

# Elucidating Elemental Fingerprints Of *Vicia Narbonensis* And *Vicia Sativa* Through Fuzzy Logic Modeling

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## Abstract

Mineral element concentrations in forage impact both plant physiology and livestock nutrition, shaping forage quality and animal health. This study investigates the elemental profiles of *Vicia sativa* and *Vicia narbonensis* using a fuzzy logic method. Concentrations of 12 chemical elements (including Ca, Mg, K, Fe, etc.) were measured in both species, and a Mamdani-type fuzzy inference system mapped their unique elemental signatures. The fuzzy logic approach allowed modeling of complex non-linear relationships and accounted for biological uncertainty. Results revealed clear differences in several major and trace elements between the species, identifying distinct elemental fingerprints. These findings suggest species-specific mineral uptake and regulation mechanisms, with nutrient levels in *Vicia sativa* and *Vicia narbonensis* determined by genetic factors and physiological adaptations to their environments.

**Key words:** Mineral content, macro mineral, micro mineral, *Vicia narbonensis*, *Vicia sativa*, Fuzzy Logic

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## INTRODUCTION

Forage legumes, including *Vicia sativa* (common vetch) and *Vicia narbonensis* (Narbon vetch), are increasingly recognized as integral components of sustainable agricultural systems due to their high nutritional quality, biological nitrogen fixation abilities, and adaptability to diverse environments (Rahmati et al., 2012), (Tomić et al., 2023). These species are widely cultivated throughout mediterranean and temperate regions (Mikic et al., 2009), serving as valuable sources of animal feed in the form of grain, hay, and silage; and supplying cost-effective, highly digestible protein and mineral content (Ramírez-Parra and la Rosa, 2023). Forage mineral composition directly influences ruminant health and productivity by serving as the primary pathway for nutrient transfer from soil to livestock (Marijanušić et al., 2017). Both macronutrients such as calcium and potassium, and micronutrients like iron and zinc are fundamental to physiological processes and livestock performance (Pandey, 2018), making mineral profiling essential for identifying nutritional deficiencies and formulating balanced diets (Zaslavskyi, 2024).

Recent studies have demonstrated significant genetic divergence between *Vicia sativa* and *Vicia narbonensis* (López-Román et al., 2024), despite their shared taxonomy. Given these genetic differences, we hypothesized that distinct mineral profiles would emerge, potentially affecting their nutritional value and requirements. To test this hypothesis, we first analyzed the macro and micromineral content of the two legumes species harvested at flowering stage, which coincides with the peak accumulation of green mass, dry matter and high crude protein content (Veklenko et al., 2023). This choice was motivated by the fact that, despite extensive research on the mineral composition of *Vicia* seeds (Samarah and Ereifej, 2009; Huang et al., 2017; Stepanova et al., 2022), studies focusing specifically on the mineral content of vegetative biomass remain limited, particularly under semi-arid conditions. We then adopted a fuzzy logic model to capture and model the non-linear relationships and inherent uncertainties within biological systems (Ilan, 2024).

Thus, the aim of this study was to compare the macro and micromineral profiles of *Vicia sativa* and *Vicia narbonensis* vegetative biomass at the flowering stage and to utilize a fuzzy logic model to assess differences and capture the complex interactions influencing their mineral composition.

## MATERIALS AND METHODS

### Characteristics of the study site

Experiments took place at Dahal Nouari, an agricultural research Farm, located in the Chirhoum region of Béni Fouda municipality. The site is geographically located at 36°15'08"N latitude and 5°29'43"E longitude, approximately 12 kilometers northeast of the city center of Sétif Province, Algeria, with an elevation of 1,199 meters above sea level. The climate of this region belongs to the semi-arid bioclimatic zone characterized by dry, hot summers and cold winter (Yerou et al., 2025). Sétif receives less than 400 mm of rainfall annually, with

precipitation concentrated in the colder months (Bouznad et al., 2020), The 2021/2022 trial year was notably dry, recording just 322 mm of rainfall or less.

**Plant Material Collection**

Two vetch species (*V. narbonensis* and *V. sativa*), each represented by distinct ecotypes, were cultivated and observed throughout their complete growth cycle from emergence to maturity. Plant samples were harvested at the flowering stage for mineral composition analysis. This developmental stage was selected because flowering represents the optimal period for forage nutritional quality and livestock feed value (Kumar et al., 2018). The samples were oven-dried at 50°C for 48 hours to preserve their biochemical integrity (Gómez-Oquendo et al., 2024), then ground through a 1 mm sieve to obtain a fine powder.

**Elemental Analysis**

For nutrient analysis, 0.5 g of dried plant samples (in triplicate) were digested using 10 mL of a nitric-perchloric acid mixture (2:3 v/v) in a microwave digestion system (Berghof Speed wave MWS-2). The digestion process involved three stages: 145°C at 75% relative humidity for 5 minutes, 180°C at 90% relative humidity for 10 minutes, and 100°C at 40% relative humidity for 10 minutes. Digested solutions were diluted with distilled water and analyzed for, Na, P, K, Mg, Ca, Co, S, Zn, Mn, Fe, Cu, and B using an Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES; Perkin-Elmer Optima 4300 DV). (Guedes et al., 2022).

**Mamdani-type Fuzzy Inference System**

A Mamdani-type fuzzy inference system was developed in the MATLAB environment to model the linkages between the concentrations of the 12 elements in each species (Figure 1).

Triangular membership functions were defined to fuzzify each input variable (elemental concentration) into fuzzy sets qualifying low, average, or high levels. Each input or output variable is fuzzified into three fuzzy intervals. A total of 144 fuzzy rules were formulated based on correlation analysis and prior knowledge of biogeochemical relationships among elements from recorded actual values. A mapping between the inputs (concentrations) and the output (species) is established in the form (If...Then). Defuzzification of fuzzy outputs into crisp numerical values was performed using the centroid method (Figure 2).

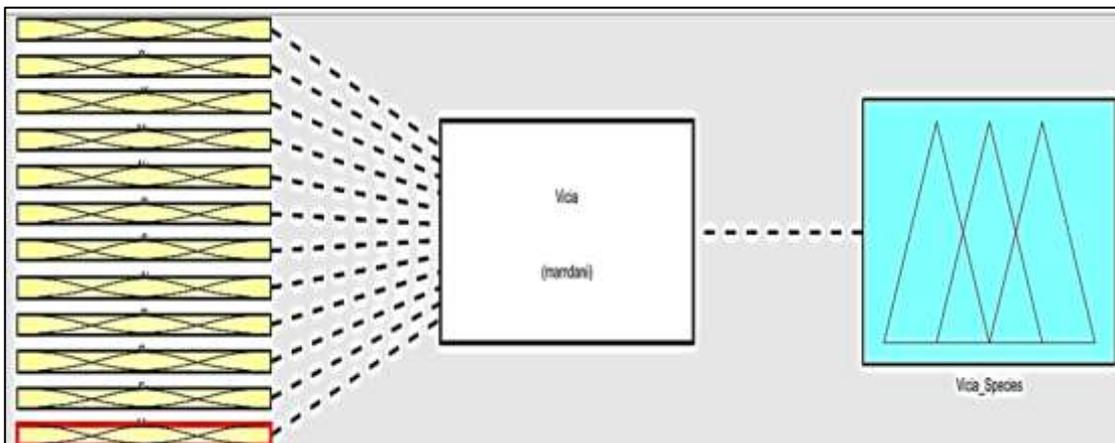


Figure 1. Fuzzy system architecture.

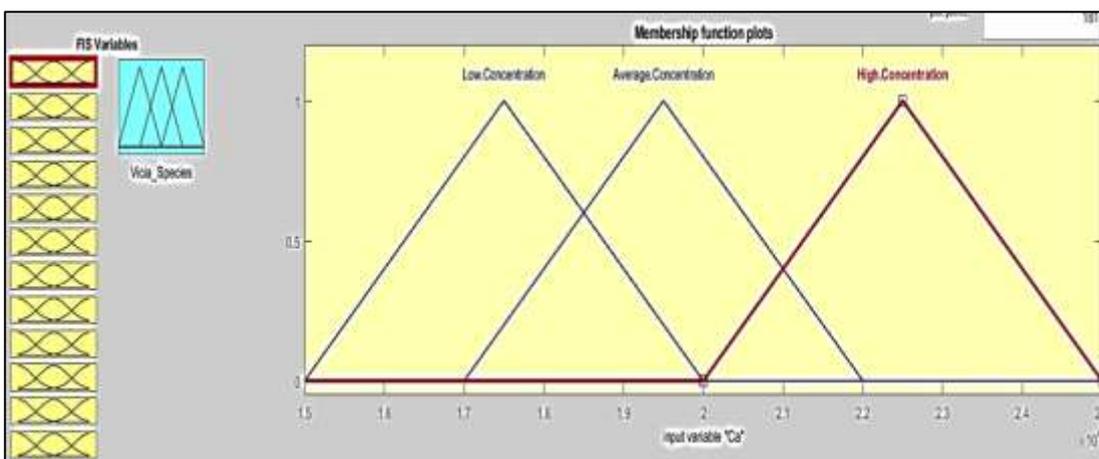


Figure 2. Defuzzification of fuzzy outputs via centroid method.

### Model Training and Validation

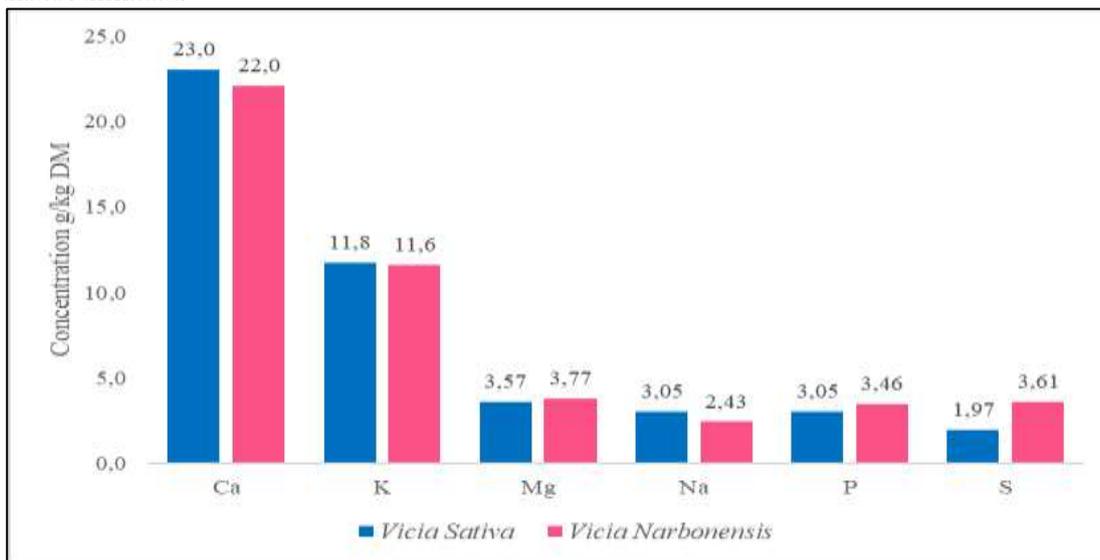
The inference system was first trained on 70% of the experimental data through a hybrid learning procedure combining a gradient descent algorithm for optimizing the premise parameters (membership functions) and a least squares estimator for the consequent parameters (fuzzy rules). The remaining 30% of the data were used for model validation by assessing prediction accuracy metrics such as root mean squared error (RMSE) and coefficient of determination ( $R^2$ ).

## RESULTS AND DISCUSSION

### Mineral content

The comparative analysis of mineral content between *Vicia sativa* and *Vicia narbonensis* forage at blooming stage reveals significant variations in the concentrations of essential macro and micronutrients (Figure 3 and 4).

#### macro-minerals



**Figure 3.** Comparative macro-mineral concentrations (g/kg DM) between *Vicia sativa* and *Vicia narbonensis*

Among macro elements, Figure 3 showed calcium and potassium concentrations were marginally higher in *V. sativa* (4.31% and 1.18%, respectively), while sodium showed a substantial 20.38% higher concentration in this species. Conversely, *V. narbonensis* exhibited superior concentrations of magnesium (5.55% higher), phosphorus (13.42% higher), and notably sulfur (83.15% higher). Both species were found to be rich in essential macro-minerals such as calcium (Ca), potassium (K), and magnesium (Mg) (Cevheri, 2013), though phosphorus (P) levels were generally lower than those of Ca and K, in agreement with findings by Badrzadeh et al. (2008) and Yolcu et al. (2009).

#### Micro-minerals



**Figure 4.** Comparative micro-mineral concentrations (mg/kg DM) between *Vicia sativa* and *Vicia narbonensis*

The microelement profile demonstrated a clear advantage for *V. narbonensis*, which showed significantly higher concentrations of copper (75.62%), iron (56.75%), zinc (26.96%), and cobalt (21.15%). Only manganese was found in slightly higher concentrations in *V. sativa* (3.86%), while boron concentrations remained virtually identical between species. The iron content is significantly higher compared to other microelements (Figure 4). Previous studies have reported that these two vetch species are rich sources of iron (Cevheri, 2013).

#### Fuzzy logic inference

The fuzzy inference system achieved satisfactory performance, with RMSE (Root Mean Square Error) values below 0.15 and  $R^2$  above 0.85 for most elements in both species during the validation phase. This demonstrates the model's ability to effectively capture the complex relationships governing multi-elemental concentrations in *V. narbonensis* and *V. sativa* (Figure 5).

This means that the system in place allows for random concentrations to be introduced at the inputs, which then allows for the automatic and immediate detection of the corresponding species at the output.



**Figure 5.** Fuzzy Logic Inference System for the Comparative Analysis of Mineral Element Profiles in *Vicia sativa* and *Vicia narbonensis*

Elemental fingerprint visualizations highlighted significant divergences between the two species for several key elements. Notably, *Vicia narbonensis* exhibited a richer mineral profile, particularly with elevated levels of sulfur (S), copper (Cu), and iron (Fe).

These variations likely arise from genetic differences influencing physiological and metabolic processes, as well as adaptations to environmental conditions. For example, *Vicia narbonensis* thrives in nutrient-poor soils, possibly due to alleles that enhance nutrient uptake and utilization (Lasky et al., 2022). Additionally, its higher crude protein and digestible dry matter content, may further promote mineral absorption and accumulation (Basbag et al., 2015). This forage legume also demonstrates remarkable adaptability to semi-arid climates, which may contribute to its distinct mineral profile; its ability to thrive in diverse conditions, including areas with low rainfall, suggests an efficient nutrient uptake and retention mechanism, potentially explaining its superior nutritional value compared to *Vicia sativa* (Berger et al., 2002) (Marijanušić et al., 2017). Such variations are crucial, as they directly influence the forage's nutritional value for livestock.

The fuzzy logic modeling approach enabled an integrative perspective on the intricate interplay between multiple elemental concentrations within each species. By accounting for non-linear relationships and biological uncertainty, this approach overcomes limitations of conventional statistical methods and provides a more nuanced understanding of elemental fingerprints (Chicco et al., 2023). Using fuzzy modelling, a result, any uncertainties or inaccuracies are reduced through the process of fuzzification (Parvathi et al., 2019).

## CONCLUSION

This study successfully employed a Mamdani-type fuzzy inference system to elucidate the distinct elemental fingerprints of *V. narbonensis* and *V. sativa*. The marked divergences observed in the concentrations of key macro and micronutrients between these two closely related species potentially illustrate the complex interaction between genetic and environmental factors that shape their physiological adaptations.

The fuzzy logic approach proved effective in capturing the complex, non-linear relationships governing multi-elemental concentrations in biological systems. Furthermore, this study showcases the potential of fuzzy logic modeling as a powerful tool for unraveling the intricate elemental landscapes underpinning plant adaptation and performance.

**Conflict of interest:** The authors have no conflict of interest to declare

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