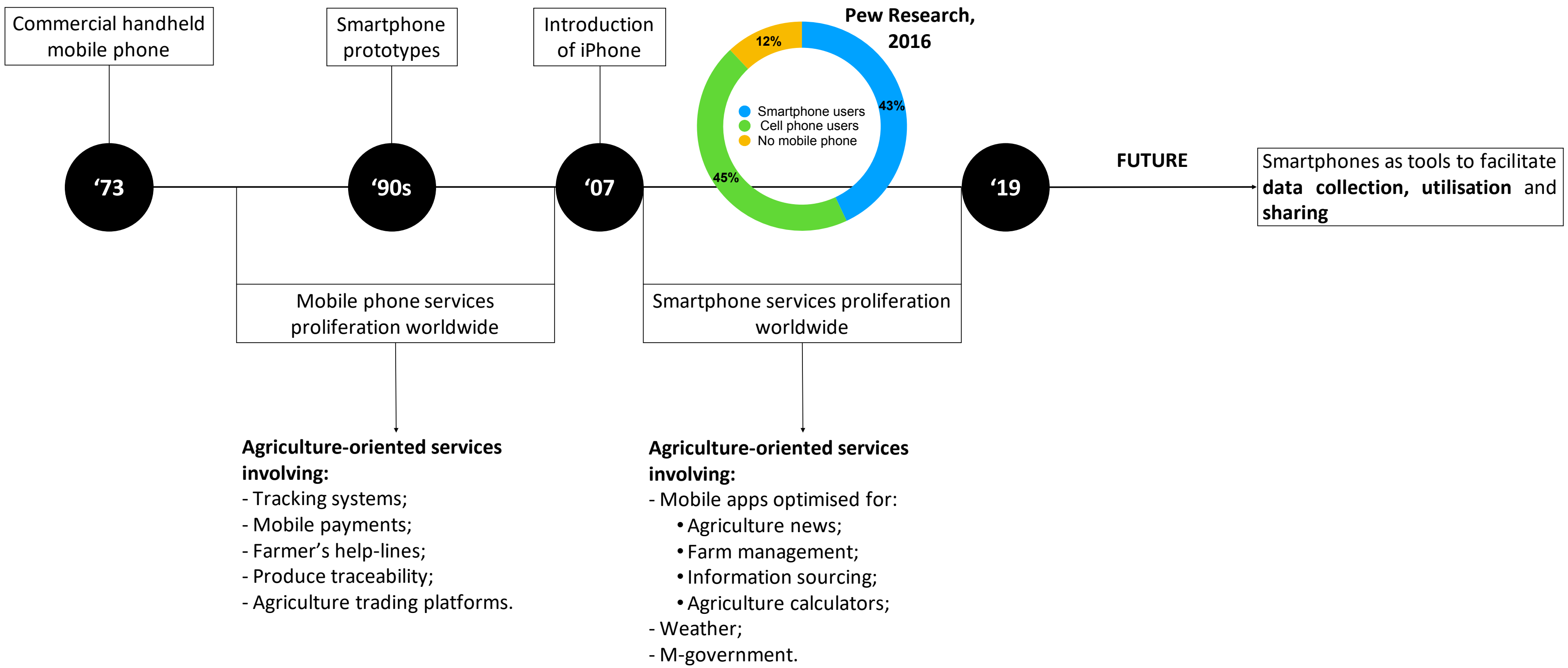


Figure 2-1. Simplified timeline of smartphone development and its application in agricultural services. First commercial devices became available in the 70s. By early 90s, their functionality was recognised by the agricultural sector, which swiftly incorporated new technology into existing business structures. With the arrival of iPhone in 2007, the smartphone 'arms race' commenced. Between 2007 and 2017, a plethora of farming-oriented applications have been developed, capitalising on the fact that 43% of global mobile device users own a smartphone. As smartphones have become more advanced, opportunities for their efficient use in data collection, utilisation and sharing have proliferated.

2.2 Opportunities and challenges for mobile technology innovation, adoption and use

2.2.1 Tools for sustainable mineral fertiliser management: Portable soil and plant analysers

Responsible nutrient management requires frequent (every 3-5 years) soil and plant matter testing (Havlin et al., 2013; Agriculture and Horticulture Development Board, 2017). However, traditional methods of soil-plant analysis are often expensive, time-consuming and labour-intensive (Omran, 2017). Smartphones have been recognised as powerful tools which can be used as portable testing devices in various sub-disciplines of agriculture (Pongnumkul et al., 2015; Kwon and Park, 2017), although there are still only a limited number of complementary apps that can inform farm workers about soil-plant nutrient content in real time.

There was an early attempt to develop a portable colorimetric analyser to determine plant available phosphate (Moonrungsee et al., 2015), whereby a smartphone was affixed onto a device used to capture a set of images of soil extract, which were analysed for RGB values via a custom-made Phosphorus Analysis App (**Figure 2-2**). Images obtained from the smartphone camera were subsequently analysed by the app and showed high correlation (R^2=0.996) with the standard spectrophotometric methods. Concurrently, Campbell et al. (2015) used a smartphone-based green chemistry enzymatic method for assessing soil P assessment in field conditions with similarly promising results (1.5-4.0 percentage error between the methods). More recently, Golicz et al. (2019) re-purposed a water quality testing app, Akvo Caddisfly, to measure soil mineral nitrogen content via the colorimetric test strip method on smallholder suburban farms in South-East China (Golicz et al., 2019; **Chapter 4)**.

Other apps such as BaiKhao - a widely popular app used to assess the level of N and potassium deficiency in rice plants (Intaravanne and Sumriddetchkajorn, 2015), and SmartSPAD, which accurately measured chlorophyll content in maize (Vesali et al., 2015), have been employed, offering an indirect measurement tool to inform farmers about the nutrient content of their soils. BaiKhao reduces errors associated with subjective comparisons of leaves against the standard leaf colour chart (correct leaf colour assignment rate = 93%) providing accurate estimates of N K inputs required during the crop growing season. SmartSPAD estimates the chlorophyll content by contact imaging and was shown to correlate well (R^2= 0.88) with a more expensive Minolta SPAD 502 meter.

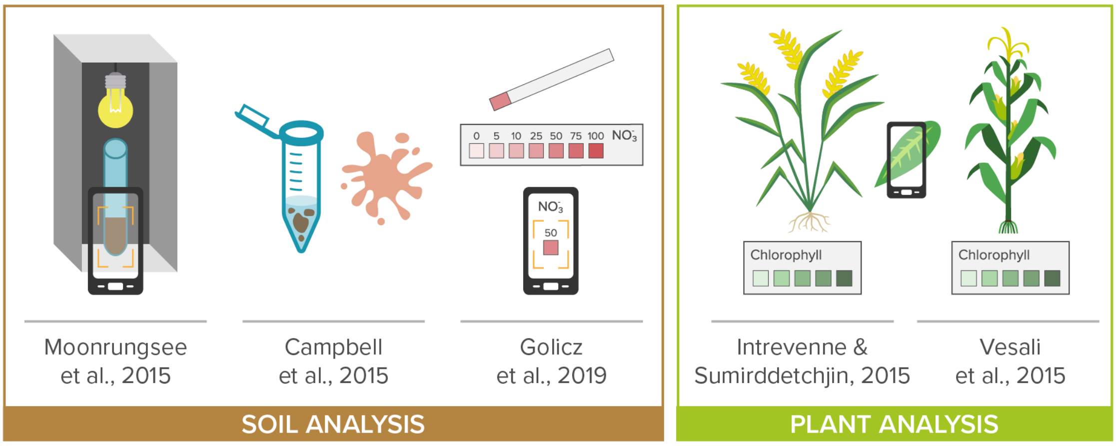


Figure 2-2. Application of smartphones in soil and plant analysis. In recent years, mobile devices have been repurposed to act as low cost alternatives to expensive laboratory tests. This shows great potential for improving fertiliser management, especially on smallholder farms. However, accuracy and precision, as well as accessibility need to improve if smartphones are to become a viable alternative to standard testing.

These apps offer a low-cost alternative for conducting soil and plant analyses, potentially enhancing farmers' capacity to improve MF application across their fields. Provided they are used alongside other sources of agronomic advice, they can contribute to minimising the economic and environmental risks associated with over- and under-fertilisation. However, few have been made fully accessible to the public, they require some form of hardware and/or reagents that are not immediately or widely available, and also lack context (with exception of BaiKhao) as they are not integrated with wider fertiliser recommendations adjusted for singular crops that can be quickly understood and applied in practice by the farmer.

2.2.2 Tools for sustainable mineral fertiliser management: Digital agronomic advisory services

In emerging economies, and especially on the African continent, MF's have been shown to increase crop yields under smallholder farming conditions, provided they were applied at the right quantity and spatial-temporal scale and accompanied by appropriate agronomic practices (Vanlauwe et al., 2014). Unless these conditions are met, investment in on-farm inputs has been shown to bring negligible benefits and to cause disfranchisement resulting from financial difficulties brought about by purchase of expensive MF's (Love et al., 2006). Therefore, both governments and international NGOs have recognised the importance of providing dynamic and location-specific nutrient information to agricultural practitioners (Patil et al., 2016).

Complex agricultural decision support tools such as the International Rice Research Institute's Nutrient Manager for Rice (NMR) have been optimised for use with smartphones and/or tablets (Saito et al., 2015). The application of NMR in the Senegal River Valley was widely successful and shown to increase yields (up to 2.3 t ha^{-1}) and incomes (by US$ 216-640 ha^{-1}) whilst decreasing inputs including water and mineral fertilisers, bringing precision agriculture to smallholder farms in West Africa. However, such apps are directed largely at extension workers and are less likely to be taken up by individual farmers without targeted training. Top-down transfer of knowledge limits the potential of mobile devices to involve multiple end users in responsible nutrient management. In contrast, Lomotey et al. (2018) surveyed Cocoa farmers in Ghana, finding that 78% of the respondents owned a smartphone and that all (100%) interviewees would be interested in using Cocoa farming-oriented apps if they were made available. Information regarding pest control and fertiliser application alongside discussion forums topped the list of desired features (Lomotey et al., 2018). The digital agronomic advisory services developed subsequently was considered 'very helpful' by 72% of end users, paving the way for informed application of on-farm inputs on Cocoa plantations.

This farmer-inclusive digital extension services model is also widely popular in India, where the IFFCO KISAN app has complemented a farmer-to-advisor helpline first implemented by the Indian Farmers Fertiliser Cooperative Limited (IFFCO) in collaboration with Airtel, India's largest mobile network provider (Singh et al., 2016). Both the helpline and the app allow farmers to access location-specific advice regarding best practices for crop cultivation, including MF recommendations. The programme is now being used by over one million farmers across the country and has been deemed successful at disseminating information to agricultural practitioners (Agashe et al., 2019).

Developed countries, which have historically had more access to additional sources of fertiliser advice, e.g. paper or computer-based (Lobry de Bruyn and Andrews, 2016) appear to lag behind developing economies in smartphone app development and uptake. However, regulatory pressures have given rise to interest in applications designed to support sustainable nutrient management planning. The Nitrogen Index is a USDA-approved software package that can assess the risk of nitrogen loss resulting from farm-specific nutrient management practices (Delgado et al., 2013). The software was adapted to smartphones, allowing for data input to be conducted away from the desktop computer thereby, providing a portable and effective tool for N management to farmers across the US.

Considering the high level of interest in utilising mobile technologies for optimal and thusly, sustainable MF use – there is little doubt that more applications will continue to be developed. In the future however, consultation with practitioners should constitute an essential part of the app development process to ensure that these tools respond to the needs of agricultural workers and can be quickly and easily made available to the interested parties. Concerns regarding the ‘black box’ approach to soil management, which ignores farmers’ experience, have been voiced with regards to a variety of decision support tools (Hamilton, 1995; Visser et al., 1998; Lacoste and Powles, 2016; Rose et al., 2016) and should be avoided in the ICT-mediated smart farming approach at all cost.

2.2.3 Tools for sustainable mineral fertiliser management: Cost calculators and fertiliser purchase facilitators

MF’s represent a substantial draw on farmers’ financial resources (Monjardino et al., 2013). A precise calculation of fertiliser needs (adjusted for expected yield and soil-plant test results) relative to their market price and the price fluctuations at the point of purchase constitute essential information for successful farming operations, regardless of their scale. Relying on mobile technology for fertiliser calculations is subsequently likely to be considered less reliable, compared to having advice from agronomists or extension workers, especially since there is no clear governmental architecture that determines who, i.e. the farmer, the software developer or the software distributor, is responsible and accountable for erroneous information provided by mobile apps (Walter et al., 2017).

Governments and NGOs have recognised this concern and are taking an active part in tool development for augmentation of fertiliser calculations. In Canada, the Saskatchewan Soil Conservation Association lists a number of state approved apps, with the Fertiliser Blend app being designed to assist in calculating a liquid and/or dry MF blend that meets crop demand whilst optimising costs (SSCA, 2019). The Government of South Australia publishes updated inventories of farming oriented apps that work on both iOS and Android, including the NPK app (South Australia Government, 2014). Bueno-Delgado et al. (2016) conducted a non-exhaustive review of similar smartphone applications alongside the introduction of the Ecofert app, designed to calculate the best combination of fertilisers whilst taking into account self-updating price of fertilisers made available via a cloud-based service (Bueno-Delgado et al., 2016).

Furthermore, the Centre for Agriculture and Bioscience International (e.g. Fertiliser Optimiser; Centre for Agriculture and Bioscience International 2019) and Food and Agriculture Organization e-Agriculture (e.g. MITRA; FAO 2017b) offer apps that can not only be used in fertiliser calculations but also offer an opportunity to facilitate the process of procuring MF's, which is associated with additional costs in emerging economies (Rware et al., 2016).

These type of apps require meticulous cross-examination to reduce the risk of calculation error, well thought-out architectural designs that account for the challenges likely to be encountered in the agricultural sector, e.g. intermittent Internet access, bandwidth fluctuations, and energy conservation necessary for prolonged in-field use (Lomotey and Deters, 2014) as well as regular post-release updates to remain relevant to the end user. This level of engagement in app development requires a robust and dynamic collaboration between farmers, governmental organizations (potentially requiring a separate regulatory body that could provide certification for verifiable apps), and related MF industry, which is not yet fully capitalised upon.

2.3 Integration of knowledge for sustainable fertiliser management

In the coming years, mobile technologies will become firmly established as a factor in addressing one of main weaknesses of rural markets in developing nations – asymmetric access to useful and relevant information (Qiang et al., 2011). As well as offering opportunities to small scale agriculture in the developed countries, where large-scale competitors have greater resources and access to technological innovations (Walter et al., 2017).

Schemes aimed at improving agricultural productivity whilst enhancing sustainability have frequently failed in recent years. In such cases, a lack of technological solutions was rarely identified as the main barrier to their adoption (Hellin and Lopez Ridaura, 2016). Instead, socio-economic problems arising from linear transfer-of-technology and top-down approaches that did not account for innovative systems and informal peer-to-peer information systems were highlighted (Rodriguez et al., 2009; Hellin and Fisher, 2019) (**Figure 2-3**).

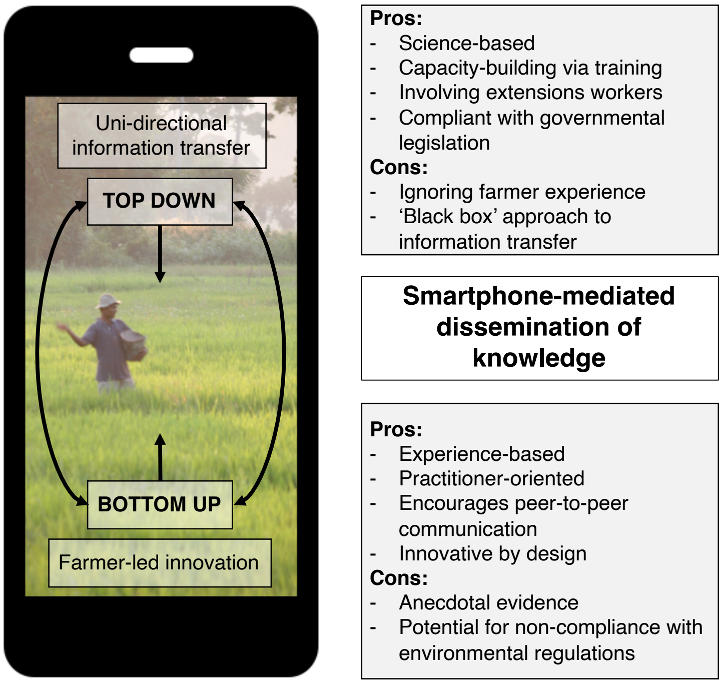


Figure 2-3. Modern technology allows for easier communication between farmers and between farmers and extension workers linking top-down and bottom-up approaches to mineral fertiliser management.

Providing agricultural practitioners with decision support tools to better manage MF's through mobile technologies constitutes a promising tactic but is insufficient in bringing about a significant behavioural change on its own. DSTs, in the form of paper guidance, email/text alerts, computer-based tools and smartphone apps, have been available for a number of years but their uptake has been limited despite of their potential value (Rose et al., 2016).

Provision of information does not equate to its full utilisation and considering the costs involved in the DST development, more research effort must be directed towards identifying what socio-economic factors might impact farmers' uptake of mobile technologies in agriculture. On-the-ground implementation strategies should constitute a significant part of the DST development process and not an afterthought.

Smartphones and smartphone apps repurposed to act as soil-plant analysers, digital agronomic advisories and fertiliser calculators must become more integrated into current farming systems. They need to be considered more trustworthy, quality-controlled and certified to address liability concerns, and emphasise connectivity by facilitating transfer of knowledge and agricultural innovation on a person-to-person basis (facilitated by extension workers), rather than focusing solely on passive information transfer. If those conditions are met, mobile technology will play an irreplaceable role in closing the gap between theoretical knowledge and on-farm MF application across the developed and the developing world.

2.4 References

Agashe R, Verma S, Singh P (2019) Opinion of Farmers Regarding Effectiveness of Information Dissemination through Kisan Suvidha Mobile Application in Surguja District of Chhattisgarh. J Krishi Vigyan 7:270–272. doi: DOI: 10.5958/2349-4433.2019.00051.5

Agriculture and Horticulture Development Board (2017) Nutrient Management Guide (RB209). Warwickshire CV8

Aguilera J, Motavalli P, Gonzales M, Valdivia C (2014) Evaluation of a Rapid Field Test Method for Assessing Nitrogen Status in Potato Plant Tissue in Rural Communities in the Bolivian Andean Highlands. Commun Soil Sci Plant Anal 45:347–361. doi: 10.1080/00103624.2013.857680

Bueno-Delgado M V., Molina-Martínez JM, Correoso-Campillo R, Pavón-Mariño P (2016) Ecofert: An Android application for the optimization of fertiliser cost in fertigation. Comput Electron Agric 121:32–42. doi: 10.1016/j.compag.2015.11.006

Campbell ER, Warsko K, Davidson AM, Campbell WH (2015) Determination of phosphate in soil extracts in the field: A green chemistry enzymatic method. MethodsX 2:211–218. doi: 10.1016/j.mex.2015.04.003

Centre for Agriculture and Bioscience International (2019) Fertiliser Optimizer

Costopoulou C, Ntaliani M, Karetsos S (2016) Studying Mobile Apps for Agriculture. IOSR J Mob Comput Appl 3:2394–42. doi: 10.9790/0050-03064449

Dehnen-Schmutz K, Foster GL, Owen L, Persello S (2016) Exploring the role of smartphone technology for citizen science in agriculture. Agron Sustain Dev 36:. doi: 10.1007/s13593-016-0359-9

Delgado JA, Kowalski K, Tebbe C (2013) The first Nitrogen Index app for mobile devices: Using portable technology for smart agricultural management. Comput Electron Agric 91:121–123. doi: 10.1016/j.compag.2012.12.008

Delgado JA, Shaffer M, Hu C, et al (2008) An index approach to assess nitrogen losses to the environment. Ecol Eng 32:108–120. doi: 10.1016/j.ecoleng.2007.10.006

Douglas C. E. (2003) The long-term effects of manures and fertilisers on soil productivity and quality: a review. Nutr Cycl Agroecosystems 66:165–180

Duncombe R (2012) Mobile Phones, Agricultural and Rural Development: A Literature Review and Future Research Directions. Eur J Dev Res 28:213. doi: https://doi.org/10.1057/ejdr.2014.60

Eichler Inwood SE, Dale VH (2019) State of apps targeting management for sustainability of agricultural landscapes. A review. Agron Sustain Dev 39:. doi: 10.1007/s13593-018-0549-8

FAO (2017a) World fertiliser trends and outlook to 2020 - Summary Report

FAO (2017b) e-Agriculture platform. In: Mob. Interv. Technol. Rural Areas. http://www.fao.org/e-agriculture/news/mitra-mobile-interventions-and-technologies-rural-areas-app-provides-advice-fertiliser-needs. Accessed 8 Nov 2019

Golicz K, Hallett SH, Sakrabani R, Pan G (2019) The potential for using smartphones as portable soil nutrient analyzers on suburban farms in central East China. Sci Rep 9:1–10. doi: 10.1038/s41598-019-52702-8

Hamilton NA (1995) Learning to Learn with Farmers. An adult learning extension project, case study: Queensland, Australia, 1990-1995

Havlin J, Tisdale S, Nelson W, Beaton J (2013) Soil Fertility and Fertilisers An Introduction to Nutrient Management, 8th edn. Pearson Education Dorling Kindersley

Hellin J, Fisher E (2019) The Achilles heel of climate-smart agriculture. Nat Clim Chang 9:. doi: 10.1038/s41558-019-0515-8

Hellin J, Lopez Ridaura S (2016) Soil and water conservation on Central American hillsides: if more technologies is the answer, what is the question? AIMS Agric Food 1:194–207. doi: 10.3934/agrfood.2016.2.194

Intaravanne Y, Sumriddetchkajorn S (2015) Android-based rice leaf colour analyzer for estimating the needed amount of nitrogen fertiliser. Comput Electron Agric 116:228–233. doi: 10.1016/j.compag.2015.07.005

Ju XT, Kou CL, Christie P, et al (2007) Changes in the soil environment from excessive application of fertilisers and manures to two contrasting intensive cropping systems on the North China Plain. Environ Pollut 145:497–506. doi: 10.1016/j.envpol.2006.04.017

Kwon O, Park T (2017) Applications of Smartphone Cameras in Agriculture, Environment, and Food: A review. J Biosyst Eng 42:330–338. doi: 10.5307/JBE.2017.42.4.330

Lacoste M, Powles S (2016) Beyond modelling: Considering user-centred and post-development aspects to ensure the success of a decision support system. Comput Electron Agric 121:260–268. doi: 10.1016/j.compag.2016.01.003

Liebig MA, Doran JW, Gardner JC (1996) Evaluation of a field test kit for measuring selected soil quality indicators. Agron J 88:683–686

Lobry de Bruyn L, Andrews S (2016) Are Australian and United States Farmers Using Soil Information for Soil Health Management? Sustainability 8:304. doi: https://doi.org/10.3390/su8040304

Lomotey R, Deters R (2014) Exploring Different Architectures to Support Crop Farmers with a Mobile Application on Pesticide Control. Int J Cloud Comput Serv Sci 3:122–132. doi: http://dx.doi.org/10.11591/closer.v3i3.6286

Lomotey RK, Mammay A, Orji R (2018) Mobile technology for smart agriculture: Deployment case for cocoa production. Int J Sustain Agric Manag Informatics 4:83–97. doi: 10.1504/IJSAMI.2018.094810

Love D, Twomlow S, Mupangwa W, et al (2006) Implementing the millennium development food security goals - Challenges of the southern African context. Phys Chem Earth 31:731–737. doi: 10.1016/j.pce.2006.08.002

Monjardino M, McBeath TM, Brennan L, Llewellyn RS (2013) Are farmers in low-rainfall cropping regions under-fertilising with nitrogen? A risk analysis. Agric Syst 116:37–51. doi: 10.1016/j.agsy.2012.12.007

Moonrungsee N, Pencharee S, Jakmunee J (2015) Colorimetric analyzer based on mobile phone camera for determination of available phosphorus in soil. Talanta 136:204–209. doi: 10.1016/j.talanta.2015.01.024

Nyi T, Varughese P, bin Hj Bujang MI, et al (2017) ASEAN Guidelines on Soil and Nutrient Management. Bangkok

Oliver MA, Gregory PJ (2015) Soil, food security and human health: A review. Eur J Soil Sci 66:257–276. doi: 10.1111/ejss.12216

Omran E-SE (2017) Will the Conventional Soil-Plant Analysis Pass into Oblivion? Rapid and Low-Cost Determination Using Spectroscopy. Commun Soil Sci Plant Anal 48:705–715. doi: 10.1080/00103624.2017.1298782

Patil MD, Anantha KH, Wani SP (2016) Digital technologies for agricultural extension. In: Raju KV, Wani SP (eds) Harnessing Dividends from Drylands: Innovative Scaling up with Soil Nutrients, 1st edn. CABI Publishing, Boston, pp 99–116

Pongnumkul S, Chaovalit P, Surasvadi N (2015) Applications of Smartphone-Based Sensors in Agriculture: A Systematic Review of Research. J Sensors 2015:. doi: 10.1155/2015/195308

Qiang Z, Kuek S, Dymond A, Esselaar S (2011) Mobile Applications for Agriculture and Rural Development. World Bank, ICT Sect Unit 1–120

Rodriguez JM, Molnar JJ, Fazio RA, et al (2009) Barriers to adoption of sustainable agriculture practices: Change agent perspectives. Renew Agric Food Syst 24:60–71. doi: 10.1017/S1742170508002421

Rose DC, Sutherland WJ, Parker C, et al (2016) Decision support tools for agriculture: Towards effective design and delivery. Agric Syst 149:165–174. doi: 10.1016/j.agsy.2016.09.009

Rware H, Kayuki C, Macharia M, Oduor G (2016) Fertiliser use optimization approach: An innovation to increase agricultural profitability for African farmers. African J Agric Res 11:3587–3597. doi: 10.5897/ajar2016.11408

Saito K, Diack S, Dieng I, N'Diaye MK (2015) On-farm testing of a nutrient management decision-support tool for rice in the Senegal River valley. Comput Electron Agric 116:36–44. doi: 10.1016/j.compag.2015.06.008

Schmidt-Traub G, Obersteiner M, Mosnier A (2019) Fix the broken food system in three steps. Nature 569:181–183. doi: 10.1038/d41586-019-01420-2

Sims JT, Edwards AC, Schoumans OF, Simard RR (2000) Integrating Soil Phosphorus Testing into Environmentally Based Agricultural Management Practices. J Environ Qual 29:60–71. doi: 10.2134/jeq2000.00472425002900010008x

Sims JT, Vasilas BL, Gartley KL, et al (1995) Evaluation of Soil and Plant Nitrogen Tests for Maize on Manured Soils of the Atlantic Coastal Plain. Agron J 87:213–222. doi: 10.2134/agronj1995.00021962008700020013x

Singh AK, Sohane RK, Aditya (2016) Leveraging mobile-based technologies for sustainable agricultural development in India. Indian J Fertil 12:164–169

Snyder CS, Bruulsema TW, Jensen TL, Fixen PE (2009) Review of greenhouse gas emissions from crop production systems and fertiliser management effects. Agric Ecosyst Environ 133:247–266. doi: 10.1016/j.agee.2009.04.021

South Australia Government (2014) Smartphone apps for smart farmers. https://data.environment.sa.gov.au/Content/Publications/Smartphone-Apps-for-Smart-Farmers-Android-edition1.pdf. Accessed 7 Nov 2019

SSCA (2019) SSCA Fertiliser Blend Calculator. https://ssca.ca/component/content/article/28-last-added-projects/71-ssca-fertiliser-blend-calculator. Accessed 7 Nov 2019

Stockdale EA, Shepherd MA, Fortune S, Cuttle SP (2006) Soil fertility in organic farming systems - fundamentally different? Soil Use Manag 18:301–308. doi: 10.1111/j.1475-2743.2002.tb00272.x

Tittonell P, Vanlauwe B, Corbeels M, Giller KE (2008) Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant Soil 313:19–37. doi: 10.1007/s11104-008-9676-3

Vanlauwe B, Wendt J, Giller KE, et al (2014) A fourth principle is required to define Conservation Agriculture in sub-Saharan Africa: The appropriate use of fertiliser to enhance crop productivity. F Crop Res 155:10–13. doi: 10.1016/j.fcr.2013.10.002

Vesali F, Omid M, Kaleita A, Mobli H (2015) Development of an android app to estimate chlorophyll content of corn leaves based on contact imaging. Comput Electron Agric. doi: 10.1016/j.compag.2015.06.012

Visser I, Cawley S, Röling N (1998) A co-learning approach to extension: Soil nitrogen workshops in Queensland, Australia. J Agric Educ Ext 5:179–191. doi: 10.1080/13892249885300301

Walter A, Finger R, Huber R, Buchmann N (2017) Opinion: Smart farming is key to developing sustainable agriculture. Proc Natl Acad Sci 114:6148–6150. doi: 10.1073/pnas.1707462114

Wolfert S, Ge L, Verdouw C, Bogaardt M (2017) Big Data in Smart Farming – A review. Agric Syst 153:69–80. doi: 10.1016/j.agsy.2017.01.023

Yadav SN, Peterson W, Easter KW (1997) Do farmers overuse nitrogen fertilizer to the detriment of the environment? Environmental & Resource Economics 9:323–340. https://doi.org/10.1007/BF02441403

Chapter 3: Adapting smartphone app used in water testing, for soil nutrient analysis

Summary: This chapter describes methodology developed to extract and analyse soil samples with paper strips and Akvo Caddisfly. The performance of Akvo Caddisfly app and test strips designated for soil nitrate and phosphate analysis is investigated. The need for development of correction equations is highlighted alongside comparisons between different smartphone models and a commercial-grade test strip reader. This research formed the basis for Chapters 3-5 and the laboratory works undertaken provided metadata for test kit development evaluation process described in Chapter 6.

Highlights:

- Smartphone-mediated soil analysis suffers from two types of limitations, i.e. those relating to paper strips and those relating to the smartphone app (Akvo Caddisfly);
- Paper strips designated for phosphate analysis are ill-suited for use with soil media;
- Test strips designed for soil nitrate-N analysis are less accurate at higher concentrations of NO_3^-;
- Akvo Caddisfly necessitates inclusion of a calibration equation prior to application in soil nitrate-N analysis;
- Akvo Caddisfly does not fully account for inter-phone differences in colour detection and therefore, it cannot fully replace commercial-grade strip readers;
- Regardless of method limitations; it is possible to employ Akvo Caddisfly as a screening tool for soil N analysis, but it must not be treated as a replacement for standard laboratory tests.

Data access: Data underlying this study is accessible through Cranfield University's repository at 10.17862/cranfield.rd.9328814.

Published as: Golicz K, Hallett S, Sakrabani R, Ghosh J (2020) Adapting smartphone app used in water testing, for soil nutrient analysis. Comput Electron Agric 175:105532. doi: 10.1016/j.compag.2020.105532

3.1 Introduction

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

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. Although, 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 during the period when crops are sown, which can be used to establish the quantity of nutrients immediately available to crops and the mineralisation potential over the growing-season (Myers, 1984). Attempts have been made to address the shortcomings of laboratory methods by developing rapid, in-field 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 autoanalyzer hydrazine reduction method. The results highly correlated, having an R^2 of 0.97 for steam distillation and an R^2 of 0.96 for the autoanalyzer. 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 (approximately 5 minutes) on nitrate extraction was also noted (Schmidhalter, 2005). Similar studies (Sims et al., 1995; Hartz et al., 2000; Aguilera et al., 2014) employed battery-operated, hand-held instruments, i.e. Nitracheck and Cardy Meter, that were initially optimised for nitrate analysis of plant sap, but were adapted for soil analysis to minimise human error associated with visual colorimetric analysis. They recognised soil colloids and colouring as factors which might negatively impact colour 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 successfully employed in a number of industrialised countries around the world (Nyi et al., 2017). The advantages of quick on-farm, in-field soil tests have already been widely recognised, although 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. The application of smartphones as colour readers has already been explored in agriculture (Intaravanne and Sumriddetchkajorn, 2015; Vesali et al., 2015; Han et al., 2016) 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 optimised 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 Indonesia as a location was to assess the feasibility of this approach in assisting smallholder horticultural farmers in planning nutrient management.

3.2 Methodology

3.2.1 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 at Cranfield University. A set of 1000mg L^{-1} stock solutions were prepared for nitrate using 6.068g of oven-dry $NaNO_3$ (Sigma-Aldrich, CAS number: 7631-99-4) diluted to 1000mL and 1mL of 1000μg mL^{-1} of P (Fisher Scientific, Catalogue number: J829805) diluted to 1000mL. 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 reaction taking place on the reactive pad. The experiment was carried out in a temperature- and humidity-controlled plant growth chamber at Cranfield University. The humidity was set at 70% and the investigated temperatures were: 15, 20, 25, 30, 35°C. Nitrate and phosphate standards were freshly prepared on the day of analysis and allowed to reach room temperature. Solution temperature was measured with a laboratory approved thermometer to confirm it matched the ambient temperature of the plant-growth chamber. Five strips were subsequently used for measurement of each standard solution for nitrate and phosphate at each temperature setting.

3.2.2 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, UK, to undergo soil nutrient testing with smartphone-mediated soil analysis. Soil analysis conducted at Cranfield University was concerned with measuring 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. Utilisation 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 summarised in **Table 3-1**.

Table 3-1. Soil characteristics of 56 soil samples used for calibration of Akvo Caddisfly.

	NO_3-N (in mg kg^{-1})	PO_4-P (in mg kg^{-1})	K (in mg kg^{-1})	OM (in %)	pH (-)
Min	0.0	0.2	20.2	0.8	4.9
Max	216.1	75.6	660.6	19.7	8.3
Average	33.7	11.8	159.7	6.8	6.5
Lithology	Alluvium (recent volcanic), Limestone, Basalt				

3.2.3 Soil analytical methods

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

3.2.4 Soil smartphone-mediated analysis

Nitrate analysis

Soil pre-treatment matched the preparation of soil samples prior to the standard laboratory method. Fifty millilitres of distilled water was used to extract 10g of field-moist and air-dried soil for available nitrate-N measurement. Distilled water was used as an extractant because it does not interfere with the colour development of the reactive pad of the test strip as opposed to concentrated extractants such as 2M KCl, 0.2MKCl or M1. The investigation of test strip; soil extractant interferences are described in Golicz et al. (2020) (**Chapter 6**: **Figure 6-2**). The samples were placed on a mechanical side-to-side shaker for 5 minutes. A smartphone-mediated soil test is expected to be a field method, therefore the time on the shaker was limited to 5 minutes as it was considered representative of the time and effort likely to be exerted in field conditions. The extractant-soil solution was transferred from 250mL polypropylene bottle into a 50mL bottle through a funnel with Whatman V4 filter paper. Filtering was considered to be completed when 75% of the bottle was filled with liquid. The Quantofix (reference number: 913 51) nitrate strips (range: 0 - 100mg L^{-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 60s for the colour to develop.

Three phone 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 installed and running before the strip was submerged in the filtrate. Each phone was placed on an 18cm tripod with the colour correction card, which accompanies the Akvo Caddisfly app (**Figure 3-1**), fitted directly underneath the camera lens. The strip was removed from the solution and placed on the black area of the colour correction card with the colour pad facing upwards and directed towards the left side of the colour correction card. The strip-specific option was selected within the app and a picture of the strip was taken after 60s.

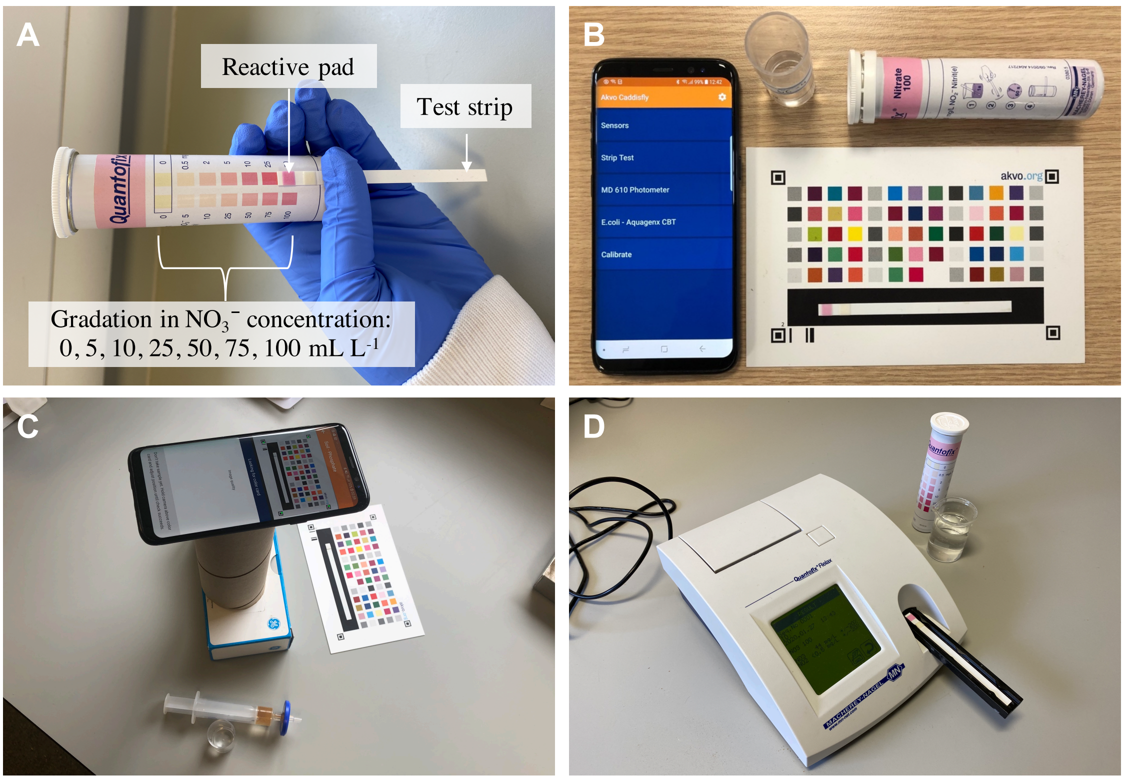


Figure 3-1. Semi-quantitative paper test strips and two types of reflectometers, i.e. devices that quantify colour. Discerning colours of the reactive pad raises issues in terms on inter-rater agreement and replicability due to gradation range and the semi-quantitative nature of test strips (A). Akvo Caddisfly set-up during the laboratory works (B), the app together with the calibration card and nitrate-

sensitive test strip (C), and 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. 18cm), within 10cm of each other. The main source of natural light was provided by the window facing the workstation.

Phosphate analysis

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 3-2**) was placed into a 250mL polypropylene bottle.

Table 3-2. 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	Description	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

Fifty milliliters of freshly prepared Mehlich-1 solution (0.05N HCl and 0.025N 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 colour 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 minutes. The extractant-soil solution was transferred from 250mL polypropylene bottle into a 50mL bottle through a funnel with Whatman 4V filter paper. The Quantofix (reference number: 913 20) phosphate strips (range: 0 - 100mg L^{-1} of PO_4^{3-}) were used for available soil P analysis. Test strip analysis followed the manufacturer's instructions, which involved (1) taking 5mL 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 (provided by the manufacturer), (3) dipping the strip for 15 seconds 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 seconds, and (5) placing the strip on top of the colour correction card and waiting for 60 seconds for the colour to develop before taking an image of the reactive section of the strip with Akvo Caddisfly. Akvo Caddisfly has embedded within it both reference colour and the reaction time corresponding to different strip types. The results were recorded and compared statistically (**Figure 3-2**).

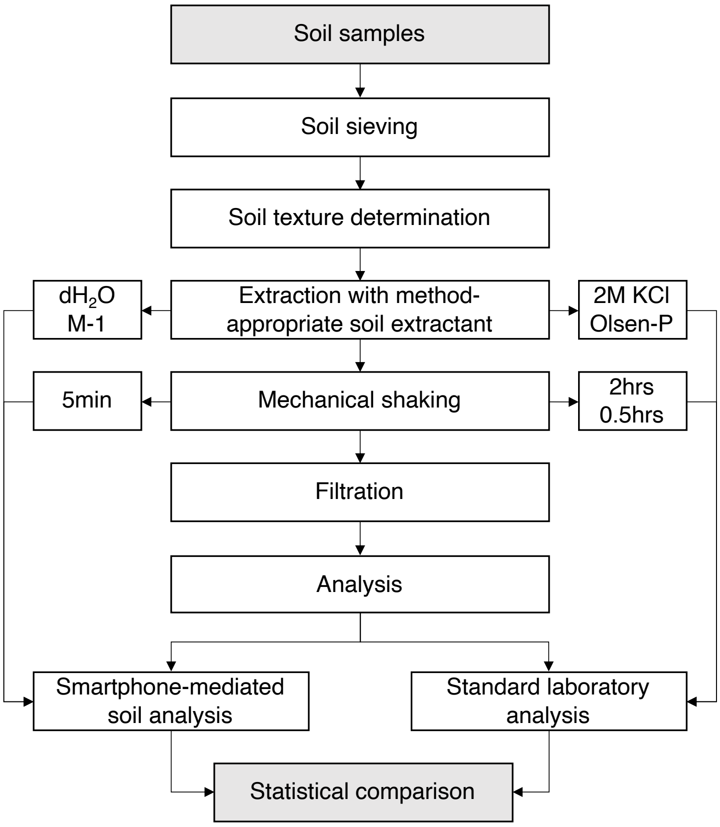


Figure 3-2. Summary of the methods. Soil pre-treatment involved soil sieving and air-drying. Smartphone-mediated soil analysis was carried out via Akvo Caddisfly app (beta ver. 10) installed on three smartphone models, i.e. OnePlus 3 (OP3), Samsung Galaxy S8 (S8) and Samsung Galaxy Tab 2 (SGT2). The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

3.2.5 Calibration equations and statistical analysis

Akvo Caddisfly was not calibrated in a way that allowed direct comparison with the standard colorimetric method unlike results obtained with the Quantofix Relax reflectometer meaning that a set of 56 samples was used to develop a calibration equation which was derived from a linear regression recorded for the standard colorimetric method vs. Akvo Caddisfly results obtained with a Galaxy S8 mobile phone (**Figure 3-3**). The calibration was carried out 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 (**Appendix A**). An attempt at developing a calibration equation for phosphate analysis showed the test strips to be prone to multiple chemical interferences, particularly in sandy soils.

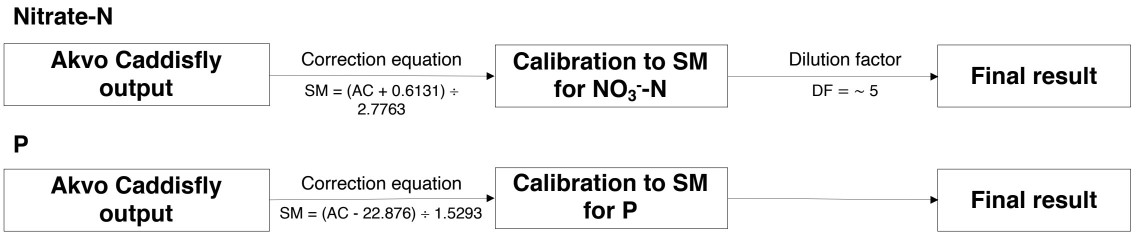


Figure 3-3.Transformation follows the standard regression equation where SM – standard method and AC – Akvo Caddisfly. The results require a multiplication by a dilution factor of 5 for the extractable nitrate-N test.

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. The B-A analysis involved constructing a scatter plot, in which the difference between the paired measurements was plotted on the y-axis, and the mean of the measurements 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 $\pm$ 1.96 SD). Analysis were carried out in R Studio (ver. 1.1.447) and the blandr package (ver. 0.5.1).

3.3 Results

3.3.1 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 (**Figure 3-4A**) and phosphate (**Figure 3-4B**). The readings obtained with the Quantofix Relax were found to be close to 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 (<50mL L^{-1}), in contrast to the trend noted for the smartphone-mediated soil analysis.

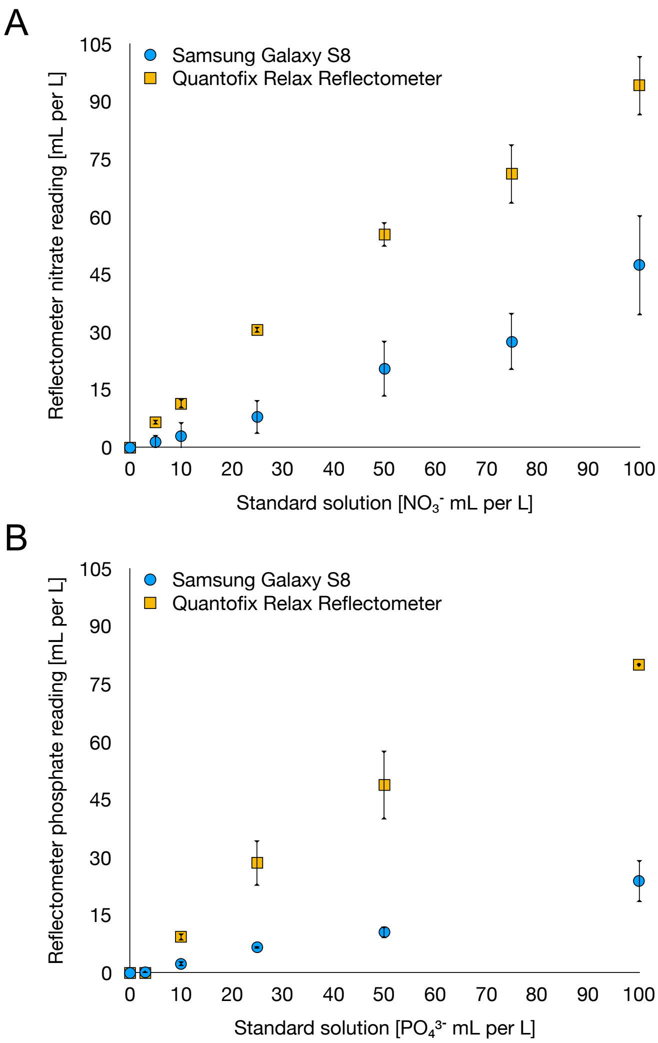


Figure 3-4. Concentration of standard stock solutions (mean ± SD) for nitrate (A) and phosphate (B) as measured with Quantofix Relax reflectometer (□) and Samsung Galaxy S8 with Akvo Caddisfly (o).

The relative standard error (RSE) between readings (N=5) was 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 RSE's recorded for readings obtained via the commercial reflectometer constituted between 4.6% to 14.6% (from 0.5 to 13mL L^{-1}; range: 5 to 100mL L^{-1}) of the estimated value for NO_3^- and 4.3% to 9.2% (0 to 9mL L^{-1}; range; from 3 to 80mL L^{-1}) for PO_4^{3-}. The uncertainty associated with readings obtained by Akvo Caddisfly with the Samsung Galaxy S8 constituted between 4.6% to 17.5% (from 0.5 to 7.7mL L^{-1}) of the estimated values for nitrate and 2.3% to 21.2% (0.1 to 5.5mL L^{-1}) for phosphate.

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

3.3.2 Agreement with standard laboratory methods

Nitrate analysis

The results obtained via Quantofix Relax and nitrate sensitive test strips showed a strong 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 overestimation of nitrate-N concentration when soil moisture content was > 60% (**Figure 3-5A-B**).

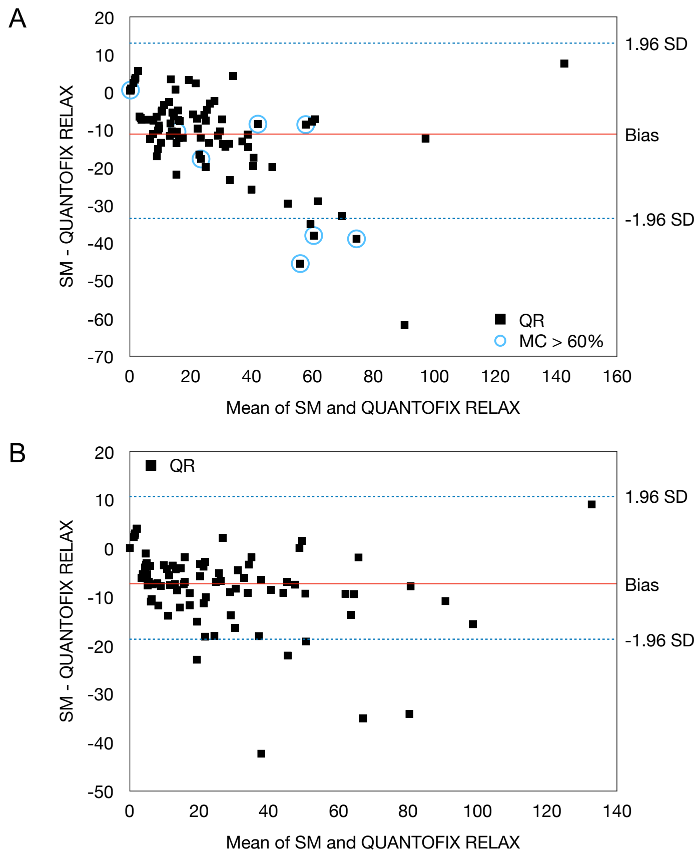
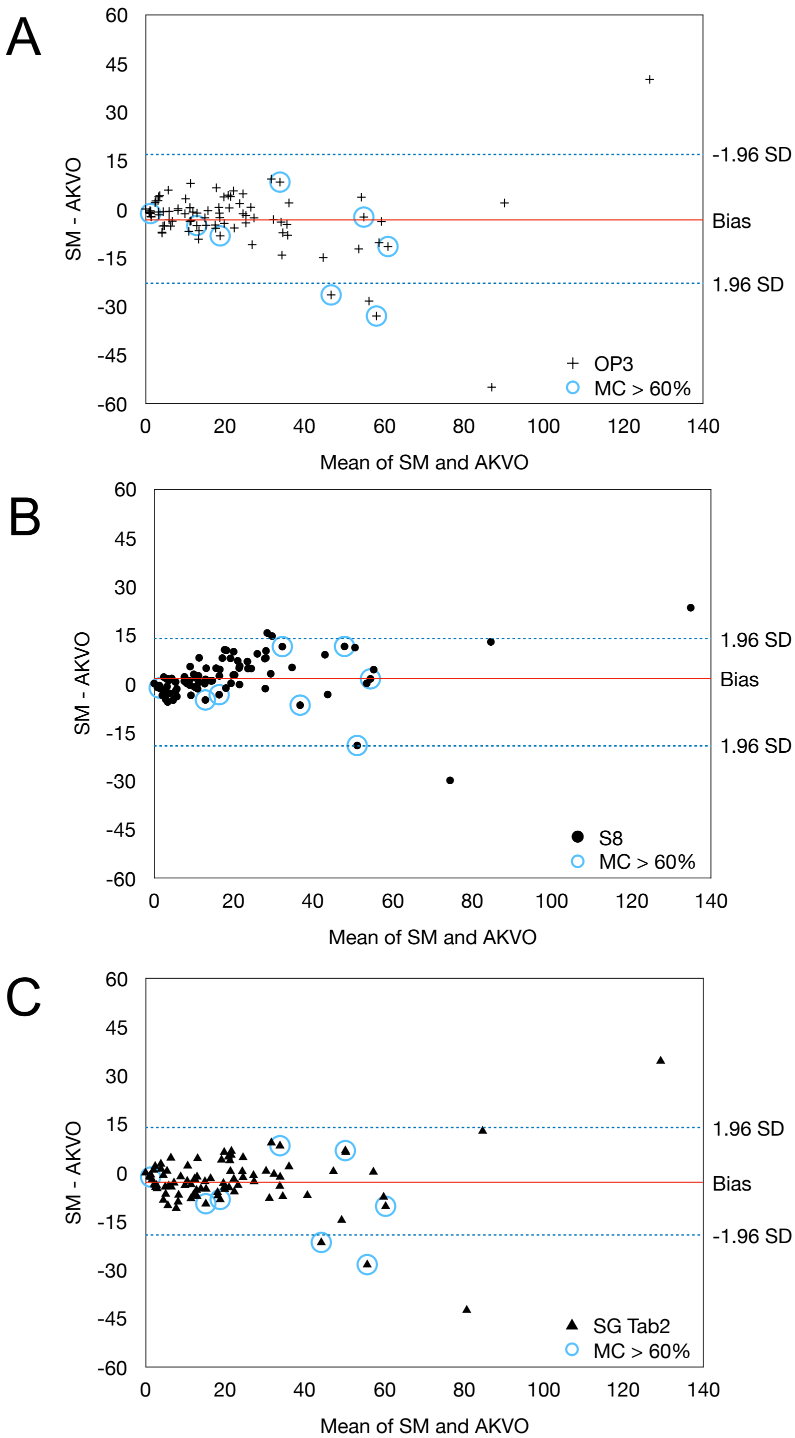


Figure 3-5A-B. Plots of the paired differences for the automatic colorimetric method and Quantofix Relax (QR) for nitrate-N determination of field-moist (A) and air-dried (B) soil samples (N=92). Blue circles represent samples with moisture content (MC) > 60%. The dashed lines represent the error tolerances defined as ± 1.96 SD.

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 to 3.25) for dry soil samples analysed with autoanalyzer using the cadmium reduction colorimetric method. 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 ± 10mg kg^{-1} 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 ± 10mg kg^{-1} of the standard method (**Figure 3-6AF**; see **Appendix A**; **Table 8-2** for detailed breakdown of Bland-Altman analysis).



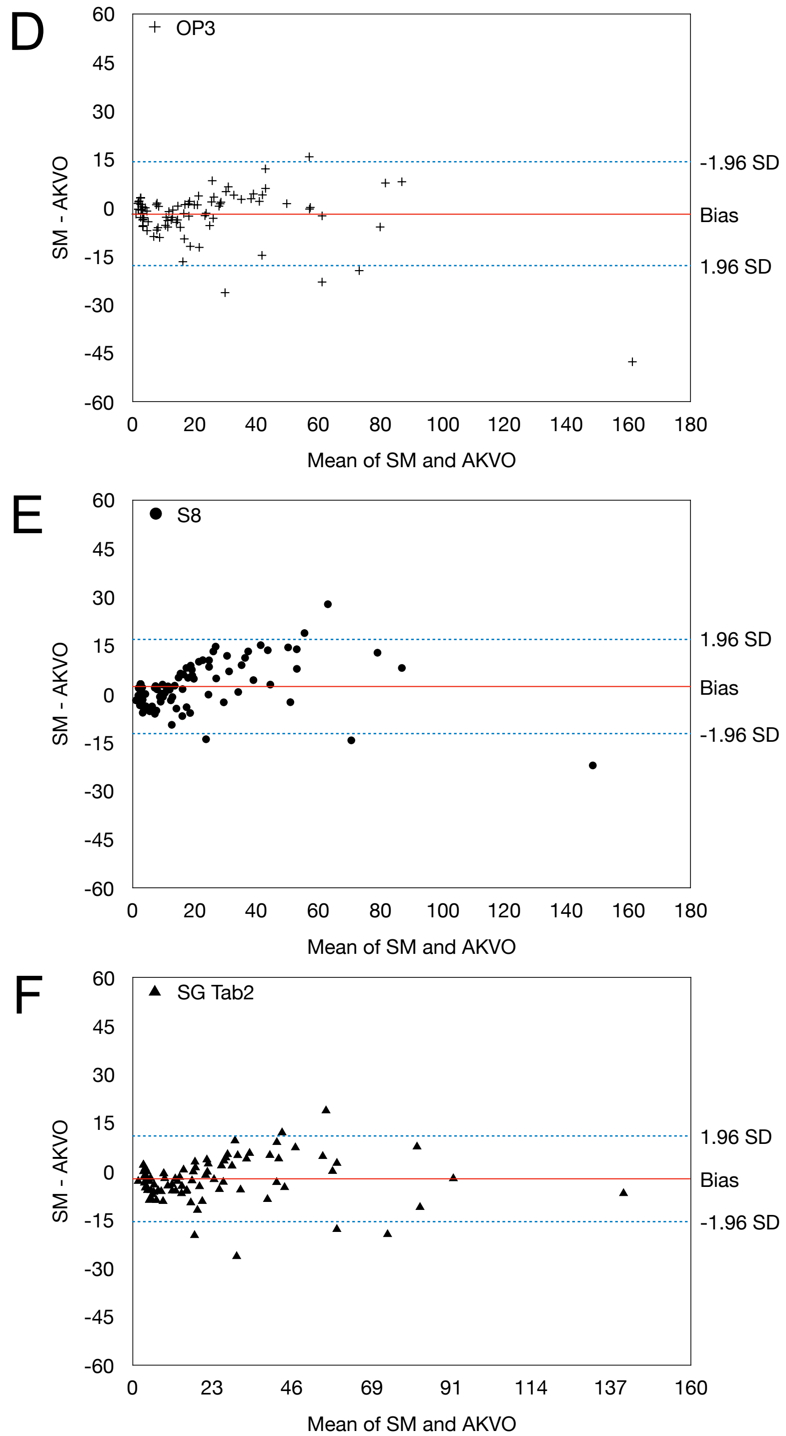


Figure 3-6A-F. Plots of the paired differences for the automatic colorimetric method; and Akvo Caddisfly installed on OnePlus 3 (A, D), Samsung Galaxy S8 (B, E), Samsung Galaxy Tab 2 (C, F) for nitrate-N determination of field-moist (A-C) and air-dried (D-F) soil samples. The dashed lines represent the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

Phosphate analysis

Olsen-P concentration of the samples investigated ranged from 0 to 64.2mg kg^{-1}. During smartphone-mediated soil testing, prevalent chemical interferences to colour development of the test strip pad were noted. Chemical interferences were exhibited either through no colour change (the reactive pad remined pearly white) or intense turquoise colour 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 2g. These outliers could not be easily discerned by the naked eye until after the comparison with standard method was conducted and as a result, test strip technology was considered inadequate for soil testing purposes.

3.3.3 Inter-smartphone variability

The differences in readings were not evenly distributed for S8 vs OP3 and SGT2, and they increased with concentration (**Figure 3-7A, 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 to 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.

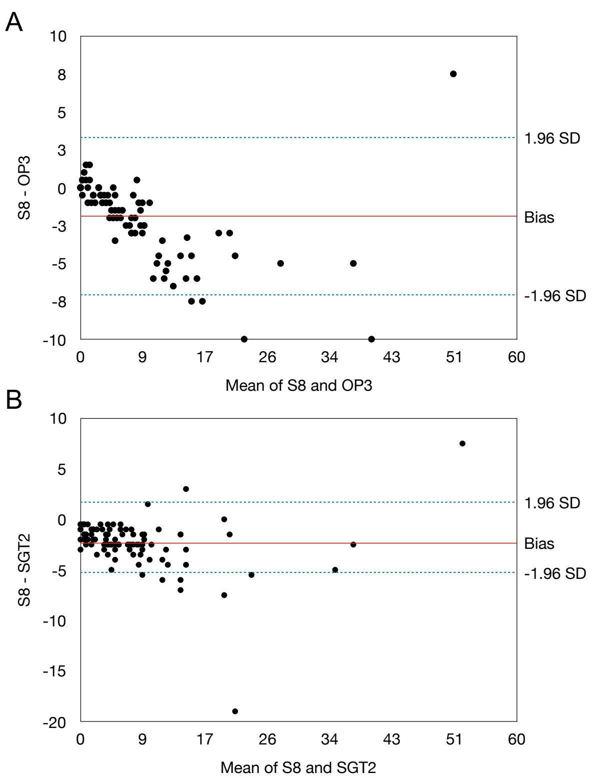


Figure 3-7A-B. Plots of the paired differences of the reference measurement, i.e. Samsung Galaxy S8 output, minus outputs for (A) mid-range smartphone One Plus 3, and (B) low-range device Samsung Galaxy Tab 2. The dashed lines represent the error tolerances.

The inter-smartphone variability in readings for phosphate was approximately three times higher than that for nitrate, reaching up to 20mg kg^{-1} for the selected electronic devices (**Table 3-3**). Similarly, for nitrate readings, the Samsung devices showed a higher degree of agreement between each other (mean bias: -0.41) than with OP3 (mean bias: -4.20 vs -3.23 for S8 and SGT2, respectively).

Table 3-3. 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 to Samsung Galaxy S8.

Nutrient	Parameter	N	Estimate	95% CI	SE
NO_3-N	**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-}-P	**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	

3.3.4 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: 15cm) and compared against fertiliser recommendations for three vegetables frequently grown in Indonesia, i.e. mung bean (*Vigna radiata*), tomato (*Solanum lycopersicum*) and mustard green (*Brassica juncea*). Smartphone-mediated soil test was shown to be a useful tool in discerning when addition of fertiliser is unnecessary with the accuracy of 93% (**Table 3-4**). The differences in fertiliser recommendations derived from results provided by the standard method and smartphone-mediated method ranged from 2.8kg ha^{-1} to -46.8kg ha^{-1} with recommendations becoming less accurate at higher soil nitrate-N concentration.

Table 3-4. Ten randomly selected test results were scaled up to kg per and compared against fertiliser recommendations for mung bean, tomato and mustard green. Fertiliser recommendations based on FAO, 2005. Shaded cells indicate soils where Nitrate-N quantity is sufficient for crop growth.

Nitrate-N in kg ha^{-1}								
			Mung bean		Tomato		Mustard green	
			Fertiliser need*		Fertiliser need**		Fertiliser need***	
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

*30kg of N fertiliser – Test value; **120kg of N fertiliser – Test value; ***110kg of N fertiliser – Test value

3.4 Discussion

3.4.1 Comparison between a commercial grade reflectometer and a smartphone-based reflectometer

There was found to be a difference in magnitude between readings obtained with Quantofix Relax and Akvo Caddisfly, with the readings obtained with Akvo Caddisfly being approximately three times lower than the readings obtained with Quantofix Relax. It is hypothesised 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 **Appendix A** for detailed breakdown of temperature effect on test strip readings). The incorporation of the calibration curve into the application constitutes a benefit as it decreases the reliance on standard stock solutions that were shown to be too expensive and difficult to procure in rural settings in a 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 100mL L^{-1} of NO_3^-; Akvo Caddisfly reads 42.5 ± 7.7mL, at room temperature equal to 20.5°C. Theoretically, the app can measure up to 200mL L^{-1} of NO_3^-, however, the test strips were optimised 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.

3.4.2 Agreement with standard methods

Mobile devices in conjunction with test strips, as analysed with 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 ± 16.7mg kg^{-1} for Samsung Galaxy S8, and 20.0 and 16.5mg 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 ± 16.2mg kg^{-1} (OP3), ± 16.7mg kg^{-1} (S8) and ± 13.3mg kg^{-1} (SGT2). These differences were higher than the difference expected between subsamples measured with the same segmented autoanalyzer during a single run of the equipment that might range from −3.8 to 10.4mg kg^{-1}, or −11.7 to 31.2 kg ha^{-1} (Golicz et al., 2019**, Chapter 4: Figure 4-5**), however, they were consistent with results reported by other test strip studies (Golicz et al., 2020; **Chapter 6: Table 6-3**). 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.

Limited success in phosphorus determination with Akvo Caddisfly was due to (1) test strips being subject to colour interferences, and (2) difficulties with P extraction caused by weak extractant and limited extraction time. Interferences to colour 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, and 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 colour development of the test strip's reactive pad and have to be avoided (Golicz et al., 2020**; Chapter 6: Figure 6-2**). 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 with test strips to the existing standard analytical methods.

Smartphone and test strip-mediated soil test is not proposed as replacement for accepted soil testing methods. The tool is optimised 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 fertiliser recommendations are the only option available to smallholder farmers (Rware et al., 2016), even limited soil nutrient information can be helpful in development of prescriptive and corrective strategies to address the crop fertiliser N needs whilst minimising the risk of overfertilisation. Colorimetric methods are already being employed in developing countries in soil analysis (Nyi et al., 2017) and increasingly in plant analysis (Singh et al., 2011; Swarbreck et al., 2019) and the use of smartphones instead of commercial test strip readers greatly reduces the costs of testing whilst reducing the potential for human error in colour 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 could also be able to provide extension advice contingent on the results, combining a testing function with a decision support capability and that it might be combined with other available smartphone-mediated tools developed to improve fertiliser management, e.g. BaiKhao (Intaravanne and Sumriddetchkajorn, 2015).

3.4.3 The effects of smartphones' camera quality on the test results

Colour perception was shown to differ between smartphone models, which has a major impact on the overall 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. Developing correction equations for multiple devices is impractical due to the extensive range of smartphone models available on the market as well as time and resource intensiveness and the associated costs it would involve. This issue can be addressed by calibrating each phone separately prior to the analysis. This approach has been successfully trialled by Yetisen et al. (2014) where no significant difference was noted between the results obtained with an iPhone 5 (with an inbuilt 8Mega Pixel camera) and a Samsung I5500 Galaxy 5 with (with a 2MP camera).

The difference in colour perception between devices was particularly pronounced during available soil P testing. In additive colour models, which are employed in smartphones' and tablets' 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.

3.4.4 Implications for future practice

The maximum difference of ± 16.7mg kg^{-1} 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. Fertiliser recommendations require scaling up of the results to the field level, i.e. from mg kg^{-1} to kg ha^{-1}. Thus, the larger the field, the more pronounced the deviation between results obtained with 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 colour detection algorithm that would reduce or eliminate differences in colour 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 with test strips might not be equivalent to results of soil analyses employed in other parts of the world. In situations, where fertiliser 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 fertiliser application advisory uses laboratory-derived extractable nitrate-N results, however, the preferred fertiliser advisory for tropical countries proposed by the Food and Agriculture Organization (Roy et al., 2007) uses 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.

3.5 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, particularly 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 colour 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 capitalised upon in the future.

3.6 References

Adesanwo OO, Ige D V, Thibault L, et al (2013) Comparison of Colorimetric and ICP Methods of Phosphorus Determination in Soil Extracts. Commun Soil Sci Plant Anal 44:3061–3075. doi: 10.1080/00103624.2013.832771

Aguilera J, Motavalli P, Gonzales M, Valdivia C (2014) Evaluation of a Rapid Field Test Method for Assessing Nitrogen Status in Potato Plant Tissue in Rural Communities in the Bolivian Andean Highlands. Commun Soil Sci Plant Anal 45:347–361. doi: 10.1080/00103624.2013.857680

Coelli TJ, Rao DSP (2005) Total factor productivity growth in agriculture: A Malmquist index analysis of 93 countries, 1980-2000. Agric Econ 32:115–134. doi: 10.1111/j.0169-5150.2004.00018.x

Du C, Zhou J (2009) Evaluation of Soil Fertility Using Infrared Spectroscopy -- A Review. In: Lichtfouse E (ed) Climate Change, Intercropping, Pest Control and Beneficial Microorganisms: Climate change, intercropping, pest control and beneficial microorganisms. Springer Netherlands, Dordrecht, pp 453–483

FAO (2005) Fertiliser use by crop in Indonesia. Accessed from: http://www.fao.org/3/y7063e/y7063e00.htm

Golicz K, Hallett SH, Sakrabani R (2020) Novel procedure for testing of soil field test kits involving paper strips. Soil Use Manag 00:1–11. doi: 10.1111/sum.12582

Golicz K, Hallett SH, Sakrabani R, Pan G (2019) The potential for using smartphones as portable soil nutrient analyzers on suburban farms in central East China. Sci Rep 9:1–10. doi: 10.1038/s41598-019-52702-8

Han P, Dong D, Zhao X, et al (2016) A smartphone-based soil colour sensor: For soil type classification. Comput Electron Agric 123:232–241. doi: 10.1016/j.compag.2016.02.024

Hartz TK, Bendixen WE, Wierdsma L (2000) The value of pre-sidedress soil nitrate testing as a nitrogen management tool in irrigated vegetable production. HortScience 35:651–656

Hein L, Leemans R (2012) The impact of first-generation biofuels on the depletion of the global phosphorus reserve. Ambio 41:341–349. doi: 10.1007/s13280-012-0253-x

Intaravanne Y, Sumriddetchkajorn S (2015) Android-based rice leaf colour analyzer for estimating the needed amount of nitrogen fertiliser. Comput Electron Agric 116:228–233. doi: 10.1016/j.compag.2015.07.005

Jemison JM, Fox RH (1988) A quick-test procedure for soil and plant tissue nitrates using test strips and a hand-held reflectometer. Commun Soil Sci Plant Anal 19:1569–1582. doi: 10.1080/00103628809368035

Jordan-Meille L, Rubæk GH, Ehlert PAI, et al (2012) An overview of fertiliser-P recommendations in Europe: Soil testing, calibration and fertiliser recommendations. Soil Use Manag 28:419–435. doi: 10.1111/j.1475-2743.2012.00453.x

Keeney DR, Nelson DW (1982) Nitrogen-inorganic forms. In: Page AL, Miller RH, Keeney DR (eds) Methods of Soil Analysis, 2nd edn. The American Society for Agronomy, New York, pp 643– 698

Maggini R, Carmassi G, Incrocci L, Pardossi A (2010) Evaluation of quick test kits for the determination of nitrate, ammonium and phosphate in soil and in hydroponic nutrient solutions. Agrochimica 54:331–341

Murphy J, Riley JP (1962) A modified single solution method for the determination of phosphate in natural waters. Anal Chim Acta 27:31–36

Myers RJK (1984) A simple model for estimating the nitrogen fertiliser requirement of a cereal crop. Fertil Res 5:95–108. doi: 10.1007/BF01049494

Nyi T, Varughese P, bin Hj Bujang MI, et al (2017) ASEAN Guidelines on Soil and Nutrient Management. Bangkok

Olsen SR, Cole CV, Watanabe FS, and Dean LA. (1954) Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. U. S. Department of Agriculture Circular No. 939. Banderis AD, Barter DH, and Anderson K. Agricultural and Advisor.

Robertson GP, Swinton SM (2005) Reconsiling agricultural productivity and environmental integrity: a grand challange for agriculture. Front Ecol Environ 3:38–46. doi: 10.1890/1540-9295(2005)003[0038:RAPAEI]2.0.CO;2

Rosi T, Malgieri M, Onorato P, Oss S (2016) What are we looking at when we say magenta? Quantitative measurements of RGB and CMYK colours with a homemade spectrophotometer. Eur J Phys 37:. doi: 10.1088/0143-0807/37/6/065301

Roy RN, Finck A, Blair GJ, Tandon HLS (2007) Plant Nutrition for Food Security. A Guide for Integrated Nutrient Management. Rome

Rware H, Kayuki C, Macharia M, Oduor G (2016) Fertiliser use optimization approach: An innovation to increase agricultural profitability for African farmers. African J Agric Res 11:3587–3597. doi: 10.5897/ajar2016.11408

Schepers JS, Raun WR (2008) Nitrogen in Agricultural Systems, 1st edn.

American Society of Agronomy, Madison, USA

Schmidhalter U (2005) Development of a quick on-farm test to determine nitrate levels in soil. J Plant Nutr Soil Sci 168:432–438. doi: 10.1002/jpln.200520521

Sims JT, Vasilas BL, Gartley KL, et al (1995) Evaluation of Soil and Plant Nitrogen Tests for Maize on Manured Soils of the Atlantic Coastal Plain. Agron J 87:213–222. doi: 10.2134/agronj1995.00021962008700020013x

Singh B, Sharma RK, Jaspreet-Kaur, et al (2011) Assessment of the nitrogen management strategy using an optical sensor for irrigated wheat. Agron Sustain Dev 31:589–603. doi: 10.1007/s13593-011-0005-5

Swarbreck SM, Wang M, Wang Y, et al (2019) A Roadmap for Lowering Crop Nitrogen Requirement. Trends Plant Sci 24:892–904. doi: 10.1016/j.tplants.2019.06.006

Thompson RB, Gallardo M, Joya M, et al (2009) Evaluation of rapid analysis systems for on-farm nitrate analysis in vegetable cropping. Spanish J Agric Res t. 7(1) p.:200–211

Vandendriessche H, van Neck T, Bijnens O, Elsen A (2011) Residual soil nitrate: A comparison between air-dried and field-moist soil samples. Commun Soil Sci Plant Anal 42:1847–1854. doi: 10.1080/00103624.2011.587575

Vesali F, Omid M, Kaleita A, Mobli H (2015) Development of an android app to estimate chlorophyll content of corn leaves based on contact imaging. Comput Electron Agric. doi: 10.1016/j.compag.2015.06.012

Wetselaar R, Smith GD, Angus JF (1998) Field measurement of soil nitrate concentrations. Commun Soil Sci Plant Anal 29:729–739. doi: 10.1080/00103629809369980

Yetisen AK, Martinez-Hurtado JL, Garcia-Melendrez A, et al (2014) A smartphone algorithm with inter-phone repeatability for the analysis of colorimetric tests. Sensors Actuators, B Chem 196:156–160. doi: 10.1016/j.snb.2014.01.077

Chapter 4: The potential for using smartphones as portable soil nutrient analysers on suburban farms in central East China

Summary: This chapter describes the field application of Akvo Caddisfly and nutrient-sensitive test strips. A field trial was conducted to establish operational limits for the smartphone-mediated soil analyses in field conditions, i.e. smallholder vegetable farms in sub-tropical South-East Asia (Objective 2 and Objective 3). The results of standard soil tests and Akvo Caddisfly were linked to fertiliser recommendations and potential production cost savings of Akvo Caddisfly's end user. The field and laboratory work undertaken provided metadata for the test kit development evaluation process described in Chapter 6 (Objective 4).

Highlights:

- Nitrate-N results obtained with Akvo Caddisfly correlated well with the yield response of *Ipomoea aquatica* (water spinach), a common peri-urban crop, across two vegetable growing seasons;
- Accuracy of smartphone mediated analysis ranged between 24 and -24 mg kg^{-1} of nitrate-N when compared to the standard laboratory method;
- Nitrate-N estimates could be applied in calculating necessary fertiliser inputs throughout the open-field vegetable growing season;
- Phosphorus test strips showed limited promise whilst ammonium test strips showed some promise for application in in-field soil testing;
- Environmental factors such as temperature and technological shortcomings such as deterioration of the colour correction card were identified as method limitations.

Data access: Data underlying this study is accessible through Cranfield University's repository at 10.17862/cranfield.rd.9328814.

Published as: Golicz K, Hallett SH, Sakrabani R, Pan G (2019) The potential for using smartphones as portable soil nutrient analyzers on suburban farms in central East China. Sci Rep 9:1–10. doi: 10.1038/s41598-019-52702-8

4.1 Introduction

Over the course of the last six decades, problems of decreasing soil fertility and imbalances in nutrient supply have been addressed by large-scale production and application of mineral fertilisers (Dawson and Hilton, 2011). Global demand for mineral fertilisers (N + P_2O_5 + K_2O) is growing annually by 1.9% and is expected to reach 201.66 million tonnes by the end of 2020 (FAO, 2017a). However, increased fertiliser use does not necessarily translate into high resource use efficiency, where the demand for nutrients is not met at the correct spatio-temporal scale (Havlin et al., 2013).

Studies have shown that plant uptake rates for N can be as low as 10-20% in horticultural systems (Ju et al., 2007). Vegetable production, both in open land and the greenhouse, involves frequent cultivation, high fertiliser application rates e.g. up to 900kg ha^{-1} for Chinese cabbage (Chen et al. 2004), low rooting density and short growing seasons – these systems are associated with high environmental risks of nutrient leaching and greenhouse gas emissions (Zhang et al., 2017). This is concerning given that the need for fresh produce, particularly vegetables, will increase alongside the awareness of the impact of poor nutrition on morbidity and mortality rates in relatively wealthy societies (Willett et al., 2019). High input, industrial monocultural practices should be considered low efficiency systems that are unlikely to produce enough food to feed the future world population whilst simultaneously absorbing the market shocks of volatile fossil fuel and fertiliser prices, along with climate change induced resource shortages.

Just as most developed countries must undertake coordinated efforts to sustainably transform their food systems, the developing nations should also take the opportunity to develop agroecologically efficient production techniques whilst building on the already available body of knowledge. Tittonell et al. (2008) compared maize yields of research-managed and farmer-managed plots and found that planting the crop early in the season with optimised planting densities, controlling pests/weeds and disease and using hybrid seeds doubled the agriculture output of smallholder farms in western Kenya. The application of mineral fertilisers could increase yields further by +1t ha^{-1} (Tittonell et al., 2008).

One of the methods used to balance soil fertility with optimal farm output involves prescriptive-corrective crop nutrient management where the employment of monitoring procedures during crop growth enables the adjustment of nutrient management practices to correct deficiencies or excesses (Havlin et al., 2013). In most developed nations, characterised by industrial scale agriculture, farmers have access to the tools necessary for agricultural monitoring, such as laboratory tests of physico-chemical characteristics of soils and/or plant tissue (Omran, 2017). Moreover, there are a number of inexpensive and useful field-based tools that can act as indicators of the soil fertility status (Muñoz-Huerta et al., 2013), and these include colorimetric test strips (Jemison and Fox, 1988). Such strips enable farmers to safeguard their businesses by optimising crop production whilst minimising financial and environmental risks arising from overfertilization.

By contrast, developing nations face challenges in accessibility to laboratory-based assessments of soil quality with common practices promoting the use of mineral fertilisers through blanket recommendations, based on region-wide soil surveying or on agroecological zoning, rather than being site and crop specific and accounting for small-scale heterogeneity in soil conditions (Tittonell et al., 2008). In China, a national project *Soil testing for formulated fertilization* had been implemented in 2005, covering > 90% of the total crop production area across the country. The implementation of the project has led to a reduction in chemical fertiliser use by approximately 3Mt by 2009 and an increase in soil organic carbon and decrease in N fertiliser induced N_2O emission from croplands (Han and Yang, 2011). The lack of access to technical services and difficulty with plot-scale soil sampling and soil analysis have been identified as barriers to household farmers benefitting from such schemes (Cheng et al., 2011). There remains a need for cheap and accessible technologies that can act as an alternative to conventional plant tissue and soil testing.

Smartphones used in conjunction with test strips offer just such a technological opportunity as they: (1) are free of human bias associated with colour detection, (2) are capable of providing precise and replicable results in contrary to the standard visual method, (3) have the capacity for storing and geotagging results for future use, (4) offer the potential for inclusion of wider extension and agronomical advice alongside immediate results and (5) offer a pragmatic alternative to expensive commercial reflectometers on offer by test strip manufacturers, such as the Quantofix Relax Reflectometer used with Quantofix test strips.

In this study, we describe how one smartphone app, Akvo Caddisfly, being available via the Android Google Play Store (https://play.google.com/store/apps/details?id=org.akvo.caddisfly&hl=en), could be used as an in-field soil nutrient analyser in suburban vegetable farm in China (**Figure 4-1**). Akvo Caddisfly is an application that transforms a smartphone into a portable reflectometer that can then be used to relate the concentration of the nutrient to the intensity of the colour of a commercially available test strip. The reading of the test strip taken with the Akvo Caddisfly app is passed through a calibration equation based on a laboratory study that has correlated a widely accepted colorimetric method of NO_3-N and Olsen-P assessment with results provided by the app. Such results offer considerably more precision than an assessment with the naked eye and a simple colour chart. The purpose of the study was to investigate the accuracy and precision of results obtained in field conditions in the sub-tropical climate and the capacity for smartphone-mediated soil analysis to monitor changes in soil nutrient status that were then used in making fertiliser recommendations. By employing Akvo Caddisfly, it is possible to provide farmers, who might otherwise have had limited access to conventional soil testing, with a simple decision support tool that can provide information about the quantity of plant available nitrate and phosphorus in the soil.

Figure 4-1. A. Small-scale, multi-crop vegetable farms typical of suburban East China. B. Study area subdivided into plots, C. A nearby waterbody showing signs of eutrophication resulting from overfertilisation.

4.2 Materials and Methods

4.2.1 Site description

A field experiment was conducted between June and September 2018 in a vegetable farm in a suburban village of Qinfeng (31°16′ N, 119°54′ E), Luhe District, Nanjing, China. The region has a sub-tropical monsoon climate (annual mean $T_{(°C)}$ = 15.6; precipitation = 1001mm). The topsoil chemical characteristics prior to the commencement of the experiment were: pH (soil: water) of 4.3, electrical conductivity (EC) of 0.34dS m^{-1}, and total N, total C and SOM content of 2.07g kg^{-1}, 20.2g kg^{-1} and 53.0g kg^{-1}, respectively. Standard wet chemistry methods were applied for topsoil assessment. The soil has a broad classification as a gleysol with gleyic reducing conditions and a particle size distribution in the upper 25cm equivalent to 5.4% sand, 42.5% silt and 52.1% clay.

4.2.2 Experiment design

The experiment was performed with water spinach (*Ipomoea aquatica*) growing over two rotations with each rotation lasting 35 days. The experiment had two fertiliser treatments as a primary factor and N application rates as a secondary factor (**Figure 4-2**). The two-fertiliser treatments involved application of normal compound inorganic fertiliser (15:15:15 NPK) and biochar organo-mineral fertiliser (15:15:10 NPK), containing 18% maize biochar. The four levels of N rates were 33%, 66%, 99% and 198% of the recommended optimum N rate for water spinach, which was 136kg ha^{-1} (World Association of Soil and Water Conservation, 2012). Test plots were constructed in accordance with the Chinese raised-bed method; three permanent raised-bed plots were isolated from another by well compacted paths. Stepping on the vegetable raised-bed plot was avoided, with weeding and watering activities taking place from the path. As the purpose of the experiment was not to accurately assess the agronomic response of the crop to the fertiliser treatment used but to measure changes in the soil nutrient concentration using non-standard soil analytical methods in conditions likely to mimic those experienced in suburban Chinese farms; no further steps to isolate the plots were taken.

The experiment was organised in a randomised complete block design, comprising 36 blocks with four replications, each block in an area of 1.05 m^2 (0.75m x 1.40m). Planting holes were located 20cm from the edge of the block and set approximately 15cm apart. Both plots and sub-plots (blocks) were clearly marked with bamboo field-markers and red tape stretching from marker to marker. Fertiliser was applied carefully within each block and incorporated into the soil in the centre of each plot. For Trial 1, the water spinach was planted on the 18th of June and harvested on the 23rd of July. Prior to the second fertiliser application, the fields were ploughed, and the quadrant markings re-established. For Trial 2, water spinach was planted on the 16th of August and harvested on the 20th of September. The fertiliser was applied once prior to sowing and no herbicides or pesticides were applied. Daily management included irrigation and removal of weeds, by hand throughout the growing period. Manual irrigation was conducted with equipment available on the farm, between 6.30 and 7.30AM daily, unless a rain event occurred in the previous 24hr period.

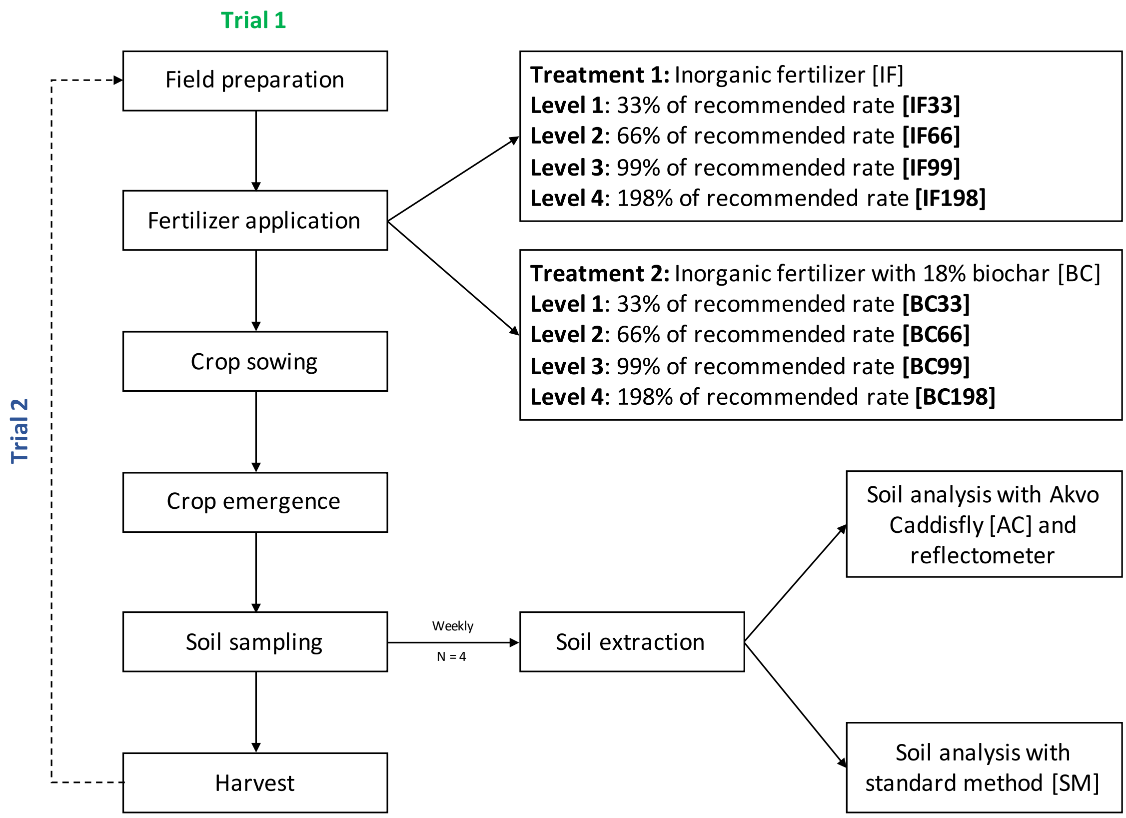


Figure 4-2. Flowchart showing the planning and execution of fieldwork activities. Field preparation involved ploughing and establishment of quadrant markings. There were two trials, which constituted two growth cycles of water spinach. Standard inorganic fertiliser (IF) and biochar-infused inorganic fertiliser (BC) was added at proportion of the recommended application rate. Soil sampling took place every week post crop emergence with four sampling events in a single growth cycle. Soil analysis was conducted immediately after sampling with standard methods and test strips assessed through Akvo Caddisfly and a commercial grade reflectometer. Trial 2 commenced three weeks after the harvest of the first crop and involved the same procedures.

4.2.3 Data collection

Soil sampling was undertaken every seven days post seedling establishment, with 150g of soil were collected from each block. The soil was placed in a labelled sealable plastic bag and placed immediately in a portable cooler box. Images of randomised blocks were then taken following the procedure outlined by Easlon and Bloom (2014). Images were analysed to establish the total leaf area of the crop within each quadrant.

A portion of the soil was analysed for available N and extractable P using the Quantofix NO_3^- and PO_4^{3-} test strips and the Quantofix Relax Reflectometer and a Samsung Galaxy S8 mobile phone with the pre-installed Akvo Caddisfly app (Beta ver. 10). The soil was sieved with a 5.6mm sieve and taken to an air-conditioned room for extraction and analysis (the sample temperature range throughout the experiment was 23-28°C). The extracts were obtained by mixing 10g of soil with 50mL of distilled water (for nitrate) and 15g of soil and 50mL of Mehlich-1 solution (for phosphate) in 250mL plastic bottles. The contents of the bottle were then shaken manually for a minimum of 5 minutes or until large blocks of soil (if present) were dissolved, the resultant mixture was then filtered through a Whatman 4V filter paper. Further dilution was added when necessary, leaving a clear extract used for testing. A test strip was wetted and placed on a colour correction card to be analysed with the Samsung Galaxy S8 after 60 seconds of reaction time. Simultaneously, another test strip was wetted and passed through Quantofix Relax Reflectometer. The test strip-mediated soil analysis was conducted during daylight hours with an average of three test strip measurements per extract. As the chief purpose of this study was to assess the viability of employing a smartphone as an in-field soil analyser, only Akvo Caddisfly results are described further. In cases when nitrite was shown to be present in quantifiable amounts (≥1mL L^{-1}, as indicated by Akvo Caddisfly), it was neutralised with amidosulfuric acid (H_3NSO_3) with a ratio of 1mL of H_3NSO_3 to 5mL of sample as to remove any effect associated with nitrite inference. Alongside the test strip measurements, the soil was analysed using standard laboratory techniques for comparison. For available N analysis, the soil was extracted with 2M potassium chloride for 1hr on an orbital shaker (set at 180rpm) with a soil to solution ratio of 1: 5 and determined colorimetrically following the standard method of Keeney and Nelson (1982). Available N analysis took place within 24hr of sample collection. The remaining soil was air-dried and extracted with 0.5M sodium hydrogen carbonate (pH: 8.5) for 0.5hr on an orbital shaker (180rpm) with a soil to solution ratio of 1: 20 following the standard method of Murphy and Riley (1962). Extractable N and P analysis then took place with the Segmented Flow Autoanalyzer (SKALAR).

The yield of each plot was obtained at harvest 35 days after planting. The harvest involved cutting water spinach at its base and transferring it to a labelled plastic bag (one bag per 1.2m^2 quadrant). Plant fresh weight was measured immediately after removal. Additionally, 1kg of water spinach was dried in an oven at 65°C for 72hr to determine the dry weight of the harvested crop.

4.2.4 Data processing and statistics

The results obtained with the standard and smartphone-mediated methods of soil analysis were multiplied by appropriate dilution factors and expressed as mg kg^{-1} and kg ha^{-1}. Four data points collected with Akvo Caddisfly were discarded as the test strip was visibly discoloured as a result of chemical interferences. Statistical tests such as correlations and ANOVA were deemed inadequate for a study involving a method comparison. Instead, Bland-Altman plots (Bland and

Altman, 2003) have been employed to investigate the degree of agreement and the absolute difference between standard laboratory and smartphone-mediated methods of nutrient analysis. The B-A analysis involves constructing a scatter plot, in which the difference between the paired measurements is plotted on y-axis and average of the measures of two methods on 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 RStudio (ver. 1.1.447) and the MethComp package. Fertiliser cost (5 CNY= £0.57) was established based on the amount of money charged in the local village shop. Cost savings were calculated to demonstrate saving potential for small (plot-scale) and large (1ha field-scale) field sizes.

4.3 Results and discussion

4.3.1 Plant response and residue soil nutrient content

The water spinach yield strongly correlated with the fertiliser treatment for both standard inorganic fertiliser, IF, ($Y=-5.941E\text{-}5x^2+0.0157x+1.0292$; $R^2=0.98$) in Trial 1 and Trial 2 and inorganic fertiliser with 18% biochar, BC, ($Y=-4.62E\text{-}5x^2+0.0159x+1.0469$, $R^2=0.95$) and ($Y=-4.631\text{-}5x^2+0.014x+0.074$, $R^2=0.97$; and $Y=-6.333E\text{-}5x^2+0.0015x+0.0812$, $R^2=0.83$, respectively). The vegetable yield was lower in Trial 2; this was likely due to lower rainfall and overfertilisation. Other studies have noted a similarly high level of responsiveness of quick-growth green vegetables, including water spinach, to experimental treatment (Li et al., 2012). High residue nitrogen was recorded for treatments BC198 and IF198, which were equivalent to 272kg of N per ha for Trial 1 and 334kg of N per ha for Trial 2.

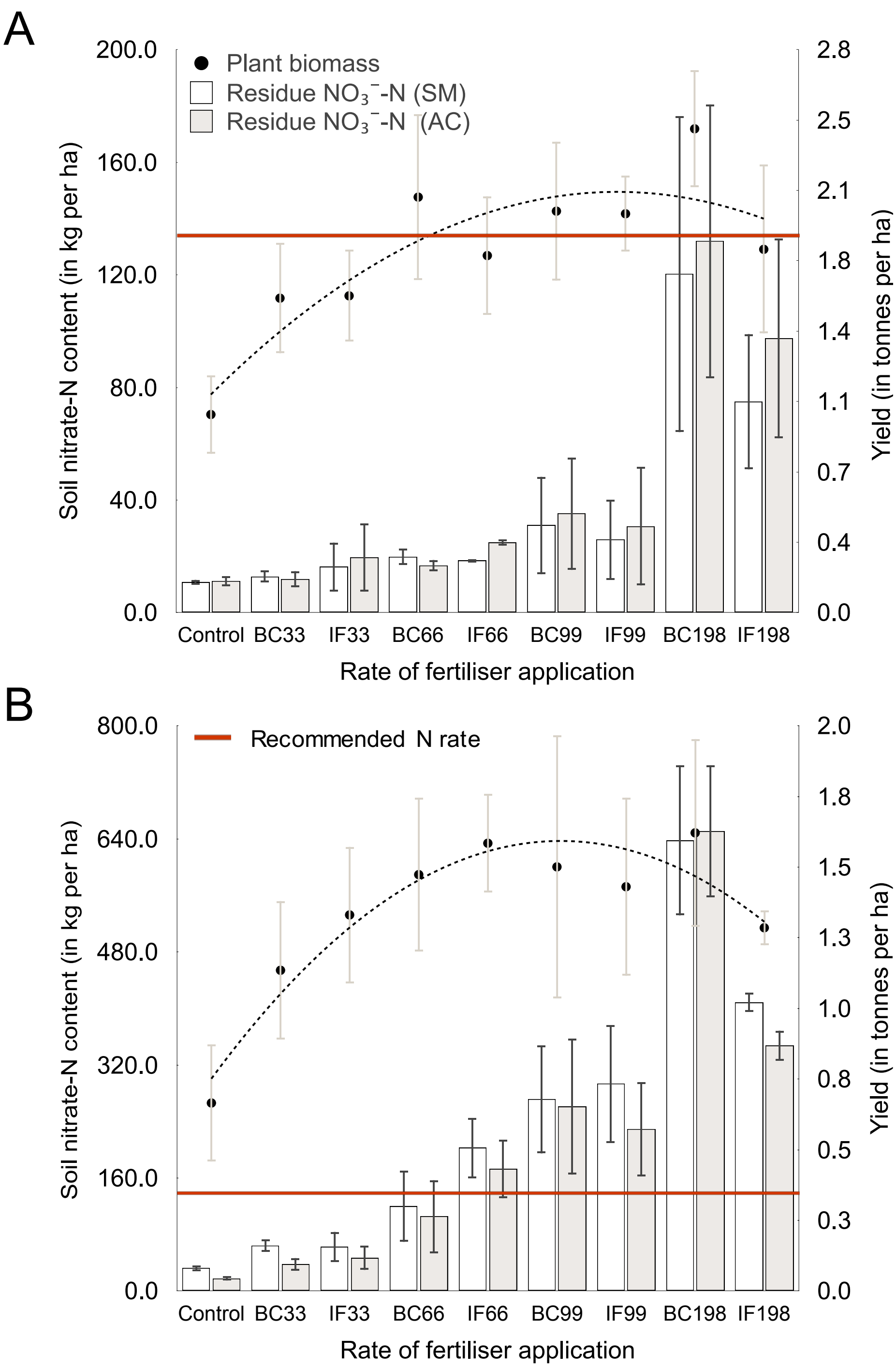


Figure 4-3**A-B. Akvo Caddisfly (AC) (grey bars) was used to assess NO_3-N level in the soil solution alongside the standard method (SM) (white bars) at harvest for Trial 1 (A) and Trial 2 (B). Disparities between the in-field and standard laboratory methods of N assessment were greater at higher NO_3-N concentrations. The red line refers to recommended N rate obtained from literature.**

The Akvo Caddisfly method was applied successfully in assessing the level of residue mineral nitrogen (NO_3-N) at harvest (**Figure 4-3A-B**). Measurement of the NO_3-N residues prior to sowing is essential for informing farmers about the potential for nitrate loss due to leaching and denitrification and the quantity of fertiliser required to be added to subsequent crops, or as a side-dressing, i.e. as intermittent application of fertilisers in a shallow band along the side of a row of crops (Havlin et al., 2013). Disparities between the in-field and standard laboratory methods of N assessment were found to be greater at higher NO_3-N concentrations, i.e. for treatments equivalent to two times the recommended fertiliser amount and during the second trial, where the growing conditions were suboptimal as a result of the less favourable time of the year. In vegetable cultivation, residue nitrogen is likely to be elevated as a result of (1) the crop being harvested prior to achieving maturity, and (2) vegetable residues incorporated into the soil being easily mineralised (Zhang et al., 2017). In temperate zones, the autumn and winter are the periods of the highest risk for nitrate leaching from the root zone; in the tropics, nitrate loss is independent of the time of the year and has been estimated to be as high as 136kg ha^{-1} for vegetable crops in the Chinese greenhouse systems (Ju et al., 2007; Zhang et al., 2017). Residual soil nitrate is a good predictor of nitrate leaching loss and as such, the Akvo Caddisfly app provides a valuable support tool for managing this risk.

4.3.2 Nutrient monitoring across the crop growing season

The Akvo Caddisfly method was found to be capable of determining the quantity of NO_3-N in the soil throughout the crop growing rotations (**Figure 4-4A-B**; See **Table 8-3** in **Appendix B** for detailed breakdown of the week-by-week changes in the soil NO_3-N concentration).

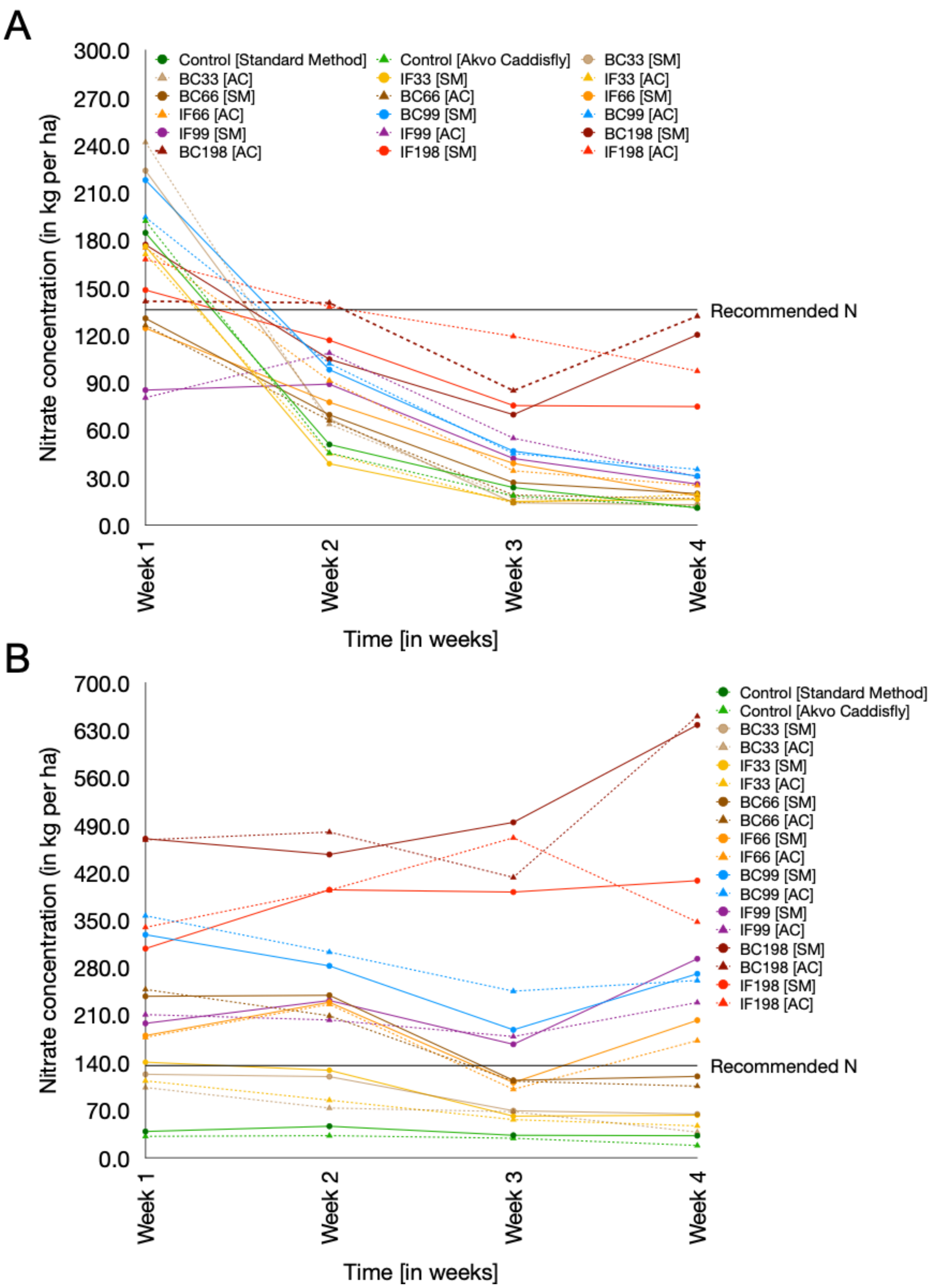


Figure 4-4A-B. Nitrate-N concentration varied across the crop growing season for Trial 1 (A) and Trial 2 (B), presented on a weekly basis. The Akvo Caddisfly method was applied to assess NO_3-N during the plant growth stage. Disparities between the in-field and standard laboratory methods of N assessment were higher during the second trial. Higher quantities of NO_3-N can be attributed to environmental factors and higher total fertiliser quantity applied.

Currently, provision of fertilisers in developing nations are either subsidised by the government making them more affordable or needs to be purchased with personal resources. While the former situation can lead to overfertilisation, the latter calls for an optimisation of resources to avoid financial losses to vulnerable communities. The ability to monitor changes in nitrate-N concentration across the vegetable growing season allows the farmer to not only fine-tune fertiliser recommendations, but also to improve resource allocation. Chinese farmers use over 4 670kg of N ha^{-1} yr^{-1} (Ju et al., 2007), which results in severe soil acidification, nutrient imbalances, heavy metal pollution and abandonment of fields within fifteen years of greenhouse construction (Song et al., 2009). Providing evidence that soil NO_3-N levels exceed plant requirements, it could encourage reduction in fertiliser inputs. In contrast, in West Africa, where minimising expenditure is essential; it would be possible to enhance resource allocation with microdosing (Aune et al., 2017) being implemented on relatively fertile sites within the field. This would allow for improved management of outfields characterised by low fertility and high erosion risk, e.g. by increasing manure applications, which alleviates these problems.

The Akvo Caddisfly method was shown to be sensitive enough to track changes in NO_3-N concentrations across the plant growing season. In contrast, soil PO_4^{3-}-P as measured with Akvo Caddisfly and Quantofix test strips revealed limited precision and accuracy. The difference between the standard method and the Akvo Caddisfly ranged from -62.7 to 57.3mg kg^{-1} (-188.1 to 171.9kg ha^{-1}) for composite samples in Week 1 of the first trial; it was impossible to determine the differences in soil P concentration across the treatments or as the crop season progressed. Phosphate-detecting test strips, as a form of ion chromatography (IC), have been previously shown to be of limited applicability as an agricultural 'quick test' in horticultural systems (Maggini et al., 2010). Similarly, laboratory use of IC has been shown to be a poor measure of extractable P due to multiple interferences and as such is discouraged (Xie et al., 2013). Other smartphone-mediated soil P tests have been proposed, which do not rely on chromatography (Pongnumkul et al., 2015) and their continued use should be explored in more detail in similar future studies.

4.3.3 Uncertainties in soil nutrient estimation with smartphone-mediated soil analysis

The error for soil subsampling defined as the difference in measurable NO_3-N resulting from taking only a small portion of the sample for analysis, ranged from -3.8 to 10.4mg kg^{-1} as measured by the autoanalyzer (**Figure 4-5A**). The error range for the difference between the smartphone-mediated and standard laboratory NO_3-N assessment was higher than for the soil subsampling error and ranged from -27.1 to 28.4mg kg^{-1} (**Figure 4-5B**). The difference is likely to be a result of

- (1) temperature effect on the test strips (Wetselaar et al., 1998),
- (2) chemical interferences (Jemison and Fox, 1988), which were more likely to occur at very high fertiliser application rates, and
- (3) deterioration of the Akvo Caddisfly colour correction card.

The latter two are likely to be responsible for a greater number of outliers recorded for Trial 2. The deterioration of the colour correction card should be taken into account if the smartphone-mediated soil test is to be conducted over long periods of time. Similar to the approach proposed by Schmidhalter (2005), it is recommended that a correction factor of 0.2 be used for every 5°C deviation from the room temperature (approx. 19.5°C), this having been deemed optimal for test strip use by the manufacturer (See **Figure 8-3** in **Appendix B** for a detailed breakdown of temperature correction factors). Addressing the temperature effect is particularly important at higher NO_3-N concentrations as higher temperatures result in greater overestimations of readings.

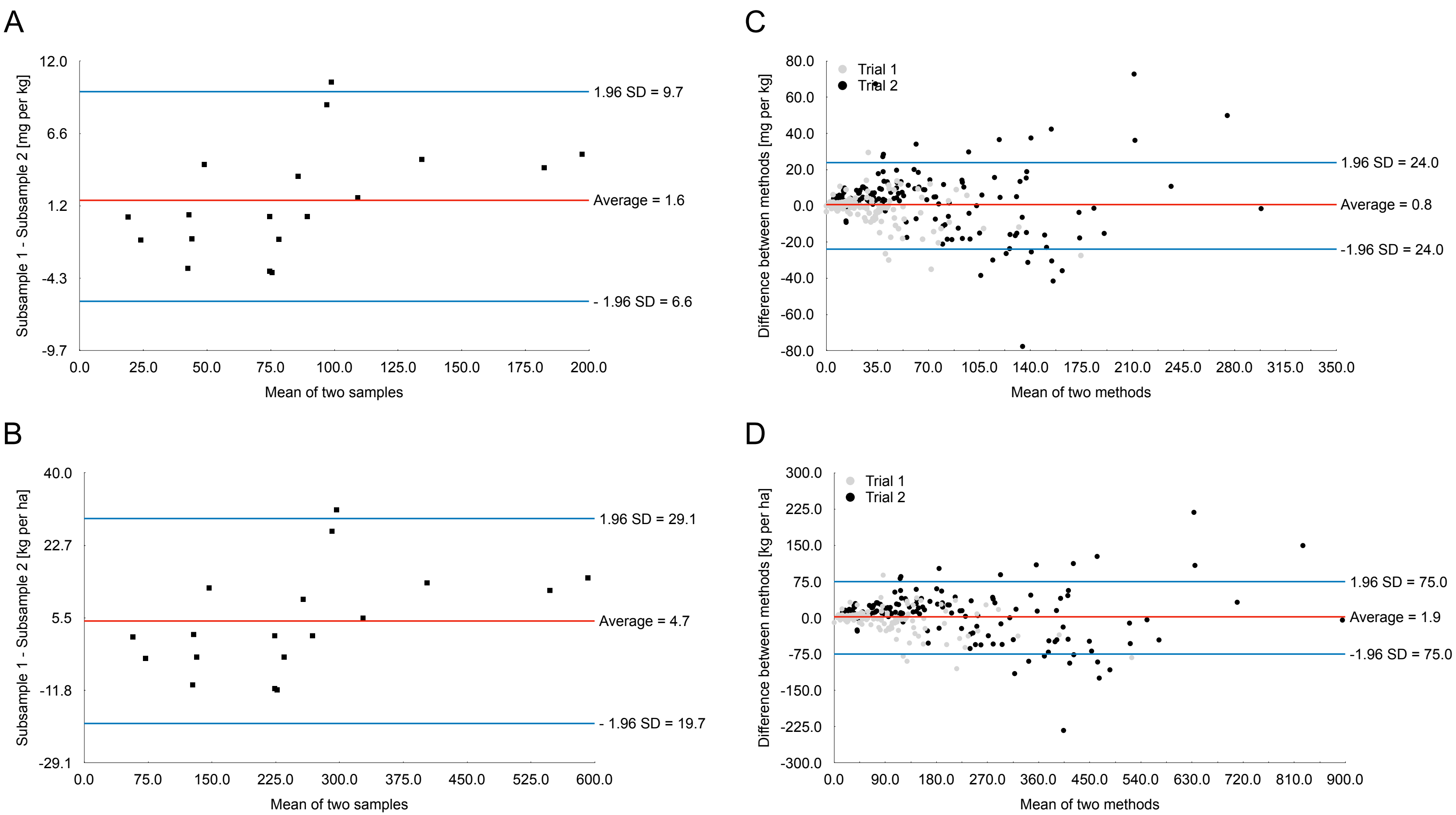


Figure 4-5. The subsampling errors measured with the standard laboratory method in mg kg^{-1} (A) and kg ha^{-1} (B) and errors between smartphone-mediated and standard soil test method for individual measurements expressed in mg kg^{-1} (C) and kg ha^{-1} (D). The error for soil subsampling, i.e. the difference in measurable NO_3-N resulting from taking only a small portion of the sample for analysis, ranged from -3.8 to 10.4mg kg^{-1} (19.7 to 29.1kg ha^{-1}). The error range for the difference between smartphone-mediated and standard laboratory NO_3-N assessment ranged from -24.0 to 24mg kg^{-1} (-75 to 75kg ha^{-1}). Differences between individual measurements were higher for Trial 2.

The mean bias (red line in **Figure 4-5**) between the subsamples was 1.58mg kg^{-1}, equivalent to 4.70kg ha^{-1}, for dry soil samples analysed with the segmented flow autoanalyzer during a single run of the equipment (**Figure 4-5A, C**). The highest difference recorded for the subsamples ranged from -3.8 to 10.4mg kg^{-1}, equivalent to -11.7 to 31.2kg ha^{-1} (**Figure 5A, B**), with the 95% limits of agreement (expressed as 1.96 x SD) of 9.7 to - 6.6mg kg^{-1} or 29.1 to -19.7kg ha^{-1}. The mean bias between the standard method and Akvo Caddisfly was 0.80mg kg^{-1}, equivalent to 1.90kg ha^{-1}, for field-moist soil samples (**Figure 4-5B, D**). The highest differences between individual measurements obtained with the standard method and smartphone-mediated soil analysis were -35.0 and 29.5mg kg^{-1}, equivalent to -63.0 to 53.1kg ha^{-1}, for Trial 1 and -77.6 and 72.8mg kg^{-1}, equivalent to -139.7 to 131kg ha^{-1}, for Trial 2 (**Figure 4-5C, D**). The 95% limits of agreement were 24.0 to – 24.0mg kg^{-1} or 75.0 to -75.0kg ha^{-1}.

Overall, 18%, or 51 out of 284, readings had errors higher or lower than 15mg kg^{-1} (45kg ha^{-1}), with 43%, or 121 out of 284, readings falling within the error range of -3.6 to 3.8mg kg^{-1} (11kg ha^{-1}). The highest absolute difference between the methods was recorded for those samples requiring dilution. The same was not found for samples that had to be neutralised with amidosulfuric acid (H_3NSO_3) to negate the effects of nitrite inference. Dilution was found to have a disproportionally high impact on the accuracy and precision of readings and as a method should be avoided whenever possible by incorporating test strips with a higher range, e.g. from 0 to 500mg kg^{-1} of nitrate as opposed to 0 to 100mg kg^{-1} as is currently available in the Akvo Caddisfly app. The presence of outliers can be mitigated by taking multiple composite samples across the field. By pooling four measurements across the fields under investigation, the analytical errors were shown to be lower than in plot differences, thereby increasing the quality of the smartphone-mediated soil test.

4.3.4 Field specific soil N level, fertiliser recommendations and cost savings

Akvo Caddisfly app has been shown to be successful at assessing the requirements for any pre- and in-season N fertiliser applications. Substantial monetary savings can be made by foregoing fertiliser applications in situations where soil N content is already sufficient or exceeds crop needs (e.g. where top soil mineral N content is higher than 136kg of N per ha., as recorded during Trial 2; treatments BC99; BC198; IF99 and IF198 (**Table 4-1**). This information could improve nitrogen use efficiency at smallholder farms, reduce associated costs, and lower risks of nitrate leaching to the environment. Quantification of soil N content could form an initial step for introducing a prescriptive-corrective crop nutrient management approach, or for use in discouraging continuous and overuse of compound fertilisers, which has been linked to increased heavy metal concentrations in the soil (Song et al., 2009). Also, whereas soil PO_4^{3}-P analysis showed limited promise, Kim and Kim (2003) reported successful employment of phosphate test strips to assess total P level in cucumber (*Cucumis sativus L.*). Akvo Caddisfly offers an opportunity to further examine and expand on those findings by using the app in plant tissue testing study.

It is important to note that the soil organic matter and the soil's capacity for N mineralisation is not taken into account by Akvo Caddisfly currently. However, a smartphone application for assessment of soil organic matter content has already been developed (Pongnumkul et al., 2015) but is to date restricted to those countries with well-developed national soil databases. In the future, the lab-on-a-chip approach could help to integrate multiple smartphone apps which can act as decision support tools to address shortcomings of and further improve available technological solutions.

Overall, optimising fertiliser utilisation rates without prior knowledge of soil conditions constitutes a two-pronged challenge. Firstly, application of insufficient quantities of fertiliser results in diminished returns on investment, especially in places where fertilisers are expensive and non-subsidised (Tittonell et al., 2008). Secondly, or conversely, applying fertiliser in excessive amounts leads to environmental pollution and mineral nutrient imbalances that negatively affect crop yields (Osvalde, 2011) and ultimately the sustainable productivity of the land, as well as unnecessary costs being borne. Considering the rate of environmental degradation and growing human population, it is crucial to move towards farming systems that are efficient, smart and sustainable (Hallett, 2017). As the use of Big Data (Wolfert et al., 2017) and technologies such as remote sensing (Goswami et al., 2017), robotics (Aravind et al., 2017), and non-destructive soil and plant tissue testing (Omran, 2017) are being increasingly embraced; it is essential to ensure that access to agricultural decision support tools is made affordable to all interested parties. Smartphones offer a promising future for the development of relatively inexpensive and user-friendly support tools for agricultural systems (Eichler-Inwood and Dale, 2019).

Table 4-1. Soil nitrate-N residue calculated based on the standard laboratory analysis (SM) and the smartphone-mediated soil analysis with Akvo Caddisfly (AC) for size of the investigated field ($36m^2$) and 1ha field together with fertiliser requirements for water spinach and the associated fertiliser costs. [1] The average concentration of nitrate-nitrogen measured across four plots; [2] Recommended rate of nitrogen application for water spinach is equal to 136kg of N per ha; [3] The price of 1kg of 15:15:15 NPK compound inorganic fertiliser (136kg of N = 906kg of 15% N inorganic fertiliser) in rural Jiangsu Province, China.

		Soil nitrate-N content[1]						Fertiliser requirement (15:15:15 NPK)[2]				Fertiliser cost (5 CNY kg^{-1})[3]			
		mg kg^{-1}		kg field^{-1}		kg ha^{-1}		kg field^{-1}		kg ha^{-1}		kg field^{-1}		kg ha^{-1}	
Treatment		SM	AC	SM	AC	SM	AC	SM	AC	SM	AC	SM	AC	SM	AC
Trial 1	CONT	4.3	4.0	0.0	0.0	12.9	12.0	3	3	821	827	15	15	4103	4133
	BC33	6.6	5.6	0.1	0.1	19.8	16.8	3	3	775	795	14	14	3873	3973
	BC66	10.3	11.7	0.1	0.1	30.9	35.1	3	2	701	673	13	12	3503	3363
	BC99	40.1	44.0	0.4	0.5	120.3	132.0	0	0	105	27	2	1	523	133
	BC198	3.6	3.7	0.0	0.0	10.8	11.1	3	3	835	833	15	15	4173	4163
	IF33	5.4	6.5	0.1	0.1	16.2	19.5	3	3	799	777	15	14	3993	3883
	IF66	6.1	8.3	0.1	0.1	18.3	24.9	3	3	785	741	14	13	3923	3703
	IF99	8.6	10.2	0.1	0.1	25.8	30.6	3	3	735	703	13	13	3673	3513
	IF198	25.0	32.5	0.3	0.4	75.0	97.5	1	1	407	257	7	5	2033	1283
Trial 2	CONT	21.4	12.6	0.2	0.1	64.2	37.8	2	2	479	655	9	12	2393	3273
	BC33	40.0	35.2	0.4	0.4	120.0	105.6	0	1	107	203	2	4	533	1013
	BC66	90.4	87.1	1.0	0.9	271.2	261.3	**Overfertilisation & Overspending**							
	BC99	212.6	216.9	2.3	2.3	637.8	650.7								
	BC198	20.9	15.6	0.2	0.2	62.7	46.8	2	2	489	595	9	11	2443	2973
	IF33	67.5	57.6	0.7	0.6	202.5	172.8	**Overfertilisation & Overspending**							
	IF66	97.7	76.3	1.1	0.8	293.1	228.9								
	IF99	136.1	115.8	1.5	1.3	408.3	347.4								
	IF198	4.3	4.0	0.0	0.0	12.9	12.0	3	3	821	827	15	15	4103	4133

4.4 Conclusions

This paper has investigated the potential for employing a smartphone app, Akvo Caddisfly, together with nitrate- and phosphate-sensitive test strips used to assess the content of plant available nutrients in the soil. The results have indicated that smartphone-mediated soil analysis can be successfully conducted for NO_3-N, but that there is currently only limited success with accurate assessments of soil PO_4^{3}-P content. Analytical errors associated with the in-field nutrient analyser can be minimised by taking multiple composite samples across the field, ensuring optimal light conditions, accounting for temperature effects, and increasing the number of test strips used per sample. Regardless of shortcomings, such as temperature dependency, chemical interferences and decreased accuracy at high nutrient concentration, this approach has the potential to provide a useful fertiliser recommendation tool in circumstances where access to conventional soil testing methods is limited. Ammonia test strips (currently incorporated into the Akvo Caddisfly) showed promise during initial trials but their applicability was later disproved (**Chapter 6, Table 6-2**). Future studies can focus on application of smartphones and test strips in plant sap measurements, to better inform agricultural management decisions at local level. Overall, employing smartphone technology, alongside local agronomic knowledge, has great potential for democratizing access to field-scale soil fertility data and improving sustainable fertiliser management throughout the world.

4.5 References

Aravind KR, Raja P, Pérez-Ruiz M (2017) Task-based agricultural mobile robots in arable farming: A review. Spanish J Agric Res 15:e02R01. doi: 10.5424/sjar/2017151-9573

Aune JB, Coulibaly A, Giller KE (2017) Precision farming for increased land and labour productivity in semi-arid West Africa. A review. Agron Sustain Dev 37:. doi: 10.1007/s13593-017-0424-z

Bland JM, Altman DG (2003) Applying the right statistics: Analyses of measurement studies. Ultrasound Obstet Gynecol 22:85–93. doi: 10.1002/uog.122

Chen Q et al. (2004) Evaluation of current fertilizer practice and soil fertility in vegetable production in the Beijing region. Nutrient Cycling in Agroecosystems 69:51–58. doi: 10.1023/B:FRES.0000025293.99199.ff

Cheng K, Pan G, Zhang B, et al (2011) Discussion on the Methodology for Quantifying Carbon Sequestration and Reduction in Greenhouse Gas E-mission Under Recommended Fertilization Project. J agro-environment Sci 30:1803–1810

Dawson CJ, Hilton J (2011) Fertiliser availability in a resource-limited world: Production and recycling of nitrogen and phosphorus. Food Policy 36:S14–S22. doi: 10.1016/j.foodpol.2010.11.012

Easlon HM, Bloom AJ (2014) Easy Leaf Area: Automated Digital Image Analysis For Rapid and Accurate Measurement of Leaf Area. Appl Plant Sci 2014 2:2–5. doi: 10.3732/apps.1400033

Eichler Inwood SE, Dale VH (2019) State of apps targeting management for sustainability of agricultural landscapes. A review. Agron Sustain Dev 39:. doi: 10.1007/s13593-018-0549-8

FAO (2017) World fertiliser trends and outlook to 2020 - Summary Report. Accessed from: http://www.fao.org/3/a-i6895e.pdf

Goswami SB, Saxena A, Matin S, Bairagi GD (2017) A Study on the application of Remote Sensing, GIS and GPS Tools in Precision Business. Int J Res Adv Eng 1:1. doi: 10.26472/ijrae.v1i12.44

Hallett SH (2017) Smart cities need smart farms. Environ Sci 26:10–17

Han H, Yang Z (2011) Analysis on Farmers' Adoptive Behavior of Soil Testing for Formulated Fertilization: Empirical Evidence from the Xuecheng District of Zaozhuang City in Shandong Province. Sci Agric Sin 44:4962–4970. doi:

10.3864/j.issn.0578-1752.2011.23.025

Havlin J, Tisdale S, Nelson W, Beaton J (2013) Soil Fertility and Fertilisers An Introduction to Nutrient Management, 8th edn. Pearson Education Dorling Kindersley

Jemison JM, Fox RH (1988) A quick-test procedure for soil and plant tissue nitrates using test strips and a hand-held reflectometer. Commun Soil Sci Plant Anal 19:1569–1582. doi: 10.1080/00103628809368035

Ju XT, Kou CL, Christie P, et al (2007) Changes in the soil environment from excessive application of fertilisers and manures to two contrasting intensive cropping systems on the North China Plain. Environ Pollut 145:497–506. doi: 10.1016/j.envpol.2006.04.017

Ju XT et al. (2009) Reducing environmental risk by improving N management in intensive Chinese agricultural systems (Proceedings of the National Academy of Sciences of the United States of America (2009) 106, 9, (3041-3046) DOI:10.1073/pnas.0813417106). Proceedings of the National Academy of Sciences of the United States of America 106:8077

Keeney DR, Nelson DW (1982) Nitrogen-inorganic forms. In: Page AL, Miller RH, Keeney DR (eds) Methods of Soil Analysis, 2nd edn. The American Society for Agronomy, New York, pp 643– 698

Kim K-R, Kim K-H (2003) Rapid nutrient diagnosis of cucumber by test strip and chlorrophyll meter. Korean J Soil Sci Fert 36:272–279

Li K yi, Zhao Y yuan, Yuan X long, et al (2012) Comparison of Factors Affecting Soil Nitrate Nitrogen and Ammonium Nitrogen Extraction. Commun Soil Sci Plant Anal 43:571–588. doi: 10.1080/00103624.2012.639108

Maggini R, Carmassi G, Incrocci L, Pardossi A (2010) Evaluation of quick test kits for the determination of nitrate, ammonium and phosphate in soil and in hydroponic nutrient solutions. Agrochimica 54:331–341

Muñoz-Huerta RF, Guevara-Gonzalez RG, Contreras-Medina LM, et al (2013) A review of methods for sensing the nitrogen status in plants: Advantages, disadvantages and recent advances. Sensors (Switzerland) 13:10823–10843. doi: 10.3390/s130810823

Murphy J, Riley JP (1962) A modified single solution method for the determination of phosphate in natural waters. Anal Chim Acta 27:31–36

Omran E-SE (2017) Will the Conventional Soil-Plant Analysis Pass into Oblivion? Rapid and Low-Cost Determination Using Spectroscopy. Commun Soil Sci Plant Anal 48:705–715. doi: 10.1080/00103624.2017.1298782

Osvalde A (2011) Optimization of plant mineral nutrition revisited : the roles of plant requirements , nutrient interactions , and soil properties in fertilization management. Environ Exp Biol 9:1–8

Pongnumkul S, Chaovalit P, Surasvadi N (2015) Applications of Smartphone-Based Sensors in Agriculture: A Systematic Review of Research. J Sensors 2015:. doi: 10.1155/2015/195308

Schmidhalter U (2005) Development of a quick on-farm test to determine nitrate levels in soil. J Plant Nutr Soil Sci 168:432–438. doi: 10.1002/jpln.200520521

Song XZ, Zhao CX, Wang XL, Li J (2009) Study of nitrate leaching and nitrogen fate under intensive vegetable production pattern in northern China. Comptes Rendus - Biol 332:385–392. doi: 10.1016/j.crvi.2008.11.005

Tittonell P, Vanlauwe B, Corbeels M, Giller KE (2008) Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant Soil 313:19–37. doi: 10.1007/s11104-008-9676-3

Wetselaar R, Smith GD, Angus JF (1998) Field measurement of soil nitrate concentrations. Commun Soil Sci Plant Anal 29:729–739. doi: 10.1080/00103629809369980

Willett W, Rockström J, Loken B, et al (2019) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393:447–492. doi: 10.1016/S0140-6736(18)31788-4

Wolfert S, Ge L, Verdouw C, Bogaardt M (2017) Big Data in Smart Farming – A review. Agric Syst 153:69–80. doi: 10.1016/j.agsy.2017.01.023

World Association of Soil and Water Conservation (2012) Optimum Fertiliser Rate For Kangkong (Ipomoea reptans L.). Accessed from: https://vtechworks.lib.vt.edu/handle/10919/67666

Xie C, Xu J, Tang J, et al (2013) Comparison of Phosphorus Determination Methods by Ion Chromatography and Molybdenum Blue Methods. Commun Soil Sci Plant Anal 44:2535–2545. doi: 10.1080/00103624.2013.811518

Zhang B, Li Q, Cao J, et al (2017) Reducing nitrogen leaching in a subtropical vegetable system. Agric Ecosyst Environ 241:133–141. doi: 10.1016/j.agee.2017.03.006

Chapter 5: An analysis of in-field soil testing and mapping for improving fertiliser decision making in vegetable production in Kenya and Ghana

Summary: This chapter describes field application of Akvo Caddisfly and nitrate-sensitive test strips for measurement of soil nitrate-N in the context of smallholder vegetable farms in Kenya and Ghana (Objective 2 and 3). It was also used to assess the nutrient profile of human waste derived fertilisers. The author of this thesis was responsible for part of the literature review, data analysis relating to smartphone-mediated soil testing, write-up of a portion of the methods and discussion sections, as well as, editing and creation of figures.

Highlights:

- Smartphone-mediated soil testing was successfully used in soil analysis across Kenya;
- Soil laboratories in Ghana used different methods for analysis of soil N, which resulted in greater disparities between Akvo Caddisfly results and Ghanaian lab results as well as the UK lab results and Ghanaian lab results;
- Smartphone-mediated soil testing correctly identified soil N deficiency in both countries within ± 20kg ha^{-1} of the standard method for 86% of the farms
- Soil N content was overestimated at 4 farms in Ghana;
- Paper test strips showed limited utility in assessing nitrate concentration in human waste derived fertilisers (HWDFs) likely due to multiple chemical interferences;
- Other limiting factors such as speed of filtration for clayey red soils were highlighted and used to offer alternatives for in-field extraction processes.

Data access: Data underlying this study is accessible through Cranfield University's repository at 10.17862/cranfield.rd.12687902.

Publication: This chapter has been submitted to Soil Use and Management as: *Mallory, A., Golicz, K., and Sakrabani, R. (2020). An analysis of in-field soil testing and mapping for improving fertiliser decision making in vegetable production in Kenya and Ghana.*

5.1 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 28.6kg ha^{-1} to arable land, respectively, compared with the global average of 137.6kg ha^{-1} (World Bank, 2018).

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; 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 on HWDF usage, which include health risks arising from poor waste treatment practices (Cofie et al., 2005) and unwillingness to use fertilisers from human waste from 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 used to fill the gaps in the HWDF nutrient profile evaluation. Semi-quantitative colorimetric methods for nutrient assessment are favoured in many developing countries, especially in the 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 pad that contains reagents that change colour in response to exposure to chemical compounds. These, in conjunction with reflectometers that quantify the reactive pad's colour, have been successfully applied in soil testing across the USA (Jemison and Fox, 1988), Germany (Schmidhalter, 2005) and Australia (Wetselaar et al., 1998). However, concerns regarding agreement between paper strips and conventional methods of nutrient analysis have been recently highlighted (Golicz et al. 2020). In this study, nitrate sensitive paper strips are used alongside Akvo Caddisfly – a smartphone app that allows the phone to be used as portable reflectometer to understand how useful the tool is as a method for assisting farmers in using HWDF.

Building on the ability to use appropriate technology to obtain improved information about soil in-field conditions, there is an increasing amount of literature citing geospatial datasets providing information on 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 Fertiliser App (**Figure 5-1)** used soil grid data from International Soil Reference and Information Centre (ISRIC) and the farm management handbook of Kenya (FAO, 2006) to provide soil information and crop recommendations across the country, based on the methods by Hengel et al. (2017). However, this service offered soil data at very low resolution (250m x 250m grids), neglecting micro-variations and real plot values when providing recommendations. Furthermore, the app lacked 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 on how to apply inputs and HWDF to increase yields.

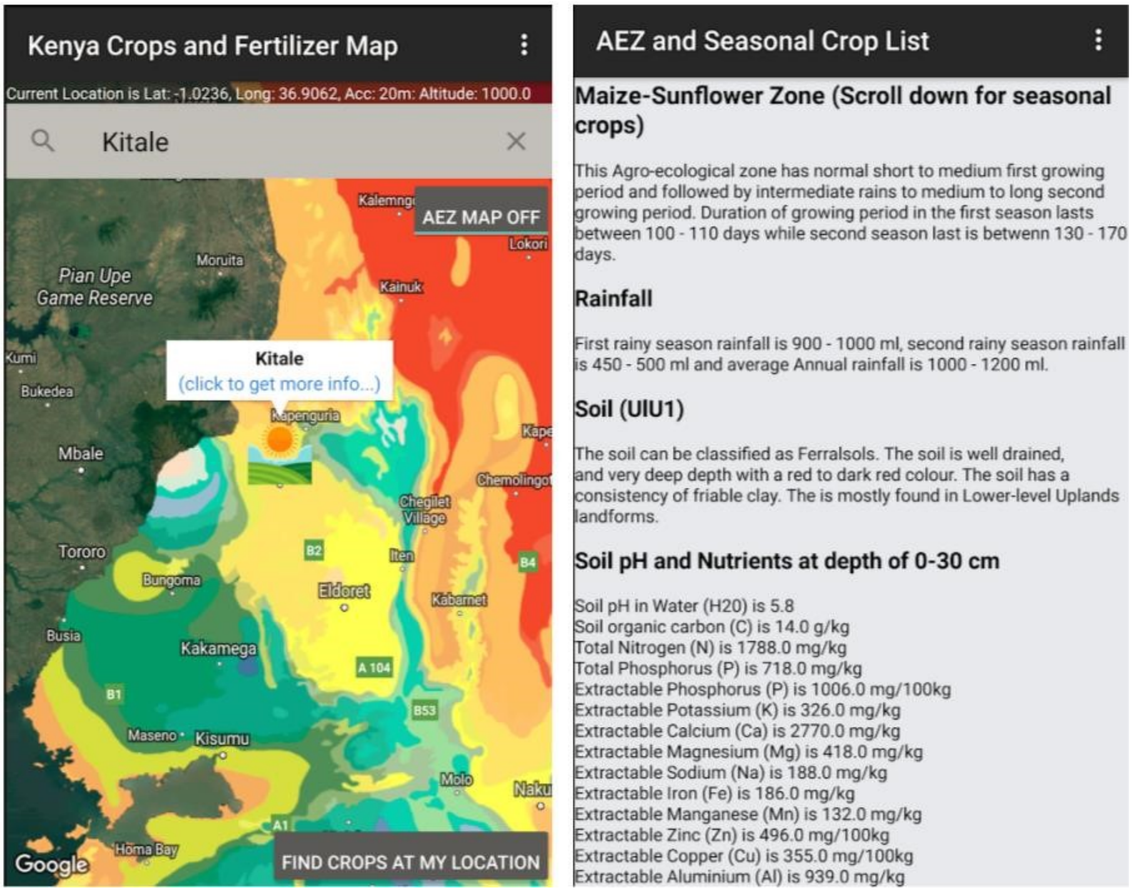


Figure 5-1. Screenshots of Kenya Crops and Fertiliser App (Google 2017).

This research aimed 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 were already companies producing treated commercial HWDF.

5.2 Methods

5.2.1 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 the 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 (**Figure 5-2A**). The farms ranged from 5-50 acres (2-20.2ha) in size.

In Ghana, the farmers using HWDF employed two irrigation schemes, Tuba and Klagon, located 40 and 50km from Accra, respectively (**Figure 5-2B**). 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 size 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 post-harvest land. A sampling rate of n=5 collected in a W pattern (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 three 5-point W's was taken on every 0.5 acre (0.2ha) of land available. This led to 24 W-shaped samples being taken totalling 120 samples.

Figure 5-2A-B. Sampling locations in Kenya (A) and Ghana (B). In Kenya, 19 farms were sampled across four counties, Embu, Machakos, Kirinyaga and Tharaka. In Ghana, 24 sites were sampled in Tuba and Klagon, located within Accra Municipality.

5.2.2 Soil and HWDF testing protocol

Samples were taken to a depth of 15cm using a hand trowel at 5 points in a W-shape across a hectare of land (**Figure 5-3**). 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. 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 by hand;
- Filter through medium grade filter paper;
- Dip paper strip into filtrate and take reading using the 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 from which three replicates were obtained. Instead of a 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.

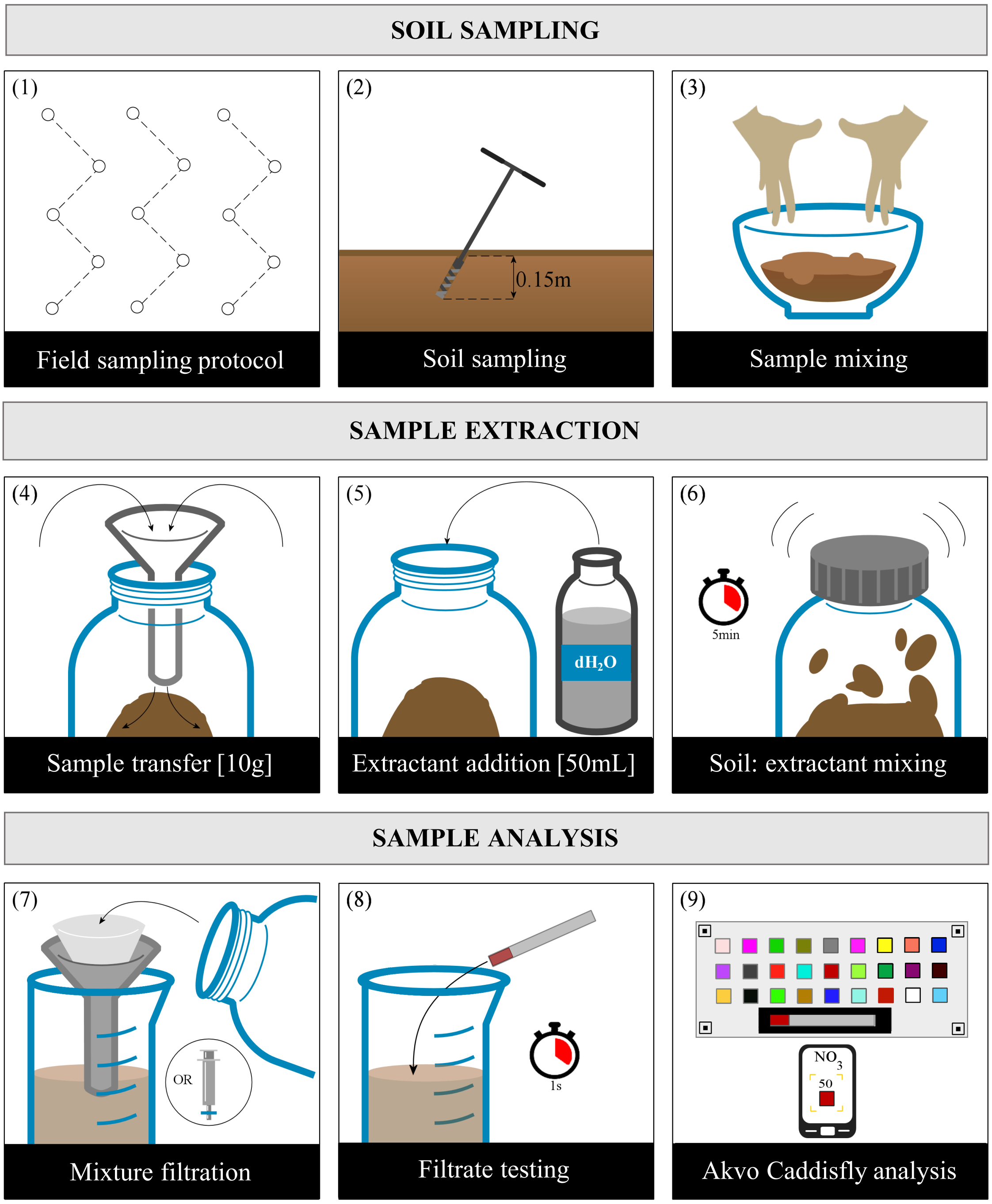


Figure 5-3. Step-by-step protocol of in-field soil sampling, extraction and analysis.

Filtrate testing was conducted using the Quantofix paper strips (manufacturer: Machery-Negel, product reference: 913 51) and the Akvo Caddisfly app, which acted as a portable reflectometer, i.e. a test strip colour reader. Akvo Caddisfly requires a calibration card to adjust colour development in the paper strip during the reaction time (for 60 seconds) and then uses the phone's camera to quantify the amount of available nitrate based on the colour intensity of the reactive pad. After field testing, equivalent numbers of soil and HWDF samples were 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 autoanalyzer (MAFF, 1986). In Ghana, the method involved sample extraction with NaOH and subsequent analysis with a spectrophotometer (Motsara and Roy, 2008). A sub-set of samples collected in Ghana was reanalysed 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 (RB427 Method 53).

5.2.3 Spatial modelling of HWDF application

Two approaches to identifying suitable HWDF landbanks were identified in consultation with stakeholders and the literature, as summarised in **Figure 5-4**. These are listed below:

1. Targeting HWDF application to raise soil organic matter content to a minimum threshold level and applying various 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 HWDF producers for identifying clients

In Scenario 1, the key criterion for identifying suitable landbanks to apply HWDF was to map spatial distribution of soil organic matter content (SOM). Data on soil organic carbon content was adapted from Hengel et al. (2017). Total organic matter content was calculated from the available dataset of organic carbon by applying the Van Bemmelen ratio of organic carbon to SOM of 0.58 (Iglesias Jiménez and Pérez García, 1992). A target minimum threshold of 3% SOM content was set based on recommendations about minimum organic carbon requirements (Adoyele and Omotoso, 2008; Patrick et al., 2013). The requirements for reaching 3% SOM were calculated based on an assumed bulk density of 1.1g cm^{-3} and a soil depth of 0.1m.

Having calculated the initial requirements for organic matter application across Kenya and Ghana, four constraints were proposed 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 on 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 accessible 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. 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.

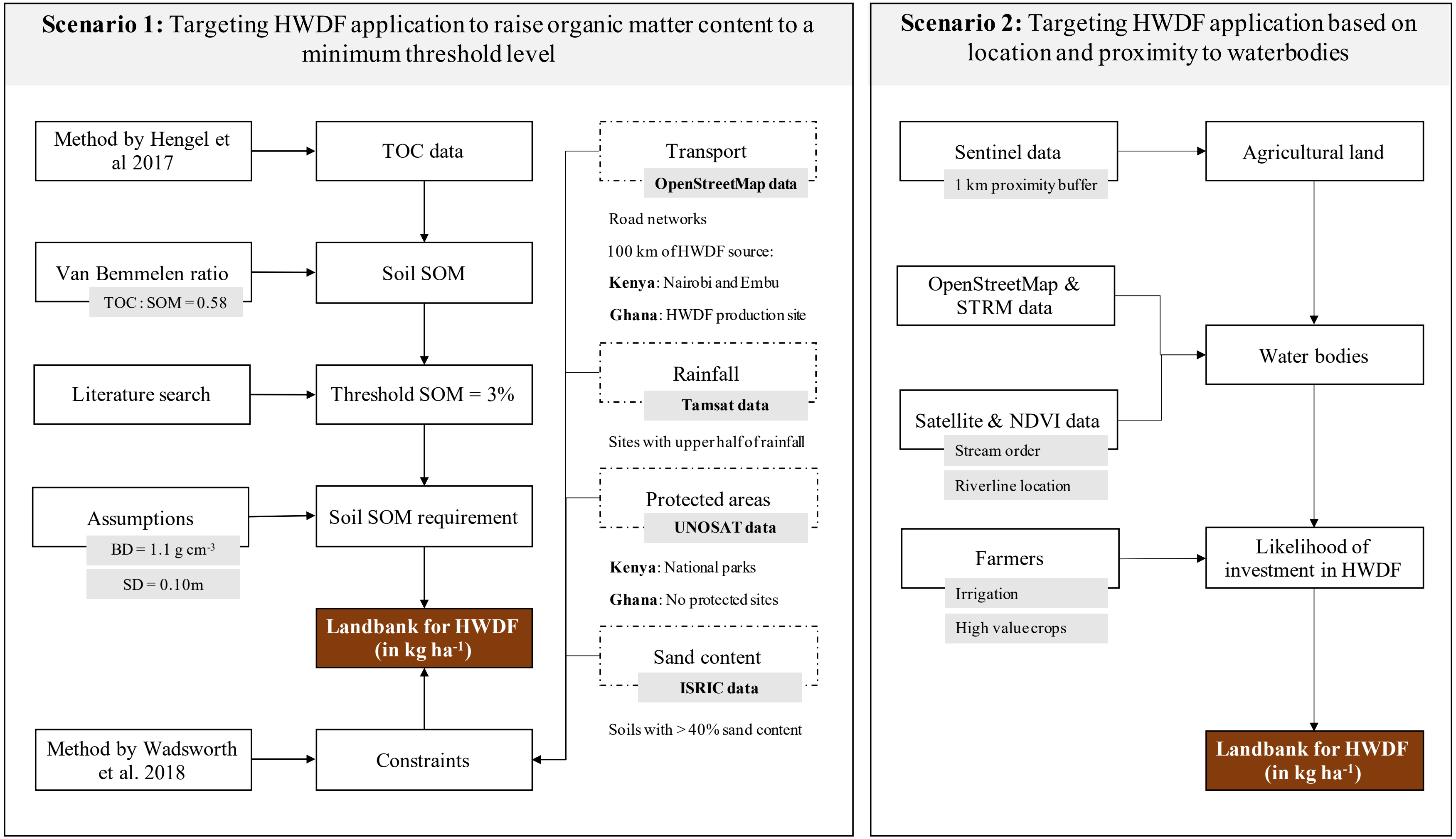


Figure 5-4. Summary of methods applied to formulate maps for identification of HWDF landbanks, for Scenario 1 and Scenario 2.

5.2.4 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. Akvo Caddisfly results were transformed as per method described in **Chapter 3** with limited use of temperature CFs. The average soil residual NO_3-N was converted from mg kg^{-1} to kg ha^{-1} (with soil depth of 15cm and assumed bulk density of 1.1 g 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.

5.3 Results

5.3.1 Background soil information

Background soil information is summarised in **Table 5-1**. In Kenya, 96% of the sampled soils had soil organic matter (SOM) content of over 3%. Soil pH was acidic with 26% of samples having a pH > 6. In Ghana, 86% of the soil samples had a SOM level lower than 3% with an average pH of 6.0. The soil has a broad classification as Ferralsol and Ferric Acrisols for Kenya and Ghana, respectively.

Table 5-1. 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
Mean	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			

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

Figure 5-5A-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 strong agreement between the paper strip readings and the conventional laboratory results with 83% of readings being within ± 8mg kg^{-1} (13.2kg 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. 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.

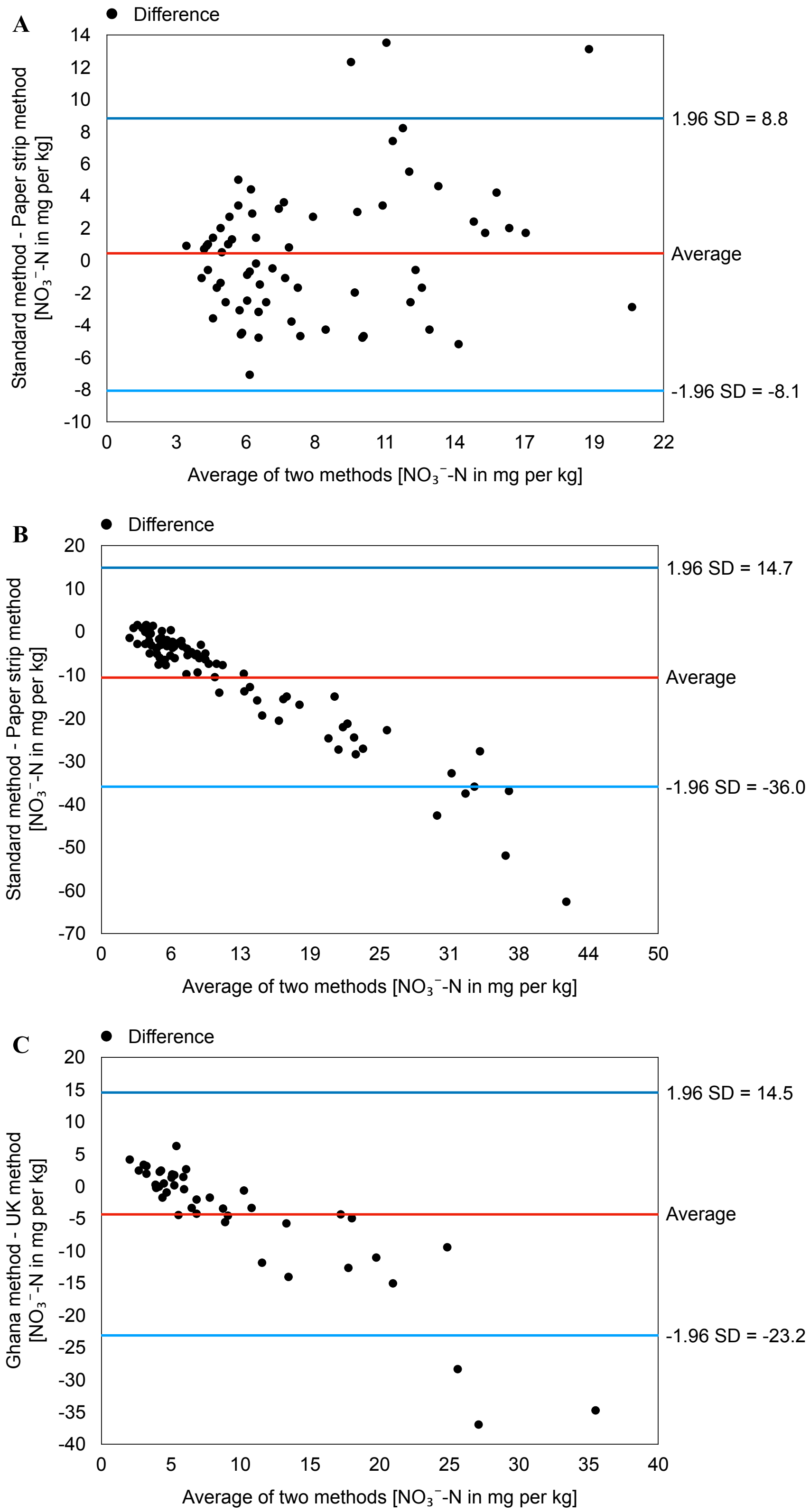


Figure 5-5A-C. Bland-Altman analysis of soil testing methods comparing (A) Kenyan Lab and Paper Strip Methods (N = 68), (B) Ghanaian Lab and Paper Strip Methods (N = 88), and (C) Ghanaian Lab and UK Lab (N = 44). All measurements given in mg kg^{-1} of NO_3-N. The dashed lines represent the error tolerances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

Testing was conducted on 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 330mg kg^{-1} of NO_3^--N with paper strips overestimating HWDF nitrate-N content. Nitrite interference was recorded for 12% of samples.

5.3.3 How this data would influence decisions when applying inputs

Soil mineral 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 20kg ha^{-1}. In Ghana, over 90% of farms had soil N content < 20kg ha^{-1}. In Kenya, the paper strips predicted the required nitrate-N to within ± 10kg ha^{-1} of the laboratory results for 90% farms and within ± 25kg ha^{-1} for all farms (**Figure 5-6A**).

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

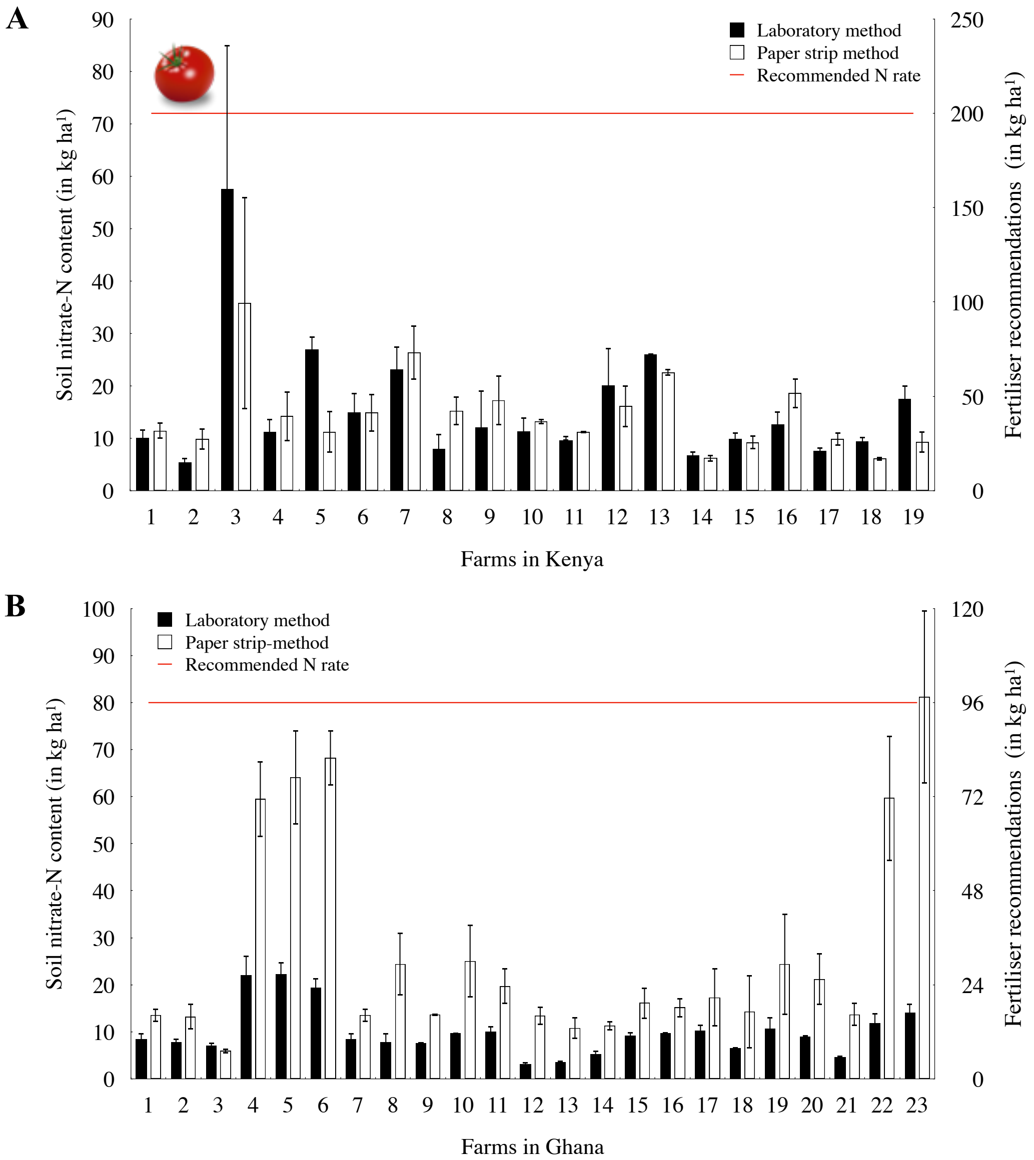


Figure 5-6A-B. Soil nitrate-N content on farms in (A) Kenya and (B) Ghana based on laboratory and in-field testing (Mean ± SE). The red line represents recommended N fertiliser rate for tomato crop as per local guidelines for Kenya and Ghana.

3.4 Mapping of Nutrients and HWDF recommendations for Kenya and Ghana

Using existing spatial datasets for soil properties and yield responses together with other available geospatial information designed to aid agricultural decision making (**Table 5-2**), maps of suitable areas and levels of application of nutrients and HWDF were formulated for Kenya and Ghana.

Table 5-2. Table of input data for mapping with justification and sources.

Data Source Required	Justification	Sources
Soil Texture	Has a large influence on possible yields and crops	WOSSAC Hengl et al., 2017 Kenyan Government Agro-Economical Zones Batjes and Gicheru, 2004
Nutrients and pH	Has a large influence on possible yields and crops	Hengl et al., 2017 Fieldwork testing
Climate	Helps determine 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

HWDF application is 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 based on two scenarios outlined in Section 5.2.3 (**Figure 5-7A-D**). In Kenya, SOM in the areas surrounding Embu was above 3% with no need for HWDF application to reach the minimum threshold (**Figure 5-7A,C**). The HWDF hotspots requiring heavy applications of organic matter were located to the East and South-East of Embu (**Figure 5-7A,C**). In Ghana, the areas surveyed had 3% SOM content and were identified as landbanks for HWDF (**Figure 5-7B, D**). The models corresponded to fieldwork results, shown in Table 1.

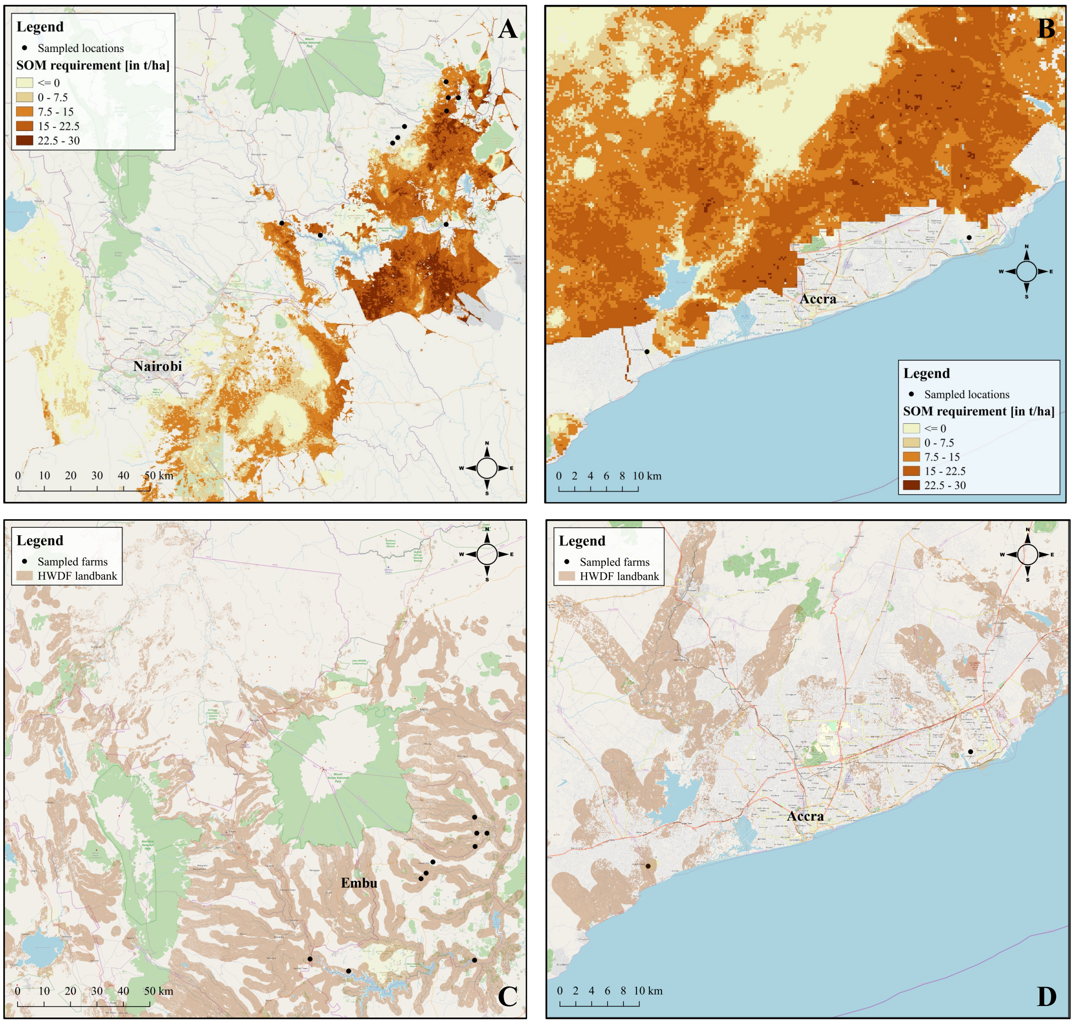


Figure 5-7A-D. Maps of soil application for Scenario 1 (A - Kenya and B - Ghana) and Scenario 2 (C - Kenya and D - Ghana).

5.4 Discussion

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

Paper strips were successfully employed 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 ± 10mg kg^{-1} (Golicz et al., 2019; **Chapter 4: Figure 4-5**). Those results are consistent with other paper strip studies, where the deviation from the standard method can range between 19.9mg kg^{-1} and –55.7mg kg^{-1} (Golicz et al., 2020; **Chapter 6: Table 6-3**).

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 nitrate-N 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 do not correspond to either paper strips or European standard methods. In soil sciences, the choice of extractant, testing methodologies, equipment, and their impact on soil test results are well documented (Pittman et al., 2005; Sikora et al., 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 the exception of five farms, in determining that the investigated soils were low in N content. This should encourage farmers to invest in mineral and HWDF-derived fertilisers. Low fertility soils are the most responsive to fertiliser treatment (Tittonell et el., 2008), and so fertiliser applications in these areas are likely to result in high return on investment with limited inputs (Aune et al., 2017). Chemical interference with colour development and high ambient temperature are likely to have contributed to overestimation of soil 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 et al., 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 measurements 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 interference (Jemison and Fox, 1988) when the concentration of interfering compounds exceeds the quantity specified by the paper strip manufacturer. Maggini et al. (2010) investigated a range of quick test kits developed for nitrate, ammonium and phosphate assessment and found that interference from foreign substances resulted in severe distortions of 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.

5.4.2 Practical considerations of soil and HWDF testing protocol

There were several practical considerations that constrained the use of the 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. Whatman 4V filter 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 Whatman 4V filter 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 5-point 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; **Chapter 6: Figure 6-2**) 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. Golicz et al., 2020 (**Chapter 6**: **Figure 6-3**) 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; **Appendix B: Figure 8-3**) to account for temperature effects, for each measurement.

5.4.3 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. These datasets were used to identify landbanks for HWDF in two different scenarios, bringing soil up to a minimum quality threshold, and using HWDF-producer criteria to target farmers who irrigate. 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 qualities 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.

5.5 Conclusion

This paper assessed the potential of two technologies to assist in 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 accurate 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 landbanks, 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 landbanks for HWDF.

5.6 References

Adoyele OJ, Omotoso OS (2008) Nutrient Management for Maize Production in Soils of the Savannah Zone of South-Western Nigeria. Int J Soil Sci 3:20–27. doi: 10.3923/ijss.2008.20.27

Aune JB, Coulibaly A, Giller KE (2017) Precision farming for increased land and labour productivity in semi-arid West Africa. A review. Agron Sustain Dev 37:. doi: 10.1007/s13593-017-0424-z

Batjes N, Gicheru P (2004) Soil data derived from Soter for studies of carbon stocks and change in Kenya (ver 1.0; GEFSOC Project). Repor 2004/01, ISRIC- World Soil Information, Wageningen

Bland JM, Altman DG (2003) Applying the right statistics: Analyses of measurement studies. Ultrasound Obstet Gynecol 22:85–93. doi: 10.1002/uog.122

Chauvin ND, Mulangu F, Porto G (2012) Food Production and Consumption Trends in Sub-Saharan Africa: Prospects for the Transformation of the Agricultural Sector. Work Pap 2012-11 76. doi: 10.1016/j.foodpol.2013.10.006

Cofie O, Adeoti A, Nkansah-Boadu F, Awuah E (2010) Farmers perception and economic benefits of excreta use in southern Ghana. Resour Conserv Recycl 55:161–166. doi: 10.1016/j.resconrec.2010.09.002

Cofie OO, Kranjac-Berisavljevic G, Drechsel P (2005) The use of human waste for peri-urban agriculture in Northern Ghana. Renew Agric Food Syst 20:73–80. doi: 10.1079/RAF200491

Dalton TJ, Yahaya I, Naab J (2014) Perceptions and performance of conservation agriculture practices in northwestern Ghana. Agric Ecosyst Environ 187:65–71. doi: 10.1016/j.agee.2013.11.015

de Putter H (2009) Tomato cultivation recommendation for the Kirinyaga area. Accessed from: https://edepot.wur.nl/13876

FAO (2015) Statistical Pocketbook: World food and agriculture. Accessed from: http://www.fao.org/3/a-i4691e.pdf

FAO (2006) Farm Management Handbook of Kenya Vol. Ii. II:319. Accessed from: https://library.wur.nl/isric/fulltext/isricu_i00023897_001.pdf

Gikonyo EW, Zaharah AR, Hanafi MM, Anuar AR (2010) Comparison of Soil Phosphorus Tests for Assessing Plant Availability of Phosphorus in an Ultisol Amended with Water-Soluble and Phosphate Rock Sources. Sci World J

10:1679–1693. doi: 10.1100/tsw.2010.174

Golicz K, Hallett SH, Sakrabani R (2020) Novel procedure for testing of soil field test kits involving paper strips. Soil Use Manag 00:1–11. doi: 10.1111/sum.12582

Golicz K, Hallett SH, Sakrabani R, Pan G (2019) The potential for using smartphones as portable soil nutrient analyzers on suburban farms in central East China. Sci Rep 9:1–10. doi: 10.1038/s41598-019-52702-8

Google (2017) Kenya Crops and Fertiliser App: Google Play Store

Guzha E, Nhapi I, Rockstrom J (2005) An assessment of the effect of human faeces and urine on maize production and water productivity. Phys Chem Earth 30:840–845. doi: 10.1016/j.pce.2005.08.028

Hallett SH, Sakrabani R, Keay CA, Hannam JA (2017) Developments in land information systems: examples demonstrating land resource management capabilities and options. Soil Use Manag 33:514–529. doi: 10.1111/sum.12380

Hengl T, Leenaars JGB, Shepherd KD, et al (2017) Soil nutrient maps of Sub-Saharan Africa: assessment of soil nutrient content at 250 m spatial resolution using machine learning. Nutr Cycl Agroecosystems 109:77–102. doi: 10.1007/s10705-017-9870-x

ICPAC (2017) ICPAC GeoPortal Maps- Kenya Protected Areas. Accessed from: http://geoportal.icpac.net/layers/geonode%3Aken_protected_areas

Iglesias Jiménez E, Pérez García V (1992) Relationships between organic carbon and total organic matter in municipal solid wastes and city refuse composts. Bioresour Technol 41:265–272. doi: 10.1016/0960-8524(92)90012-M

Jemison JM, Fox RH (1988) A quick-test procedure for soil and plant tissue nitrates using test strips and a hand-held reflectometer. Commun Soil Sci Plant Anal 19:1569–1582. doi: 10.1080/00103628809368035

Korentajer L (1991) Review of the agricultural use of sewage sludge. Benefits and potential hazards. Water SA 17:189–196

Mallory A, Crapper M, Gyasi SF, Boamah B (2016) A socio-economic analysis of different approaches to faecal sludge treatment in Sunyani, Ghana. In: WEDC International Conference. pp 1–6

Mallory A, Crapper M, Holm RH (2019) Agent-Based Modelling for Simulation-Based Design of Sustainable Faecal Sludge Management Systems. Int J Environ Res Public Health 16:1125. doi: 10.3390/ijerph16071125

Mariwah S, Drangert JO (2011) Community perceptions of human excreta as fertiliser in peri-urban agriculture in Ghana. Waste Manag Res 29:815–822. doi: 10.1177/0734242X10390073

Mnkeni PNS, Austin LM (2009) Fertiliser value of human manure from pilot urine-diversion toilets. Water SA 35:133–138. doi: Article10.4314/wsa.v35i1.76717

Nyi T, Varughese P, bin Hj Bujang MI, et al (2017) ASEAN Guidelines on Soil and Nutrient Management. Bangkok

Omran E-SE (2017) Will the Conventional Soil-Plant Analysis Pass into Oblivion? Rapid and Low-Cost Determination Using Spectroscopy. Commun Soil Sci Plant Anal 48:705–715. doi: 10.1080/00103624.2017.1298782

Parker BMA, Mesa RSB (2017) Evaluating the Efficacy of Fertilisers Derived from Human Excreta in Agriculture and Their Perception in Antananarivo, Madagascar. Waste and Biomass Valorization 0:0. doi: 10.1007/s12649-017-0113-9

Patrick M, Tenywa JS, Ebanyat P, et al (2013) Soil Organic Carbon Thresholds and Nitrogen Management in Tropical Agroecosystems: Concepts and Prospects. J Sustain Dev 6:. doi: 10.5539/jsd.v6n12p31

Pittman JJ, Zhang H, Schroder JL, Payton ME (2005) Differences of phosphorus in Mehlich 3 extracts determined by colorimetric and spectroscopic methods. Commun Soil Sci Plant Anal 36:1641–1659. doi: 10.1081/ CSS-200059112

Schmidhalter U (2005) Development of a quick on-farm test to determine nitrate levels in soil. J Plant Nutr Soil Sci 168:432–438. doi: 10.1002/jpln.200520521

Sikora, F. J. Howe, P. S. Hill, L. E. Reid, D. C. Harover DE (2005) Comparison of Colorimetric and ICP Determination of Phosphorus in Mehlich3 Soil Extracts. Commun Soil Sci Plant Anal 36:875–887. doi: http://dx.doi.org/10.1081/CSS-200049468

Tittonell P, Vanlauwe B, Corbeels M, Giller KE (2008) Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant Soil 313:19–37. doi: 10.1007/s11104-008-9676-3

Wadsworth R, Hallett S, Sakrabani R (2018) Phosphate acceptance map: A novel approach to match phosphorus content of biosolids with land and crop requirements. Agric Syst 166:57–69. doi: 10.1016/j.agsy.2018.07.015

Wetselaar R, Smith GD, Angus JF (1998) Field measurement of soil nitrate concentrations. Commun Soil Sci Plant Anal 29:729–739. doi:

10.1080/00103629809369980

World Bank (2018) Fertiliser consumption (kilograms per hectare of arable land). Accessed from: https://data.worldbank.org/indicator/AG.CON.FERT.ZS

Vandendriessche H, van Neck T, Bijnens O, Elsen A (2011) Residual soil nitrate: A comparison between air-dried and field-moist soil samples. Commun Soil Sci Plant Anal 42:1847–1854. doi: 10.1080/00103624.2011.587575

Chapter 6: Novel procedure for testing of soil field test kits involving paper strips

Summary: This chapter combines data collected across laboratory and field experiments to design a process that can assist with streamlining testing procedures for in-field soil test kits involving paper strips (Objective 4). It also emphasises the importance of employing appropriate statistical methodology to assess the level of agreement (not association) between two methods by revisiting results of other published paper strip-oriented studies.

Highlights:

- Four types of nutrient-sensitive test strips were investigated in relation to agreement with standards and standard deviations associated with reflectometer readings;
- Extractants frequently employed in soil science were found to impact the colour development of the test strips' reactive pads;
- Environmental factors such as temperature and in-field dilution were found to decrease the accuracy of test strip readings;
- A number of qualitative observations was summarised based on field work experiences;
- A decision support tree, which outlined every step that was found to be important for test strip application in soil science, was proposed to streamline testing of similar products prior to field work;
- Explanation of Bland-Altman statistic was included, and the method proposed as an alternative to correlations and regressions usually employed in test strip-oriented studies.

Data access: Data underlying this study is accessible through Cranfield University's repository at https://10.17862/cranfield.rd.11193668.

Published as: Golicz K, Hallett SH, Sakrabani R (2020) Novel procedure for testing of soil field test kits involving paper strips. Soil Use Manag 00:1–11. doi: 10.1111/sum.12582

6.1 Introduction

Soil testing is one of the oldest and most well established tools in agricultural management (Sims et al., 2000). For decades, agronomists have used soil tests to stipulate fertiliser recommendations in order to safeguard the economic viability of agricultural operations and to limit the environmental impacts associated with the continuous use of commercial fertilisers (Gartley et al., 2002; Dawson and Hilton 2011; Zhang et al., 2017). However, soil testing can prove costly, time-consuming, impractical to carry out as the crop season progresses, prone to sampling and laboratory errors, and often requiring the use of noxious chemicals as part of standard analytical procedures (Omran, 2017). These limitations can impede the incorporation of soil testing as a method for assessment of soil physical, chemical and biological properties and can further discourage agricultural workers from utilising them at the recommended time intervals. This is significant as, in the UK, there is an increased emphasis on soil health (Department for Environment Food and Rural Affairs, 2020), and the means to monitor contributory soil conditions. Tools are required for such assessments that are simple to use and widely accessible to landowners.

The lack of access to effective, low-cost and site-specific alternatives to current soil testing methods has been recognised as one of the factors contributing to mismanagement of fertiliser resources (Prager and McKee, 2014). In developed countries such as the US and Australia, only about a quarter of farmers undertake soil testing which is noted to be infrequent and conducted at low densities (Lobry de Bruyn and Andrews, 2016). In emerging economies, this rate is not only lower but is often arbitrary and not site-specific (Ju et al., 2009) with overfertilisation being the common outcome, regardless of the severe consequences for agricultural productivity and the wider environment (Song et al., 2009). Recently, there has been renewed interest in creation of soil test kits optimised for agronomical field use as a result of increasing access to technology such as portable sensors (Piikki et al., 2016). Key to this is the rising ubiquity of smartphones which are being increasingly used in environmental management applications (Aitkenhead et al., 2014) and soil science (Delgado et al., 2013; Aitkenhead et al., 2015; Stiglitz et al., 2017).

Semi-quantitative test strips, used in combination with a reflectometer able to quantify test strip colour has been proposed as a method of quick in-field assessment of soil nutrient status in the US, Germany, Spain, and Australia (Jemison and Fox, 1988; Wetselaar et al., 1998; Schmidhalter, 2005; Thompson et al., 2013). Such strips are frequently included in field soil test kits. In developing countries, in particular, they are a preferred method by which extension workers collect soil information to better inform agronomic decisions of smallholder farmers (Nyi et al., 2017). Non-governmental organisations concerned with sustainable development such as Akvo (www.akvo.org) have shown interest in utilising test strips in environmental analysis by employing smartphones to act as portable reflectometers to relate the colour of the test strip to the quantity of measured chemical more precisely than can the naked eye. This technology offers great prospects for soil testing for fertiliser recommendation purposes in near future.

The aim of this work is to provide a comprehensive set of procedures that needs to be considered at the developmental stage of new in-field soil test kits that involve semi-quantitative colorimetric test strips.

6.2 Methods

6.2.1 Test strips and reflectometers

The set of procedures was developed based on metadata collected across two long-term (>2 years long) experiments undertaken at Cranfield University, UK, where laboratory works were conducted; and Nanjing Agricultural University, People's Republic of China (PRC), where fieldwork was conducted. The laboratory in the UK provided the preparatory work, which supported the field study in PRC. The reason for considering field study in PRC, where soil samples were collected from smallholder vegetable farms, was due to limited access to soil information resulting in sub-optimal fertiliser use and associated diminished economic returns and potential for environmental damage resulting from overfertilisation, especially in relation to multi-season horticultural crops. The experiments constitute a part of an ongoing study testing viability of employing smartphones and test strips as a practicable method of soil analysis.

Four test strips types were selected for use during those experiments:

- Quantofix (reference number: 913 51) nitrate strips (range: 0-100mg L^{-1} of NO_3^-);
- Quantofix (reference number: 913 20) phosphate strips (range: 0-100mg L^{-1} of PO_4^{3-});
- Quantofix (reference number: 913 15) ammonium strips (range: 0-400mg L^{-1} of NH_4^+); and,
- Merck KGaA® (reference number: 117985) potassium strips (range: 0-1500mg L^{-1} of K).

At the commencement of this study, another nitrate test strip (Hatch) was selected for testing, however, its production was discontinued and thus, Quantofix (reference number: 913 51) was given preference. Two types of reflectometers were employed during testing, i.e. Quantofix Relax Test Strip Reader (**Figure 6-1**) and Akvo Caddisfly app (ver. 10) installed on a Samsung Galaxy S8 phone. Comparison between the commercial grade reflectometer and the smartphones application will not be explored in detail in this paper.

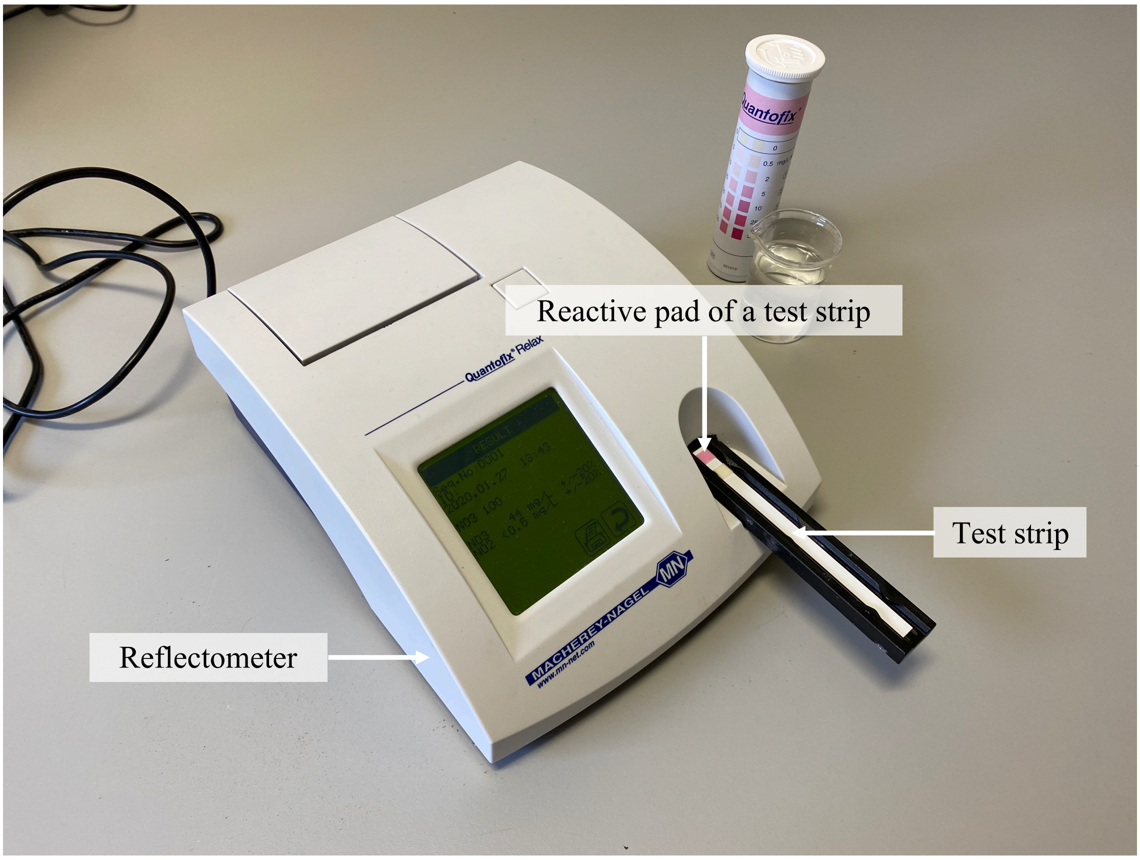


Figure 6-1. Test strip and reflectometer used as a method of in-field soil nutrient assessment.

As the need for accurate in-field soil nutrient measurement is particularly great amongst smallholder farmers, the test strips were tested in relation to:

- How strongly they agreed with standard solutions;
- Standard deviation expected for readings at different concentrations;
- Interferences to colour development caused by soil test extractants;
- Sensitivity to chemical interferences likely to be encountered in the soil media and other environmental factors.

6.2.2 Laboratory study

Standards were prepared in accordance with standard operating procedures developed by Cranfield University. A set of 1000ppm stock solutions were prepared for nitrate using 6.068g of oven-dry $NaNO_3$ (Sigma-Aldrich, CAS number: 7631-99-4) diluted to 1000mL, 1mL of 1000μg of P (Fisher Scientific, Catalogue number: J829805), 3.819g of NH_4Cl (Fisher Scientific, CAS number: 12125029) diluted to 1000mL and 2.590g of KNO_3 (Fisher Scientific, CAS number: 7757791) diluted to 1000mL. The stock solutions were then diluted to concentrations stipulated by the test strip manufacturer in matrix-matched solutions, which correspond to the extractants frequently used in soil analysis (**Table 6-1**).

Table 6-1. Stock standards diluted to concentrations stipulated by test strip manufacturers in matrix-matched solutions. Selected matrix solutions correspond to those frequently utilised in soil analysis.

	Standards						Unit	Matrix
	1	2	3	4	5	6		
Nitrate	5	10	25	50	75	100	mL L^{-1}	dH_2O, 2M KCl, 0.2KCl, 0.02KCl, M-1*
Phosphate	3	10	25	50	100	N/A	mL L^{-1}	dH_2O, M-1, Olsen-P**, MM***
Ammonium	10	25	50	100	200	400	mL L^{-1}	dH_2O, 0.2KCl, 0.02KCl, 0.02M $CaCl_2$
Potassium	250	450	700	100	1500	N/A	mL L^{-1}	dH_2O, M-1, 1M NH_4NO_3

*Mehlich-1 [0.05 N HCL + 0.025 N H_2SO_4]; **Olsen-P [0.5 N $NaHCO_3$ adjusted to pH 8.5], ***Modified Morgan [0.62M NH_4OH + 1.25M CH_3COOH]

The reflectometer was used to investigate the agreement with stock solutions in distilled water (dH_2O), the standard deviations associated with readings obtained with the reflectometer and the impact of different extractants on colour development on the test strips' reactive pads. The stock solutions and extractants were made on the day of measurement. Employment of test strips during testing followed the manufacturer's instructions. Readings were taken on the same day, under constant laboratory temperature of 20.5°C. As temperature was identified as a significant factor influencing the reaction time and thus, colour change of the test strip; a set of experiments was carried out to quantify its effect. Two test strip types, i.e. Quantofix nitrate and phosphate, were considered to have the highest potential for use in the context of soil science and thus, selected for the experiment conducted in a plant growth chamber [Weiss Technik SGR Series of

Fitotron walk-in-rooms; model: SGR221 LED], which is part of the Agriculture Engineering Precision and Innovation (AgriEPI) Centre, located at Cranfield University. AgriEPI forms part of the national Agritech facility in the UK. The humidity was set at 70% and the investigated temperatures were: 15, 20, 25, 30, and 35°C. Solution temperature was measured with a laboratory approved thermometer to confirm it matched the ambient temperature of the plant-growth chamber. Each standard solution for nitrate and phosphate was measured with 5 test strips at every temperature setting.

6.2.3 Field study

Furthermore, consideration was given to field-ready practicality of soil extraction process and lack of precision and accuracy relating to reduced access to laboratory equipment in field conditions. Multiple soil to extractant ratios, i.e. 1:1, 1:2.5 and 1:5 were investigated with latter having been found to be the most practical for field-use, especially in relation to heavy clays. Two soil standard reference materials (Sigma Aldrich CRM700 and CRM702) were used to investigate how dilution impacts precision of the best performing test strip type. The samples were extracted with distilled water for 2hr on a side-to-side shaker and then, diluted. Sample dilution factors were 2, 3.3, 5, and 10, then being analysed with the reflectometer. A field sample was extracted and diluted in non-laboratory conditions, as part of the field study carried out in People's Republic of China (See **Chapter 4** for details) with the results of in-field dilution being compared to results of in-lab dilution.

6.2.4 Statistical analysis

It is of particular note that care is needed when employing statistical tests such as correlations and ANOVA in method comparison studies, as the bias and absolute (Δ) difference between standard laboratory and 'quick tests' might be less likely to be highlighted. Bland and Altman (2003) advocated the use of Bland-Altman (B-A) plots to investigate the degree of agreement between two methods. The B-A analysis involves constructing a scatter plot, in which the difference between the paired measurements is plotted on y-axis and average of the measures of two methods on 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). This approach should be employed alongside scaling the results from mg kg^{-1} to kg ha^{-1}, which is more relevant for soil practitioners but is often overlooked in test strip studies.

6.3 Results

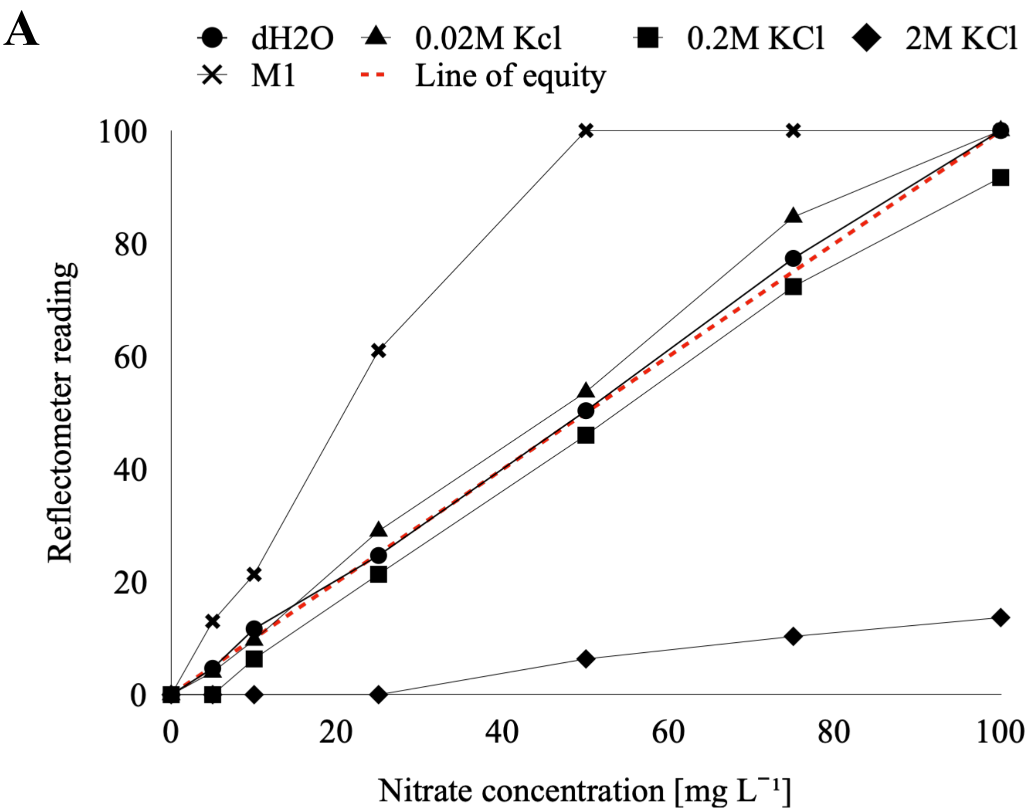
6.3.1 Laboratory based evaluation and validation of four test strip types currently available for purchase

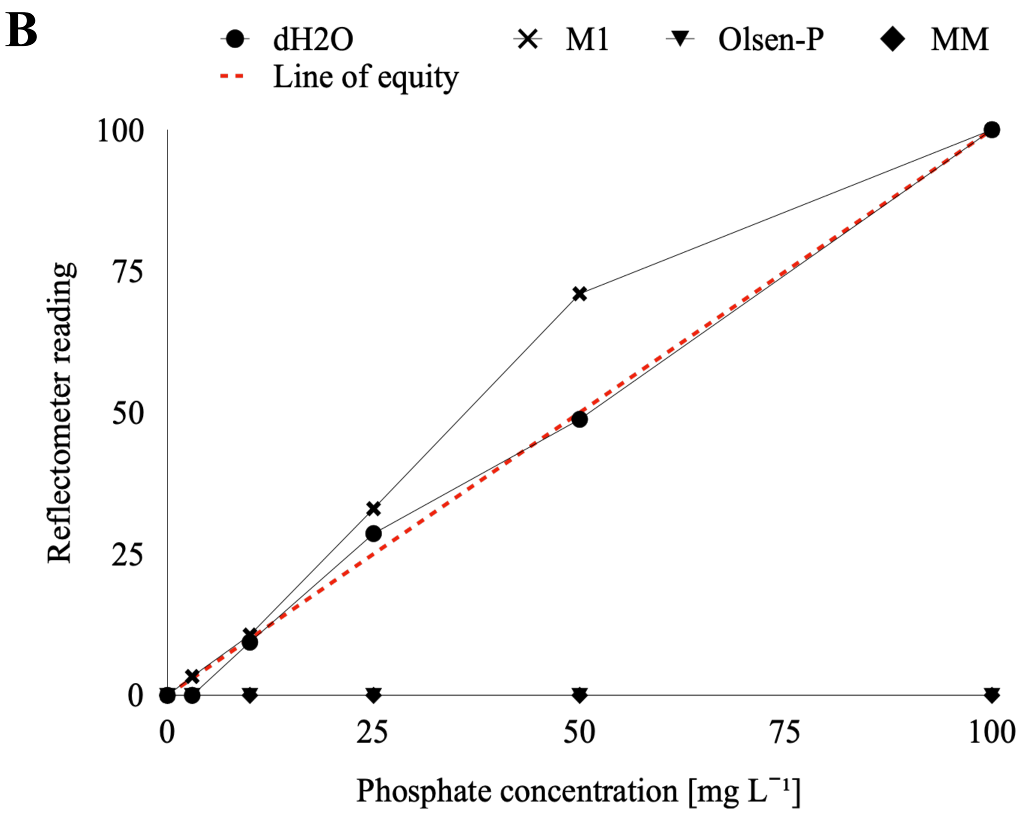
The agreement (± SD) between four test strip types and corresponding stock standards was assessed **(Table 6-2**). Test strips developed to measure nitrate and phosphate had the highest agreement with stock standards and the lowest standard deviation associated with reflectometer readings.

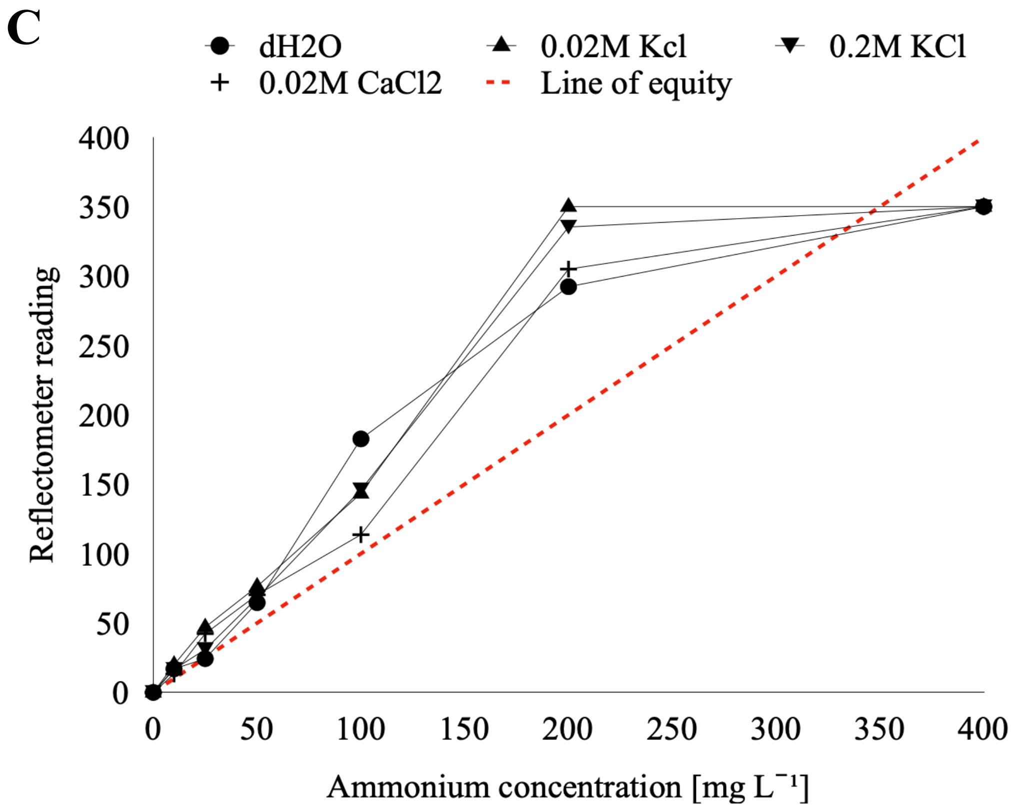
Table 6-2. Deviation from the standard (in dH_2O). Red denotes deviation > 5ppm; green denotes deviation < 5ppm. Standard deviations of reflectometer readings for standards in dH_2O.

	Standards (in dH_2O)					
	1	2	3	4	5	6
	Deviation from the standard [Mean, N=5]					
Nitrate	2	0	0	-2	-2	0
Ammonium	-7	1	-15	-83	-92	0
Phosphorus	3	0.6	-3.6	-1.2	0	N/A
Potassium	-42	-58	-50	-70	-213	-230
	Standard deviation of reflectometer readings [STDV, N=5]					
Nitrate	2.1	0.9	2.5	3.3	4.0	0
Ammonium	5.0	2.0	2.0	22.0	31.0	0
Phosphorus	0.6	0.6	4.6	2.6	0.0	N/A
Potassium	7.6	2.9	7.6	4.0	11.4	0

The level of agreement between test strips and stock standards was reduced when a soil extractant was utilised as a matrix (**Figure 6-2A-D**). Highly concentrated extractants were found to cause severe interferences to colour development in all test strip types. Interferences were also noted for extractants with low molar concentrations, such as Mehlich-1 (0.05M HCl in 0.025M H_2SO_4) and 0.02 KCl, with distilled water consistently providing the best results.


A
dH2O
0.02M Kcl
0.2M KCl
2M KCl
M1
Line of equity
Reflectometer reading
0
20
40
60
80
100
Nitrate concentration [mg L⁻¹]


B
dH2O
M1
Olsen-P
MM
Line of equity
Reflectometer reading
0
25
50
75
100
Phosphate concentration [mg L⁻¹]



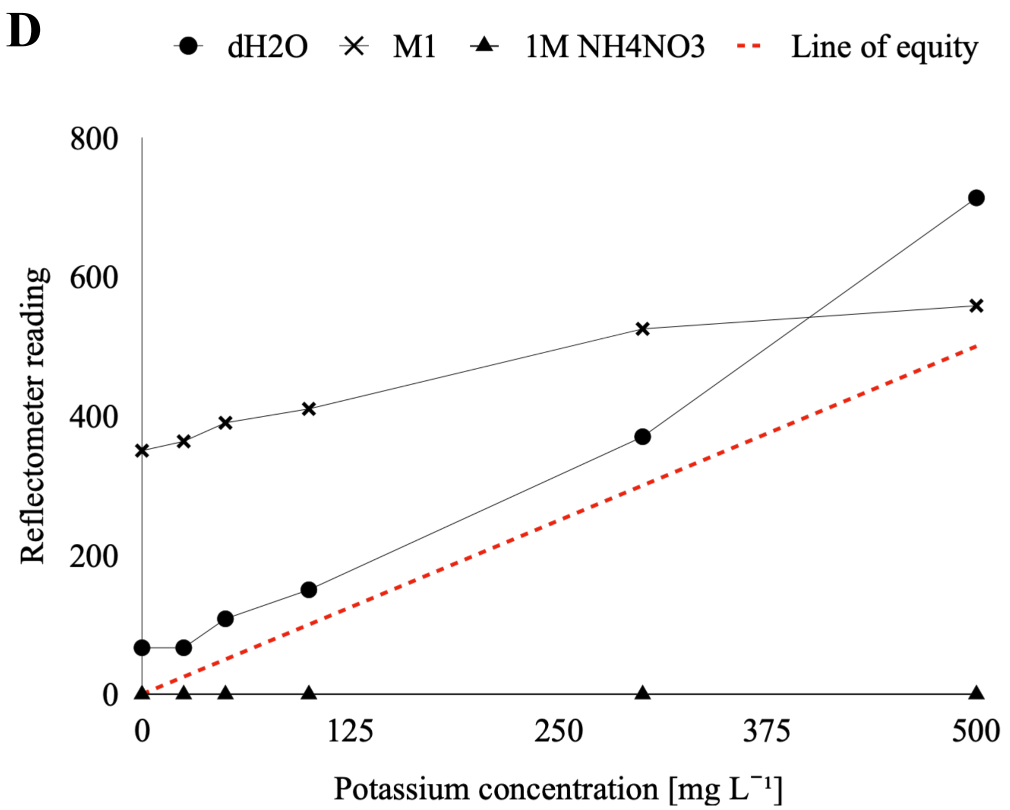
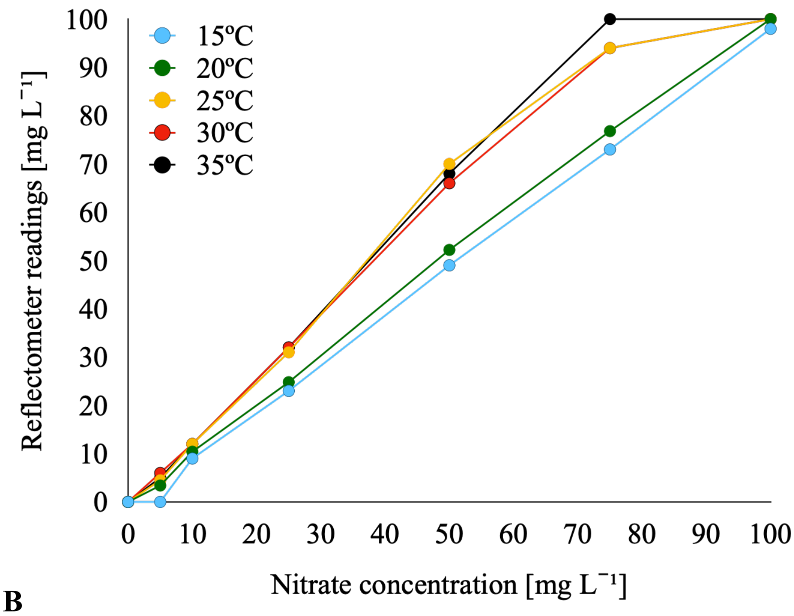


Figure 6-2A-D. Impact of extractants on four commercial test strip types used for measurement of nitrate (A), phosphate (B), ammonium (C) and potassium (D).

Furthermore, test strips were found to be susceptible to environmental factors, particularly temperature effects. At high temperatures, the concentration of measured chemical present in the solution is severely overestimated, e.g. at 35°C, reflectometer readings overestimate standard concentration by 25mg L^{-1} for NO_3^- (**Figure 6-3A**) and 30mg L^{-1} for PO_4^{3-} (**Figure 6-3B**).

A



B

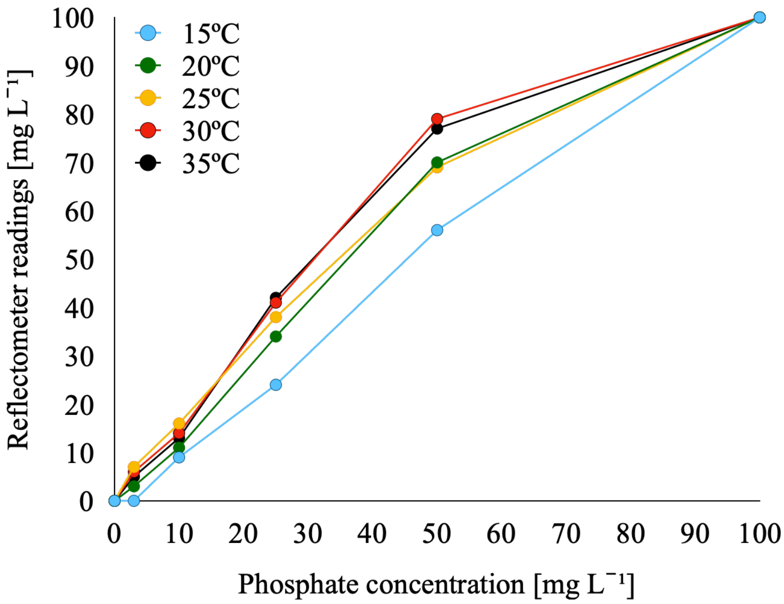


Figure 6-3A-B. Impact of temperature on test strip colour development and subsequent reflectometer reading. At high temperatures; the readings are overestimated.

6.3.2 Insights from field experiments

When recently fertilised fields were sampled, test strips with low range, i.e. 0 to 100 mL L^{-1} of NO_3^-, required sample dilution. Dilution was shown to be effective in the laboratory environment where access to suitable equipment is facilitated (**Figure 6-4A**), but it reduced the accuracy of the method in the field conditions (**Figure 6-4B**).

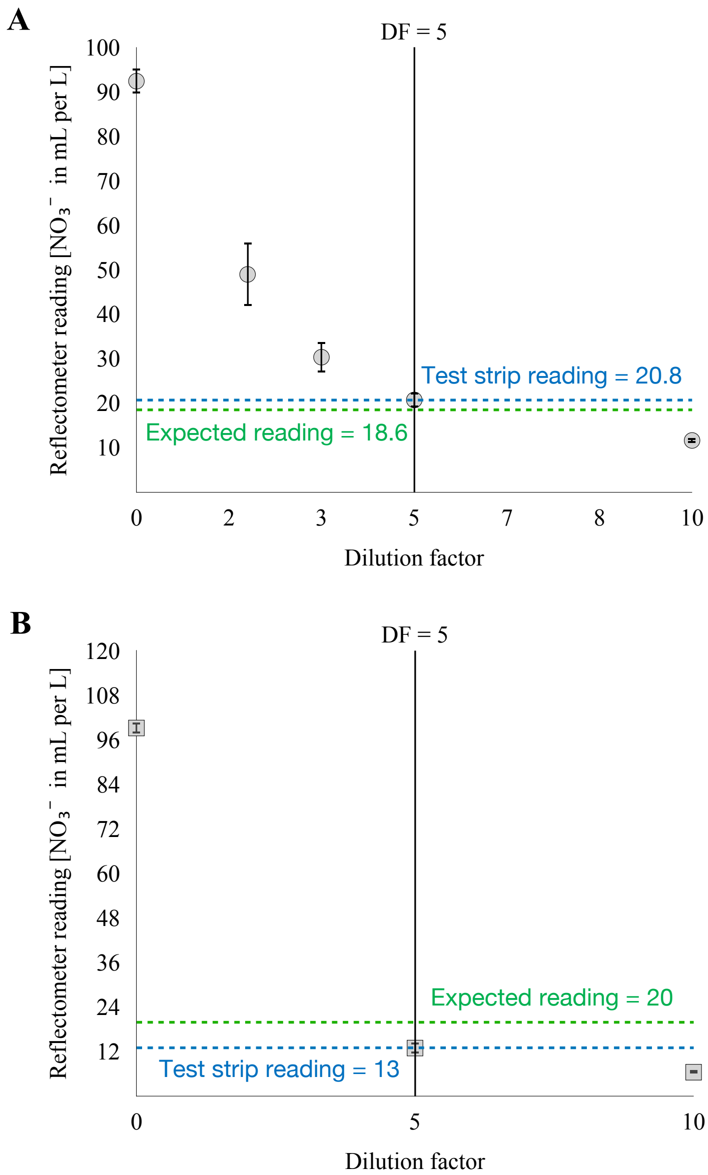
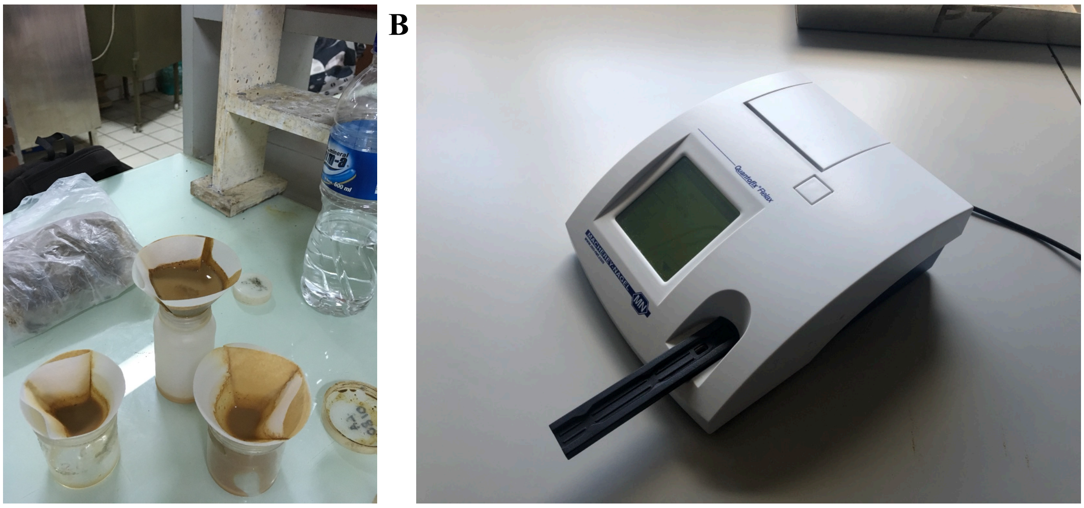


Figure 6-4A-B. In-lab dilution (A) vs in-field dilution (B), and its effect on the reflectometer readings' accuracy.

Similarly, whereas filtration in controlled laboratory conditions is allowed to take up to a few hours when soil to extractant ratio is high, this approach was highly impractical in the field conditions (**Figure 6-5A**). Furthermore, during field trials, multiple issues with hardware, i.e. the reflectometer were identified, including: (1)

low resistance to humidity, (2) high battery consumption, and (3) abrasion caused by sand (**Figure 6-5B**).



A: Impractical soil to extractant ratio

B: 1. Expensive; 2. Low resistance to humidity / radiation; 3. High battery consumption; 4. Abrasion caused by wind / sand; 5. Hard to get replacement parts; 6. Works with limited test strips types

Figure 6-5A-B. Factors to be considered during the planning stage of a field study designed to test the accuracy and precision of soil field test kits. Field experiments might expose unexpected issues with equipment and methodology that would not have been noted in a study conducted under the controlled laboratory conditions.

6.3.3 Proposed procedure for preliminary testing of soil field test kits involving paper strips

Multiple variables were investigated to optimise choices for selection of soil field test kit apparatus during laboratory and field studies, which considered the viability of employing semi-quantitative colorimetric test strips in soil analysis. As the experiments were conducted throughout two years alongside other studies, there was a limited sequence to the actions taken.

Whereas formulation of new methodology for test strip use (for detailed examples see Hartz, 1994 and Jemison & Fox, 1988) will always involve an element of trial and error, a summary of organised actions designed to streamline testing procedures is described in **Figure 6-6**.

This set of procedures is presented as a decision support tool and was derived from the laboratory and field studies and field observations. Each step can be considered separately or as a sequence of steps to identify limitations at the developmental stage of new in-field soil test kits involving paper strips.

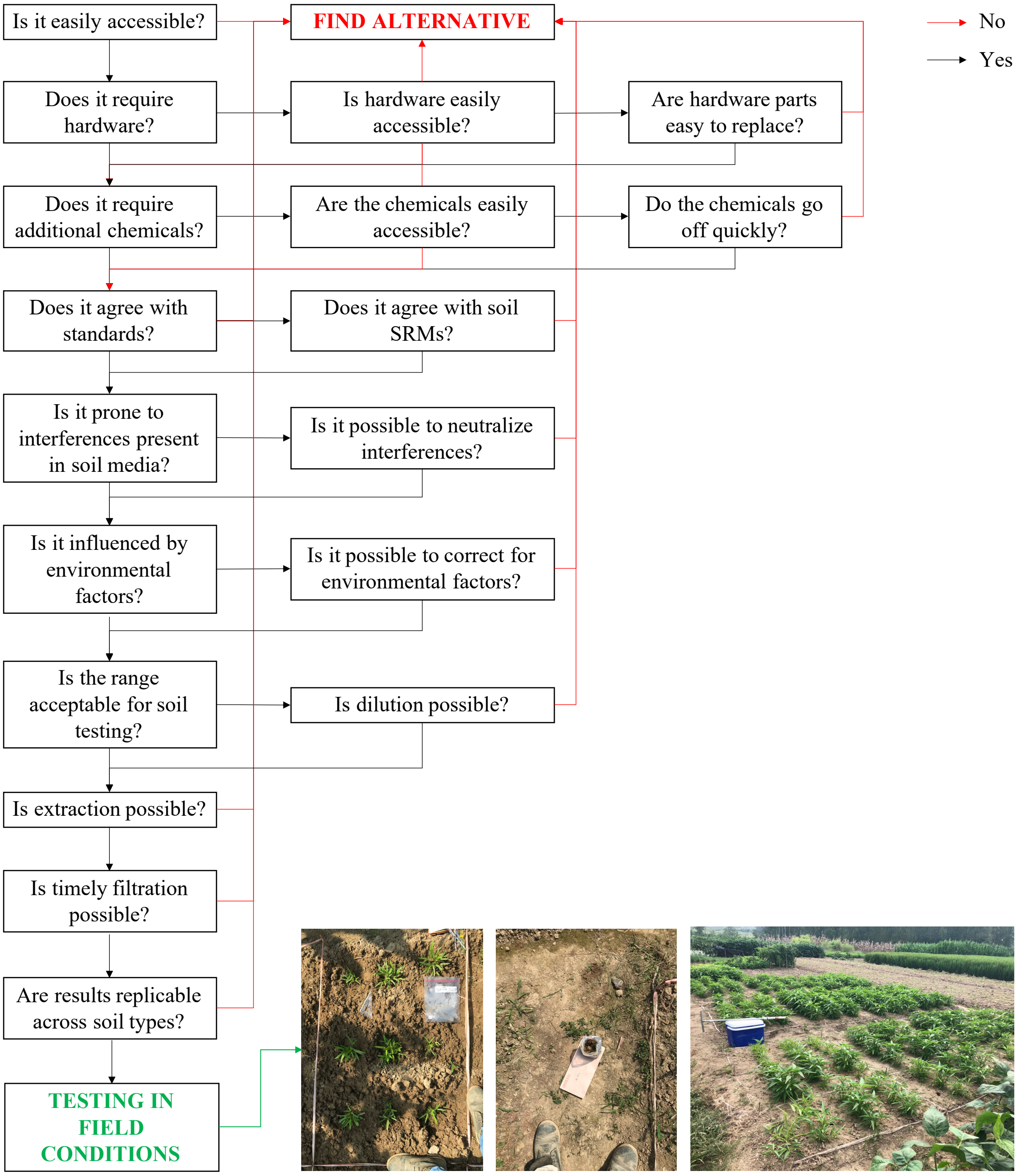


Figure 6-6. Proposed testing sequence of laboratory experiments to be performed as part of field test kit development. Additional chemicals encompass chemicals required for the test strip reaction to occur and chemicals used during the soil extraction process; environmental factors refer primarily to temperature and humidity. Acronym used: SRM – soil reference material.

6.3.4 Limitations of current statistical methods used in method comparison studies

Table 6-3 shows a subset of results presented in test strip-oriented studies conducted between 1988 and 2018. WebPlotDigititizer (ver. 4.2) was used to extract the results from published charts. The errors, defined as the difference between the standard method and the test strip method, ranged between 19.9mg kg^{-1} and -55.7mg kg^{-1} or 35.9kg ha^{-1} and -100.2kg ha^{-1} (assuming a sample depth of 15cm and a bulk density of 1.2g cm^{-3}). The magnitude of error was ignored in lieu of reporting high R^2 (range: 0.94 to 0.97).

Table 6-3. Selected subset of results from test strip studies conducted between 1988 and 2018. Results obtained from published charts with WebPlotDigititizer (ver. 4.2). Difference between measurement is calculated by subtracting the value obtained with the test strip result from the value obtained with the standard method.

Reference	Standard method	Test strip	Difference [mg kg^{-1}]	Difference [kg ha^{-1}]	Reported R^2 values
Hartz, 1994	131.6	113.9	17.7	31.9	$R^2 = 0.94$
	71.5	90.6	-19.0	-34.3	
	65.6	82.0	-16.4	-29.4	
	46.1	59.0	-12.9	-23.2	
	58.9	40.9	18.0	32.5	
	25.9	31.5	-5.6	-10.0	
Wetselaar et al., 1998	57.6	60.7	-3.0	-5.4	$R^2 = 0.957$
	43.5	32.8	10.7	19.3	
	36.7	30.1	6.6	11.9	
	30.9	26.3	4.6	8.3	
	2.7	5.6	-2.9	-5.3	
	13.7	11.3	2.4	4.3	
Schmidhalter, 2005	78.3	88.5	-	-10.2	$R^2 = 0.966$
	70.9	54.3	-	16.7	
	34.0	19.3	-	14.7	
	20.9	4.4	-	16.5	
	26.7	38.4	-	-11.7	
	59.6	45.3	-	14.3	
Loo et al., 2017	185.0	175.0	10.0	17.9	$R^2 = 0.96$
	84.0	139.7	-55.7	-100.2	
	62.5	96.2	-33.7	-60.6	
	42.5	77.7	-35.2	-63.3	
	122.0	147.4	-25.4	-45.7	
	63.5	52.6	10.9	19.6	

6.4 Discussion

6.4.1 Insights from laboratory work

Assessment of the agreement between test strips and stock standards alongside estimation of acceptable limits for standard deviation (SDs) of readings should be conducted at the beginning of any test strip oriented study. This will facilitate the choice of the best strip types for further works. Furthermore, if SD's are high at higher concentrations, this information can be used to inform the methodology, e.g. by extracting lower quantities of soil but incorporating dilution factors. Ideally, test strips should be also checked against soil standard reference material (SRM) following the initial testing with stock standards in dH_2O. SRM contains a series of compounds, which can be found in the soil media, at concentrations likely to cause interference with the colour development of the test strip's reactive pad. By using SRM for quality assurance of colorimetric strips, those that are highly sensitive to interference can be replaced with an alternative in a timely manner.

Test strips constitute a form of chromatography and thus, are intrinsically prone to chemical interference (Xie et al., 2013). Potential interferences are stipulated in the instruction manual provided by the manufacture, e.g. nitrite is identified as interference-causing agent for Quantofix strips (test strip reference number: 913 51) and silica is identified as interference-causing agent for Quantofix strips (test strip reference number: 913 20). Both cause overestimation of readings, however, only the former's impact on the test strips' colour development can be easily discerned and thus, neutralised (Wetselaar et al., 1998). It is also essential to consider the combination effects of chemicals, e.g. whereas the impact of individual substances might have been investigated by the manufacturer and specified in the manual, combining chemicals even at low concentrations can result in unexpected interferences to colour development of the reactive pad as even low-concentration extractants such as Mehlich-1 (0.05M HCl in 0.025M H_2SO_4) or 0.02 KCl were shown to have an impact on the agreement with standards.

6.4.2 Insights from fieldwork

The accessibility of equipment such as reflectometers and test strips themselves requires careful consideration as selecting expensive or niche products, which require additional support in the form of removable parts or chemical compounds, might make the final product more difficult to use by interested parties. For example, Aguilera et al. (2014) reported issues with in-field application of Cardy nitrate meters in the highlands of Bolivia due to limited access to the standard solutions necessary to calibrate the tool. Similarly, over the course of this study, production of one of selected test strip types was discontinued. Additionally, certain test strips, e.g. Quantofix phosphate and ammonium test strips, might be supplied together with the chemical reagents necessary for the reaction to take place. It is considered essential to obtain the required amounts of chemicals and assess the likelihood of impact by time since opening and/or environmental factors such as temperature before commencement of any field-based experiments. The latter remains true for any potential extractant. In field conditions, weather might be unpredictable and high ambient temperatures could render certain solvents unusable.

Another factor, which impacts performance of test strips, involves environmental variables such as temperature and humidity. Temperature, in particular, affects the rate of reaction (Schmidhalter, 2005), which results in lower colour intensity at lower temperatures, and higher colour intensity at higher temperatures. Different test strips might require separate temperature correction factors and thus, should be investigated separately prior to any field study.

Development of an in-field test kit involves an iterative learning process. Conducting experiments and analysis in the field will result both in the discovery of unexpected drawbacks in the proposed analytical procedure, and the implementation of further improvements to the method. For example, it is essential to consider extraction, filtration and replicability of proposed methodology across different soil types, especially with regard to soil texture. In laboratory conditions, extraction can be facilitated through the use of consistent mechanical shakers, whereas in field conditions manual shaking might prove to be limited by the user's physical ability. Filtration in controlled laboratory conditions might take up to a several hours when the soil to extractant ratio is high, as proposed in Jemison & Fox, (1988); but this approach would be highly impractical in field conditions. If an extractant is to be used; its impact on the test strip accuracy has to be accounted for and its longevity and accessibility considered in full. As lightly textured soils (sands and sandy loams) are easy to extract and filter, they should not be used to guide method development, with heavy clays being given a priority during final stages of in-field soil test kit evaluation. Finally, if a reflectometer is to be used, then it is important to consider certain factors, e.g. low resistance to humidity and dust, high battery consumption or difficulties in replacement of internal parts, that might make it impossible for use in field conditions.

6.4.3 Application of appropriate statistical methodology to establish operational limits of agreement between field test kit and standard soil analytical methods

Robust statistical methods need to be employed to ensure that the results obtained with the in-field soil test kit can be used to inform management activities on farms or in similar settings. The most commonly used statistical method in papers promoting test strip use utilise regressions and correlations. It is to be expected that two methods designed to measure the same parameter will be highly correlated. However, high correlation coefficients might obscure the lack of agreement between two methods expressed as high mean difference bias, unequal distribution of errors, e.g. greater differences at higher concentrations or vice versa, making it more difficult to assess the nature, size and frequency of errors. Alternative statistical approaches such as Bland-Altman plots (Bland and Altman, 2003; Phatak and Nimbalkar, 2017) can be used to highlight the differences between two methods and help either to modify an existing methodology or to adopt a more critical approach regarding test strip application in soil and plant tissue analysis. Papers that describe the use of in-field soil test kits ought to focus on the agreement between methods and associated operational limits, i.e. the point where the errors are too large to be of practical use for agronomic management purposes, whilst taking into account the need for sample replication. Furthermore, the variability of soil testing methodologies between laboratories, regions and countries must be considered. Therefore, more than one method of soil analysis should be employed to compare the results against, in order to ensure transferability across regions. If the results agree only with certain country-specific methods, then, more suitable alternatives might have to be sought.

6.5 Conclusions

Results obtained from experiments, involving test strips, conducted in the laboratory and field conditions were used to highlight important factors that are likely to influence the precision and accuracy of in-field soil analytical methods. The compilation of results allowed for development of a novel procedure for preliminary testing of soil field test kits involving paper strips. We have emphasised the need to employ robust statistical methodologies to explore and compare data obtained with the in-field and standard methods of soil analysis to improve current approach to assessment of practical limits to the use of in-field soil testing methods.

6.6 References

Aguilera J, Motavalli P, Gonzales M, Valdivia C (2014) Evaluation of a Rapid Field Test Method for Assessing Nitrogen Status in Potato Plant Tissue in Rural Communities in the Bolivian Andean Highlands. Commun Soil Sci Plant Anal 45:347–361. doi: 10.1080/00103624.2013.857680

Aitkenhead MJ, Donnelly D, Coull MC, Hastings E (2014) Innovations in environmental monitoring using mobile phone technology – a review. Int J Interact Mob Technol 8:50–58

Aitkenhead MJ, Donnelly D, Sutherland L, et al (2015) Predicting Scottish topsoil organic matter content from colour and environmental factors. Eur J Soil Sci 66:112–120. doi: 10.1111/ejss.12199

Bland JM, Altman DG (2003) Applying the right statistics: Analyses of measurement studies. Ultrasound Obstet Gynecol 22:85–93. doi: 10.1002/uog.122

Dawson CJ, Hilton J (2011) Fertiliser availability in a resource-limited world: Production and recycling of nitrogen and phosphorus. Food Policy 36:S14–S22. doi: 10.1016/j.foodpol.2010.11.012

Delgado JA, Kowalski K, Tebbe C (2013) The first Nitrogen Index app for mobile devices: Using portable technology for smart agricultural management. Comput Electron Agric 91:121–123. doi: 10.1016/j.compag.2012.12.008

Department for Environment Food and Rural Affairs (2020) Agriculture Bill. London

Gartley KL, Sims JT, Olsen CT, Chu P (2002) Comparison of soil test extractants used in mid-Atlantic United States. Commun Soil Sci Plant Anal 33:873–895. doi: 10.1081/CSS-120003072

Golicz K, Hallett SH, Sakrabani R, Pan G (2019) The potential for using smartphones as portable soil nutrient analyzers on suburban farms in central East China. Sci Rep 9:1–10. doi: 10.1038/s41598-019-52702-8

Hartz TK (1994) A quick test procedure for soil nitrate-nitrogen. Commun Soil Sci Plant Anal 25:511–515

Jemison JM, Fox RH (1988) A quick-test procedure for soil and plant tissue nitrates using test strips and a hand-held reflectometer. Commun Soil Sci Plant Anal 19:1569–1582. doi: 10.1080/00103628809368035

Ju XT, Xing GX, Chen XP, et al (2009) Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proc Natl Acad Sci U S A 106:8077. doi: 10.1073/pnas.0902655106

Lobry de Bruyn L, Andrews S (2016) Are Australian and United States Farmers Using Soil Information for Soil Health Management? Sustainability 8:304. doi: https://doi.org/10.3390/su8040304

Nyi T, Varughese P, bin Hj Bujang MI, et al (2017) ASEAN Guidelines on Soil and Nutrient Management. Bangkok

Omran E-SE (2017) Will the Conventional Soil-Plant Analysis Pass into Oblivion? Rapid and Low-Cost Determination Using Spectroscopy. Commun Soil Sci Plant Anal 48:705–715. doi: 10.1080/00103624.2017.1298782

Phatak AG, Nimbalkar SM (2017) Method comparison (agreement) studies: Myths and rationale. J Clin Diagnostic Res 11:JI01–JI03. doi: 10.7860/JCDR/2017/23897.9314

Piikki K, Söderström M, Eriksson J, et al (2016) Performance evaluation of proximal sensors for soil assessment in smallholder farms in Embu County, Kenya. Sensors (Switzerland) 16:. doi: 10.3390/s16111950

Prager K, McKee A (2014) Use and awareness of soil data and information among local authorities, farmers and estate managers. Accessed from: https://www.hutton.ac.uk/sites/default/files/files/Use%20of%20soil%20information_final%20report_14Jan2014.pdf

Schmidhalter U (2005) Development of a quick on-farm test to determine nitrate levels in soil. J Plant Nutr Soil Sci 168:432–438. doi: 10.1002/jpln.200520521

Sims JT, Edwards AC, Schoumans OF, Simard RR (2000) Integrating Soil Phosphorus Testing into Environmentally Based Agricultural Management Practices. J Environ Qual 29:60–71. doi: 10.2134/jeq2000.00472425002900010008x

Song XZ, Zhao CX, Wang XL, Li J (2009) Study of nitrate leaching and nitrogen fate under intensive vegetable production pattern in northern China. Comptes Rendus - Biol 332:385–392. doi: 10.1016/j.crvi.2008.11.005

Stiglitz R, Mikhailova E, Post C, et al (2017) Soil colour sensor data collection using a GPS-enabled smartphone application. Geoderma 269:108–11. doi: 10.1016/j.geoderma.2017.02.018

Thompson BR, M PF, Gallardo M, Peña-Fleitas M T (2013) Improved nitrogen management practices for vegetable production. In: Karoline D'Haene, Bart Vandecasteele, Raf De Vis, Sara Crappé, Danny Callens, Els Mechant, Georges Hofman SDN (ed) NUTRIHORT : Nutrient management, innovative techniques and nutrient legislation in intensive horticulture for an improved water quality. Book. Ghent, p 388

Wetselaar R, Smith GD, Angus JF (1998) Field measurement of soil nitrate concentrations. Commun Soil Sci Plant Anal 29:729–739. doi: 10.1080/00103629809369980

Xie C, Xu J, Tang J, et al (2013) Comparison of Phosphorus Determination Methods by Ion Chromatography and Molybdenum Blue Methods. Commun Soil Sci Plant Anal 44:2535–2545. doi: 10.1080/00103624.2013.811518

Zhang B, Li Q, Cao J, et al (2017) Reducing nitrogen leaching in a subtropical vegetable system. Agric Ecosyst Environ 241:133–141. doi: 10.1016/j.agee.2017.03.006

Chapter 7: Integrated discussion

Summary: This chapter contains a synthesis of the research on smartphone and test strip-mediated soil testing presented in the preceding chapters. The main findings are summarised in a thematic manner – considering the technological shortcomings and benefits of the tool, the agronomic implications and agricultural innovation, as well as the proposed framework for evaluating field test kit. The study limitations are discussed and are complemented with a conceptual suggested future work plan. Contributions to knowledge are highlighted.

Highlights:

- Summary of smartphone and test strip-related strengths and weaknesses discovered during this research project,
- Discussion of agronomic implications for utilising Akvo Caddisfly,
- Discussion of the importance of pre-fieldwork testing and calibration of field test kits in terms of the kit assessment framework described in Chapter 6,
- Agricultural innovation presented in terms of technology as well as essential 'human' factors contributing jointly to its uptake,
- Presentation of study limitations and proposition of a research project to build on the body of knowledge presented in this thesis,
- Summary of the intellectual contributions to knowledge of this research.

7.1 Discussion of research findings

As the value and consumption of fertilisers is rising across the world, it is now more important than ever to ensure that agricultural workers are equipped with the best tools to optimise crop yields without compromising the health of the natural environment. This PhD project resulted in the development of a smartphone and test strip-mediated soil analytical method, which can be used as a screening tool to aid nitrogen fertiliser recommendations.

7.2 Smartphone-mediated soil testing – advantages and disadvantages

7.2.1 Smartphone technology

This thesis has presented an evidence-based assessment of the trade-offs between utilising Akvo Caddisfly app instead of the Quantofix test strip reader **Figure 7-1**). Employing a smartphone as a reflectometer addresses the concerns raised by previous test strip studies with the naked eye nutrient concentration assessment (Schaefer, 1986) and the low likelihood of farmers willing to invest in expensive equipment (Aguilera et al., 2014).

Test strip readers constitute a delicate instrument, which has been shown to have low resistance to adverse environmental conditions (**Figure 6-5**), this was further evidenced during a field study described in **Chapter 4**. Whereas, although the colour correction card approach developed by Akvo.org was also shown to degrade with heavy use and exposure to heat/humidity throughout the duration of this study, the costs associated with replacement of the card are much lower than those associated with the test strip reader. Furthermore, the Quantofix Reflectometer has been optimised for use with Quantofix products whereas any test strip-oriented smartphone application can be calibrated to account for a number of test strip types developed by different manufacturers.

However, smartphones are not infallible – there is a difference in camera colour perception depending on smartphone model (**Chapter 3**), which lowers the reliability of readings compared to commercial test strip readers. This issue can be remediated by calibrating each smartphone model separately which is time and resource intensive, or by redesigning the app so it quantifies colour across the concentration scale with each use, as described in Yetisen et al. (2014).

Furthermore, commercial test strip readers are calibrated in controlled laboratory conditions whereas Akvo Caddisfly was calibrated in a way that necessitated incorporation of a calibration equation to harmonise results presented by the app with results of the soil test. Calibration equations presented an exciting opportunity for limiting the measurement bias frequently reported in comparisons between standard and novel testing methods (Bland and Altman, 2003) as well as potential for correcting for the impact of extractant that facilitates soil filtration (**Chapter 1**). However, the disparity between readings obtained by different smartphone models reduces their utility as the calibration equations were obtained with a single smartphone model, i.e. Galaxy S8, as proposed by Akvo Foundation.

Test strip readers		Smartphones	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
High reliability of readings Calibration in controlled laboratory conditions	High cost Calibration only to specific test strip types Low resistance to environmental stressors Low portability Difficult to replace parts	Affordable Accessible Adaptable Portable Record keeping Low battery consumption Resistant to environmental conditions Calibration to many different test strip types Calibration to soil tests to remove measurement bias	Phone memory requirement Intermittent Internet access Careful calibration procedure is required Between-smartphone differences in readings High standard deviations between readings

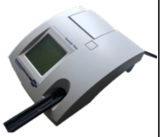


Figure 7-1. Advantages and disadvantages of commercial test strip readers vs smartphone repurposed to act as a reflectometer.

7.2.2 Test strip technology

Test strips have been employed in soil and water analysis for over 50 years. High availability and low cost make them an attractive screening tool for environmental monitoring. However, attempts at turning semi-quantitative paper strips into a fully quantitative tool poses a number of challenges.

Test strips measuring nitrate have been found to have the best agreement with laboratory standards whereas test strips measuring phosphate, ammonium and potassium had lower accuracy of readings (**Figure 6-2**). Nitrate test strips also showed limited susceptibility to interferences found in soil media as opposed to, for example, phosphate test strips (**Chapter 3**), which ultimately made them appropriate for use in soil analysis.

Once employed, good correlations were obtained by comparing nitrate-sensitive test strips with standard methods as previously reported (Jemison and Fox, 1988; Wetselaar et al., 1998; Thompson et al., 2009). In-depth analysis and employment of Bland-Altman plots revealed a measurement bias to exist between test strip readings obtained with the commercial reflectometer and the standard method of soil analysis (**Figure 3-5**). For smartphone-mediated soil tests, the limits of agreement were shown to be ± 10mg kg^{-1} (**Figure 3-6**) in laboratory conditions and ± 24mg kg^{-1} in 'imperfect' field conditions (**Figure 4-5**). No previous test strip study has investigated the limits of agreement using Bland-Altman plots and the analysis has highlighted the spread of results previously masked by high correlation coefficients (**Table 6-3**). The disparities identified between test strip results and standard methods of soil analysis point to test strips being best considered as a semi-quantitative tool, with screening potential, that should be employed for fertiliser recommendations with caution.

7.3 Agronomic implications of utilising Akvo Caddisfly

Soil testing is one of the most commonly employed tools to inform agricultural management (Sims et al., 2006). However, soil testing is used infrequently by insufficient number of practitioners, e.g. approximately 30% of farmers across US and Australia (Du Bruyn and Andrews, 2016). In the developing world, the uptake and access to soil testing remains low (World Bank, 2017). Whereas the ICT alone is insufficient to meet agronomic needs of smallholder farmers, it has come a long way to address concerns with access to essential information (**Chapter 2**).

Akvo Caddisfly offers a promising opportunity for screening agricultural soils for nitrate content that provides farmers with site-specific information regarding the state of their soil. This information is especially important in the context of vegetable production as it necessitates high fertiliser inputs whilst remaining an attractive cash-crop option for smallholders (Mariyono, 2018). The results provided by the app, harmonised through utilisation of the correction equation and incorporation of temperature dependency, have been shown to be successful in assessing if the soils are:

- **Overfertilised** in the context of intensive vegetable production in South-East China. Overfertilisation was identified across plots, where fertiliser addition was high, pointing out financial losses associated with further MF addition as well as highlighting environmental risks such as soil acidification and nitrate leaching into the wider environment (**Chapter 4**).
- **Underfertilised** in the context of low-productivity fields in Sub-Saharan Africa, where addition of low amounts of fertiliser can result in substantial increase in productivity (**Chapter 5**).

The accuracy and precision of readings are imperfect, and this study has shown that nitrate is the only chemical compound that can be successfully estimated with test strips. As the results are consistent methodologically, it is possible to monitor relative change in soil N fertility and thus, provide agricultural practitioners with longitudinal records and enable them to adjust their inputs across the crop growing season. However, there is a trade-off between utilising cheap and easily available field kits as opposed to well established laboratory methods for soil testing. Field test kits provide good screening potential, but some degree of accuracy is sacrificed because of their simplicity. Therefore, implementing agronomic advice obtained via Akvo Caddisfly must always be considered on a case by case basis and its limitations should not be ignored.

7.4 Field soil test kit development framework

It is essential to commence any ICT in Agriculture intervention by focusing on the need that the intervention is expected to address such as site-specific fertiliser recommendations, as opposed to the need for new ICT solutions. This research has uncovered a number of smartphone and test strip related strengths and weaknesses.

The test strip limitations are of particular importance as the interest in their application is growing (**Chapter 6**). Test strip manufacturers release a number of paper strip types that are meant to measure different chemical compounds. Their potential for incorporation into cost effective tools for agricultural management can be quickly assessed via the proposed framework described in detail in **Chapter 6**.

Test strip limitations for instance the impact of temperature, which was addressed in this study by developing temperature correction factors, has to be identified early in the method development process. Early warnings of potential barriers to test strip use will result in fewer trials and lower costs of field trials.

The framework was created in such a way as to be easily adapted to test the viability of other soil testing field kits, which might not involve test strips, prior to expending resources on their application in field conditions. It is hoped that quantitative and qualitative insights gathered during the laboratory and field-based investigations of Akvo Caddisfly can be used to inform future efforts to develop similar tools.

7.5 Synthesis of research outputs and their impact on the state of knowledge relating to smartphone technology and paper strip use in soil science

This thesis has presented a series of works that outline the development of smartphone-mediated soil analysis. The key findings presented in **Chapters 3-6** advance our understanding of using smartphones and test strips as a tool to aid in site-specific fertiliser application (**Figure 7-2**).

Soil testing procedures were developed by building upon previous studies (Fox et al., 1989; Bischoff et al., 1996; Wetselaar et al., 1998; Hartz et al., 2000; Schmidhalter, 2005). Different smartphone models were evaluated to ensure that they could provide a viable alternative to test strip readers, and test strips were critically appraised in terms of their precision and accuracy as well as their potential to be used to analyse soil extracts. Test strip technology deficiencies were addressed by proposing solutions such as nitrite neutralisation and temperature-dependency correction factors. Novel statistical approaches were applied to ensure robust analysis of test strip results. Finally, a framework was designed to facilitate future experiments of this nature so the time and costs associated with development of in-field soil test kits might be reduced.

These combined approaches have allowed for development of a smartphone-mediated screening tool that can be used by Akvo Foundation and its collaborators to advise farmers on how to manage their fields more efficiently. This approach has the potential to save money for smallholders, increase their agronomic outputs and minimise negative impacts of imprecise fertiliser use on the natural environment.

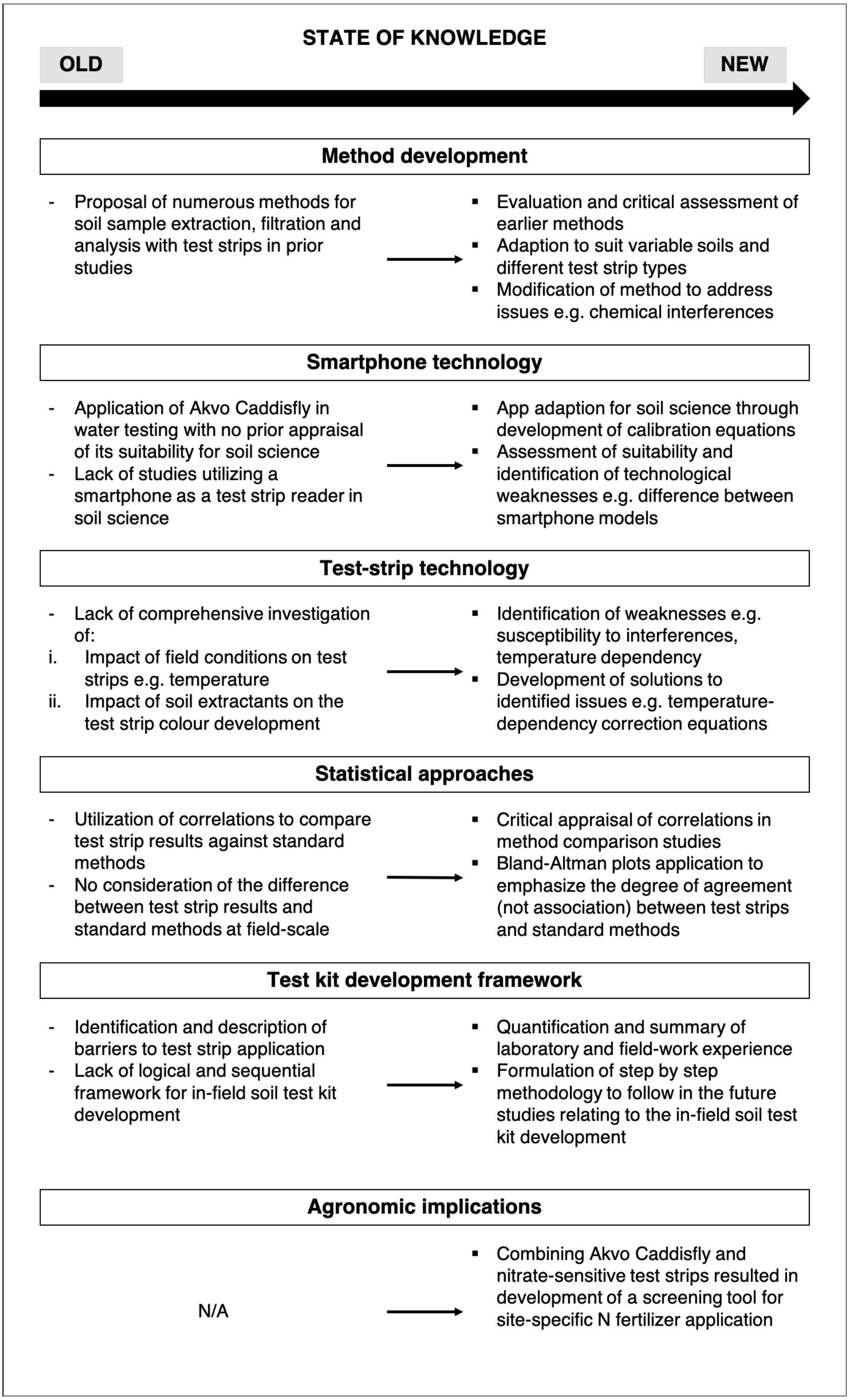


Figure 7-2. Summary of research outputs and their impact on the advancement of smartphone technology and test strip use in soil science.

7.6 Thinking one step ahead: Smartphone technology as a means not an end to agricultural development

Agriculture is no exception to the worldwide digital revolution which has moved beyond a simple adoption of information and communication technologies. The World Bank have identified five key drivers of this phenomenon, i.e. low cost and pervasive connectivity, adaptable and more affordable tools, advances in data storage and exchange, innovative business models and partnerships, and democratisation of information (The World Bank, 2012). Modern digital agriculture allows for creating and accessing relevant information in a timely manner and adds to available services that can contribute to making farming more profitable and sustainable.

Akvo Caddisfly is an example of digital agricultural technologies (DAT), i.e. 'innovation that enable farmers and agribusiness to increase their productivity, efficiency, and competitiveness, facilitate access to markets, improve nutritional outcomes and enhance resilience to climate change' (The World Bank, 2012, Trendov et al., 2019). DAT are on the rise globally and they are being continuously incorporated into the food and agriculture sector across the world (**Chapter 2**). It is important to study digital agriculture technologies in detail.

This PhD has focused on the technical aspects of the tool in order to adapt it for use in soil testing. However, it is essential to consider smartphone and test strip technology as a proverbial 'tip of the iceberg' (**Figure 7-3**). Innovation, agricultural or otherwise, is at its core a social process. It involves adapting and incorporating knowledge and is guided by the needs, ability and capacity of members operating within a specific social setting (Brown et al., 2018; Spielman, 2009). Smallholders are risk averse, as the costs associated with purchase and use of technological innovations are immediate, but the agronomic benefits might not be reaped for a number of years (Rockenbaugh et al., 2019). In order to empower farmers to harness tools such as Akvo Caddisfly effectively, there is a great need for novel policy, one that requires direct monitoring of agri-tech adoption and impact as part of its funding strategy (Vanlauwe et al., 2017) and investment for capacity building to take place.

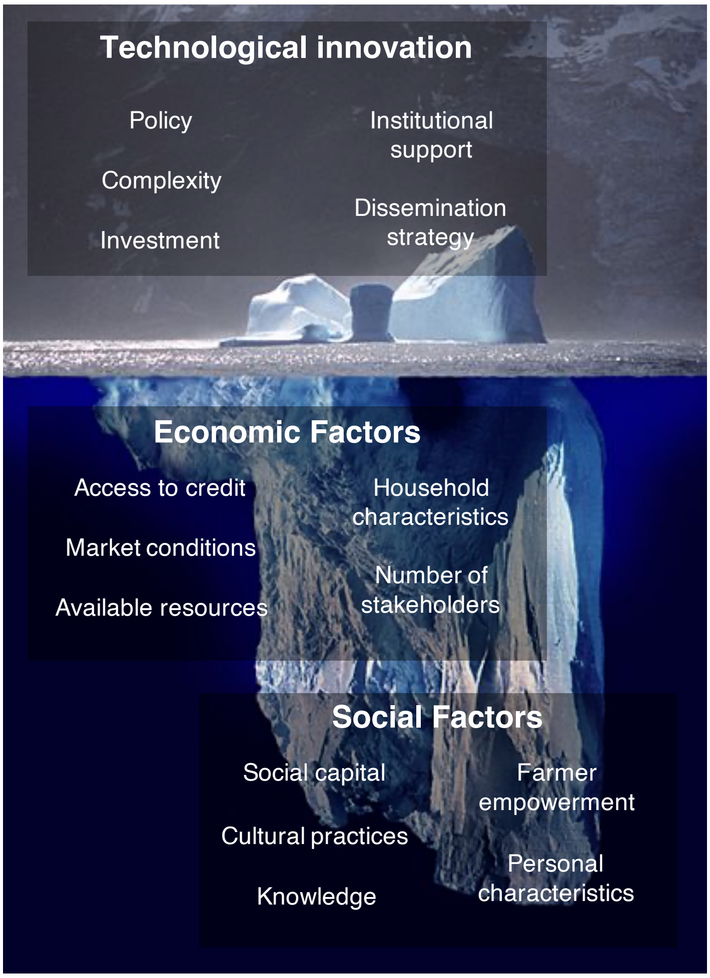


Figure 7-3. Technological innovations have to be considered in terms of uptake, which is controlled by economic and social factors and not solely the quality of the proposed tools. Image source: free to use Wikimedia Commons.

7.7 Discussion of study limitations and future work

In-field methods of soil analysis are imperfect. They are developed in such a way as to act as screening tools and their precision and accuracy is lower than that of laboratory methods. It is essential to consider them in terms of **overall effectiveness** at providing advice that can make agricultural activities more efficient, scalable and sustainable.

For example, the Food and Agriculture Organisation (FAO) of the United Nations (UN) released a series of training manuals directed at Soil Doctors, i.e. farmers trained to promote the practice of sustainable soil management and to address the lack of extension services (FAO, 2020). They use very simple soil testing methods to establish, e.g. soil pH, organic matter content, salinity and biodiversity. These guidelines do not currently embrace mobile app solutions.

The series of works presented in this thesis have only investigated soil fertility expressed as plant-available nitrate-N content. However, soil constitutes a highly complex medium that depends on interactions between soil biological, chemical and physical properties. It is highly recommended that further investigation be conducted to establish if simplistic soil test kits are accurate and precise enough to have a measurable positive impact on small-scale crop production when they are employed together. There is a marked lack of long term (> 2 growing seasons) and comprehensive studies, which assess the utility of technological solutions generated to address the lack of site-specific soil data.

7.7.1 Conceptual future works plan

In order to complement the works conducted during this PhD research, a field-based experiment is proposed as following work. The experiment would be conducted across three experimental sites in one of the developing regions of the world.

The goal of the experiment would be to assess effectiveness of multiple basic soil field test kits developed by FAO (FAO, 2020), USDA Soil Quality Test Kit (NRCS, 2001), and a number of carefully selected smartphone apps such as Akvo Caddisfly, which are available for download. The information gathered through in-field soil test kits would be used to inform agricultural management including addition of lime and/or ash, mineral fertiliser and/or manure, on the given sites.

As per standard agronomic experiments involving randomised blocks design, the fields would be divided into sections (with four replicates) and put under management guided by soil test results obtained with FAO, USDA and smartphone apps. The control would follow standard agronomic practices used in the region. The proposed research aims to investigate if the information provided by in-field soil test kits (digital or otherwise) is sufficient to improve on-farm yields.

7.8 Contributions to knowledge

This thesis has provided a contribution to knowledge by investigating practical limits for smartphone-mediated soil analysis and developing processes which may enable effective assessment of in-field soil test kits.

Specifically:

- Exploring, critically assessing and selecting laboratory and field-based experiments that are best suited for testing a smartphone-mediated tool designated for soil analysis;

- Developing a methodology for use in smartphone-mediated soil analysis and conducting a method comparison study complemented by a robust statistical approach,

- Evaluating the use of smartphones in soil analysis and establishing operational limits for using test strips in soil analysis, which was based on identification of interfering factors that have a negative impact on the final result,

- Conducting a study which was the first of its kind involving using smartphone and test strip mediated soil analysis to track nutrient uptake across two growing cycles of a vegetable, water spinach, in contrast to previous research that focused on snapshots of soil nutrient status across multiple, non-related agricultural fields,

- Creation of a methodology for effective assessment of soil testing field test kits involving paper strips with additional focus placed on critical evaluation of statistical methods appropriate for use in method comparison studies.

Ultimately, the development of a methodology employed in smartphone-mediated soil testing, through validation under laboratory and field conditions and employment of robust statistical approaches, can be considered as a sound starting point for improving efficiency and fertiliser use in smallholder vegetable farming. It is hoped that the insights gained through this research will be utilised and drawn upon by the industry and the NGO sector who are investing resources into agri-tech development. Smartphones and test strips are not a replacement for ‘wet chemistry’ methods, but they can be invaluable as precursors to increasing the knowledge base in screening soils for nutrients to ensure resilient and sustainable farming systems of the future.

7.9 References

Aguilera J, Motavalli P, Gonzales M, Valdivia C (2014) Evaluation of a Rapid Field Test Method for Assessing Nitrogen Status in Potato Plant Tissue in Rural Communities in the Bolivian Andean Highlands. Commun Soil Sci Plant Anal 45:347–361. doi: 10.1080/00103624.2013.857680

Bland JM, Altman DG (2003) Applying the right statistics: Analyses of measurement studies. Ultrasound Obstet Gynecol 22:85–93. doi: 10.1002/uog.122

Brown B, Nuberg I, Llewellyn R (2018) Research capacity for local innovation: the case of conservation agriculture in Ethiopia, Malawi and Mozambique. J Agric Educ Ext 24:249–262. doi: 10.1080/1389224X.2018.1439758

De Bruyn LL, Andrews S (2016) Are Australian and United States farmers using soil information for soil health management? Sustain 8:1–33. doi: 10.3390/su8040304

Food and Agriculture Organisation of the United Nations. Global Soil Parentship. Accessed on 12 May 2020 from: http://www.fao.org/global-soil-partnership/pillars-action/2-awareness-raising/soil-doctor/en/

International Bank for Reconstruction and Development (2012) Agricultural Innovation Systems. Washington DC

Jemison JM, Fox RH (1988) A quick-test procedure for soil and plant tissue nitrates using test strips and a hand-held reflectometer. Commun Soil Sci Plant Anal 19:1569–1582. doi: 10.1080/00103628809368035

Mariyono J (2018) Profitability and Determinants of Smallholder Commercial Vegetable Production. Int J Veg Sci 24:274–288. doi: 10.1080/19315260.2017.1413698

Rockenbauch T, Sakdapolrak P, Sterly H (2019) Do translocal networks matter for agricultural innovation? A case study on advice sharing in small-scale farming communities in Northeast Thailand. Agric Human Values 36:685–702. doi: 10.1007/s10460-019-09935-0

Schaefer NL (1986) Evaluation of a hand-held reflectometer for rapid quantitative determination of nitrate. Commun. Soil Sci. Plan. 17(9): 937-951

Sims JT, Edwards AC, Schoumans OF, Simard RR (2000) Integrating Soil Phosphorus Testing into Environmentally Based Agricultural Management Practices. J Environ Qual 29:60–71. doi: 10.2134/jeq2000.00472425002900010008x

Spielman DJ, Ekboir J, Davis K (2009) The art and science of innovation systems inquiry: Applications to Sub-Saharan African agriculture. Technol Soc 31:399–405. doi: 10.1016/j.techsoc.2009.10.004

Thompson RB, Gallardo M, Joya M, et al (2009) Evaluation of rapid analysis systems for on-farm nitrate analysis in vegetable cropping. Spanish J Agric

Res t. 7(1): 200–211

Trendov NM, Varas S, Zeng M (2019) Digital technologies in agriculture and rural areas. Brief Pap FAO 26

United States of America Department of Agriculture: Natural Resources Conservation Service. Soil Quality Test Kit. Accessed on 12 May 2020 from: https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/health/assessment/?cid=nrcs142p2_053873

Wetselaar R, Smith GD, Angus JF (1998) Field measurement of soil nitrate concentrations. Commun Soil Sci Plant Anal 29:729–739. doi: 10.1080/00103629809369980

Vanlauwe B, AbdelGadir AH, Adewopo J, et al (2017) Looking back and moving forward: 50 years of soil and soil fertility management research in sub-Saharan Africa. Int J Agric Sustain 15:613–631. doi: 10.1080/14735903.2017.1393038

Appendices

8.1 Appendix A: Supplementary Material to Chapter 3

Calibration equations

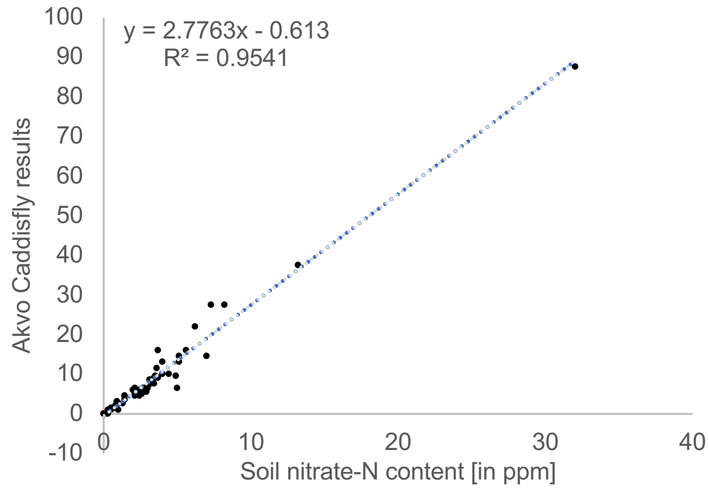


Figure 8-1. Nitrate-N samples (N=54) were prepared simultaneously and analysed within 24hr of each other. The output of Samsung Galaxy S8 was used to generate the calibration equation. Samples analysed with test strips were analysed at constant temperature and light conditions on the same day to avoid any environmental effects on Akvo Caddisfly readings.

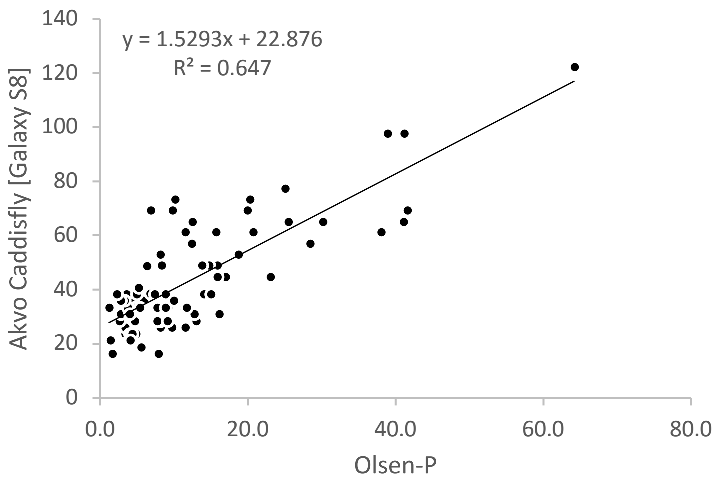


Figure 8-2. Phosphate-P samples (N=83) were prepared simultaneously and analysed within 48hr of each other. The output of Samsung Galaxy S8 was used to generate the calibration equation. Samples analysed with test strips were

analysed at constant temperature and light conditions on the same day to avoid any environmental effects on Akvo Caddisfly readings.

Detailed break-down of the impact of temperature on test strip readings discussed in Chapter 3.

Table 8-1. The influence of temperature on Quantofix test strips assessed via Quantofix Relax Test Strip Reader. Median ± SD; N=5, unit of measurement = mL L^{-1}.

Standard	15°C	20°C	25°C	30°C	35°C
			Nitrate		
0	0	0	0	0	0.
5	0±1.8	3±2.1	4.5±0.6	6±0.4	5±1.6
10	9±1.0	10±0.9	12±0.9	12±1.7	12±1.1
25	23±2.1	25±2.5	31±1.9	32±2.3	32±3.0
50	49±4.0	52±3.3	70±4.8	66±2.0	68±5.1
75	73±3.0	77±4.0	94±5.2	94±3.3	100±2.5
100	98±6.0	100	100	100	100
			Phosphate		
0	0	0	0	0	0
3	0	3±0.6	5	6	7±1.0
10	9±1.2	11±0.6	13±0.6	14±0.6	16±1.5
25	24±4.6	34±4.6	42±2.3	41±3.6	38±3.6
50	56±4.0	70±2.6	77±2.5	79±0.6	69±2.6
>80	100	100	100	100	100

Detailed breakdown of Bland-Altman analysis accompanying graphs 3-6A-F (Table 8-2).

Table 8-2. Bland-Altman analysis including the bias (mean difference) and the limits of agreement together with 95% confidence intervals and standard errors for OnePlus 3 (OP3), Samsung Galaxy S8 (S8), and Samsung Galaxy Tab 2 (SGT2) compared against the standard laboratory method for calculating nitrate-N present in the soil solution.

Nutrient	Parameter	N	Estimate	95% CI	SE
			OP3		
NO_3-N [moist soil]	Mean difference	93	-2.94	-4.98 to -0.91	9.82
	95% Lower LoA		-22.19	-25.68 to -18.71	
	95% Upper LoA		16.30	12.82 to 19.79	

	S8				
	Mean difference	93	1.85	0.47 to 3.23	6.67
	95% Lower LoA		-11.22	-13.59 to -8.85	
	95% Upper LoA		14.92	12.55 to 17.29	
	SGT2				
	Mean difference	93	-2.68	-4.39 to -0.97	8.24
	95% Lower LoA		-18.83	-21.76 to -15.90	
	95% Upper LoA		13.47	10.55 to 16.40	
	OP3				
NO_3−N [dry soil]	Mean difference	93	-1.99	-3.65 to -0.32	8.08
	95% Lower LoA		-17.82	-20.67 to -14.96	
	95% Upper LoA		13.85	10.99 to 16.70	
	S8				
	Mean difference	93	2.32	0.82 to 3.84	7.34
	95% Lower LoA		-12.07	-14.67 to -9.48	
	95% Upper LoA		16.72	14.13 to 19.32	
	SGT2				
	Mean difference	93	-2.43	-3.79 to -1.06	6.62
	95% Lower LoA		-15.41	-17.75 to -13.07	
	95% Upper LoA		10.57	8.22 to 12.90	

8.2 Appendix B: Supplementary Material to Chapter 4

Temperature correction factors for Quantofix test strips: NO_3^- (Figure 8-3) and PO_4^{3-} (Figure 8-4). The correction factors were determined by dividing the median readings (N=5) by a given quantity of the standard solution.

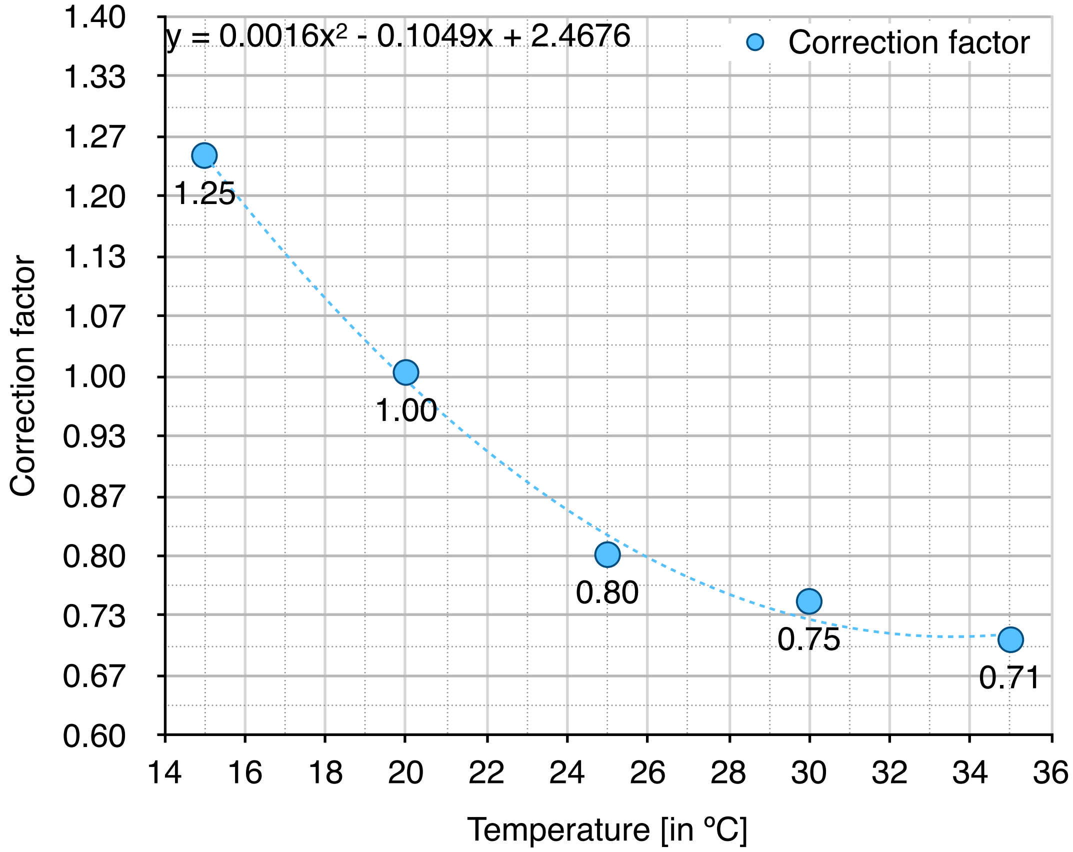


Figure 8-3. Correction factors developed for nitrate test strips through Quantofix Relax to account for temperature dependency. Temperatures investigated comprised: 15, 20, 25, 30, 35 °C, at a humidity of 70%. The study was conducted in a temperature-controlled plant growth chamber at Cranfield University.

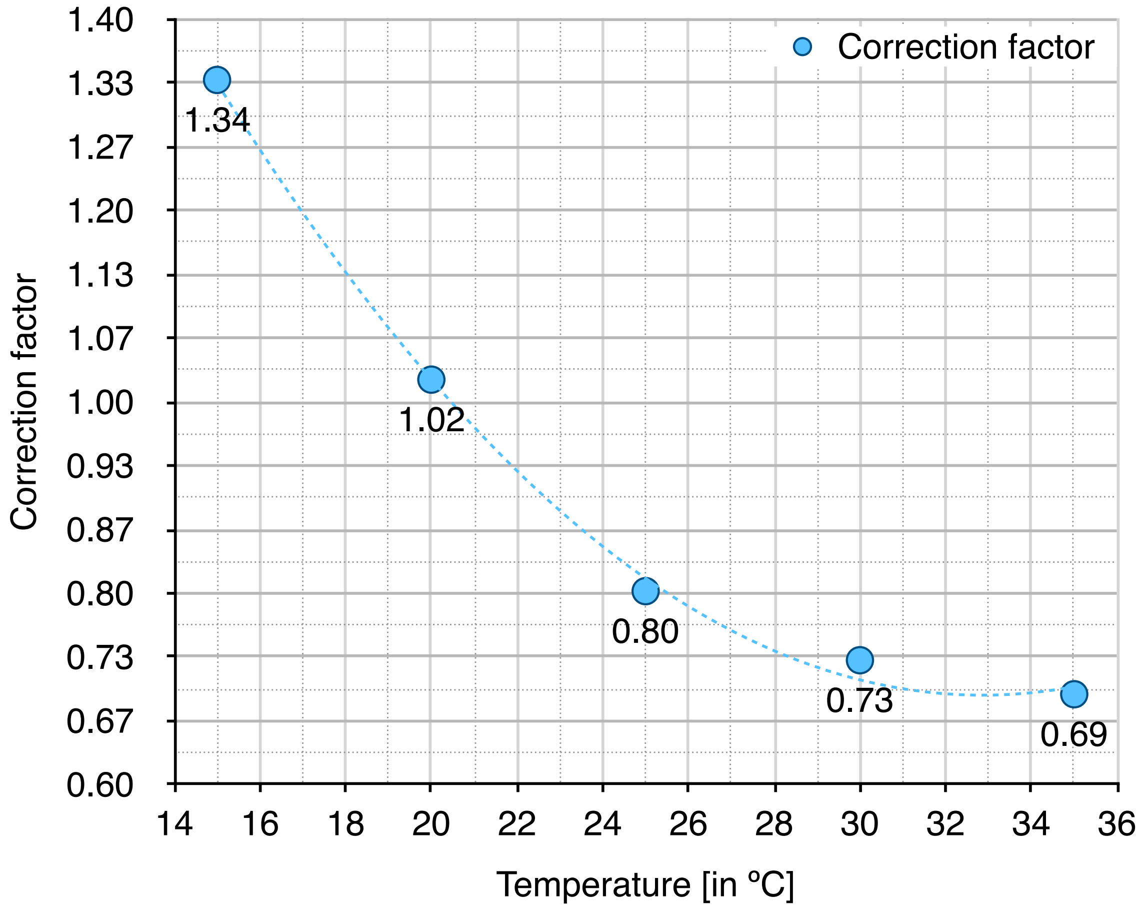


Figure 8-4. Correction factors developed for phosphate test strips through Quantofix Relax to account for temperature dependency. Investigated temperatures constituted: 15, 20, 25, 30, 35 °C, at humidity of 70%. The study was conducted in a temperature-controlled plant growth chamber at Cranfield University.

Detailed account of soil nitrate-N concentration measured during Trial 1 and Trial 2 (Table 8-3)

Table 8-3. Comparison of soil nitrate-N level across the crop growing trials (N=4).

				TRIAL 1				TRIAL 2			
				Autoanalyzer		Akvo Caddisfly		Autoanalyzer		Akvo Caddisfly	
Week	**Treatment**	**Fertiliser type**	**N**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
1	0	Control	4	184.7	192.2	148.1	179.2	38.6	7.5	31.4	13.2
1	0.33	Biochar	4	224.0	241.9	177.1	221.2	122.9	24.8	103.4	21.6
1	0.66	Biochar	4	130.6	126.2	50.9	47.1	237.9	40.0	248.0	101.2
1	0.99	Biochar	4	218.0	194.5	70.3	81.3	328.7	77.7	356.7	125.6
1	1.98	Biochar	4	177.2	141.4	55.0	59.1	470.2	189.7	468.5	125.2
1	0.33	Inorganic	4	176.2	171.2	89.6	119.3	140.8	29.5	113.3	34.4
1	0.66	Inorganic	4	124.4	175.2	24.2	111.3	180.0	29.9	177.5	66.7
1	0.99	Inorganic	4	85.3	80.5	25.4	38.6	198.0	53.5	210.9	60.6
1	1.98	Inorganic	4	148.5	167.9	91.4	106.6	308.3	42.9	339.5	68.1
2	0	Control	4	50.9	45.5	28.9	29.2	46.4	17.9	32.5	20.3
2	0.33	Biochar	4	67.1	63.7	25.5	28.3	119.5	33.6	73.2	18.2
2	0.66	Biochar	4	69.7	66.1	28.7	30.5	239.4	128.2	209.2	130.4
2	0.99	Biochar	4	98.2	102.1	44.4	48.0	282.8	67.3	303.1	98.8
2	1.98	Biochar	4	104.7	140.4	26.9	41.3	446.9	71.0	480.0	98.8
2	0.33	Inorganic	4	38.8	45.2	35.2	45.1	128.9	25.5	84.8	20.1
2	0.66	Inorganic	4	77.6	91.3	19.7	28.2	229.1	76.0	226.1	93.1
2	0.99	Inorganic	4	89.0	108.8	55.4	81.7	231.8	11.2	203.0	54.6
2	1.98	Inorganic	4	116.8	138.0	70.3	97.5	395.0	56.2	394.2	48.8

3	0	Control	4	23.7	18.5	21.5	17.2	33.0	8.7	28.7	12.8
3	0.33	Biochar	4	14.1	17.2	13.1	11.0	69.2	33.0	67.8	20.4
3	0.66	Biochar	4	26.9	19.0	10.2	12.4	114.0	28.7	112.8	45.7
3	0.99	Biochar	4	46.7	45.2	26.3	29.2	188.5	69.4	245.5	186.0
3	1.98	Biochar	4	69.8	84.9	47.9	66.5	494.3	385.4	413.2	283.7
3	0.33	Inorganic	4	14.9	14.0	12.2	12.7	61.2	34.1	56.1	19.8
3	0.66	Inorganic	4	39.0	34.3	22.7	18.1	110.8	27.2	100.7	27.9
3	0.99	Inorganic	4	42.1	54.9	37.1	59.4	167.1	104.7	178.6	131.6
3	1.98	Inorganic	4	75.5	119.3	65.2	119.5	391.6	43.9	471.6	52.1
4	0	Control	4	10.8	11.2	1.6	3.3	32.4	8.0	18.0	6.7
4	0.33	Biochar	4	12.8	11.9	4.1	5.8	64.3	16.9	37.7	17.7
4	0.66	Biochar	4	19.9	16.7	5.8	3.9	119.9	100.7	105.5	102.7
4	0.99	Biochar	4	31.0	35.2	34.6	39.7	271.1	152.3	261.2	192.3
4	1.98	Biochar	4	85.1	132.0	49.7	97.3	637.9	212.7	650.8	186.9
4	0.33	Inorganic	4	16.2	19.6	17.4	24.2	62.7	42.4	46.9	34.1
4	0.66	Inorganic	4	18.4	25.0	0.9	2.1	202.6	85.7	172.7	82.7
4	0.99	Inorganic	4	25.9	30.7	28.6	42.2	293.2	166.3	228.8	132.4
4	1.98	Inorganic	4	74.9	97.4	48.1	71.0	408.4	27.7	347.5	42.4

8.3 Appendix C: Preliminary Findings and Supplementary Material to Chapter 6

Part I: Test strips: Extractant type and temperature effects

Test strips are based on a chromatographic principle of mixture separation with a goal of measuring the relative proportions of analytes in a mixture. Chromatographic paper might be influenced by the type of analytes present in the mixture and the temperature range within which chemical reactions take place. Thus, it was considered essential to measure the impact of (1) **extractant type** and (2) **ambient temperature** on the reaction time and thus, colour intensity of test strips.

Extractant types: there is a range of available soil extractants, i.e. chemical solutions used for extraction of plant available nutrients. Some are universal and can be used to extract multiple elements, others are applicable to a single chemical element. A total of five extractants, i.e. distilled water, Mechlich-1 solution (0.0125 M H_2SO_4 + 0.05 M HCl), 0.5M sodium bicarbonate ($NaHCO_3$), Modified Morgan (0.62M NH_4OH + 1.25M CH_3COOH) and 0.01M $CaCl_2$ were chosen to establish if there are any interferences caused by the type of extractant applied.

QUANTOFIX Phosphate test strips [ref. number: 91320] could not detect phosphorus when exposed to 0.5M sodium bicarbonate ($NaHCO_3$) and Modified Morgan (0.62M NH_4OH + 1.25M CH_3COOH) extractants regardless of the amount of P added during the trial (min. added: 0ppm; max added: 25ppm of P). The use of 0.01M $CaCl_2$ results in underestimation of P concentration. Mechlich-1 (M-1) solution causes overestimation of P concentration in comparison to distilled water, however, it stabilised the strip readings at higher P concentrations (Figure 8-5). Thus, M-1 was deemed preferable to other extractants.

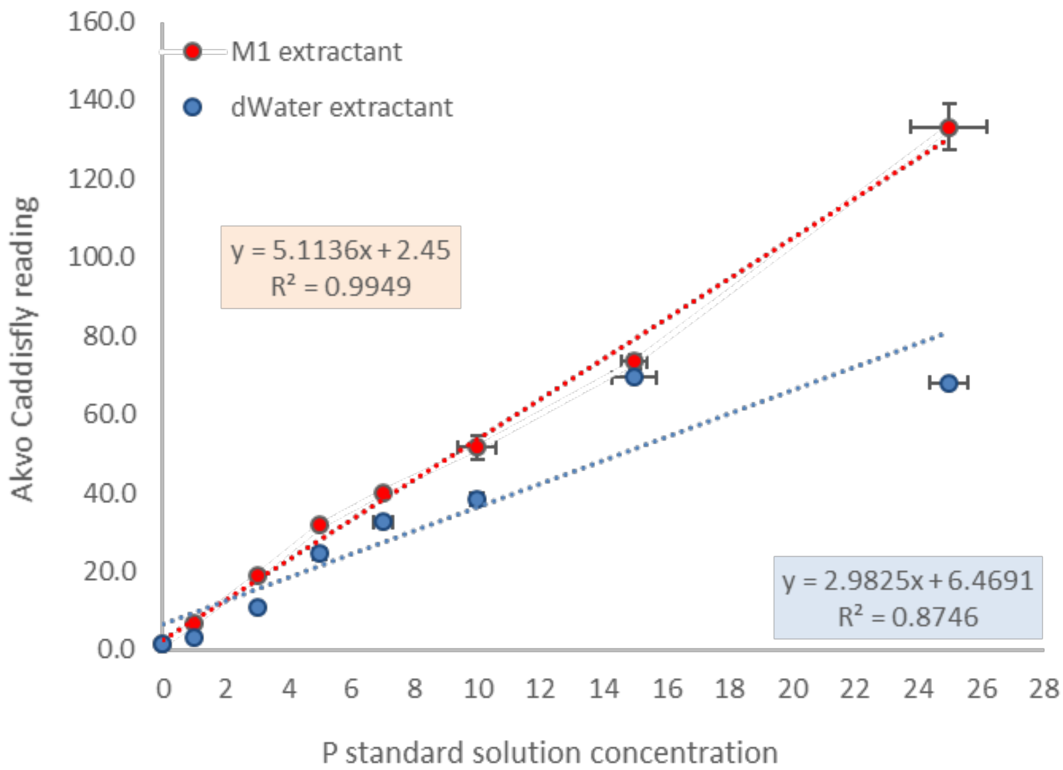


Figure 8-5. Akvo Caddisfly measurements for phosphorus standard solutions. Readings differ relative to the type of extractant used. M1 extracts overestimate P concentration by 51% at 25ppm of P but have a higher correlation coefficient (R2=0.99) in comparison to dH2O (R2=0.87). Phone model used: OnePlus3.

Merck Potassium test strips [ref. numbers: 117985] overestimate the amount of potassium when exposed to Modified Morgan (0.62M NH_4OH + 1.25M CH_3COOH) extractant, 1M ammonium nitrate, and M-1 at low potassium concentration. When the strips are exposed to MM and 1M NH_4NO_3, they invariably indicate potassium concentration as >1000 K. In comparison, M-1 underestimates the amount of potassium at high (1000 K^+) concentrations and overestimates the values at low (0 K^+) concentrations (Figure 8-6). However, M-1 solution stabilises the reaction and causes limited orange staining of the colour card and thus, was selected as the preferable extractant.

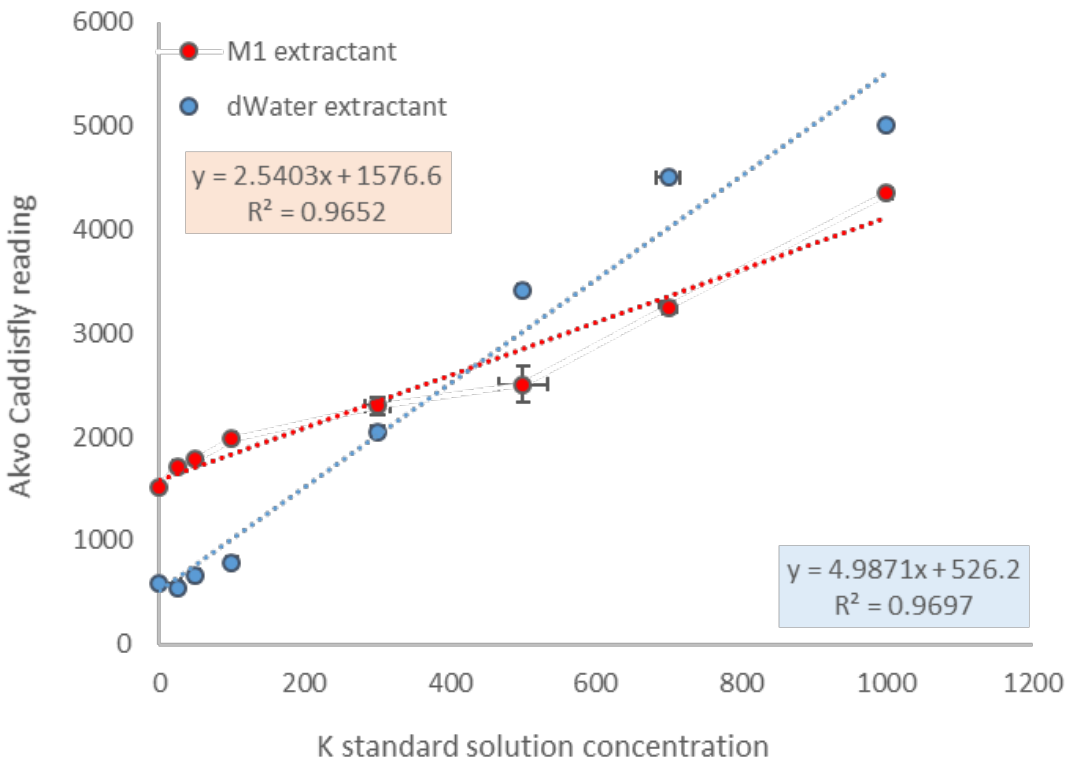


Figure 8-6. Akvo Caddisfly measurements for potassium standard solutions. Readings differ relative to the type of extractant used. In comparison to dH2O, M1 extracts underestimate K concentration by 12% at 1000ppm of K and overestimates K concentration 40% at 0ppm. Phone model used: OnePlus3.

Nitrate test strips [ref number: 2745425] have been tested with 2M KCl, which results in no reaction. They were subsequently tested with 0.02M KCl, 0.2M KCl and M1 extractants. Overall, extractants with high ion and anion concentrations are not recommended in similar trials. Extractant type needs to be taken into account during Akvo Caddisfly calibration.

Ambient temperature: During laboratory works, it was observed that the solution temperature has an impact on Akvo Caddisfly readings. There is a measurable direct relationship between ambient temperature and test strip reaction time, i.e. the higher the temperature, the higher the reaction time and thus, the deeper the colour. Overestimation of soil P content caused by high ambient temperatures (Figure 8-7) is likely in tropical regions of the world, thus, it is essential to account for those effects during the app calibration process. These findings were confirmed during subsequent temperature-dependency experiments carried out in a temperature-controlled plant chamber at Cranfield University.

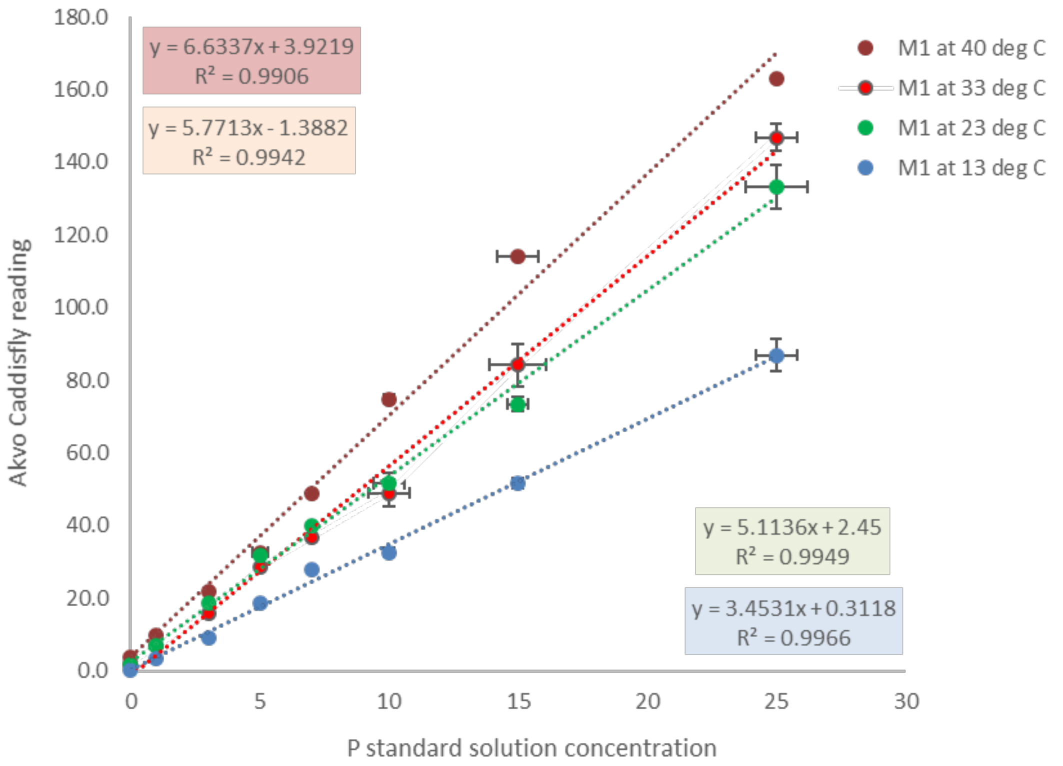


Figure 8-7. Akvo Caddisfly measurements for P standard solutions. Readings differ relative to ambient temperature. Reproducibility of the results decreases as the solution concentration increases.

Other interferences: Highly alkaline soil (pH > 8.2) cannot be tested for phosphorus due to high quantity of Ca^{+} ions. Attempts were made to precipitate calcium ions with 48% NaOH and KaOH, however, interferences remain unchanged, severely underestimating soil P content. Similarly, high quantities of sulfates are prohibitive while using the Quantofix phosphorus test strips (colour change to bright orange as opposed to turquoise). No such interferences were observed for potassium strips.

Part II: Phosphate test results

Phosphorus extraction was carried out in three ways: (1) Olsen-P extraction followed by spectrometric analysis, (2) Modified Morgan (1969) extraction of samples with pH < 7.2 and (3) Akvo Caddisfly analysis after suitable soil pre-treatment. Standard laboratory methods followed standard operating procedures developed by Cranfield University. In contrast, Akvo Caddisfly results were obtained via a trial-and-error method with pre-treatment methods involving air drying and sieving (sieve pore size: 2mm), pH measurement, and texture class analysis. Sample mass designated for Akvo Caddisfly analysis was adjusted for texture classes, i.e. 2g for sand and loamy sand, (2) 5g for sandy loam and loam and (3) 7.5g for heavy loam and light loam (clay). All samples were extracted with 50mL of freshly prepared M-1 solution. The extraction time was 5 minutes for all texture classes.

The correlation coefficient between Akvo Caddisfly and standard laboratory method was statistically significant with $R^2 = 0.74$, $p = < .001$ (Figure 8-8). The correlation coefficient is lower for Galaxy Tab 2 than for OnePlus 3 (Figure 8-9). There is a difference between selected phone models with a mid-range OnePlus 3 performing better than the low range Galaxy Tab 2. Both phones correlate well with Quantofix Relax strip reader (R^2= 0.77 and R^2 = 80; results not shown).

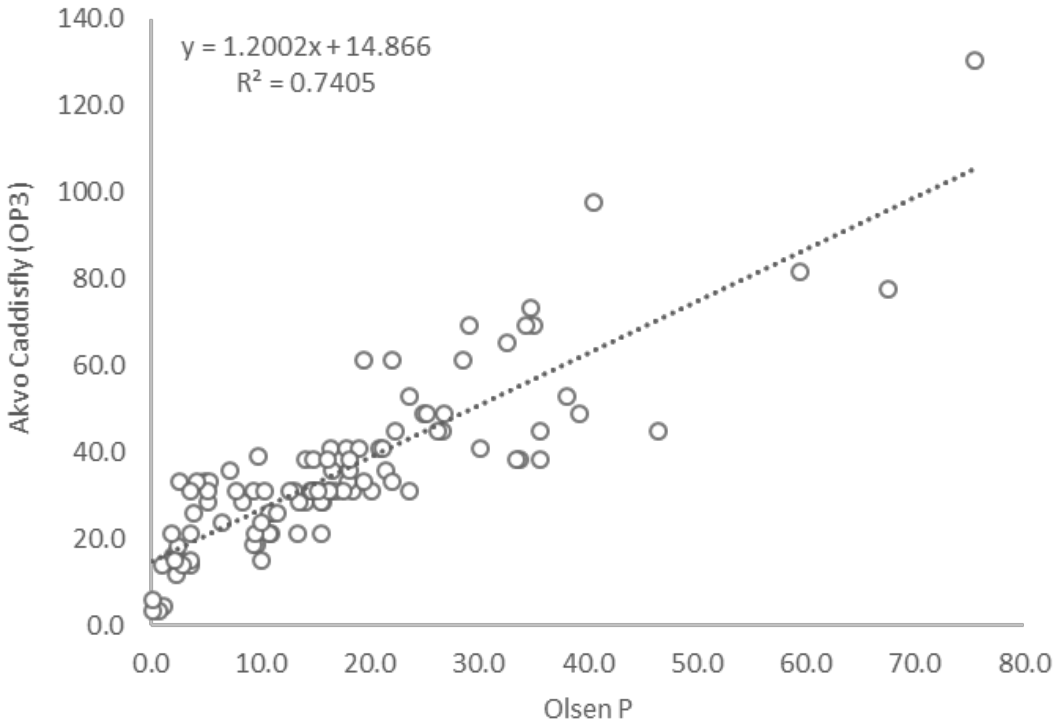


Figure 8-8. There was a positive correlation between Akvo Caddisfly results recorded with OnePlus 3 and Olsen-P results (r = .74, p = < .001, n = 105 at 95% CI).

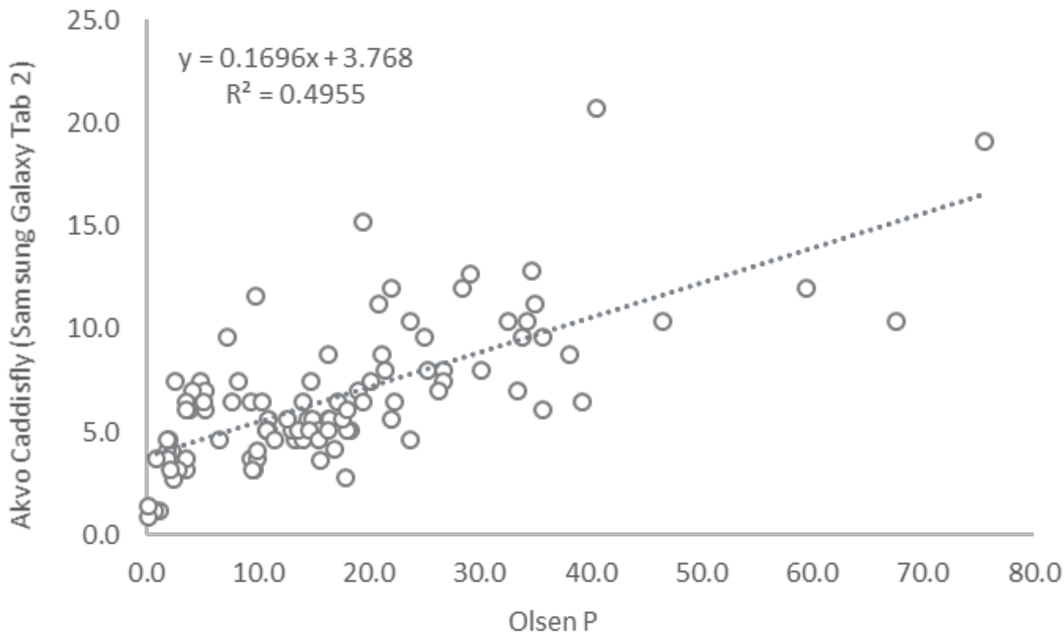


Figure 8-9. There was a positive correlation between Akvo Caddisfly results recorded with Samsung Galaxy Tab 2 and Olsen-P results (r = .50, p = < .001, n = 105 at 95% CI).

In addition to technical challenges in turquoise colour detection, test strip applicability for P analysis was reduced as more samples continued to be tested from across Indonesia. Multiple chemical interreference were noted, for both clayey and sandy soils, which called the applicability of colorimetric method in P assessment into question. These results are summarised in Chapter 3.

Part III: Potassium test results

Potassium extraction was two-fold: (1) 1M ammonium nitrate extraction followed by atomic absorption, and (2) Akvo Caddisfly analysis after suitable soil pre-treatment. Potassium extraction and analysis followed standard operating procedures developed by Cranfield University. In contrast, Akvo Caddisfly results were obtained via a trial and error method, which were based on previous literature and existing standard soil analytical methodology, with the pre-treatment methods involving air drying and sieving (sieve pore size: 2mm). Potassium strips are characterised by a higher range of values. Thus, a higher quantity of soil was considered necessary for analytical purposes. In order to find out the best soil: solution ratio, three groups of samples with evenly distributed texture classes were selected. The first group followed texture class dependent mass selection (as in P analysis), the second group used 10mL of soil and the third group used 20mL of soil sample. All groups were extracted with 50mL of M-1 solution (extraction time: 5 minutes). The best results were obtained for Group 3. Thus, 52 Indonesian soil samples were re-analysed with a 2:5 soil to solution ratio (Figure 8-10; Figure 8-11; Figure 8-12). The test strips were shown to lack in accuracy although they could be used as a rough guide for when the soil has more than 300ppm for at least one phone model (OnePlus 3). A detailed value range-based classification system, e.g. RB209, cannot be applied.

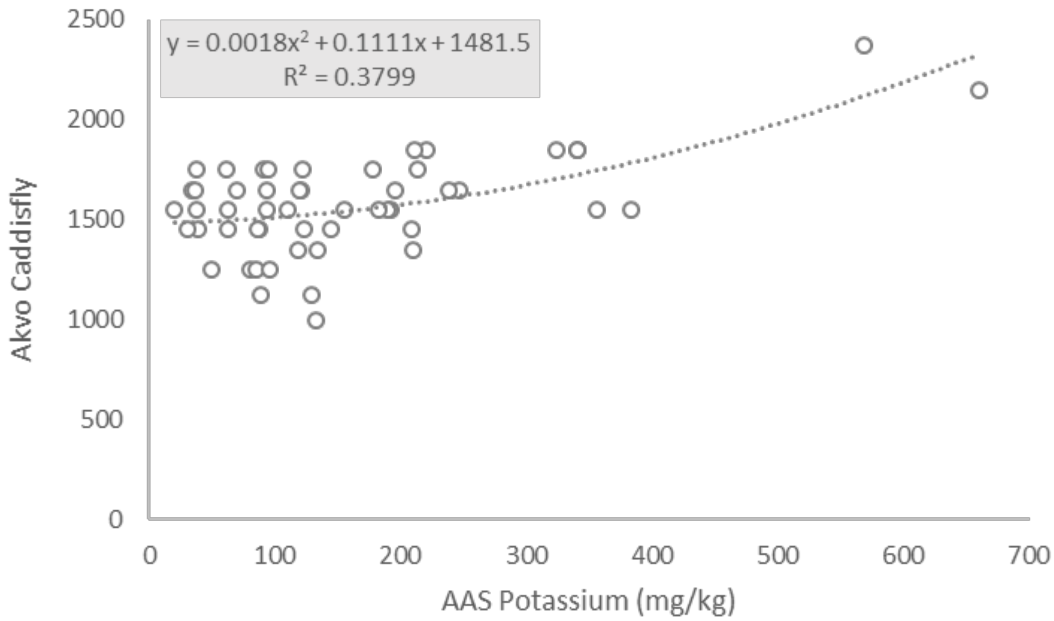


Figure 8-10. Soil potassium measurements recorded with Akvo Caddisfly (loaded on Samsung Galaxy S8) and AAS were weakly correlated (r = .38, p = .046, n = 52 at 95% CI).

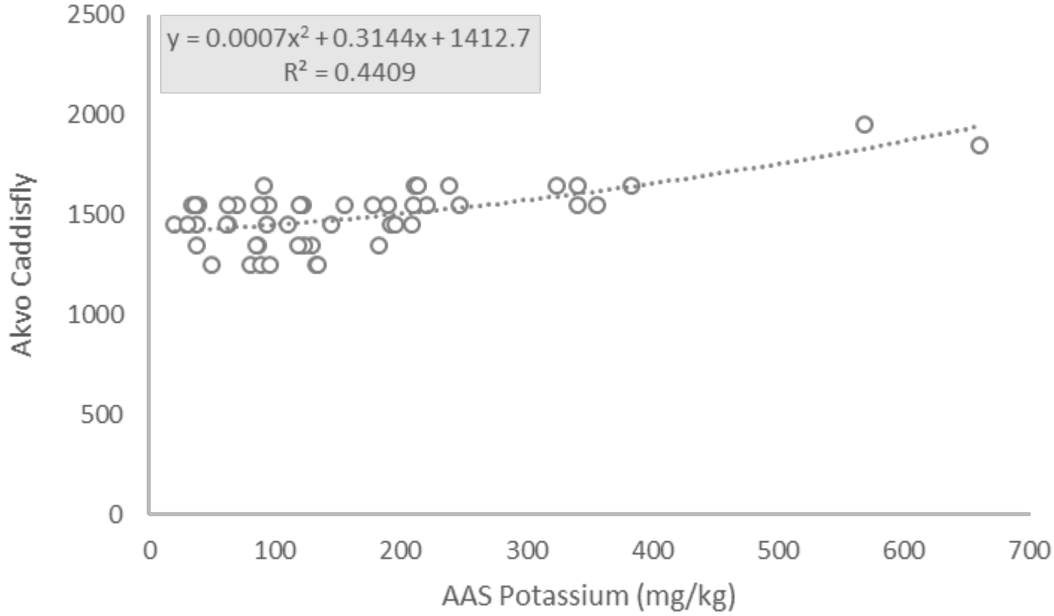


Figure 8-11. Soil potassium measurements recorded with Akvo Caddisfly (loaded on OnePlus 3) and AAS were weakly correlated (r = .44, p < .001, n = 52 at 95% CI).

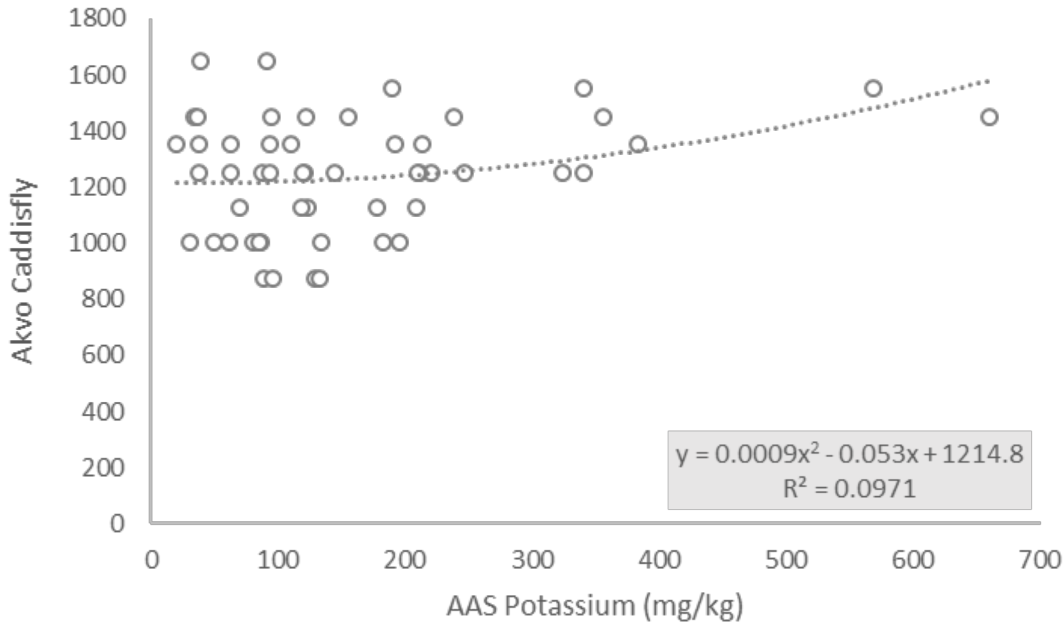
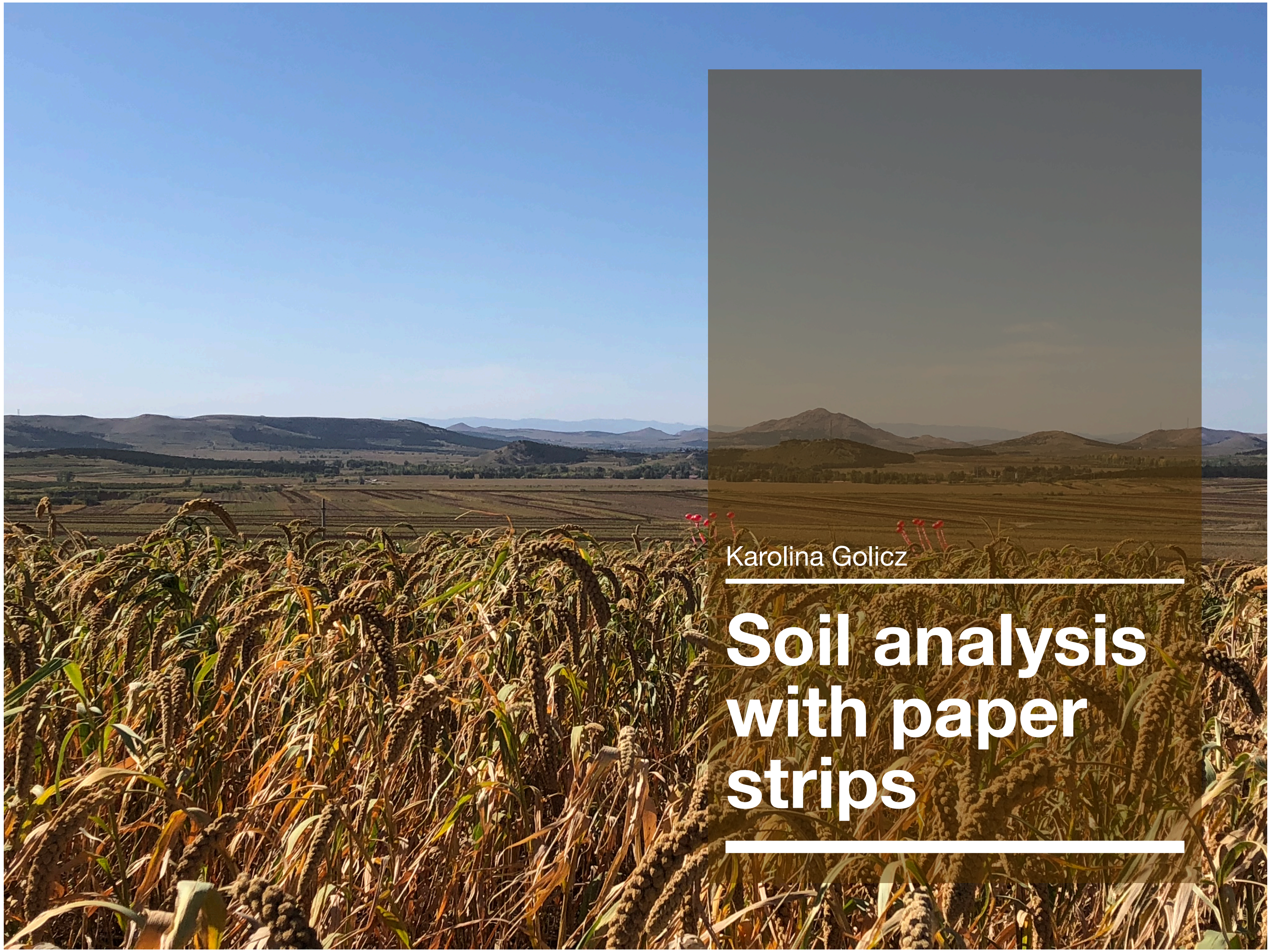


Figure 8-12. Soil potassium measurements recorded with Akvo Caddisfly (loaded on Samsung Galaxy Tab 2) and AAS were not correlated (r = .10, p = 0.482, n = 52 at 95% CI).

Outreach

How to Use Paper Strips and Akvo Caddisfly for Soil Nitrate-N Analysis

What follows overleaf is a printed template for a guide for farmers on the preferred approaches to adapt in using paper strips and the Akvo Caddisfly app in-field. Developed by the author, this leaflet could be used in conjunction with a campaign by Akvo Foundation to encourage use of the app as an in-field soil analytical tool.



Karolina Golicz

Soil analysis with paper strips

Method introduction

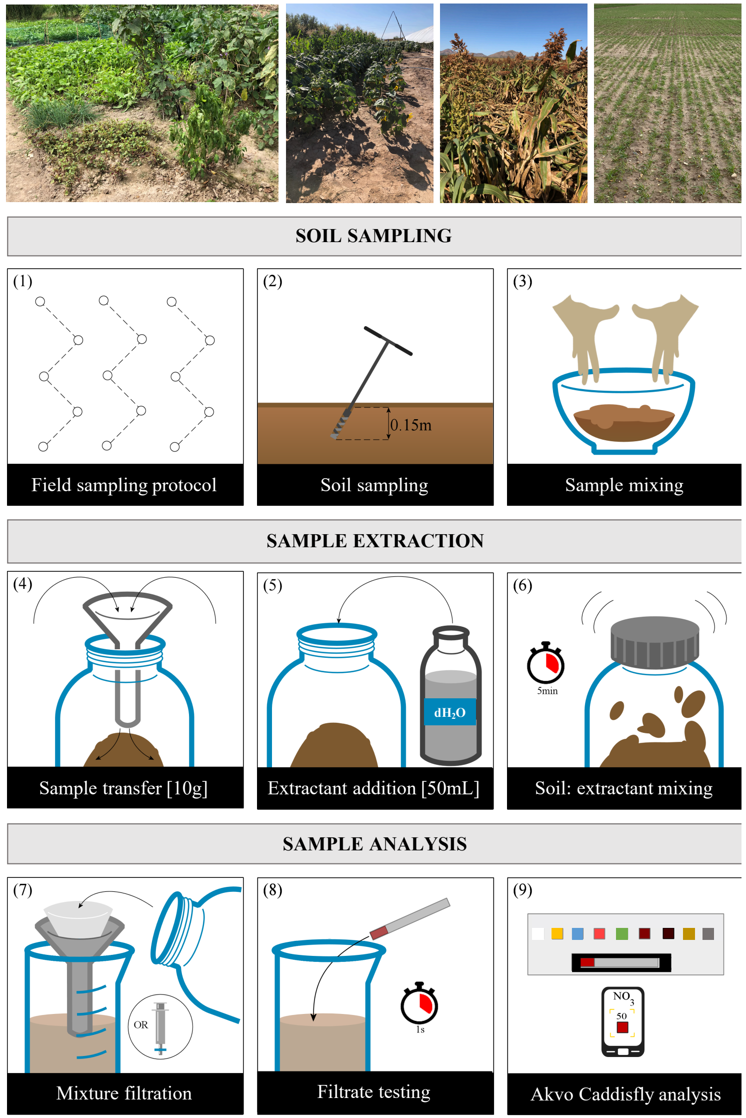
To smartphone and test strip mediated soil analysis

Soil sampling

Soil extraction

Soil analysis

Important method limitations and how to address them

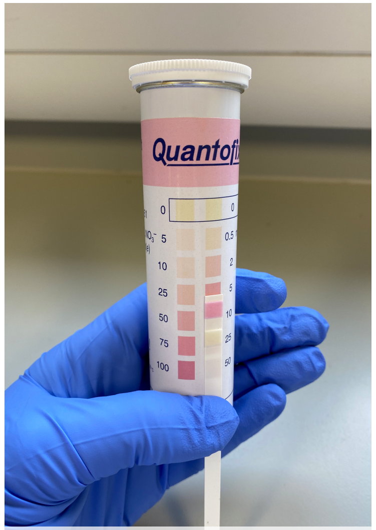


Paper strips

Paper test strips consist of a long plastic strip equipped with a reactive pad that contains reagents that change colour in response to certain chemical compounds.

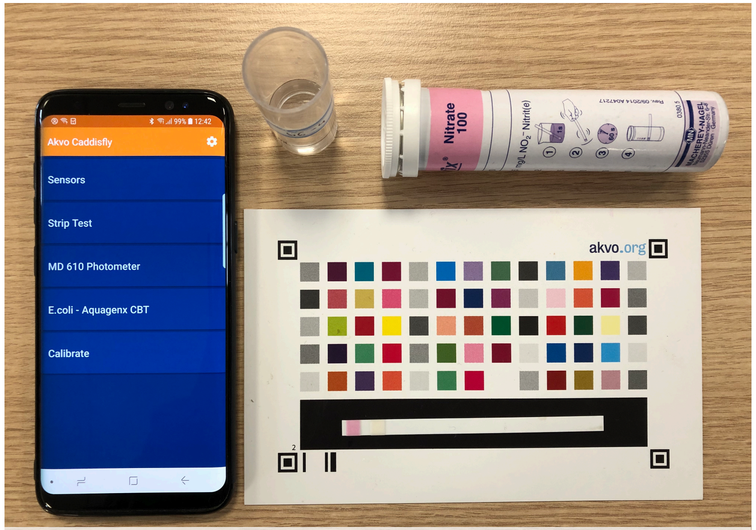
Paper strips, in conjunction with reflectometers that quantify the reactive pad's colour, have been successfully applied in soil testing across the USA, Germany, Spain, and Australia since 1980s. Nowadays, smartphones can act as (much cheaper!) reflectometers.

3



Paper strips

Reflectometer



Akvo Caddisfly app

Soil sampling

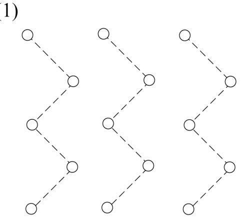
Soil test results are only as good as the way soil samples were collected. Appropriate soil sampling techniques are the first step in determining the average nutrient status in a field as well as the nutrient variability across a field.

Fertiliser recommendations based on samples not representative of a field may result in over-application or under-application of nutrients. This can have a negative impact on both economics and the environment.

During soil sampling, it is important to take into account:

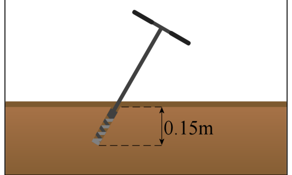
- Field area to sample
- Sampling method
- Time of sampling
- Sampling tools
- Sampling depth
- Amount of sample
- Sampling process

(1)



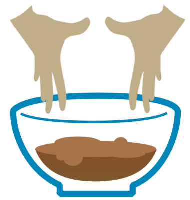
Field sampling protocol

(2)



Soil sampling

(3)



Sample mixing

Field area to sample: A representative soil sample should be collected from an area with the same crop history, and soil characteristics such as colour, texture, slope and drainage.

Time of sampling: Soil sampling should take place after harvest, but before planting. For test strip analysis, it is important not to sample after heavy rains as it influences the quantity of soil taken for analysis.

Sampling tools: A shovel or an auger are recommended.

(1) Sampling process: Dividing the field in a zig-zag manner ensures that the sample is representative. There are many sampling methods available.

(2) Sampling depth: Test strips are most frequently employed to analyse surface soil samples (15cm or 6 in). Sub-soil sampling needs to be also considered.

(3) Amount of sample: At least 20 soil cores should be taken and mixed. The method developed for test strips requires 10g of well-mixed soil sample.

Additional references:

- https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_051273.pdf
- https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_052523.pdf
- http://www.fao.org/tempref/FI/CDrom/FAO_Training/FAO_Training/General/x6706e/x6706e02.htm
- http://archive.sbreb.org/brochures/SoilSampling/soilsamp.htm

Soil extraction

After the representative soil sample is taken, it needs to be extracted.

Sample preparation: To optimise soil testing with paper strips, soil sample should be sieved. If sieving is not possible, care should be taken to remove all visible roots and stones, and break any blocks of soil with your fingers prior to analysis.

(4) Sample transfer: Ten grams of soil should be weighted out and added into a bottle. A wide-mouth funnel facilitates transfer of soil into the bottle. It is important to ensure the sample is not too wet (**>50%**). In-field soil moisture content (MC) assessment is recommended whenever possible. MC is needed to calculate the dilution factor (DF) as wet soil means having less soil available for analysis*.

DF = 50mL ÷ 10g

[when the soil is dry]

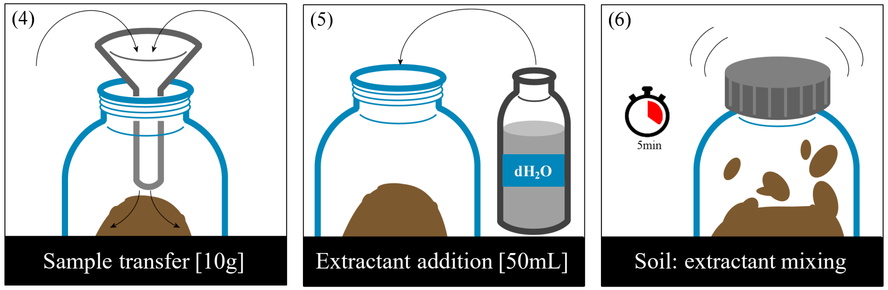


Table 1. Soil moisture content assessment (adapted from Iowa State University Extension Service).

Soil Moisture Content	Medium: (Coarse) Texture	Medium: (Fine) Texture	Fine and Very Fine Texture
100 percent soil moisture	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand
75 percent available soil moisture remaining	Forms a ball, is pliable	Forms a ball, is pliable, sticks readily	Easily ribbons out between fingers, slick
50 percent available soil moisture remaining	Forms a ball, somewhat plastic	Forms a ball, somewhat plastic, will stick slightly with pressure	Forms a ball, ribbons out between thumb and forefinger

(5) Extractant addition: Fifty millilitres of extractant should be added into the bottle. Recommended extractant consists of distilled water. However, if the sampled soil is **clayey** or **reddish in hue**, it might be necessary to employ a coagulant. Only weak extractants e.g. 0.02M KCl can be used in conjunction with test strips.

(6) Soil: extractant mixing: The mixture must be vigorously shaken for at least 5 minutes or until large blocks of soil are dissolved.

Additional references:

- https://www-pub.iaea.org/mtcd/publications/pdf/tcs-30_web.pdf
- https://crops.extension.iastate.edu/encyclopedia/how-evaluate-soil-moisture-field

* e.g. 25% soil moisture content means that the soil weight is reduced by 25%. Thus, the DF is equal to 50mL ÷ 7.5g i.e. 6.7

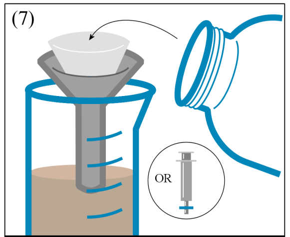
Soil analysis

After extraction, the mixture needs to be be filtered.

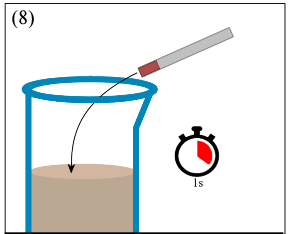
(7) Mixture filtration: Filtration can take place through a large pore-size filter paper such as Whatman's 4V filter paper. If the soil is **clayey**, the process of filtration can take excessive time. In such case, using a syringe with a filter is recommended.

(8) Filtrate testing: After a clear extract is obtained, a new test strip should be taken out of its box and placed in the filtrate for 1 second as per the paper strip manufacturer's instructions. The instructions are incorporated into Akvo Caddisfly and are displayed prior to the test taking place.

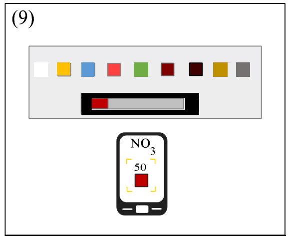
- Official website: akvo.org
- Akvo Caddisfly app: https://play.google.com/store/apps/details?id=org.akvo.caddisfly&hl=en
- **Akvo Caddisfly cannot be used without Akvo Flow [a paid service]**



Mixture filtration



Filtrate testing



Akvo Caddisfly analysis

After taking the test strip out of the filtrate, excess liquid should be shaken off so the quantity of light reflecting off the paper strip is limited.

(9) Akvo Caddisfly (AC) testing: Prior to putting the test strip into the filtrate, a **clean** calibration card should be placed on a flat surface. The card needs to be illuminated in a uniform manner.

Use a well-charged phone to open Akvo Caddisfly app. Multiple testing options will become visible within the app. Tap the tab called 'Test strip test' and select a test for nitrate.

Follow the instructions provided by the app and calibrate the phone by placing it over the calibration card. Once calibrated, place the wetted test strip on the black section of the card and wait for 60 seconds for the colour to develop on the reactive pad of the paper strip. It is recommended to use 3 paper strips per sample.

The results needs to be passed through the calibration equation:

Soil nitrate-N =

[(AC result + 0.6131) ÷ 2.7763] *

Additional references:

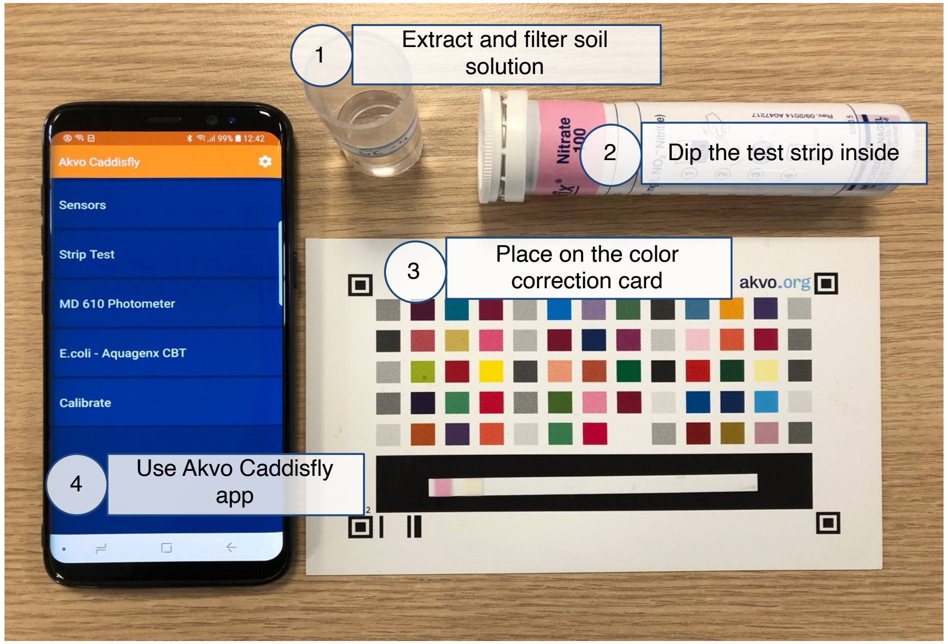
- https://ftp.mn-net.com/english/Instruction_leaflets/QUANTOFIX/91351en.pdf

* × Dilution Factor (50mL ÷ Moisture Corrected Soil Weight)

Let's recap

Smartphone

Used as reflectometer in multiple studies (Yetisen et al. 2014; Intaravannea and Sumriddet chkajorn 2015 ; Vesali et al. 2015)



Test strips

Used in soil science since the 70s in:
- the US (Jemison & Fox, 1988),
- **Australia** (Wetselaar et al. 1998),
- **Germany** (Schmidhalter, 2005),
- Spain (Thompson et al. 2009)

In-field soil testing apparatus. It is recommended to use Samsung Galaxy for Akvo Caddisfly testing (displayed: Samsung Galaxy S8).

* × Dilution Factor (50mL ÷ Moisture Corrected Soil Weight)

Method limitations

Temperature-dependency: Test strips overestimate nitrate concentration at higher temperatures (>20°C). Thus, it is important to monitor ambient temperature and implement a correction factor based on the curve developed for Akvo Caddisfly (shown on the right).

In high (or low) temperatures, the Akvo Caddisfly reading should be multiplied by the appropriate correction factor.

Chemical interferences: Nitrate-sensitive test strips are prone to chemical interferences caused by nitrite ions. Nitrite interference occurs when the second reactive pad turns pink or red. It is possible to neutralise nitrite interference with 1 drop (per 5mL of filtrate) of 10% amidosulphuric acid (H_3NO_3S).

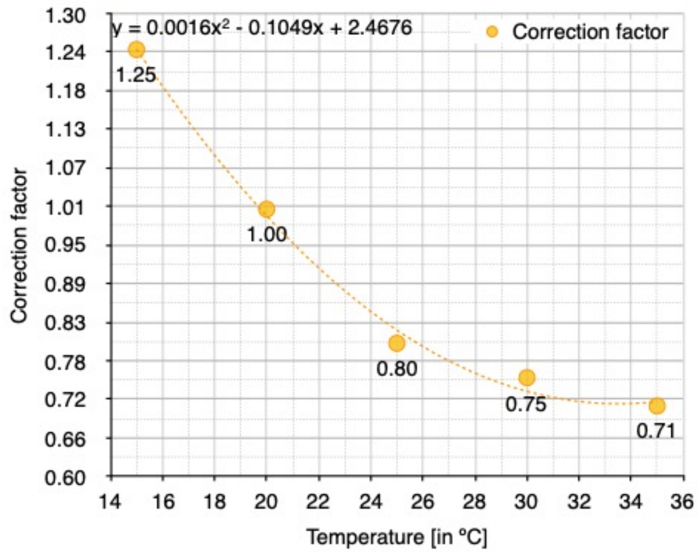
No high molarity extractants can be used alongside paper strips.

High concentration: When sample concentration exceeds 100mL NO_3^-, it needs to be diluted prior to analysis. Dilution should take place by taking ***2.5mL of the aliquot*** and adding ***2.5mL of distilled water***, and stirring the mixture. The reading should be multiplied by ***2*** to account for sample dilution.

Degradation of colour correction card: Care should be taken to clean the card and ensure it is not stained during testing. When clearly worn, it needs replacing.

Smartphone model: Akvo Caddisfly app does not fully correct for variations in colour readings by different smartphone models. Samsung Galaxy (S8) phones are recommended for testing.

Dilution: Ratio of the solute to the final volume of the diluted solution e.g. 1 part aliquot to 2 parts diluent = 1 + 2 = 3. The aliquot concentration must be multiplied by 3 to account for dilution.



ADDITIONAL NOTES: Paper strips alongside Akvo Caddisfly constitute a screening tool and should not be treated as an alternative to standard laboratory methods.

Landmark Piece

What follows overleaf is a short piece written for Landmark in order to disseminate information to a wider (and not solely academic) audience. More actions ought to be taken to ensure knowledge sharing between scientists and practitioners.

Smartphone technology in modern agriculture

Karolina Golicz believes that the agricultural sector is underusing the potential of smartphones to act as powerful, multi-purpose tools in farming throughout the world. Here she explains why…

Worldwide, today more people have access to mobile phones than to clean water. Smartphones are increasing in number year-on-year, first disrupting, and then subsequently integrating completely within almost every industry. Agriculture is firmly at the forefront of this technological revolution.

Our adaptation and rapid response to changing conditions will be key in safeguarding worldwide food production systems to a projected nine billion people by 2050. In order to provide sufficient quality nutrition to the growing population, we need to hasten the uptake of efficient, information-driven and sustainable agricultural practices. However, the full potential for utilising smartphone technology in informing agricultural management decisions at local and international level remains largely unrealised.

The role of smartphones

Powerful, portable microcomputers, demanding little IT literacy, smartphones provide the means to access information at will. From acting as irrigation decision support tool in Colorado to connecting farmers in Ghana, and fine-tuning fertiliser recommendations in Thailand, they have a potential to contribute to the development of a new generation of agriculture-oriented information technology architecture, where data is instantly received, recorded and either shared between interested parties or stored in the cloud.

Farmers have been engaging with mobile technology since its inception. Especially in the developing world, where mobiles and agriculture-oriented apps have been repurposed to act as tracking systems, mobile payment terminals, farmer-oriented helplines, and for operating trading platforms.

Apps that make use of inbuilt smartphone sensors are capable of equipping farmers with real-time and site-specific assistance, providing a portable soil testing capability, improving irrigation scheduling or modelling nitrogen losses.

Hundreds of farming-oriented apps are available in the various app stores (Figure 1). Choices exist between high quality methods, which are often not publicly available, or apps developed by unknown parties with no evidence of thorough testing. Scientifically sound testing and government-mediated quality standards of apps should be a priority given the pressing public and scientific interest in developing smartphone technology to enhance agriculture.

The dissemination of information involving agricultural practices and farm management could be advanced through easily accessible, quality-assured and user-friendly apps. Ideally, those apps would emphasise connectivity and the ability to transfer knowledge and agricultural innovation on a person-to-person basis, rather than focusing solely on passive information transfer. They should be widely accessible across the world and in multiple languages.

Schemes aimed at improving agricultural productivity while enhancing sustainability have failed frequently over the years with knowledge intensive practices being less likely to be adopted. However, in such cases the lack of technological solutions has rarely been identified as the chief barrier. Instead, socio-economic problems are highlighted, rising from linear transfer-of-technology and top-down approaches that did not account for innovative systems that constitute elements of feedback loops, iterative interactions and learning processes. Employing elements of communication technology within such approaches could help foster agricultural innovation systems, replacing top-down extension approaches, and could further act as a medium for the introduction of climate change adaptation and mitigation strategies.

Figure 1. Google Play Store showing a search of the term 'Agriculture'. India is at the forefront of agriculture-oriented app development, having developed 59% of the first 100 top rated (4*) apps and downloading them over 1.6m times. Countries such as India and Malta use apps as a way to provide extension services and trading platforms. However, a lack of suitable frameworks impedes smartphone app incorporation into agricultural management across the world

What does this all mean?

There is little doubt that smartphones will become more widespread and that their adoption into agri-business will increase and deepen. However, the success of smartphone apps as multi-purpose tools, able to collect and share financial, environmental and social data, will depend on suitable conditions, which make scientific, business and social sense.

Firstly, the smartphones ought to be viewed as tools, acting to support the development of efficient and data-driven precision agriculture. As such, they require well thought-out architectural designs, which account for challenges likely to be encountered in the agricultural sector. For example, intermittent internet access, bandwidth fluctuations, and energy conservation necessary for prolonged in-field use. Secondly, there must be a clear link between the needs of the user and the app being developed. Thirdly, it is important to recognise that isolated development and meticulous cross-examination of smartphone apps will remain solely an unconnected endeavour if they are not made widely available and updated regularly.

Furthermore, app availability and usefulness needs clear communication to intended users. This requires a certain level of trust to be established between the technology developers and its users, and can only be achieved through well-established extension services or intermediaries. Finally, integration of frameworks that can ensure quality standards and improved accessibility will remain of paramount importance. This level of integration requires a robust and dynamic collaboration between individual farmers, governmental organisations, and related industry.

By increasing engagement with agriculture-oriented information technology, the collaboration between farmers and the tech industry will surely push the future development of high-quality apps, ensure their continuous updates, and hasten the uptake of information-driven agriculture throughout the world.