UNIVERSIDADE FEDERAL DE LAVRAS

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IMPROVING END-OF-SEASON CORN NUTRITIONAL DIAGNOSIS: A NEW METHODOLOGY FOR CORN STALK POTASSIUM AND NITRATE ANALYSIS

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Monografia apresentada à Universidade Federal de Lavras, como parte das exigências do Curso de Agronomia, para a obtenção do título de Bacharel.

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Abstract

Effective nutrient management is essential for developing corn (*Zea mays* L.), especially potassium (K), which is needed in large quantities. Tissue tests are crucial for improving K fertilizer recommendations. Despite the current use of corn stalk nitrate (NO_3^--N) test (CSNT) to assess nitrogen (N) management, there is still no equivalent methodology for diagnosing K nutrition. This study evaluated deionized water as an extractant for measuring K and NO_3^--N concentrations in corn stalks. It compared this approach to the established CSNT methodology and examined the relationship between stalk-K critical concentrations and yield. Field trials were conducted in 2023 in Arkansas (Fayetteville, Colt [two sites], and Jonesboro) on silt loam soils with K levels ranging from very low to optimal. Fertilizer-K rate treatments were 0, 45, 90, 134, 179, and 224 kg K_2O ha^{-1}, applied preplant as muriate of potash. Stalk samples were collected at 15-35 cm from the soil, dried (55 °C), ground (< 2 mm), and extracted with deionized water and 2 mol L^{-1} of KCl for K (ICP-AES) and NO_3^--N (colorimetry) analysis. Corn yield responded significantly ($P < 0.05$) to K fertilization in Jonesboro and one of the trials in Colt, with increases of 46% and 72% of the Relative Grain Yield, respectively. There was no response in Fayetteville and one of the Colt trials. Nitrate-nitrogen extracted with water was highly correlated ($R^2 = 0.99$) to that extracted with KCl, validating its use for CSNT. Water-extractable K in the stalks showed a strong relation with soil-test K ($R^2 = 0.74$) and a moderate relation with corn grain yield ($R^2 = 0.95$). The results indicate that likewise N, K accumulates in corn stalks and that end-of-season stalk NO_3^--N and K analysis is a viable tool for diagnosing the adequacy of N and K fertilization. Deionized water is a promising extractant for adjusting K and N recommendations, although further studies are needed.

Keywords: Corn Production, Plant Nutrition, Nutrient Management, Soil Fertility, Tissue Testing.

Resumo

A correta utilização de nutrientes é essencial para o desenvolvimento do milho (*Zea mays* L.), especialmente o potássio (K), que é necessário em grandes quantidades. Os testes de tecidos são cruciais para melhorar as recomendações de fertilizantes com K. Apesar do uso atual do teste de nitrato (NO_3^--N) no caule do milho (CSNT) para avaliar o manejo do nitrogênio (N), ainda não existe uma metodologia equivalente para diagnosticar a nutrição de K. Este estudo avaliou a água deionizada como um extrator para medir as concentrações de K e NO_3^--N em colmos de milho. Esse estudo comparou esta abordagem com a metodologia CSNT estabelecida e examinou a relação entre as concentrações críticas de K no caule e o rendimento. Os ensaios de campo foram realizados em 2023 no Arkansas (Fayetteville, Colt [dois locais] e Jonesboro) em solos franco-siltosos com níveis de K que variavam de muito baixos a ótimos. Os tratamentos de taxa de fertilizante-K foram 0, 45, 90, 134, 179 e 224 kg K2O ha-^{1}, aplicados antes da plantação como muriato de potássio. O rendimento do milho respondeu significativamente ($P < 0{,}05$) à fertilização com K em Jonesboro e em um dos ensaios em Colt, com aumentos de 46% e 72% do rendimento relativo de grãos, respetivamente. Não houve resposta em Fayetteville e num dos ensaios de Colt. O nitrato extraído com água foi altamente correlacionado ($R^2 = 0{,}99$) ao extraído com KCl, validando seu uso para CSNT. O potássio extraível em água nos colmos mostrou uma forte relação com o K testado no solo ($R^2 = 0{,}74$) e com o rendimento de grãos de milho ($R^2 = 0{,}95$). Os resultados indicam que, da mesma forma que o N, o K se acumula nos colmos do milho e que a análise de NO_3^--N e K do colmo no final da estação é uma ferramenta viável para diagnosticar a adequação da fertilização com N e K. A água deionizada é um extrator promissor para ajustar as recomendações de K e N, embora sejam necessários mais estudos.

Palavras-chave: Produção de milho, nutrição de plantas, gestão de nutrientes, fertilidade do solo, análise de tecidos.

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1. Introduction

Corn is among the world's most valuable agricultural commodities, with an annual production of approximately 1.13 billion metric tons (USDA, 2024). Corn holds significant importance for human consumption, animal feed, and the production of biofuels (FAO, 2023). Corn occupies a particularly strategic role in the United States (US), the world's largest producer. In 2023, 380 million tons of corn were cultivated, with most of the production occurring in the "Corn Belt" notably in states such as Iowa and Illinois. Approximately 40% of US corn production is dedicated to ethanol, 35% is used for animal feed, and the remaining portions are allocated for exports and food products. These statistics underscore the vital importance of corn in the global economy and highlight the sustainability of various value chains (USDA, 2023).

Corn fertilization is crucial for promoting optimal growth and achieving high yields, with nitrogen (N), phosphorus (P), and potassium (K) being the primary nutrients needed by the plant. Each nutrient fulfills a distinct role in plant development. Nitrogen is vital for vegetative growth, while P facilitates energy transfer, K, on the other hand, is essential for enhancing corn yields by supporting various physiological functions within the plant (Subedi *et al*., 2009). Potassium plays a key role in regulating water, activating enzymes, and transporting carbohydrates, contributing to stronger stalks and improved drought resistance. Research indicates that K fertilization significantly enhances corn's ability to absorb N, a critical factor for increasing yields (Wang *et al*., 2013). This effect is particularly pronounced under water-stressed conditions, where K helps mitigate the adverse effects of drought, resulting in better grain yield and overall plant performance (Sami Ul-Allah, 2020). Additionally, N and K possesses the remarkable ability for luxury nutrient consumption, allowing plants to absorb more nutrients than they immediately require for their growth and development. This capacity enables them to stockpile essential nutrients, such as NO_3^--N and K which can be particularly advantageous in nutrient-poor soils or during periods of environmental stress (Bartholomew, 1929). For corn, luxury consumption can enhance resilience against adverse conditions, promote accelerated growth rates, and improve overall yields, as the stored nutrients can be utilized during critical growth stages. This strategy allows corn plants to optimize nutrient availability in varied environmental conditions, ensuring sustained productivity despite limited nutrient supplies (Chad J. Penn *et al*., 2023).

Early work reported that nutrient deficiencies, such as K, were more pronounced in the nutrient concentrations in leaves than in different plant parts (Tyner, 1946; Tyner and Webb, 1946). Since then, numerous studies have utilized the concentration of K in the ear-leaf to assess the K status of corn in studies examining grain yield responses. The value of the ear-leaf tissue test should be reconsidered given that numerous studies have shown that K fertilization often increases ear-leaf K concentration when grain yield is not improved (Randall *et al*., 1997; Ebelhar and Varsa, 2000; Rehm and Lamb, 2004). Also, research with N (Cerrato and Blackmer, 1991) and P (Stammer, 2018) indicated that the ear-leaf concentration does not appropriately evaluate the availability of these nutrients in the optimum to above-optimum availability range. Like K, NO_3^--N also accumulates in plant tissues due to the corn plant's luxury consumption. There is already an established method for corn stalk nitrate test (CSNT) to evaluate the adequacy of the N management program. This end-of-season test helps producers differentiate between fertilizing for maximum greenness and fertilizing for maximum profit (Mallarino *et al.*,1994). Likewise for N, a better understanding of corn tissue-K dynamics and end-of-season stalk-K testing can be an invaluable tool for fine-tuning fertilizer-K recommendations and maintaining farm profitability. However, there is currently no method for corn stalk-K concentration analysis, and there is a need to identify an effective extractor for evaluating K in corn stalks, leading to a new methodology. The primary objective of this study is to analyze deionized water as an extractor for a novel analytical method to determine K and NO_3^--N in corn stalks for optimal corn production.

2. Literature Review

2.1 Corn Production

Corn botanically belongs to the family Poaceae (*Gramineae*), tribe Maydeae. It is an entirely domesticated crop and one of the most productive food plants. Being a C4 plant, it has very high photosynthetic activity and holds the highest theoretical potential yield of carbohydrates per unit area daily. Although corn originated in the tropics, its cultivation has extended over a wide range of climates from 58°N in Canada to 40°S in Argentina (Paliwal *et al*., 2000).

Corn is largely produced for grain feed, with countries such as the US, China, and Brazil accounting for over 60% of the world's production. During the 2023/2024 marketing year, total corn production reached 1,224,326 metric tons in the world (USDA, 2024). During the past century, corn's output has significantly increased due to the development of agronomic practices and technologies. Corn yield in the US has increased from an average of 1,522 kg ha^{-1} to approximately 10,136 kg ha^{-1} over 84 years (Nielsen, 2023). This is a sixfold yield increase despite corn being planted on fewer total hectares compared to the 1930s. Since then, the average annual growth in the US yield is about 113 to 125 kg ha-1. (NCGA, 2023).

Different forms of corn, including cornmeal, corn oil, or high-fructose corn syrup, widely used as a sweetener in processed foods, have been a main ingredient in the food industry. Corn is also used in large quantities as animal feed in livestock and poultry farming due to the different carbohydrates and proteins it contains, which are necessary for their nutritional requirements (Loy *et al*., 2019). Additionally, corn plays a critical role in the biofuel sector, where it is used to produce ethanol, a renewable fuel that helps reduce greenhouse gas emissions. Beyond food and energy, corn derivatives are used in industrial products such as biodegradable plastics, adhesives, and pharmaceuticals (Mohanty *et al*., 2019).

2.2 Fertilizer Application and Nitrogen

For a long time, the primary purpose of applying fertilizers has been to supply essential nutrients to plants to enhance or maintain optimal crop productivity. Increasing the efficiency of fertilizers in terms of nutrient absorption and crop performance is a key concern for both manufacturers and farmers. However, improper use of natural, inorganic, or organic fertilizers can negatively impact the environment (Chien, 2009). In recent decades, significant efforts have been directed toward enhancing the efficiency of synthetic nitrogen (N) fertilizers while minimizing their environmental impact. Grain corn requires large amounts of N fertilizer for optimal yields and quality. However, the recovery of applied N in above-ground plant biomass is relatively low, often averaging less than 50% (Cassman *et al*., 2002; Ladha *et al*., 2005; Chien *et al*., 2009; Gagnon and Ziadi, 2010). This low N uses efficiency in corn can also lead to nitrate losses from the soil, particularly when N application rates surpass the crop's requirements (Andraski *et al*., 2000).

Nitrogen is an essential nutrient that significantly influences plant growth and development. As the primary form of N absorbed by plants, NO_3^- or NH_4+ are crucial for synthesizing proteins and enzymes, which are vital for numerous physiological processes (Maurya *et al*., 2020). Additionally, it plays a key role in chlorophyll production, enabling efficient photosynthesis and energy capture. Adequate N levels promote healthy vegetative growth and optimize crop yields, while deficiencies, known as chlorosis, can lead to stunted growth and yellowing leaves. Furthermore, N supports the production of adenosine triphosphate (ATP), the energy currency of cells, facilitating essential biochemical reactions. Effective management of N levels through fertilization strategies is critical for sustaining agricultural productivity and ensuring optimal plant health (Qian Wang *et al*.,2024).

2.3 Potassium in the Soil

The available potassium (K) concentration in the soil varies with the degree of weathering and parent material, directly affecting its supply. Soil K exists in four forms: structural, exchangeable (readily available), non-exchangeable or fixed (slowly available), and solution K (Rehm and Schmitt, 2002). Over 90% of soil K is found in primary minerals, while only about 0.2% exists in the soil solution, the primary source for plant uptake. Structural K, often termed fixed or inert K, constitutes most of total soil K and is largely unavailable to plants. While weathering gradually releases structural K, this process is too slow to meet crop demands. Fixed K also influences soluble K concentrations in the soil solution (Jakovljević *et al*., 2003).

Considering K exchange reactions and retention in soil, K moves only short distances through the soil and slightly more than phosphorus. The amount of K reaching the root surface with water mass flow is insufficient to meet plant requirements, and K ion diffusion through the soil solution is the predominant mechanism of plant K uptake (Wakeel A. *et al*., 2021). This characteristic has several important implications. Potassium uptake can be limited by factors that limit either the K diffusion rate or the root growth rate and the root system's size. Cold temperature and low moisture limiting diffusion and root growth are included, as soil physical properties inhibit root growth and diseases or pests impair root function. Thus, induced K deficiency can occur even with adequate soil-test K levels. Under these circumstances, placing applied K near young plant roots may stimulate plant growth and yield more than the broadcast application (Bundy and Andraski, 1999).

Most soil K contains unweathered primary minerals such as feldspars and micas (muscovite, biotite, and others). The top layer of most soils contains thousands of ppm of mineral K, but the K in the crystal structure of these minerals is released very slowly over dozens or hundreds of years and has no relevance for crop nutrition. The other soil K pools contain dissolved

K+ ions, solution K, exchangeable K, and slowly exchangeable. Often referred to as nonexchangeable K in most textbooks. Readily plant-available K includes the solution and exchangeable K fractions, and there is rapid equilibrium between these two fractions in response to K additions and plant uptake or leaching. The exchangeable K fraction contains hydrated K+ ions weakly absorbed to the negatively charged surfaces of mineral soil particles and organic matter. It can rapidly replenish the solution K pool as plants take up K (Bell, M. J *et al.*, 2021)

2.4 Potassium in the Plant

Potassium (K) is an essential nutrient for plants and is the most abundant inorganic ion in plant cells, making up as much as 10% of their dry weight (Leigh *et al.*, 1984). Potassium is widely recognized as a key factor that limits crop yield and quality, because plays a crucial role in plant metabolism, acting as a stabilizer and osmotic agent that supports cellular hydrostatic (turgor) pressure, growth, and adaptation to environmental changes. Maintaining a high and stable K concentration in specific cell compartments is essential for various processes, including enzyme activation, protein synthesis stabilization, neutralizing negative charges on proteins, generating membrane potential in coordination with the proton motive force, and regulating cytosolic pH homeostasis (Sharma *et al.*, 2013).

Potassium is a highly mobile nutrient within plants, moving from older to younger tissues. As a result, K deficiency symptoms typically appear first on the lower leaves and gradually progress upward as the deficiency becomes more severe (Hoffer, 1938). The timing of potassium uptake varies among plant species, but plants generally absorb most of their potassium earlier in the growth cycle compared to nitrogen (N) and phosphorus (P). Studies on corn show that 70–80% of K is taken up by the silking stage, with complete uptake occurring within three to four weeks afterward. Unlike N and P, the translocation of K from leaves and stems to the grain is minimal, indicating that the grain formation stage is not as critical for K supply (Nielsen, 2000).

The adequate presence of K in plants is essential for enhancing resistance to diseases, pests, and environmental stresses (Prabhu *et al.* 2007). Potassium participates in protein synthesis and the strengthening of cell walls, resulting in a more robust plant with greater structural integrity. This reduces susceptibility to pathogens such as fungi and bacteria and increases the plant's ability to recover from damage caused by adverse conditions (Perrenoud, 1990). In situations of water stress, K regulates the opening and closing of stomata, optimizing water use and helping the plant cope with moisture deficiency. Moreover, K influences the movement of water, organic, and inorganic solutes into and within the xylem by reducing the water potential in xylem vessels and maintaining charge balance for negative ions (Baker and Weatherley, 1969; Mengel and Simic, 1973; Rufty et al., 1981).

Potassium is essential for maximizing crop productivity. It directly affects the quality of seeds, being crucial for increasing both yield and the nutritional quality of plants (Copeland and McDonald, 1995). Potassium deficiency can lead to reduced growth, leaf spots, low disease resistance, and consequently, lower agricultural productivity. Therefore, balanced K application in the soil is critical to ensure good harvests, improve product quality, and maintain plant health (Amtmann *et al*., 2008).

2.5 Tissue Analyses

The pioneering work of Macy (1936) and Steenbjerg (1951) significantly advanced the chemical analysis of plants, mainly through tissue testing. Their research laid the foundation for understanding the relationship between nutrient concentrations in plant tissues and the sufficiency of those nutrients for achieving maximum dry matter yield. Plant and soil analyses are crucial in evaluating soil nutrient availability and diagnosing nutrient-related stress in plants. With proper techniques for partitioning specific components, this method can quantify nutrients present as soluble elements in plant sap or incorporated into structural tissues. It is also an effective method for detecting hidden nutrient deficiencies or early signs of nutrient shortages and can provide reliable fertilizer recommendations tailored to different crops (Wakeel, 2021).

A post-season nitrogen (N) management tool called the Corn Stalk Nitrate Test (CSNT) was created in the Corn Belt to assess the effectiveness of a corn producer's N fertilization program (Binford *et al*., 1990, 1992; Blackmer and Mallarino, 1996). The CSNT determines the amount of nitrate-nitrogen (NO_3^--N) present at the mature corn stalk's base. At maturity, NO_3^--N will collect and accumulate in the corn stalk if too much N is absorbed by the plant and not used in the growing grain (Binford *et al*., 1990). Until the plant has enough N available to reach its optimum grain output, the concentration of NO_3^--N in the stalks at maturity remains low. As N availability increases beyond the level needed for maximum grain production, CSNT levels also rise. The CSNT data indicates that N uptake is sufficient to meet the plant's N requirements, however, it is not possible to determine whether the N rate or N loss is limiting the accumulation of NO_3^--N in the corn stalk. By assessing the N status of a producer's current corn crop, the CSNT provides information on potential adjustments to N fertilizer rates for future corn crops. The CSNT measures the amount of NO_3^--N at maturity using samples taken from the corn stalk segment 15 to 35 cm above the soil surface. This test is innovative because it identifies when corn has access to excess nitrogen, whereas conventional tissue tests can only differentiate between adequate and deficient nitrogen levels in the plant (Greub *et al.*, 2018). Nitrogen availability is classified as low (0 to 249 mg NO_3^--N kg^{-1}), marginal (250 to 699 mg NO_3^--N kg^{-1}), optimal (700 to 1999 mg NO_3^--N kg^{-1}), and excessive (>2000 mg NO_3^--N kg^{-1}), based on the CSNT values described by Blackmer and Mallarino (1996). There is a high likelihood that N was limiting corn grain yield in fields within the low category. In the marginal and optimal categories, there was likely sufficient N to maximize crop yield. Fields in the excessive category likely received more N than needed to achieve the highest grain yield. Corn stalk NO_3^--N values between 700 and 2000 mg NO_3^--N kg^{-1} were identified as optimal in the first study conducted in Iowa (45 site-years) (Binford *et al.*, 1992). The suitability of these concentration limits for different production systems and regions has since been investigated. Brouder *et al.* (2000) found that a NO_3^--N concentration of 1670 mg kg^{-1} was sufficient to distinguish between corn in Indiana with adequate and excessive N availability. Additionally, the study revealed that at CSNT concentrations of 2970 mg NO_3^--N kg^{-1}, the agronomic efficiency (yield increase per unit of N fertilizer applied) dropped to 0%, with no grain yield return from applied fertilizer N.

However, when we think about K, there is no specific methodology developed yet. However, research conducted by Ketterings (2017) showed that there are some options, such as aluminum sulfate ($Al_2(SO_4)_3$), aluminum ammonium sulfate [$Al_2(SO_4)_3 \cdot (NH_4)_2SO_4$], and deionized water, which can also be used for the CSNT. Therefore, deionized water seems to be the best option for extracting K, as water holds the title of the universal solvent and is the greenest solvent (Simon and Li, 2012). In other words, it is an environmentally friendly chemical solvent used in green chemistry. Moreover, it is inexpensive, readily and widely available, and nonflammable.

3. Material and Methods

Corn trials were established in 2023 across different University of Arkansas System Division of Agriculture (UADA) properties targeting soils with diverse physical and chemical properties and geographic locations representing Arkansas corn production systems (Table 1). Based on initial soil-test results, all studies in 2023 received a banked P application (0 or 101 kg P_2O_5 ha^{-1} as triple superphosphate; 0-46-0), sulfur (S; 22 kg S ha^{-1} as ammonium sulfate; 21-0-0-24), and N (34 kg N ha^{-1} as urea [46-0-0] or ammonium sulfate) before planting to ensure adequate nutrient availability for corn growth and development. After planting, each trial received 224 kg N ha^{-1} as urea at the V8 growth stage and a foliar application of Zn (1.12 kg Zn ha^{-1}) at the V2 growth stage.

Each trial was arranged as a randomized complete block design with four replicates, with each plot being four rows wide (91 to 97 cm raised beds) and 9-m long. Corn (a high-yielding hybrid representing Arkansas corn acreage) was seeded in single rows on the top center of raised beds at 84,000 seeds ha^{-1}. All crop management practices (*e.g.,* pest and weed control, P, N, S, and Zn fertilization, and irrigation) closely followed the University of Arkansas Cooperative Extension Service recommendations for furrow-irrigated corn. A summary of the site-years location, soil-test values, and corn hybrids is provided in Table 1.

3.1 Soil Sampling and Analysis

The soil sampling protocol for each trial consists of six to eight 2.5-cm diameter soil cores collected from the 0-to-15-cm depth for each composite soil sample. Composite soil samples were collected right before fertilizer application and planting. Soil samples were oven-dried at 55 °C for 48–72 h, passed through a mechanical grinder, and sieved with a 2-mm scream opening. The soil was analyzed for pH in a 1:2 v/v soil-to-water mixture (Sikora & Kissel, 2014), soil organic matter (SOM) by weight loss on ignition (Schulte & Hopkins, 2015), and Mehlich-3 extractable nutrients (1:10 w/v soil-to-solution mixture) determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES; Arcos-160 SOP; Zhang *et al.*, 2014).

3.2 Site and Treatment Description

Research was established in 2023 across different UADA properties to investigate furrow-irrigated corn yield and corn stalk-K response to fertilizer-K rates (0, 45, 90, 135, 179, and 224 kg

K_2O ha^{-1}; applied as muriate of potash [MOP, 0-0-60]) applied preplant and incorporated on soils with varying K availability. Four single site-year trials were established at the Milo J. Shult Agricultural Research and Extension Center (SAREC) in Fayetteville, AR, Pine Tree Research Station (PTRS), near Colt, AR, and at the Northeast Rice Research & Extension Center (NERREC), near Harrisburg, AR on soils targeting a range in soil-test K from Very Low (<61 mg K kg^{-1}) to Optimum (131-175 mg K kg^{-1}). The main soil characteristics and agronomic information for each site are presented in Table 1.

Table 1. Site location, cultivar, soil series, soil-test K category, and Mehlich-3 extractable K (M3K) in the 0- to -15-cm depth before fertilizer-K application in corn stalk-K response trials conducted during the 2023 growing season.

Site#	Year	Location	Cultivar [a]	Previous Crop	Soil Series [b]	Soil Test K Category	M3K (mg kg^{-1})
1	2023	SAREC$_{\text{-E5}}$	P1464VYHR	Soybean	Johnsberg	Optimum	146
2	2023	NERREC	P1718VYHR	Soybean	Henry	Low	69
3	2023	PTRS$_{\text{-C3}}$	P1718VYHR	Soybean	Calloway	Low	69
4	2023	PTRS$_{\text{-D20}}$	P1718VYHR	Soybean	Calloway	Low	65

[a] P, 'Pioneer' (Johnston, Iowa); DK, 'DeKalb' (DeKalb, Illinois).

[b] Predominant soil series: Johnsberg (fine-silty, mixed, active, mesic Aquic Fragiudults); Henry (Coarse-silty, mixed, active, thermic Typic Fragiaqualfs); Calloway (Fine-silty, mixed, active, thermic Aquic Fraglossudalfs); Captina (Fine-silty, siliceous, active, mesic Typic Fragiudults); Loring (Fine-silty, mixed, active, thermic Oxyaquic Fragiudalfs).

Fonte: do Autor, 2025.

3.3 Plant Stalk Sampling and Analysis

Corn stalk samples were collected within 1 to 2 weeks after the R6 growth stage (Ritchie *et al.*, 1996) or kernel black layer formation (physiological maturity) from five random, representative plants within the two center rows of each plot. The samples were collected by cutting a 20-cm corn stalk section between 15 and 35 cm above the soil surface, and then dried leaf sheaths were removed from the 20-cm stalk segment (Binford *et al.*, 1992) and passed through a mechanical grinder, and sieved with a 2-mm scream opening.

To compare the impact of different chemical extractions on corn stalk-K concentrations, stalk samples were analyzed using deionized water. In addition, the same extractants were tested for NO_3^--N concentration and compared with the standard 2 mol L^{-1} KCl extraction (Binford *et al*., 1990; Greub *et al*., 2018). Therefore, 0.5 g of sample was weighed and placed in a 50 mL centrifuge tube, 30 mL of deionized water was added, and the mixtures were shaken at 120 opm for 30 minutes in a reciprocal shaker. After that, the extract was filtered using an 8-µm filter (FilterMate), separated into two ~15 mL subsamples, and stored in a refrigerator for further analysis. One subsample determined the K concentration in deionized water, following acidification with one drop of concentrated hydrochloric acid (HCl). The additional subsample was used for NO_3^--N concentration (deionized water and KCl extractants) analysis colorimetrically (Mulvaney, 1996) using a SKALAR Segmented Flow Auto Analyzer (SanSystem, Brenda, Netherlands).

3.4 Corn Yield

At maturity (R6), the two center rows in each plot were harvested using a small plot combination. Both grain weight and moisture content were determined, and grain yield was adjusted to a uniform moisture content of 155 g H_2O kg $grain^{-1}$ and expressed as kg ha^{-1}. Relative grain yield was determined by dividing the corn grain yield of each plot within a site replicated by the maximum grain yield achieved by the site replicate (the highest mean grain yield for any treatment within each of the four replicates per site) and multiplying by 100 to express values as a percentage.

3.5 Data analysis

Each experiment was carried out in a randomized complete block design, with four replicates. Regression was performed using R version 4.4.1 and differences were considered significant when the P-value was <0.05. For the experiment, regression analysis was performed using the REG procedure of R to evaluate the relationship between corn stalk-K concentration and relative corn grain yield, and the relationship of corn stalk-K and NO_3- concentrations using different extractors. The linear plateau model was used to analyze the relationship between the average relative grain yield and corn stalk-K concentration.

4. Results and Discussion

Corn stalk-K concentration was positively affected ($R^2 = 0.72$; $p = 0.002$) by soil K availability (Figure 1), showing that the plant accumulates K in the stalks when grown in soils with greater K availability. This phenomenon is attributed to luxury K consumption by the corn plant, this occurs when they absorb nutrients, in amounts exceeding their immediate needs for growth and development. This excess uptake does not enhance yield but can deplete soil nutrients unnecessarily (Bartholomew, 1929). A similar trend is observed with NO_3^--N, which also accumulates in the plant tissues with increased N availability (Chad J. Penn *et al*., 2023). The end-of-season Corn Stalk Nitrate Test (CSNT) was successfully developed in the Midwest (Binford *et al*., 1990, 1992; Blackmer and Mallarino, 1996) and Midsouth US (Greub *et al*., 2018) corn production systems to diagnose de adequacy of the N management program and adjust fertilizer-N rates for the next growing season to ensure optimal yield and farming profitability. The strong relation of stalk-K concentration with Mehlich-3 extractable K indicates stalk-K analysis is sensitive to changes in soil K availability and may be used to diagnose corn-K nutrition like the existing CSNT.

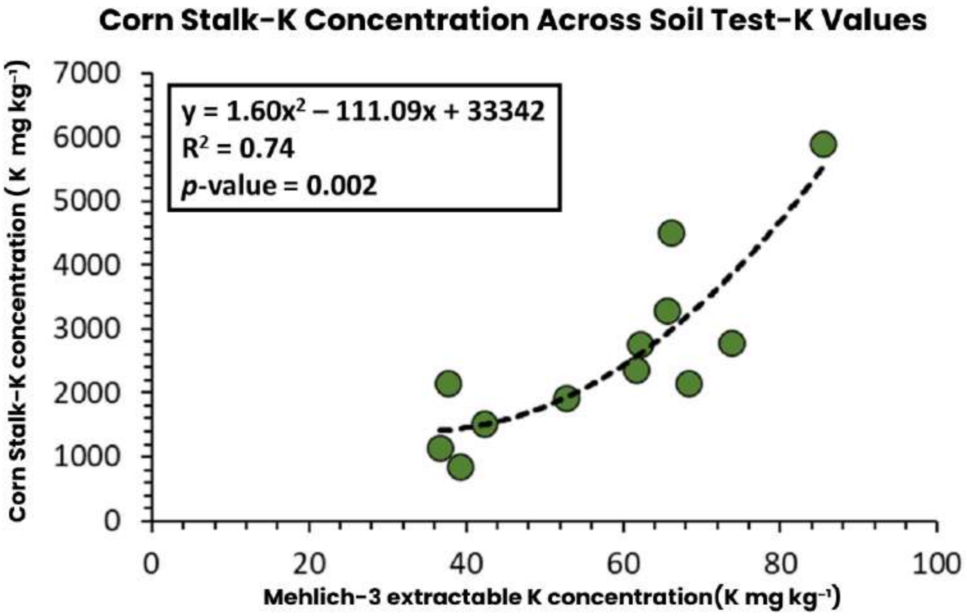

Figure 1. Corn stalk potassium concentration as affected by Mehlich-3 K concentration in 3 silt loam soils (NERREC, PTRS [DC3 and D20]) and in Arkansas during the 2023 growing season.

Corn stalk-K concentration ranged from 844 up to 24929 mg K kg^{-1} and showed a strong relationship (R^2 = 0.95) with relative corn grain yield (Figure 2). Corn yield increased as corn stalk-K concentration reached a plateau of 89% of relative grain yield at 3515 mg K kg^{-1}. Thereafter, increased stalk-K concentration did not affect corn yield, indicating luxury consumption. This behavior indicates that end-of-season stalk-K analysis is sensitive to diagnosing corn K nutrition and predicting corn yield and can be used to assess the adequacy of the K management program. Similar behavior occurs with NO_3^--N, where research by Greub (2018) showed that increased NO_3⁻‑N availability only benefits corn yields up to a certain point, and excessive N fertilization increases expenditures without yield benefit.

The different fields in the experiment had different responses to K fertilization, due to the different soil-test K levels. At SAREC, for instance, has an optimum level of K in the soil, so there was no level of significance when comparing the means (table 1). On the other hand, when comparing the means at the NERREC station, where the soil has a low K level, a difference in relative productivity was observed. However, when we looked at the levels of K concentration in the stalk, there was a difference in both locations, with the concentration rising as the amount of K applied to the soil increased. The lack of yield response at PTRS-D20 on soil with low soil-test

K was unexpected and may, to some extent, be attributed to wildlife damage from feral hogs within the trial area, which likely increased yield variability among replicates.

Table 2. Influence of potassium (K) fertilizer rate on mean (n = 4) corn relative yield (%) at four locations during 2023.

K Fertilizer Rates	Locations			
	SAREC	NERREC	PTRS–C3	PTRS–D20
(kg de K_2O ha^{-1})	Relative Yield (%)			
0	97	52 c	19 b	79
45	90	70 bc	62 ab	88
90	89	86 ab	85 a	96
135	98	82 ab	85 a	95
179	90	95 a	91 a	94
224	90	96 a	86 a	93
P-Value	0.3927	0.0005	0.0005	0.3911
C.V. (%)	8.7	10.9	39	11.9

SAREC = Milo J. Shult Agricultural Research and Extension Center, Fayetteville, AR.; NERREC = Northeast Rice Research and Extension Center, Harrisburg, AR.; PTRS = Pine Tree Research Station, Colt, AR. (sites “C3” and “D20”).

Means within a column followed by the same letter are significantly different ($P < 0.05$).

C.V.(%) = Coefficient of variation.

Fonte: Do autor, 2025

Corn stalk nitrate-N test values developed for Arkansas (Greub *et al.*, 2018) show that CNST below 170 mg NO_3^--N kg^{-1} indicates that N availability may have restricted corn grain yield, and that increased N fertilization rate could have boosted grain yield. The optimal category of the CSNT ranges from 170 to 1000 mg NO_3^--N kg^{-1}, indicating that adequate nitrogen was available to the crop to achieve near-maximum yield. Likewise, our research shows that Corn stalk-K concentrations of 3515 and 3253, 2956 and 2360 mg K kg^{-1}, produced near maximum and 80, 70, and 50% of relative corn yield. The relationship observed for corn stalk-K and NO_3^--N follows the principle described by the ‘Law of Diminishing Returns’, which is commonly observed between crop yields and nutrient levels in the soil. This principle shows that, initially, an increase in tissue-K and N concentration promotes a significant gain in productivity. However, as the levels approach concentrations for adequate crop nutrition, there are marginal increases in production up to the point of no yield benefit from increased nutrient concentration. This reflects the natural limitations of production systems, reinforcing the importance of managing nutrients rationally to avoid waste and economic losses. While additional research needs to be developed to improve the database and the predictions model, the similar trend of corn stalk-K concentration and CSNT indicated that sufficiency ranges of stalk-K concentration can be developed for K like for N and assist producers in decision making.

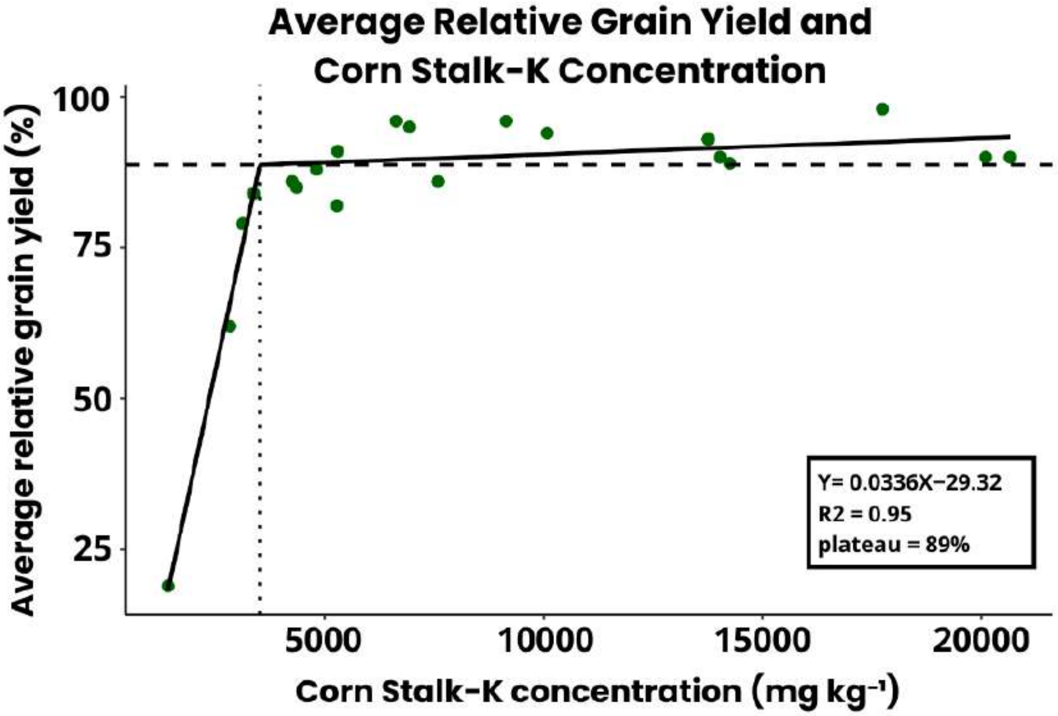

Figure 2. Relationship between average relative grain yield (%) and corn stalk potassium (K) concentration (g kg^{-1}). The linear plateau model explains the relationship with an R^2 value of 0.94. The plateau represents 89% of the relative yield.

In the end-of-season CSNT protocols, potassium chloride (KCl) has typically been used as the extractor for NO_3^--N (Binford *et al*., 1992; Brouder *et al*., 2000; Greub *et al*., 2018). However, research by Ketterings *et al*. (2017) indicated that deionized water is just as adequate as KCl and aluminum sulfate ($Al_2(SO_4)_2$) for extracting NO_3^--N from corn stalks. When comparing the two extraction methods, deionized water and KCl, we observed a strong relation ($R^2 = 0.99$; $p < 0.0001$) between them (Figure 3), suggesting that deionized water can effectively replace KCl in the CSNT. Furthermore, our research shows that a single extractant, as simple as water, can be used effectively to analyze both K and NO_3^--N in corn stalks, saving time and costs associated with chemical reagents. This behavior is key to simplifying tissue testing protocols, as a producer can diagnose both K and N management by submitting a single sample to an agricultural diagnostics lab.

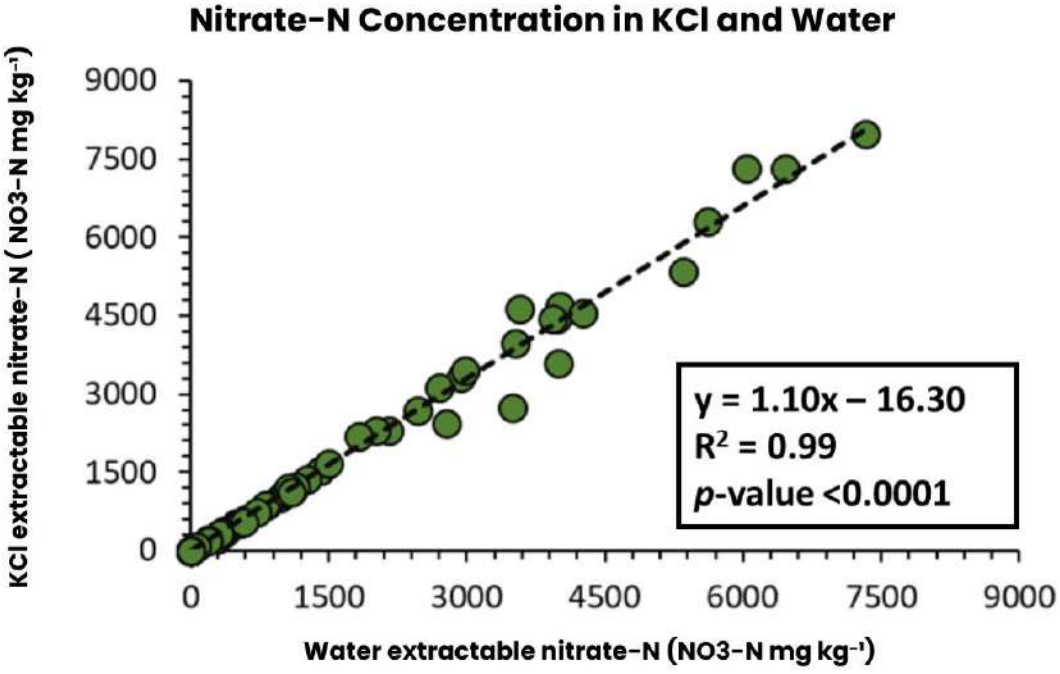

Figure 3. Relationship between nitrate-N concentration (NO_3^--N, g kg^{-1}) extracted using KCl and water. The linear regression model (y = 1.10x – 16.30) demonstrates a strong relation with $R^2 = 0.99$ and a p-value < 0.0001, indicating significant agreement between the two extraction methods.

5. Final consideration

This study proposed a novel approach to enhancing nutritional diagnostics for corn by suggesting using deionized water as an extractor for analyzing potassium (K) and nitrate-N (NO_3^--N) in corn stalks. The findings revealed that the water-extractable K and NO_3^--N have a strong relation with established extraction methods, thus presenting a viable alternative for tissue testing. This methodology's potential applications extend beyond corn production, offering a framework for more comprehensive agricultural nutrient management strategies. Additionally, our findings underscore the vital role of K in improving corn growth and yield potential, particularly in soils with suboptimal K availability, reinforcing the importance of up-to-date soil-test-based fertilizer-K recommendations and tissue testing tools for precise nutrient management strategies.

While our study shows promising results to fine-tune K and N management with end-of-season tissue testing, the trials were conducted in specific locations in Arkansas, which may restrict the generalizability of the findings to other regions with different soil and climate conditions. Additionally, the methodology needs further validation across various agricultural systems to confirm its broader applicability and reliability. This study enhances agricultural practices by offering a cost-effective and accessible method for nutrient diagnostics, promoting more sustainable and efficient corn production systems.

6. Conclusion

This research demonstrates the potential use of stalk-K analysis as an end-of-season K nutritional diagnostics tool. Moreover, the strong correlations between water-extractable NO_3^-N with traditional extraction methods confirm the potential of this methodology to replace more expensive and labor-intensive techniques. The study demonstrated that corn stalk-K concentration is a sensitive indicator of soil K availability and crop yield potential. By establishing a relationship between stalk K levels and relative grain yield, this research contributes to refining fertilizer recommendations, ultimately promoting better resource utilization and reducing environmental impacts. Finally, the methodology proposed in this study offers a promising tool for optimizing nutrient management in corn production. While additional research is required to validate these findings across diverse agroecosystems, the results provide a solid foundation for further agricultural diagnostics and sustainability advancements.

7. References

ADNAN, M. Role of potassium in maize production: A review. **Open Access Journal of Biogeneric Science and Research**, v. 3, n. 5, p. 1-4, 2020.

ANDRASKI, T. W.; BUNDY, L. G.; BRYE, K. R. Crop management and corn nitrogen rate effects on nitrate leaching. **Journal of environmental quality**, v. 29, n. 4, p. 1095–1103, 2000.

AMTMANN, A.; TROUFFLARD, S.; ARMENGAUD, P. The effect of potassium nutrition on pest and disease resistance in plants. **Physiologia plantarum**, v. 133, n. 4, p. 682–691, 2008.

BARTHOLOMEW, R. P.; JANSSEN, G. Luxury consumption of potassium by plants and its significance. **Agronomy journal**, v. 21, n. 7, p. 751–756, 1929.

BELL, M. J. *et al.* Considering soil potassium pools with dissimilar plant availability. **Improving potassium recommendations for agricultural crops**. p. 163-190, 2021.

BINFORD, G. D.; BLACKMER, A.; MEESE, B. G. Optimal Concentrations of Nitrate in Cornstalks at Maturity. **Agronomy Journal**, v. 84, n. 5, p. 881–887, 1992.

BROUDER, S. M.; MENGEL, D. B.; HOFMANN, B. S. Diagnostic efficiency of the blacklayer stalk nitrate and grain nitrogen tests for corn. **Agronomy journal**, v. 92, n. 6, p. 1236–1244, 2000.

BUNDY, L. G.; ANDRASKI, T. W. **Diagnostic tests for site-specific recommendations for nitrogen**. Madison: University of Wisconsin, 1995. Disponível em: https://extension.soils.wisc.edu/wp-content/uploads/sites/68/2016/07/Bundy-Andraski.pdf. Acesso em: 14 jan. 2025.

CASSMAN, K. G.; DOBERMANN, A.; WALTERS, D. T. Agroecosystems, nitrogen-use efficiency, and nitrogen management. **AMBIO: A Journal of the Human Environment**, v. 31, n. 2, p. 132–140, 2002.

CERRATO, M. E.; BLACKMER, A. M. Relationships between leaf nitrogen concentrations and the nitrogen status of corn. **Journal of production agriculture**, v. 4, n. 4, p. 525–531, 1991.

CHIEN, S. H.; PROCHNOW, L. I.; CANTARELLA, a H. Recent developments of fertilizer production and use to improve nutrient efficiency and minimize environmental impacts. **Advances in agronomy**, v. 102, p. 267-322, 2009.

USDA. **Corn: production.** Disponível em: https://www.fas.usda.gov/data/production/commodity/0440000. Acesso em: 14 jan. 2025.

EBELHAR, S. A.; VARSA, E. C. Applications in sustainable production: Tillage and potassium placement effects on potassium utilization by corn and soybean. **Communications in soil science and plant analysis**, v. 31, n. 11-14, p. 2367-2377, 2000.

GAGNON, B.; ZIADI, N. Grain corn and soil nitrogen responses to sidedress nitrogen sources and applications. **Agronomy Journal**, v. 102, n. 3, p. 1014-1022, 2010.

GAGNON, B.; ZIADI, N.; GRANT, C. Urea fertilizer forms affect grain corn yield and nitrogen use efficiency. **Canadian Journal of Soil Science**, v. 92, n. 2, p. 341-351, 2012.

GREUB, C. E. *et al*. Evaluating Tissue Tests to Improve Nitrogen Management in Furrow-Irrigated Mid-South Corn Production. **Agronomy Journal**, v. 110, n. 4, p. 1580–1588, 2018.

GUILHERME, Eliezer A. *et al*. Nitrogen-utilization efficiency during early deficiency after a luxury consumption is improved by sustaining nitrate reductase activity and photosynthesis in cotton plants. **Plant and Soil**, v. 443, p. 185-198, 2019.

KRUEGER, K. *et al*. Phosphorus and potassium fertilization effects on soybean seed quality and composition. **Crop science**, v. 53, n. 2, p. 602–610, 2013.

NIELSEN, R.L.B. **Historical corn grain yields in the U.S.** Corny News Network Agronomy Dept., Purdue Univ. 2023 Disponível em: https://www.agry.purdue.edu/ext/corn/news/timeless/YieldTrends.html. Acesso em: 14 jan. 2025.

HOFFER, G. N. Potash in Plant Metabolism Deficiency Symptoms as Indicators of the Role of Potassium. **Industrial & Engineering Chemistry**, v. 30, n. 8, p. 885–889, 1938.

IMAKUMBILI, M. L. E. *et al*. Plant tissue analysis as a tool for predicting fertilizer needs for low cyanogenic glucoside levels in cassava roots: An assessment of its possible use. **PLOS ONE**, v. 15, n. 2, p. e0228641, 2020.

JAKOVLJEVIC, M., D.; KOSTIC, N., M.; ANTIC-MLADENOVIC, S., B. The availability of base elements (Ca, Mg, Na, K) in some important soil types in Serbia. **Zbornik Matice srpske za prirodne nauke**, n. 104, p. 11–21, 2003.

LADHA, J. K. *et al*. Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. **Advances in Agronomy.** v. 87, p. 85-156, 2005.

LEIGH, R. A.; WYN JONES, R. G. A hypothesis relating critical potassium concentrations for growth to the distribution and functions of this ion in the plant cell. **New Phytologist**, v. 97, n. 1, p. 1–13, 1984.

LOY, D. D.; LUNDY, E. L. Nutritional properties and feeding value of corn and its coproducts. In: **Corn.** AACC International Press, p. 633-659, 2019.

MACY, P. The quantitative mineral nutrient requirements of plants. **Plant physiology**, v. 11, n. 4, p. 749–764, 1936.

MALLARINO, A. P.; BLACKMER, A. M. Profit-maximizing critical values of soil-test potassium for corn. **Journal of Production Agriculture**, v. 7, n. 2, p. 261–268, 1994.

MALLARINO, A. P.; HIGASHI, S. L. Assessment of potassium supply for corn by analysis of plant parts. **Soil Science Society of America Journal**, v. 73, n. 6, p. 2177–2183, 2009.

MAURYA, J.; BANDYOPADHYAY, T.; PRASAD, M. Transcriptional regulators of nitrate metabolism: Key players in improving nitrogen use in crops. **Journal of Biotechnology**, v. 324, p. 121–133, 2020.

MOHANTY, Sujit K.; SWAIN, Manas R. Bioethanol production from corn and wheat: food, fuel, and future. In: **Bioethanol production from food crops**. Academic Press, p. 45-59, 2019.

MULVANEY, R. L. Nitrogen-inorganic forms. In: *SSSA Book Series*. Madison, WI, USA: Soil Science Society of America, **American Society of Agronomy**, p. 1123–1184, 2018.

NIELSEN, R. L. **Corn growth & development what goes on from planting to harvest?** Disponível em: <https://www.agry.purdue.edu/ext/pubs/agry-97-07_v1-1.pdf>. Acesso em: 3 fev. 2025.

PALIWAL, R. L **Tropical maize: improvement and production**. Food and Agriculture Organization of the United Nations. Rome, 2000.

PENN, C. J.; CAMBERATO, J. J.; WIETHORN, M. A. How much phosphorus uptake is required for achieving maximum maize grain yield? Part 1: Luxury consumption and implications for yield. **Agronomy,** v. 13, n. 1, p. 95, 2022.

REHM, G. W.; LAMB, J. A. Impact of banded potassium on crop yield and soil potassium in ridge-till planting. **Soil Science Society of America Journal**, v. 68, n. 2, p. 629-636, 2004.

RITCHIE, S. W.; HANAWAY, J. J.; BENSON, G. O. **How a corn plant develops**. Spec. Rep. 48. Ames: Iowa State University of Science and Technology, Cooperative Extension Service, 1996.

SCHULTE, E. E.; HOPKINS, B. G. Estimation of soil organic matter by weight loss-on-ignition. **Soil organic matter: Analysis and interpretation**, v. 46, p. 21-31, 1996.

SHARMA, T.; DREYER, I.; RIEDELSBERGER, J. The role of K+ channels in uptake and redistribution of potassium in the model plant *Arabidopsis thaliana*. **Frontiers in Plant Science**, v. 4, p. 224, 2013.

SIKORA, F. J.; KISSEL, D. E. Soil pH. In: SIKORA, F. J.; MOORE, K. P. (Eds.). **Soil Test Methods from the Southeastern United States**. Southern Cooperative Series Bulletin 419. University of Georgia, 2014. p. 48–53.

SPARKS, Donald L. Potassium dynamics in soils. In: **Advances in soil science**. New York, NY: Springer New York, p. 1-63, 1987.

SPARKS, D. L.; HUANG, P. M. Physical chemistry of soil potassium. **Potassium in agriculture**, p. 201-276, 1985.

STAMMER, A. J.; MALLARINO, A. P. Plant tissue analysis to assess phosphorus and potassium nutritional status of corn and soybean. **Soil Science Society of America Journal**, v. 82, n. 1, p. 260–270, 2018.

TYNER, E. H.; WEBB, J. R. The relation of corn yields to nutrient balance as revealed by leaf analysis1. **Agronomy Journal**, v. 38, n. 2, p. 173–185, 1946.

UL-ALLAH, S. *et al*. Potassium application improves grain yield and alleviates drought susceptibility in diverse maize hybrids. **Plants**, v. 9, n. 1, p. 75, 2020.

VEGA, A.; O'BRIEN, J. A.; GUTIÉRREZ, R. A. Nitrate and hormonal signaling crosstalk for plant growth and development. **Current Opinion in Plant Biology**, v. 52, p. 155–163, 2019.

WAKEEL, A.; ISHFAQ M.; WAKEEL, A.; ISHFAQ, M. Potassium Dynamics in Soils. **Potash Use and Dynamics in Agriculture**, p. 7-17, 2022

WANG, N. *et al.* Impacts of nitrogen (N), phosphorus (P), and potassium (K) fertilizers on maize yields, nutrient use efficiency, and soil nutrient balance: Insights from a long-term diverse NPK omission experiment in the North China Plain. **Field Crops Research**, v. 318, n. 109616, p. 109616, 2024.

ZHANG, H.; HARDY, D. H.; MYLAVARAPU, R.; WANG, J. J. Mehlich-3. In: SIKORA, F. J.; MOORE, K. P. (Eds.). **Soil test methods from the southeastern United States.** Southern Cooperative Series Bulletin 419, p. 109–118, 2014. Disponível em:

https://aesl.ces.uga.edu/sera6/PUB/MethodsManualFinalSERA6.pdf. Acesso em: 14 jan. 2025.