

Review Article

Review of the Innovations and Challenges in Developing Rapid Colorimetry and Turbidity NPK Soil Test Kits for Commercial Soil Nutrient Analysis

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ABSTRACT

This study reviews the progress and challenges in developing rapid colorimetric and turbidimetric test kits for commercial soil nutrient analyses, focusing on nitrogen, phosphorus, and potassium. Although common laboratory analytical techniques are accurate, they are often expensive and require advanced technical skills. Consequently, commercial *in situ* soil test kits have gained attention as potential alternatives to these tests. These kits use universal extractants that can simultaneously extract multiple nutrients and colorimetry and turbidimetry for nutrient determination. A critical aspect of these kits is the selection of suitable extractants that are effective under various soil conditions, chemically safe, compatible with analytical systems, and have a long shelf life. This review assesses the efficacy of several extractants in conjunction with colorimetric and turbidimetric reagents. Examples include H3A-4 and Kelowna extractants using the zinc–Griess reagent, salicylic method, molybdenum yellow method, and sodium tetraphenyl boron method for nitrate, ammonium, phosphorus, and potassium, respectively. These extractants and reagents have been highlighted for their adaptability, safety, rapid color formation, and minimal compatibility issues, making them promising candidates for rapid test kit development. However, rapid soil test kits are designed to provide a general understanding of soil nutrient status. They are not intended

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to replace detailed laboratory analyses in situations where precision is critical. Additionally, these kits should be validated against standard laboratory methods to determine their accuracy and reliability. This review highlights the importance of balancing practicality and accuracy when developing rapid soil test kits for soil nutrient analysis.

Keywords: Colorimetry, commercial soil nutrient rapid test kit, NPK, turbidity, universal extractant

INTRODUCTION

Integrated soil fertility management has significantly improved crop yields, bolstered resistance to environmental stresses, and curbed greenhouse gas emissions (Roobroeck et al., 2016). However, farmers often face challenges due to uncertainty in determining the appropriate quantity and type of fertilizer required to maintain soil fertility. This uncertainty underscores the significance of conducting soil nutrient analyses before fertilization to ensure optimal crop yield and quality.

Conventional farming practices have increasingly led to the overapplication of chemical fertilizers, contributing to the global wastage of approximately 50–65% of N and P in agricultural fields (Ritchie, 2021). Such practices not only squander farmers' resources but also pose environmental hazards, including eutrophication, harmful effects on aquatic ecosystems, and adverse effects on human health. Conversely, insufficient nutrient levels can result in poor crop quality and yield, highlighting the need

for appropriate fertilizer application for sustainable farming.

Despite offering comprehensive and highly precise data, laboratory soil nutrient analysis is typically not feasible for smallholder farmers because of high costs, lengthy time requirements, and technical complexity. This process involves handling hazardous chemicals, using specific extraction methods for each nutrient, and using expensive equipment such as inductively coupled plasma (ICP) mass spectrometry, atomic absorption spectroscopy (AAS), and auto analyzers. In Malaysia, the service cost per nutrient element is at least MYR 30, and results are obtained in days to months. These constraints made the analysis inaccessible for many smallholders, thereby impeding effective fertilization programs and crop production.

Commercial colorimetric soil nutrient test kits have emerged as viable alternatives in response to these challenges. These kits categorize soil nutrient concentrations into practical levels (low, medium, and high) and provide approximate readings visible to the naked eye. The affordability and capacity to yield immediate results, with costs ranging between MYR 15 and 40 in Malaysia, represent significant advancements. However, concerns arise because despite the availability of over 90 types of rapid soil test kits online, more than half lack validation by credible independent authorities (Dimkpa et al., 2017). Scientific assessments have shown that the accuracy of these kits varies from 33 to 94% compared with analytical

laboratory results (Faber et al., 2007). This variability raises questions about reliability. Nevertheless, when accuracy and precision are ensured, rapid test kits that provide approximate readings are still acceptable for an immediate understanding of soil nutrient status.

This review thoroughly examined the efficacy of rapid soil nutrient testing using colorimetric and turbidimetric systems, focusing on their accuracy, precision, and practicality in fertilization management.

METHODOLOGY

The literature search used ScienceDirect (<https://www.sciencedirect.com>) and Google Scholar (<https://scholar.google.com>) with the following initial sets of keywords: “soil nutrient analysis”, “NPK extraction”, “universal extractant”, “rapid soil test kits”, “colorimetry”, and “turbidimetry”. Subsequently, the search was refined by incorporating specific keywords such as “Morgan”, “Kelowna”, “SrCl₂ universal extractant”, and “H3A” to focus on universal extractants. For colorimetric and turbidimetric methods, the targeted keywords included “Nessler”, “Berthelot–salicylic method”, “Griess method”, “NO₃⁻ salicylic method”, “molybdenum blue P method”, “molybdenum yellow P method”, “sodium tetraphenyl boron turbidimetry reagent”, and “crown ether-modified gold particles”. This approach identified scholarly articles discussing the simultaneous extraction of NPK in the context of colorimetric and turbidimetric methods using specific universal extractants and reagents.

Articles were selected based on their relevance to the study objectives and the timeline for publication. This approach traced the evolution of NPK assessment methodologies from pioneering studies to more recent advancements. The emphasis was placed on publications published after 2010 that were aligned with the latest developments in NPK soil nutrient analysis methodologies.

The initial search yielded 187 relevant papers. Of these, 75 were chosen because of their substantial contribution to the literature on rapid soil NPK nutrient analysis. The selection process prioritized studies that focused on universal soil extraction methods and colorimetry- and turbidimetry-based determination methods. These studies have significantly enriched the discussion of contemporary soil nutrient assessment methodologies, with a specific focus on NPK analysis. This rigorous selection process ensured the collation of pertinent literature for this review, thereby providing a comprehensive overview of the current state of soil nutrient analyses.

RAPID SOIL NPK TEST KIT DEVELOPMENT

Bünemann et al. (2018) reported that the testing frequency for N, P, and K in soil was greater than that for other soil quality indicators. It is unsurprising given the significance of N, P, and K in plants.

NO₃⁻ and NH₄⁺ are key N sources in plant roots and influence plants’ physiological and morphological aspects. The effects of phytohormones include

genome regulation, seed dormancy, floral induction, and phytohormone regulation (Hachiya & Sakakibara, 2016).

Soil P, often in its organic form, undergoes mineralization to orthophosphate (Pi), primarily as dihydrogen P (H_2PO_4^-) and hydrogen P (HPO_4^{2-}) ions. These ions diffuse into plant roots and are transported through symplastic pathways to the xylem and cytoplasm. Plants use P for several critical functions, including energy generation, nucleic acid synthesis, photosynthesis, respiration, metabolic regulation, and membrane synthesis and stability (Vance et al., 2003).

Vascular plants actively absorb K through specialized transporters and channels. This uptake is essential for various plant functions, including enzyme activation, membrane transport, anion neutralization, osmoregulation, photosynthesis facilitation, and assimilation product transport (Y. Wang & Wu, 2013). Therefore, assessing soil N, P, and K levels has become a priority in developing rapid test kits, given their crucial role as macronutrients essential for plant health.

Developing a rapid soil test kit typically begins with the simultaneous extraction of multiple targeted nutrients, such as N, P, and K, from soil samples using a single extractant, often referred to as a universal soil extractant. The concentrations of nutrients in the extractant supernatant were visually assessed using colorimetry and turbidimetry. The pioneering work of Morgan (1941), who introduced a colorimetric and turbidimetric diagnostic system using a

universal extractant, represents a significant advancement in rapid laboratory testing protocols. This methodology has served as a foundational reference for the innovation and development of commercial rapid soil test kits, facilitating quicker and more accessible nutrient analysis.

NPK Universal Soil Extractant

A universal soil extractant, or multiple-nutrient extractant, is a single solution that simultaneously extracts multiple nutrients from soil samples (Haney et al., 2010; Jones Jr., 1990). Numerous studies have compared their results with those obtained using specific standard extractants to evaluate the efficacy of such extractants. For instance, 2 N potassium chloride (KCl) is typically used to extract NH_4^+ and NO_3^- ; Olsen, Bray, and Mehlich extractants are used for P, and 1 M ammonium acetate (NH_4OAc) and Mehlich-3 are used for K (De Silva et al., 2015; Sahrawat, 1979; Simard & Deschênes, 1992; Simard et al., 1991; van Lierop, 1986). This comparative approach is crucial for determining the effectiveness of a universal extractant for extracting various nutrients from soil, thereby validating its use in soil nutrient analysis.

Morgan Extractant

The Morgan universal extractant, composed of 0.73 M sodium acetate ($\text{C}_2\text{H}_3\text{NaO}_2$) and 0.52 N acetic acid (HOAc), was introduced in 1941 as a pioneering solution capable of simultaneously extracting various elements from soil, including NO_3^- , NH_4^+ , P, K, Ca, Mg, other micronutrients, and heavy

metals (Morgan, 1941). A validation study conducted in the 1970s demonstrated that the Morgan extractant achieved over 80% recovery of inorganic N in sandy clay loam soils from an old alluvium series (Sahrawat & Prasad, 1975). Further research comparing NH_4^+ extraction methods in tropical rice soils found that the Morgan extractant performed comparably with 2 N KCl in five of the seven tested soils (Sahrawat, 1979).

In 1982, Wolf modified the Morgan extractant by adding diethylenetriaminepentaacetic acid (DTPA) and performing a vigorous shaking step for 5 min (Jones Jr., 1990). Although the Morgan–Wolf extractant extracted less K than the other methods, it showed a moderately significant variation in P extraction; it extracted more P in high-pH soils, dissolving calcium–phosphate, but less P in low-pH soils, where it struggled to dissolve iron–phosphate and aluminum–phosphate (Masjkur, 2009). In 2015, a strong correlation ($r=0.73$) was established between the Morgan reagent and the Olsen method, indicating the suitability of the Morgan reagent for rapid colorimetric P determination in mildly acidic to basic soils (De Silva et al., 2015). The original Morgan and modified Morgan–Wolf extractants have been recommended for use in acidic soils (Kumawat et al., 2017).

Kelowna Extractant

The NH_4OAc with ammonium fluoride (NH_4F) extractant, a modification of the Morgan and Bray extractants, was

developed to enhance the extraction of multiple nutrients, particularly P and K, in acidic soils (McIntosh, 1969). Later, the Kelowna extractant, comprising 0.25 N HOAc and 0.015 N NH_4F , demonstrated a strong linear correlation ($r = 0.99$) with the 2 N KCl method when using steam distillation alongside Devarda alloy for NO_3^- determination (van Lierop, 1986). The results also showed strong correlations with both the Bray-1 and Olsen methods ($r > 0.99$) for acidic and calcareous soils. It extracted approximately 2.5 times more P than the Olsen method. The Kelowna extractant was developed to improve the Bray solution, a recognized P extraction solution for acidic soils, by substituting 2 N hydrochloric acid (HCl) with 0.25 N HOAc (van Lierop, 1988). Additionally, the Kelowna extractant exhibited a strong linear correlation ($r = 0.99$) with 1 N NH_4OAc to extract K from acidic and calcareous soils (van Lierop & Gough, 1989). In 1996, the Kelowna multiple-nutrient extractant was used as a reference for extracting NO_3^- , P, K, Ca, Mg, Na, and sulfur from agricultural soils in British Columbia (Gough, 1996).

Moreover, the Kelowna extractant demonstrated a 1:1 relationship and a high coefficient for NO_3^- determination, and it correlated strongly with the Mehlich-3 extractant. However, it was 25 and 51% lower for P and K extractions, respectively. Therefore, it has been successfully applied to NPK ion-selective electrodes (ISE) for real-time soil nutrient analysis (Kim, 2006). In a recent study, the combination of Kelowna extraction with K-ISE showed a highly significant linear correlation compared

with the reference method, 1 M NH_4OAc with AAS, for determining K content (Manatthammakul et al., 2023). Sarker et al. (2014) found that the Kelowna extractant exhibited weaker P extraction ability than Bray and Kurtz-1 and Mehlich-3 but was stronger than the Olsen method. Kelowna is an ideal extractant for potentiometric determination of soil P content using portable extractors (Sukatton et al., 2017).

Salt Extractant

The 0.02 M strontium chloride–0.05 citric acid (SrCl_2 –citrate) extractant, which is capable of extracting inorganic N, P, K, and other micronutrients, demonstrated significant efficacy in extracting P by showing strong correlations with the Olsen and Mehlich methods ($r > 0.97$) in acidic and alkaline soils (Simard et al., 1991). Subsequent studies revealed that SrCl_2 –citrate exhibited slightly higher NO_3^- and NH_4^+ extraction and strong correlations ($r > 0.70$) with the 2 M KCl extractant. It also showed a notably significant linear relationship with K extraction compared with 1 M NH_4OAc and Mehlich-3 ($r > 0.90$) (Simard & Deschênes, 1992). Furthermore, SrCl_2 –citrate extraction demonstrated higher K extraction than SrCl_2 and barium chloride (BaCl_2) extraction, demonstrating its ability to reliably predict the quantity of plant-available K in soil (Simard & Zizka, 1994). In another study, white precipitation was observed when the SrCl_2 –citrate supernatant was combined with the Murphy and Riley method, a colorimetric P determination technique (Li et al., 2006).

In 2012, an evaluation of 0.01 M Ca chloride (CaCl_2), 0.02 M SrCl_2 , and 0.01 M BaCl_2 as universal extractants concluded that 0.02 M SrCl_2 and 0.01 M BaCl_2 could serve as substitutes for conventional laboratory-based methods for determining available P across all soil types. For NO_3^- analysis, 0.02 M SrCl_2 was suitable for basic soils, whereas 0.01 M BaCl_2 was optimal for acidic and neutral soils. However, compared with the 1 M NH_4OAc method, these three universal extractants exhibited lower efficacy in extracting K (Bibiso et al., 2012). Moreover, among the evaluated universal extractants — 0.01 M CaCl_2 , 0.01 M BaCl_2 , 0.1 M BaCl_2 , 0.02 M SrCl_2 , Mehlich-3, and ammonium bicarbonate (NH_4HCO_3)–diethylenetriaminepentaacetic acid (DPTA)—0.02 M SrCl_2 exhibited the strongest and most significant correlation with standard laboratory-based methods for NO_3^- , P, K, Ca, and Mg across a soil pH range of 4.75–8.22 (Bibiso et al., 2015).

H3A Extractant

Haney et al. (2006) introduced an H3A soil extractant comprising lithium citrate, citric acid, malic acid, oxalic acid, ethylenediaminetetraacetic acid (EDTA), and DTPA. Their study demonstrated that the H3A extractant exhibited a highly significant correlation with water and 1 M KCl ($r > 0.90$) for inorganic N extraction. Additionally, it showed significant correlations with water, Mehlich-3, and Olsen ($r > 0.61$) for extractable P across various soil conditions, including diverse clay contents, organic carbon levels, and

pH. The pH of the H3A extractant also significantly influences the extraction of P. Subsequently, H3A was modified to generate H3A-2 by eliminating EDTA and DTPA while adjusting the concentrations of lithium citrate, malic acid, oxalic acid, and citric acid at pH 4.4. This adaptation enhanced the estimation of inorganic N, P, K, Ca, and Zn, resulting in a clearer filtrate. It also significantly reduced the shaking time required for extraction from 30 min in the case of H3A-1 to a more efficient duration of just 5 min. H3A-2 demonstrated its ability to prevent overestimation or underestimation of soil P under various soil conditions. It also displayed significant correlations with water, Mechlich-3, Bray 1, and Olsen methods ($0.64 < r < 0.86$) for P, along with a strong correlation with 2 M KCl for inorganic N ($r = 0.97$) and NH_4OC for K ($r = 0.95$) estimation (Haney et al., 2010). H3A-2 was further modified to produce H3A-3, composed of 0.006 M lithium citrate, 0.002 M citric acid, 0.004 M malic acid, and 0.003 M oxalic acid.

Evaluation using ferroaluminum oxide (FeAlO_3) strips, considered a “gold standard” for assessing plant-available P, revealed that H3A-3 yielded comparable results with <10% relative error and displayed a high correlation ($r = 0.98$) with FeAlO_3 strips. Consequently, H3A-3 has been proposed as a viable alternative method for determining plant-available P in soil, providing a cost-effective and time-saving solution compared with FeAlO_3 strip analysis (Haney et al., 2016). The following issues with lithium citrate cause

turbidity in highly weathered soils with low pH and high Fe and Al concentrations, leading to complications in laboratory assays. Hence, researchers have attempted to eliminate lithium citrate from H3A-3. It resulted in the development of H3A-4, which consisted of 0.004 M citric acid, 0.008 M malic acid, and 0.005 M oxalic acid buffered at pH 3.75. The application involved using a soil-to-H3A-4 ratio of 1:10, followed by 10 min of shaking and 5 min of centrifugation to extract soil nutrients. H3A-4 notably produced a clear supernatant and maintained a strong linear relationship with H3A-3 for NO_3^- , NH_4^+ , P, K, and Ca ($r > 0.80$) (Haney et al., 2017).

Universal Extractants for Alkaline- and Carbonate-rich Soils

Previously, a 1 M NH_4HCO_3 and 0.005 M DTPA solution at pH 7.6 was used as a multiple-nutrient extractant for alkaline soils, which displayed high correlations exceeding 0.90 with phenoldisulfonic acid NO_3^- test and Olsen P (Soltanpour & Schwab, 1977). More recently, a solution buffered at pH 8.5 consisting of 0.45 M sodium bicarbonate (NaHCO_3) and 0.374 M sodium sulfate (Na_2SO_4) was used to extract NH_4^+ , P, and K from the calcareous soils of central China. This research demonstrated a strong linear relationship with standard laboratory methods using colorimetric reagents and a self-developed portable photoelectric system to determine NH_4^+ , P, and K content ($r > 0.90$) (Ma et al., 2020).

Colorimetric and Turbidimetric Systems

Pansu and Gautheyrou (2006) recommended various standard methods for determining soil nutrients, including steam distillation–titration and the indophenol blue reaction for NH_4^+ ion analysis; copper cadmium reduction with Griess reagent or NO_3^- electrodes for NO_3^- determination; molybdenum-based colorimetric methods, ICP, or AAS for P assessment; and flame photometry, AAS, or ICP spectrometry for K analysis. However, these methods require specialized machines and instruments, making them impractical for commercial use because of their initial cost, maintenance requirements, and technical complexity. Therefore, developing commercial NPK rapid test kits using colorimetric and turbidimetric methods is recommended. The description of color and turbidity is always subjective; hence, colorimetry and turbidimetry offer objective numerical systems to measure the color and cloudiness of a solution (Gilchrist

& Nobbs, 1999). After nutrient extraction, these methods use specific reagents to visualize nutrient concentrations (Figure 1). It allowed for the estimation of nutrient content by visually comparing the color and turbidity of the solution to provide standard charts indicating low, moderate, and high concentrations (Table 1).

Ammonium

Nessler’s reagent was first described in 1856 (Neßler, 1856). In 1961, this method was introduced as a rapid testing method for soil and plant assays to measure NH_4^+ levels in small laboratories. However, certain interferences have raised turbidity issues, such as 5-ppm manganese, 500-ppm Mg, 5,000-ppm Ca, and 20-ppm Fe (Schuffelen et al., 1961). In the 2010s, a modified Nessler reagent was used in the wastewater industry, and it exhibited enhanced sensitivity and stability within the wavelength range of 400–425 nm (Jeong et al., 2013). This modified reagent has

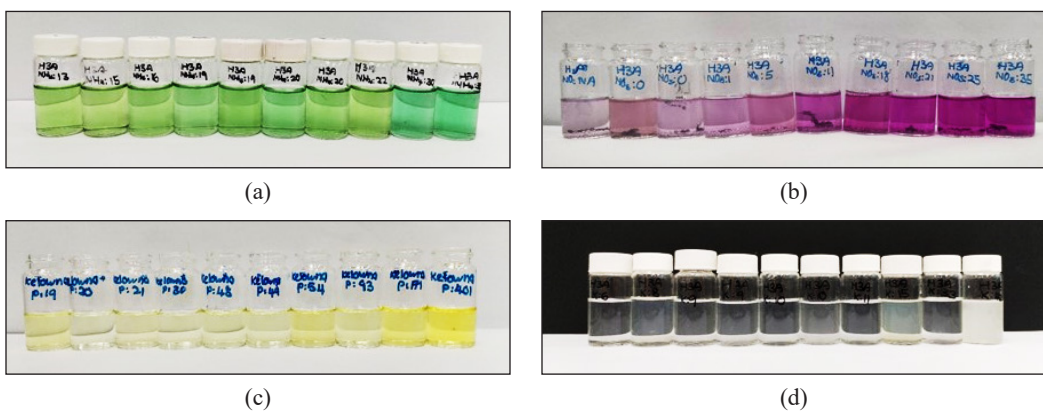


Figure 1. Variation in the color intensity of the H3A-4 soil extractant mixed with the simplifying Berthelot–salicylic method for NH_4^+ (a), the H3A-4 soil extractant mixed with the Zn–Griess reagent method for NO_3^- (b), the Kelowna soil extractant mixed with the molybdenum yellow method for P (c), and the H3A-4 soil extractant mixed with the sodium tetraphenyl boron method for K (d), arranged from low to high concentrations

Table 1

Guidelines for interpreting NPK levels in soil test results (Horneck et al., n.d.)

Nutrient concentration level	NO ₃ ⁻ (ppm)	P (Acidic soil) (ppm)	P (Alkaline soil) (ppm)	K (ppm)
Low	<10	<20	<10	<150
Medium	10–20	20–40	10–20	150–250
High	20–30	40–100	20–40	250–800
Excessive	>30	>100	>50	>800

Note. NH₄⁺ was excluded because it does not tend to accumulate in the soil due to its conversion to NO₃⁻, usually within the 2–10 ppm range, and it can be higher under cold, wet conditions or in the presence of fertilizer residues

also been used in paper-based microfluidic devices to evaluate NH₄⁺ levels in wastewater ranging from 0 to 5 ppm (Nxumalo et al., 2020). The nesslerization method is the standard method for NH₄⁺ analysis of water and wastewater (American Public Health Association et al., n.d.).

Furthermore, the reaction of NH₄⁺ with phenol and hypochlorite, which is catalyzed by Na nitroprusside to form blue indophenol, has been known as Berthelot's reaction or the phenol method since 1859 (Berthelot, 1859). NH₄⁺ formed by the Kjeldahl digestion of soil and plant tissues has traditionally been determined using distillation–titration. The salicylic method is an alternative method that involves replacing phenol with Na salicylate. It is simpler and quicker, exhibiting over 99% recovery with precision and accuracy. This substitution was attributed to the carcinogenic nature of phenol (Baethgen & Alley, 1989). The salicylic method is recommended for total ammonia N (TAN) detection in aquaculture because it exhibits superior TAN concentrations, precision, and accuracy (Le & Boyd, 2012). Over time, a simplified version of the Berthelot – the

salicylic method used a single reagent, achieving a 0.015-ppm NH₄⁺ detection limit when combined with water samples and analyzed using an autonomous sensing platform at 660 nm (Cogan et al., 2014).

Nitrate

Peter Griess, renowned for his pioneering work on diazo compounds, laid the foundation for significant advances in chemical analysis techniques and began his research in 1858 (Heines, 1958). Griess refined analytical methods over time, developing soil matrix spectrophotometric flow injection analysis (FIA) systems in 2007 and 2009. These systems precisely measure NO₂⁻ and NO₃⁻ levels by modifying the Griess–Ilosvay method. The process involves reducing NO₃⁻ to NO₂⁻ using Cd, followed by its reaction with Griess reagent to form a distinctive pink to reddish-purple azo dye complex, which is measured at 543 nm for accuracy (López Pasquali et al., 2007, 2010). Remarkably, the Cd reduction technique using the modified Griess–Ilosvay method remains the predominant method for determining NO₃⁻ levels (Gelderman & Beegle, 2011).

However, because of the hazardous nature of Cd exposure, researchers have focused on finding alternatives. For example, vanadium chloride (VCl_3) has emerged as an alternative to Cd, generating a single VCl_3 -Griess reagent that reduces toxic waste and simplifies its use. Nevertheless, this reagent shows a slow pink color development at room temperature (at least 4 hr) or when heated in a 60°C water bath for 2 hr (Doane & Horwáth, 2003). Additionally, the VCl_3 -Griess reagent was successfully applied in automatic FIA to determine water samples, which showed no significant difference from the Cd column reduction method, and the recovery was above 89% (S.Wang et al., 2016).

Moreover, Zn reduction with Griess reagent has been proposed as a substitute for Cd reduction and high-performance liquid chromatography standard methods, showing no significant difference in NO_2^- and NO_3^- assays by running a paired t-test in food studies (Merino, 2009). Recently, a hydromonitrix NO_3^- portable test kit using the Zn-Griess reagent was successfully developed to accurately detect 0.5–45 ppm NO_3^- in freshwater within 10 min (Murray et al., 2017).

In summary, the colorimetric detection of NO_2^- and NO_3^- using the Griess reagent involves the reduction of NO_3^- to NO_2^- using either Cd, VCl_3 , or Zn, followed by diazotization of NO_2^- with sulfanilamide and its coupling with N-(1-naphthyl) ethylenediamine to form a pink-purple azo dye.

In parallel with these methods, the NO_3^- salicylic acid method was introduced in 1975 for the rapid colorimetric determination of NO_3^- in plant tissues. The sample was mixed with 5% salicylic acid in concentrated sulfuric acid and 2 N sodium hydroxide (NaOH), resulting in a yellow solution detected at 410 nm (Cataldo et al., 1975). In 1990, researchers demonstrated that NO_3^- salicylic acid and Cd reduction methods obtained similar results for soil NO_3^- ($r = 0.99$) (Vendrell & Zupancic, 1990). The International Organization for Standardization (2020) has standardized salicylic acid as a colorimetric reagent for water-soluble NO_3^- determination.

Phosphorus

Murphy and Riley's technique, also known as the molybdenum blue (MB) method, was originally designed to measure soluble phosphate levels in seawater. It is a single-color reagent composed of ammonium molybdate, K antimony tartrate, ascorbic acid, and sulfuric acid, which quickly develops a bluish-purple color in the presence of phosphate and is detectable at 882 nm (Murphy & Riley, 1962). MB reactions involve a sequence of complex chemical processes that convert orthophosphate (PO_4^-) into phosphomolybdenum blue species, which require a strong acid molybdenum source and reducing agent. The MB method is widely used in analytical chemistry (Nagul et al., 2015).

The vanadomolybdophosphoric acid or molybdenum yellow (MY) method was

introduced in 1971 (Kaylor, 1971). When implementing P monitoring via microsystem technology (MST), the MB method was disregarded because of the reagent's short shelf life and tendency to form small precipitates, leading to channel blockages in microfluidic systems and cuvette wall coatings. Instead, the researchers found that the MY method was compatible with MST. It offered the following advantages: it did not precipitate, maintained its performance after a year of storage, and operated effectively under a spectrum of 380 nm absorbance. This method successfully determined P within the 0–50 ppm range, with a remarkable detection limit of 0.2 ppm (Bowden et al., 2002). Furthermore, the MY method was successfully implemented in a microfluidic paper-based analytical device to evaluate P in water (Waghwanani et al., 2019).

Potassium

Sodium cobaltinitrite ($\text{CoN}_6\text{Na}_3\text{O}_{12}$) reacts with K to form potassium sodium cobaltinitrite ($\text{K}_2\text{NaCo}(\text{NO}_2)_6 \cdot \text{H}_2\text{O}$) precipitate, which was used in 1933 to rapidly determine K levels in plant tissues (Morris & Gerdel, 1933). In 1950, the same $\text{CoN}_6\text{Na}_3\text{O}_{12}$ reagent was used for K determination in soil extracts, forming a methyl orange cobaltinitrite precipitate (Whittles & Little, 1950).

The discovery of Na tetraphenyl boron ($\text{Na}(\text{C}_6\text{H}_5)_4\text{B}$) in 1949, which forms a white insoluble compound with K ions in NaOH solution, presented a more effective

method for determining the K value of Morgan-extracted soil than the flame test, especially in samples with elevated Na levels and minimal interference from NH_4^+ ions. The turbidimetric reagents were composed of 1.2% $\text{Na}(\text{C}_6\text{H}_5)_4\text{B}$ and mixed with aluminium hydroxide powder, 40% NaOH, and formaldehyde solutions to avoid interference from impurities such as NH_4^+ (Paul & Gibson Jr., 1959; Ståhlberg, 1979). An integrated approach combining colorimetric NPK determination with irrigation decision-making technology has recently emerged. This system uses a $\text{Na}(\text{C}_6\text{H}_5)_4\text{B}$ turbidimetric reagent incorporating EDTA disodium salt, sodium tetraborate solution, and formaldehyde as masking agents. This method accurately determined K in compound NPK fertilizers with an error margin of <5% at 430 nm (Liu et al., 2021).

Similarly, in medical research, the detection of K in urine samples was performed using crown ether-modified gold (Au) nanoparticles (Au NPs) using either a colorimetric sensor with an absorption ratio of $A_{620 \text{ nm}}/A_{520 \text{ nm}}$ or paper-based colorimetric array test strips. Rapid color formation involves the reaction of the crown ester (4-aminobenzo-18-crown-6, ABC) with K^+ ions to form a 2:1 stable sandwich complex — the amino groups of the ABC- K^+ complex and Au NPs form Au-N bonds. The color of the wine-red Au NP solution changed to violet or gray when K^+ was present (Chitbankluai et al., 2021; Qiu et al., 2019).

DISCUSSION

The swift development of soil test kits has commercialized the rapid and precise determination of soil nutrient concentrations. Extensive research has been conducted on universal extractants and colorimetric and turbidimetric systems for determining nutrient content. However, published protocols are based on laboratory routines and often lack direct applicability to rapid commercial test kits. Nonetheless, these studies serve as valuable guidelines for adaptation and highlight crucial criteria for further research into rapid test kit development. Some pivotal criteria include ensuring the suitability of the universal extractant for various local soil conditions, ease of convenient use, avoidance of hazardous chemicals, compatibility of the extractant with colorimetric and turbidimetric systems, and long shelf life. These considerations form the cornerstone for successfully developing rapid soil test kits in the commercial sphere.

Criterion 1: Suitability of Universal Extractant under Various Local Soil Conditions

Soil can be categorized as acidic, alkaline, calcareous, or noncalcareous. Researchers commonly used 2 M KCl for NH_4^+ and NO_3^- , along with NH_4OAc for K^+ , to validate the performance of the universal extractant. However, variations in the P extraction methods, such as Olsen and Bray, were adopted because of the soil pH and calcareous characteristics. The Food and Agriculture Organization of the United

Nations (FAO) (2021a, 2021b) delineated the suitability of Bray for soil pH below 6.8 and Olsen for calcareous and alkaline soils. Notably, Bray II extraction in alkaline soil tends to overestimate P because of its acidity, potentially neutralizing or excessively extracting P from calcium phosphate. The optimal P extraction principles were mirrored in the Morgan extractant buffered at 4.8 for acidic soil and 0.45 M NaHCO_3 + 0.374 M Na_2SO_4 buffered at 8.5 solution for alkaline and calcareous soils.

In contrast, H3A-4 and Kelowna can be used in all types of soils. H3A, which contains artificial organic root-exclusion compounds, fosters an actively rooted rhizosphere by simulating organic acid root exudates to alleviate plant nutrient deficiencies (Haney et al., 2006). Although Morgan and Kelowna contained HOAc, Kelowna's lower HOAc normality and shorter shaking time helped prevent excessive P extraction under calcareous soil conditions (Table 2).

Criterion 2: Ease of Use

The universal extractant, colorimetric and turbidimetric methods typically require a mechanical shaker and a spectrometer, which poses challenges in field handling. Many studies using universal extractants used shaking for at least 5 min to ensure homogeneous extraction (Table 2). Manual vigorous shaking for 1 min is recommended to adapt to field conditions. However, shorter time and nonuniform shaking

speed may affect nutrient extraction efficiency. Colorimetric and turbidimetric methods have been developed using portable spectrometers, FIA, paper-based microfluidic devices, and MST (Bowden et al., 2002; Liu et al., 2021; Ma et al., 2020; S. Wang et al., 2016; Waghvani et al., 2019). However, these innovations are geared toward rapid professional testing rather than commercial testing because of high investment costs, the need for skilled technicians, and high maintenance costs.

A standardized color chart for identifying soil nutrient deficiency, sufficiency, and excess is sufficient for commercial use. Additionally, quicker color changes and turbid forms are preferable. For instance, the Zn–Griess reagent is superior to the VCl₃–Griess reagent because its color is formed within 10 min. Furthermore, rapid soil test kits must strongly correlate with standard laboratory-based methods to ensure accuracy. By referring to approximate or categorical nutrient concentration standards, these kits can offer fertilization recommendations tailored to local commercial crops and promote sustainable farming practices.

Criterion 3: Avoid Hazardous Chemicals

The rapid test kit is intended for commercial use. Users may not be professionals when handling chemicals; hence, dangerous components must be avoided. As shown in Table 3, formulations containing strongly corrosive, hazardous, or carcinogenic compounds, such as NO₃⁻ salicylic acid, NH₄⁺ Nessler, and phenol methods,

are not recommended because of the potential dangers to users and the risk of environmental pollution.

Criterion 4: Compatibility of Extractants with Colorimetric and Turbidimetric Systems

Most studies on universal extractants and nutrient determination using colorimetry and turbidimetry have been conducted independently. Therefore, the compatibility of the universal extractant (Table 2) with the colorimetric and turbidimetric reagents (Table 3) is unclear. For example, when mixed using the Murphy and Riley method, a 0.02 M SrCl₂–0.05 citric acid extractant obstructs color formation (Li et al., 2006). Therefore, it is essential to evaluate compatibility to facilitate the development of rapid test kits.

Criterion 5: Long Shelf Life

Commercialized rapid soil test kits must account for their shelf life. Unlike in laboratory settings, where extractants and reagents can be freshly prepared as needed, the extended longevity of these reagents requires further investigation. Prolonged storage may alter extraction efficiency and sensitivity to color development. For example, ascorbic acid in MB has limited stability and requires daily preparation (Bowden et al., 2002; FAO, 2021b). The ideal shelf life of rapid test kits is at least one year. Extensive research on the stability and preservation of these components is crucial for ensuring their effectiveness and accuracy over extended periods.

Table 2
Universal extractants' composition, pH buffer, nutrient extraction, suitable soil, shaking time, and soil extraction ratio

Universal extractant	Composition	pH buffer	Extracted nutrient (NPK)	Suitable soil type	Shaking time	Soil: extraction ratio	Reference
Morgan	0.73 M C ₂ H ₃ NaO ₂ and 0.52 N HOAc	4.8	NH ₄ ⁺ , NO ₃ ⁻ , P, and K	Acidic soil	15 min	1:4	Morgan (1941)
0.02 M SrCl ₂	0.02 M SrCl ₂		NO ₃ ⁻ , P, and K	Basic and calcareous soils	30 min	1:10	Bibiso et al. (2012)
0.01 M BaCl ₂	0.01 M BaCl ₂		NO ₃ ⁻ , P, and K	Acidic and neutral soils	30 min	1:10	Bibiso et al. (2015)
H3A-4	0.004 M citric acid + 0.008 M malic acid + 0.005 M oxalic acid	3.75	NH ₄ ⁺ , NO ₃ ⁻ , P, and K	All types of soil	10 min shaking + 5 min centrifuge	1:10	Haney et al. (2017)
Kelowna	0.25 N HOAc + 0.015 N NH ₄ F		NH ₄ ⁺ , NO ₃ ⁻ , P, and K	All types of soil	5 min	1:10	van Lierop (1988)
Ma et al. universal extractant	0.45 M NaHCO ₃ + 0.374 M Na ₂ SO ₄	8.5	NH ₄ ⁺ , NO ₃ ⁻ , P, and K	Neutral and calcareous soil	10 min	1:20	Ma et al. (2020)

Note. C₂H₃NaO₂ = Sodium acetate; HOAc = Acetic acid; SrCl₂ = Strontium chloride; BaCl₂ = Barium chloride; NH₄F = Ammonium fluoride; NaHCO₃ = Sodium bicarbonate; Na₂SO₄ = Sodium sulfate

Table 3
The color form, absorbance wavelength, and limitation of colorimetric and turbidimetric reagents

Nutrient	Method	Color form	Absorbance wavelength (nm)	Limitation	Reference
NH ₄ ⁺	Modified Nessler reagent	Yellow-brown	400–425	Contains mercury (II) iodide as a hazardous element	Jeong et al. (2013)
	Phenol method	Indophenol blue		Contains phenol as a carcinogenic compound	Berthelot (1859)
	Simplifying Berthelot-salicylic method	Green	660	Not yet tested with other universal extractants	Cogan et al. (2014)
NO ₃ ⁻	Salicylic acid method	Yellow	410	Contains concentrated sulfuric acid as a corrosive chemical	Cataldo et al. (1975) Vendrell and Zupancic (1990)
	Modified Griess-Ilosvay method	Pink	543	Contains cadmium as a carcinogenic chemical	López Pasquali et al. (2007, 2010)
	VCl ₃ -Griess reagent	Pink	543	Requires at least 4 hr of color formation at room temperature	Doane and Horváth (2003)
	Zn-Griess reagent	Pink	543	Not yet tested with other universal extractants	Murray et al. (2017)
P	Molybdenum blue	Blue	883	Short shelf life	Murphy and Riley (1962)
	Molybdenum yellow	Yellow	400	Not yet tested with other universal extractants	Kaylor (1971)
K	Sodium cobaltinitrite	Yellow precipitate		Relatively not precise, sensitive, and user-friendly	Whittles and Little (1950)
	Sodium tetraphenyl boron method	White precipitate	430	Not yet tested with other universal extractants	Liu et al. (2021)
	Crown ether-modified gold particles	Violet or gray	620	Expensive	Qiu et al. (2019)

As rapid soil test kits have advanced to meet the demands of modern agriculture, they offer significant advantages in terms of affordability, accessibility, and quick results. However, in addition to these benefits, inherent limitations require careful consideration.

Advantages of Rapid Soil Test Kits for Agricultural Practices

Advantage 1: Lower Price

Farmers in tropical countries, such as Nigeria, the Democratic Republic of Congo, Ethiopia, India, and Bangladesh, face significant challenges that hinder their productivity. These constraints make it difficult for these people to fully comprehend soil profiles, which are essential for successfully growing crops and improving livelihoods. The State of the Tropics 2020 Report highlights the extreme poverty prevalent in these regions and the often-limited infrastructure (James Cook University [JCU], 2020). It makes wet chemistry analysis for soil testing unaffordable for impoverished farmers. Consequently, alternative soil testing methods, such as rapid nutrient testing, are being deployed in Africa, offering more affordable rates (Dimkpa et al., 2017).

Advantage 2: In situ Soil Testing/Higher Accessibility

The traditional approach encompasses a series of detailed steps for farms aiming to perform soil nutrient analysis. Initially, soil samples are collected and dispatched to a laboratory, where they are dried, sieved

to a standard size of 2 mm or smaller, and then subjected to nutrient extraction using specific chemicals. Specialized equipment, such as ICP and AAS, is used to quantify the extracted nutrients. This procedure, culminating in calculating soil nutrient levels, is intricate and time-intensive, presenting challenges for those not specialized in the field.

In contrast, rapid soil test kits offer a more streamlined and user-friendly alternative. These kits bypass the need to send samples to a laboratory, allowing on-site nutrient analysis. Users can easily determine the soil nutrient content by comparing the color saturation of the test with that of the provided color chart, which yields immediate results. This efficiency enables farmers to rapidly evaluate their soil nutrient status and develop appropriate nutrient management strategies to enhance agricultural productivity and sustainability.

Advantage 3: Instantaneous or Faster Results

Traditional vegetable farmers, particularly those dependent on their land for income, frequently bypass wet chemistry analysis to determine soil nutrients because of the lengthy duration. This reluctance is especially pronounced in areas with very short crop cycles, sometimes as short as 25 days. Such rapid turnaround times require swift decision-making regarding fertilization and overall crop management to maximize yield and profitability. The standard wet nutrient chemistry analysis process, which can span several days to

months, is impractical for these farmers. Immediate information is required to prepare fertilization strategies for imminent planting cycles. Therefore, instant soil nutrient testing methods are indispensable for these farmers, offering prompt and practical insights to facilitate effective crop management under the constraints of short crop cycles.

Limitations of Rapid Soil Test Kits

Although rapid soil test kits offer an accessible solution for soil nutrient analysis in resource-limited regions at a lower cost and provide instant *in situ* results, they cannot entirely replace standard wet chemistry analysis for several reasons.

Limitation 1: User Dependency and Error

The accuracy and reliability of the results obtained from rapid soil test kits depend heavily on user proficiency. Improper sampling techniques, inadequate mixing of soil and reagents, and misinterpreting colorimetric readings can lead to erroneous results. Without adherence to standardized protocols, users may obtain inconsistent or unreliable results, emphasizing the importance of user proficiency and protocol adherence to ensure the accuracy of rapid soil test kit results.

Limitation 2: Interference with Soil Properties

Soil properties, including texture, organic matter content, pH, and mineral composition, are dynamic factors that can significantly

affect the performance of rapid soil test kits. These variations can introduce interference during testing and lead to inaccurate results. For instance, H3A-3 has exhibited turbidity issues in soils with low pH and high Fe and Al concentrations (Haney et al., 2017). Additionally, the suitability of universal extractants for various local soil conditions must be considered, as shown in Table 1. Different soil types require different extraction methods and reagents to ensure accurate nutrient analysis.

Limitation 3: Result Interpretation

Rapid soil test kits categorize soil NPK levels to determine appropriate fertilization strategies. These strategies vary with crop type, soil texture, and climate. However, some farmers may struggle to interpret the results effectively to enhance soil fertility. Therefore, soil test kits should include fertilization recommendations tailored to different soil conditions and crops to aid farmers in making informed decisions regarding optimal soil management and crop productivity.

Limitation 4: Validation Challenges

The reliability of commercially available rapid soil test kits is often under scrutiny because of a significant lack of validation, which is a concern underscored by Dimkpa et al. (2017). Furthermore, the validation of several commercial test kits has been documented in only one study based on outdated information from Faber et al. (2007). Our literature review revealed a scarcity of comprehensive

discussions on the complete NPK rapid test kit methodology, with most research focusing on individual aspects, such as universal extractants and colorimetric and turbidimetric reagents. This fragmentation hinders the synthesis of the research findings. Therefore, it is essential to conduct further validation studies of the latest developments in rapid soil test kits to confirm their reliability and accuracy for effective use.

Limitation 5: Accuracy and Precision

The effectiveness of rapid soil test kits in delivering accurate and precise results is hindered by several factors, such as dependence on the user's skill, interference from unique soil properties, challenges in interpreting results, and validation constraints. Despite technological progress, these kits may not always provide reliable results because of soil analysis's complex nature and inherent limitations. Moreover, despite being commercially available, these kits have not yet reached maturity in terms of development and validation. Overcoming these obstacles is crucial for improving the dependability and utility of rapid soil test kits for accurate nutrient evaluations, thereby supporting optimal agricultural practices.

Given these considerations, rapid test kits and standard wet chemistry analyses should ideally be used as supplementary instruments. The latter continues to be essential for thoroughly assessing and managing soil fertility, underscoring the importance of integrating both methods to

achieve a comprehensive approach to soil health and crop management.

CONCLUSION

The development of rapid *in situ* soil NPK test kits revolutionizes conventional, expensive, and time-consuming laboratory methods. These kits rely on universal extractants for multiple soil nutrient extractions and use colorimetric and turbidimetric reagents for nutrient determination. For commercial viability, these kits, along with standardized categorical value color charts, must embody the traits of speed, accuracy, durability, simplicity, affordability, and safety.

Among the options, the inclusion of H3A-4 or Kelowna coupled with Zn using Griess reagent for NO_2^- and NO_3^- , salicylic method for NH_4^+ , molybdenum yellow method for P, and $\text{Na}(\text{C}_6\text{H}_5)_4\text{B}$ for K emerged as the most optimal development choices. H3A-4 and Kelowna demonstrated versatility across soil types, whereas the other reagents offered longer shelf life, safety, quicker color formation, and fewer reported compatibility issues. Refining these rapid test kits requires meticulous testing and validation against standard laboratory methods to determine their accuracy before widespread application. Patience and thorough validation are critical steps in model development.

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