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Research Article

Fuzzy Logic Expert System for Classifying Solonchaks of Algeria

Samir Hadj Miloud,[1,2] **Kaddour Djili,**[1] **and Mohamed Benidir**[3]

[1]*Soil Science Department, Higher National Agronomic School (ENSA-ES1603), BP 16200 El Harrach, Algeria*
[2]*Department of Agronomics, Faculty of Natural Science and Life, University Saad Dahlab, Soumâa, BP 270 Blida, Algeria*
[3]*Unit of Sétif, Institut National de la Recherche Agronomique (INRAA), El Harrach, Algeria*

Correspondence should be addressed to Samir Hadj Miloud; shadjmiloud@gmail.com

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Under arid and semiarid regions of the North of Africa, the soils considered as Solonchaks contain both calcium carbonate and gypsum. When these elements are presented at high quantities, these Solonchaks are getting close to Calcisol or Gypsisol. The World Reference Base (WRB) for soil classification does not take into account the soil as a continuum. Instead, this international soil system classification is based on threshold values that define hierarchical diagnostic criteria. Consequently, the distinction between Solonchaks, Calcisol, and Gypsisol is still not clear. To avoid this situation, fuzzy logic based on the Mamdani inference system (MFIS) was used to determine to what extent soil classified as Solonchak in WRB can interfere with Calcisols and Gypsisols. For that purpose, membership values of Solonchaks (Is), Calcisols (Ic), and Gypsisols (Ig) indices were calculated from 194 soil profiles previously classified as Solonchak in WRB. Data analyses revealed that Solonchaks soils were subdivided into Solonchaks (61%), Calcisols (1%), Gypsisols (0.5%), Solonchaks-Calcisols intergrades (29%), Solonchaks-Gypsisols intergrades (5%), and Solonchaks-Calcisols-Gypsisols intergrades (2%). Moreover, Is, Ic, and Ig showed high significant correlations with almost all WRB diagnostic criteria ($P < 0.05$). Under our study, soil classification obtained by employing MFIS was analogous to that provided by WRB; however, MFIS exhibited high precision concerning the membership value between soils and their intergrades. Therefore, the application of MFIS for other soil classifications in the world is possible and could lead to improvement in conventional soil classification.

1. Introduction

Soil classification is considered as an important means of communication at both national and international levels [1, 2]. However, few soil classification studies have been published [3]. The lack of soil classification reduces our knowledge and affects our land use decision. This difficulty is compounded by the fact that the hierarchical classifications are often built on criteria that vary greatly from one to the other. The classical reference proposed by Baize and Girard [4] reduces the number of hierarchical levels, mitigates these challenges, and represents a significant improvement. Both conventional classifications (i.e., hierarchical and classical reference) are the most used. However, there are many other national classifications, such as the Australian classification system [5], Canadian [6], and French [7]. Currently, the International Union of Soil Science promotes the development of a universal soil classification system [8] in which all the soils of the world find a place in its hierarchy. Preliminary results suggest that the objective and pedometric approaches can support the planned development of a universal soil classification system.

As the soil is part of an ecological continuum, the usual classifications are facing major challenges which require a choice, often questionable [9], between the base characters and their importance on the hierarchy of taxonomic units. Conventional classifications define several intergrades between the main units. Hierarchical classification systems are based partly on the judgment of the expert on soil formation. 40 years ago, the first attempts at the numerical soil classification was made [10, 11]. McBratney and Odeh [12] argued that a system of discrete soil classes is not adequate for soil classification and proposed a numerical classification based on fuzzy sets. Numerical approaches can deal with

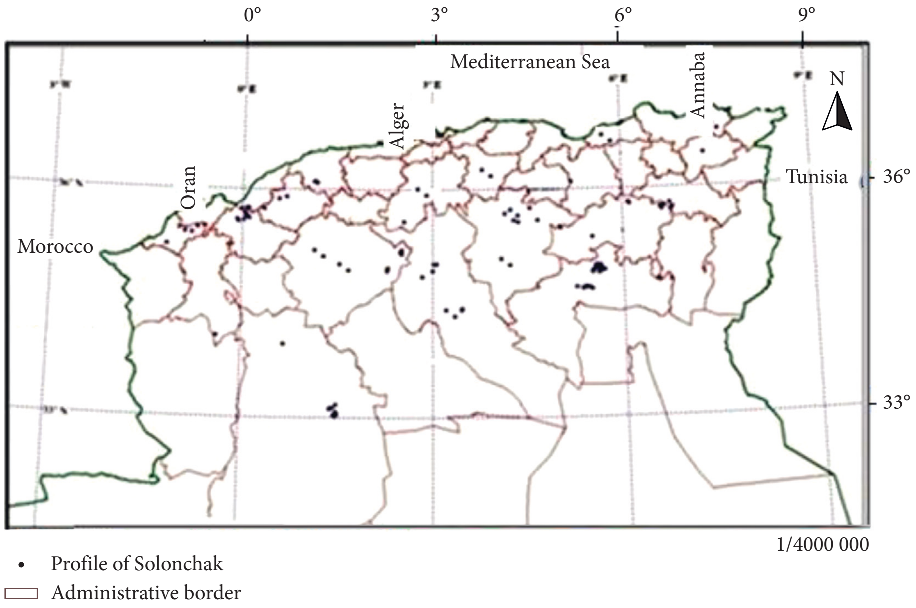

Figure 1: Solonchaks location map.

a large number of properties simultaneously. Currently, there are numerical classification systems that attempt to be an objective classification, which are based on the actual differences between morphological and analytical characteristics of the soils. Their main goal is to minimize intragroup variations and maximize intergroup variations according to objective criteria [13]. WRB [14] has been favored by the International Union of Soil Science and the European Union as a correlation system between the soils [15]. It defines the different groups of soil horizons in terms of references, properties, and diagnostic materials; each criterion is quantitative and well differentiated. Some studies have shown that WRB compared to Soil Taxonomy [16] is well suited for classifying calcareous soils [17] and gypsum soils [18, 19].

Similarly, at the end of the 16th World Congress of Soil Science, it was recommended to strengthen conventional methods of mapping by other methods, such as fuzzy logic and artificial intelligence to assess the inherent uncertainties in soil mapping [20]. Fuzzy logic has become widespread in recent years in many scientific fields, such as soil science [21–23]. It aims at dealing with the uncertainty due to the imprecision [24]. Fuzzy systems belong to the class of systems based on knowledge or expert systems. Their main purpose is to implement a human skill, or linguistic rules, by a computer program. Fuzzy logic provides a mathematical formalism with uncertain linguistic concepts. This mathematical method, which is based on set theory, has been introduced by Zadeh [25]. Thus, many studies have focused on fuzzy logic to the study of soils and their classifications. It follows that fuzzy logic allows the creation of nonhierarchical continuous classes defined by their centers of gravity [12]. The notion of intergrade soils has been formally recognized by using the concept of fuzzy sets [12]. The fuzzy logic-based algorithms can estimate the number of soil intergrades [26]. The combination of fuzzy clustering to other techniques is currently used in the development of models for the prediction of soil properties [27, 28]. In general, this theory has great potential in soil science [12]. The use of this system can replace the Boolean variable, which is poorly suitable to the presentation of most natural phenomena, by using linguistic concepts that will be transformed into multilanguage values. There are several fuzzy inference systems that were used in different applications; the most commonly used is the Mamdani fuzzy inference system (MFIS), which will be used in this research. The advantages of MFIS are reputed as intuitive; it is the most widespread acceptance and better suited to human cognition [29].

In arid and semiarid regions of the North of Africa, the calcium carbonate accumulations are frequently associated with gypsum and soluble salts. In many cases, soils are at the same time saline, calcareous, and gypsic [30]. Rahmouni [31] studied soil classification in Algeria (semiarid area) using WRB. This author revealed high similarity between Gypsisols and Solonchak and concluded that the soil studied could be considered as an intermediary group between Gypsisols and Solonchaks. To improve WRB soil classification, the fuzzy classification (continuous) is of great importance to group all soil types into continuous classes with membership values [12], to avoid imprecise and ambiguous classification. In this context, the expert system based on MFIS was used to (1) determine the degree of membership between Solonchaks in northern Algeria and both Calcisols and Gypsisols based on WRB criteria and (2) to see to what extent these Solonchaks may constitute Calcisols or Gypsisols.

2. Materials and Methods

2.1. Studied Soil Characteristics. This research focused on the study of 194 profiles identified by Djili [30] (Figure 1) in the north of Algeria. Using WRB [14] criteria, all these profiles were considered as Solonchaks. The characteristics of the diagnostic horizons of all profiles are shown in Table 1.

Table 1: Characteristics of diagnostic horizons of studied Solonchaks.

Parameters	Minimum	Maximum	Mean	SD	CV (%)
pH	7	8.9	7.83	0.3	4
EC_e (dS/m) at 25°C	15	96	30	17	56
Calcium carbonate equivalent (%)	1	67	23	13	56
Gypsum (%) (by mass)	0	73	9	10	115
E (cm)	15	1.5	69	38	55

Note. E: thickness of the diagnostic horizons; EC_e: electrical conductivity; SD: standard deviation; CV: coefficient of variation.

The main features of the whole horizons are summarized as follows:

(i) Electrical conductivity (EC_e) of saturated soil-paste varies between 15 and 96 dS/m with an average of 30 dS/m. These Solonchaks are marked by a very high salinity [32] that varies highly (CV = 56%) from a soil to another.

(ii) Calcium carbonate equivalent is variable (CV = 56%) and is between 1% and 67% with a mean of 23%. These Solonchaks can therefore be very little calcareous, or, conversely, very heavily filled in calcium carbonate equivalent. Some of these horizons follow the criteria of the calcic horizon.

(iii) Gypsum content is highly variable (CV = 115%). They range from less than 1% to 73% (by mass) with an average of 9%. Therefore, diagnostic horizons of these soils are extremely gypsic. Some of these horizons follow the criteria of the gypsic horizon.

(iv) Soil pH of the saturation extract values is between 7 and 8.9 with an average of 7.83, which indicates an alkaline soil reaction.

(v) The thickness of the diagnostic horizons (E) is highly variable (CV = 55%), and these Solonchaks may have diagnostic horizons moderately thick to very thick. These characteristics suggest that these Solonchaks are related to Calcisols than Gypsisols.

The variables or physical values used for the three groups studied soils (Solonchaks, Calcisols, and Gypsisols) are presented in Table 2. All studied Solonchaks have $EC_e \geq 15$ dS/m, and therefore the pH is no taken into account according to WRB classification.

Among the 194 studied Solonchaks profiles, 74% are Calcic Solonchak, 10% are Gypsic Solonchak, 4% are Gypsic Calcic Solonchak, and 12% are Solonchak, which are neither Gypsic nor Calcic. Despite the high content of calcium carbonate equivalent and gypsum, we observed a lack of petrocalcic and petrogypsic qualifiers because of the absence of more diagnostic criteria.

2.2. Decision-Making. The expert system based on MFIS requires three steps, the fuzzification, inference, and defuzzification, as shown in Figure 2.

Table 2: Physical quantities of soil groups recommended by WRB [14].

Soil groups (output variables)	Variables used [14] (input variables)
Solonchaks	(i) EC_e (dS/m) (ii) E (cm) (iii) EC_e × thickness of the diagnostic horizons ($EC_e \times E$)
Calcisols	(iv) Calcium carbonate equivalent (%) (iv) E (cm) (vi) Secondary carbonate (%) by volume
Gypsisols	(vii) Gypsum content (%) (by mass) (viii) E (cm) (ix) Thickness of diagnostic horizons × content in gypsum ($E \times$ gypsum)

2.2.1. Fuzzification. The fuzzification is a process of converting numeric values (or physical parameters of the diagnostic criteria) of each group of soil (Table 2) into fuzzy variables. Compared to other numerical classifications as distance metrics method [33], neither crisp data (nonfuzzy) nor model assumptions are required [34–37], which is considered as one of the major advantages of MFIS.

During this step, we firstly defined the membership function of all variables, and then, we proceeded to the passage from the physical quantities to the linguistic variables. The membership functions describe the membership degree of a fuzzy variable (the EC_e in this case) to a fuzzy subset A (little ECe value, medium, or great), and it is noted as $\mu_A(x) = [01]$ six $\in$ Aet $\mu_A(x) = 0$ six $\notin A$.

Fuzzification of all physical variables has been applied using the Gaussian membership function and the fuzzy set. The fuzzy variables (input) were divided into three subsets using linguistic variables (little value (L), medium value (M), and great value (G)). On the other hand, the output was also divided into three subsets (little value (L), medium value (M), and great value (G)) (Table 2, Figures 3 and 4). The advantage of this method, using linguistic variable, is to avoid threshold values that are not adequate for continuum soil.

The boundaries of linguistic variables of calcium carbonate equivalent, gypsum, electrical conductivity, secondary carbonates (SC), and thickness of diagnostic horizon L (0–30%), M (30–80%), and G (80–100%) are shown in Figure 3. The electrical conductivity was divided into L (0–30 dS/m), M (30–80 dS/m), and G (80–100 dS/m) linguistic variables. For the thickness of the diagnostic horizon, three subsets were defined as cited above (L (0–30 cm), M (30–80 cm), and G (80–100 cm)), and finally, for both thickness of the diagnostic horizons × EC_e and thickness of the

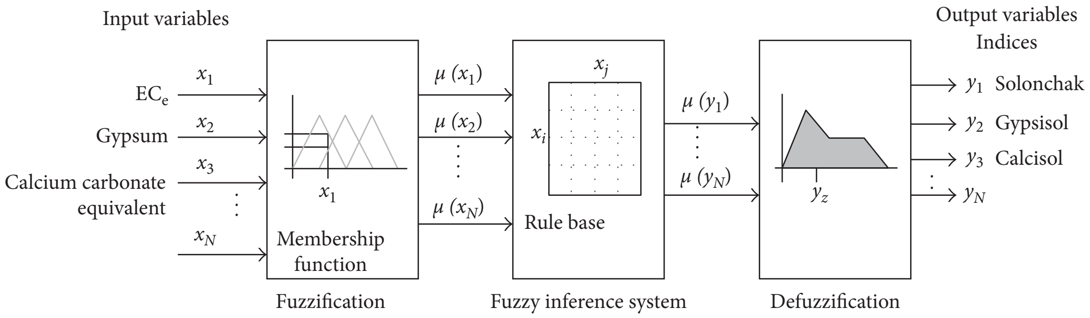

Figure 2: Reasoning of the database schema by a fuzzy inference system.

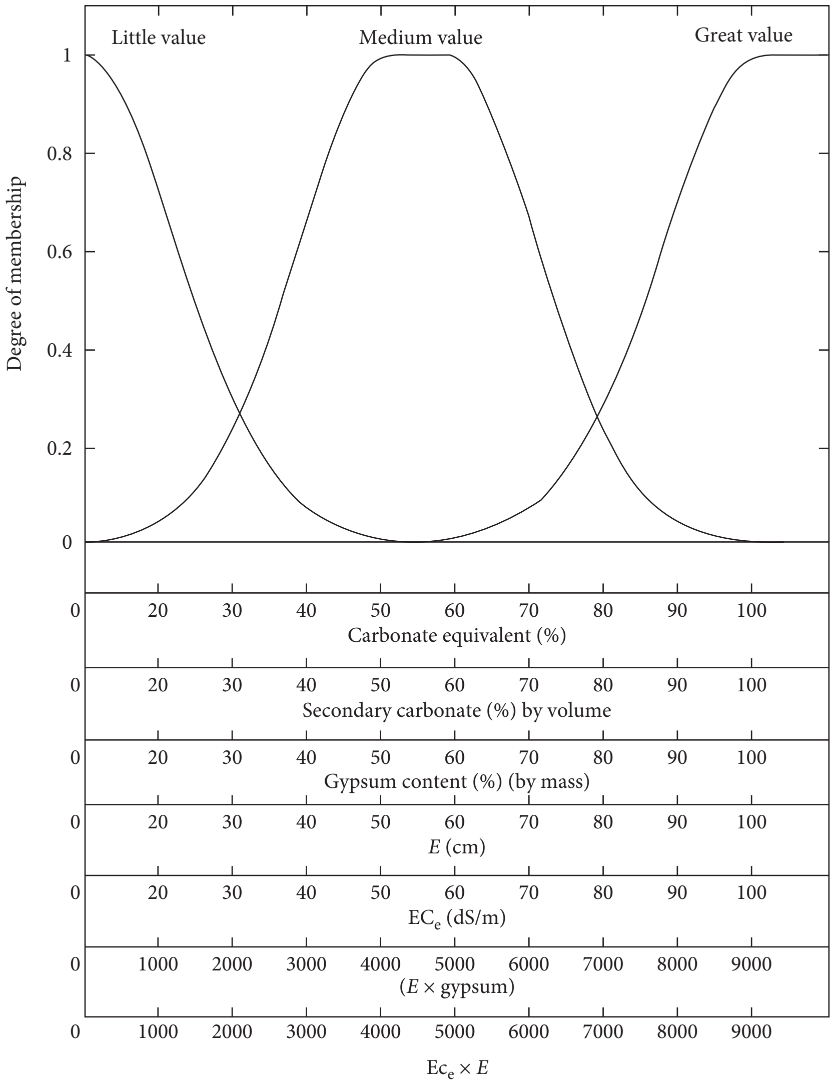

Figure 3: Membership function of input variables.

diagnostic horizon × gypsum, the linguistic variables were L (0–2000), M (2000–7000), and G (7000–9000). These boundaries of linguistic variables are based on the human knowledge from field experiences. The same procedure was performed for the output variables which have been translated into Solonchaks indices, Calcisols indices, and Gypsisols indices as shown in Figure 4.

2.2.2. The Inference Rules. The inference rules were developed using the 9 input data (diagnostic criteria or physical variables) previously divided into three subgroups that represent Solonchak, Calcisol, and Gypsisol, respectively (Table 2). The soil was classified Solonchak if all its diagnostic criteria were great (G). The same was applied for Calcisol and Gypsisol. For example, if our soil presented

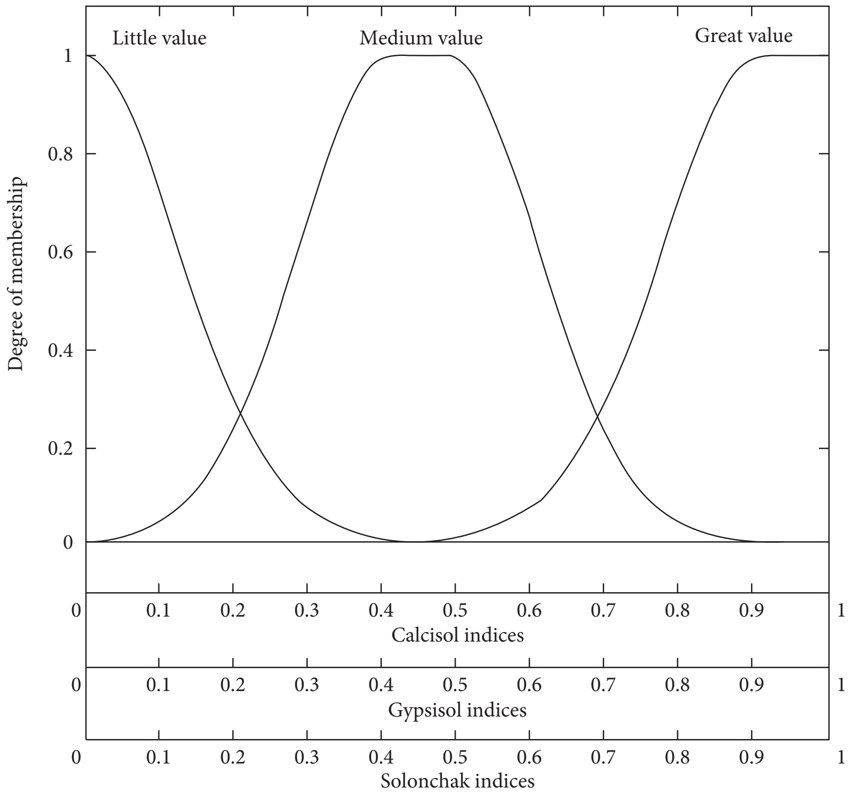

Figure 4: Membership function of the output variables.

little calcium carbonate equivalent and (SC) (that characterize Calcisol), medium gypsum content (that characterize Gypsisol), and great EC_e (that characterize Solonchak), the soil will be classified as Solonchak. These rules are expressed as single conditions (IF) or combined with other conditions (AND, OR) to achieve a linguistic result. Each rule consists of an antecedent part (condition or input) expressed by IF and a substantial portion (conclusion or output) expressed by THEN. For example, IF $\mathbf{EC_e}$ is G AND $\mathbf{(EC_e \times \mathit{E})}$ is G AND $\boldsymbol{E}$ is G (Solonchak criteria), AND **calcium carbonate equivalent** is L AND **SC** is L (Calcisol criteria), AND **gypsum content** is L AND $\mathbf{(\mathit{E} \times gypsum)}$ is L (Gypsisol criteria) THEN **Solonchak** is G, **Calcisol** is L, **Gypsisol is** L.

In this study, the degree of membership between the soils studied was highlighted using 9 physical variables (three for each soil) and 3 linguistic variables (Little, Medium, and Great). (1) In total, 171 inference rules that represent all diagnostic criteria combinations were developed by the following relation:

$$\left(\left(3 \times C_3^1 + 3 \times C_3^2 + C_3^3\right) \times 9\right) \quad (1)$$

where C is combination.

2.2.3. Defuzzification. Inference methods provide membership function $\mu_{\text{res}}(y)$ for the output variable "y" (Solonchak, Calcisol, and Gypsisol). Defuzzification is the transformation of this fuzzy information into measured information. A centroid (Z) method was employed [38] (Figure 5). The expression of Z is given by the following equation:

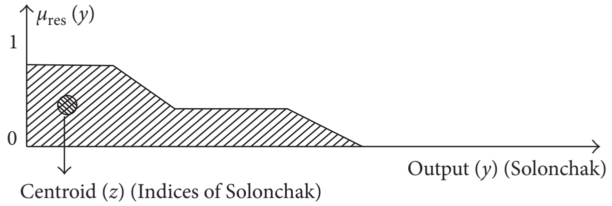

Figure 5: A method of the centroid used for defuzzification.

$$Z = \left(\frac{\left(\int_D y \times \mu_{\text{res}}(y) \times dy\right)}{\left(\int_D \mu_{\text{res}}(y) \times dy\right)}\right). \quad (2)$$

In this study, Z represents the Solonchak indice, Calcisol indice, or Gypsisol indice obtained by MFIS.

The correlations between indices of soil obtained by MFIS and all soil classification criteria considered by WRB (EC_e, calcium carbonate equivalent, gypsum content, and thickness of diagnostic horizons) were conducted. From the 171 rules estimated, only 21 inference rules were selected under our conditions. The selection of these 21 inference rules was based on high significant correlation ($P < 0.05$) between the different Solonchaks (Is), Calcisol (Ic), and Gypsisol (Ig) indices and WRB diagnostic criteria (except for diagnostic horizon thickness criteria). Finally, the key rules obtained are as follows:

Rule 1: IF **EC_e** is G AND **($EC_e \times E$)** is G AND ***E*** is G AND **calcium carbonate equivalent** is L AND **SC** is L AND **gypsum content** is L **(*E* × gypsum)** is L THEN **Solonchak** is G, **Calcisol** is L, **Gypsisol** is L.

Rule 2: IF **EC_e** is L AND **(ECe × *E*)** is L AND ***E*** is L AND **calcium carbonate equivalent** is G AND **SC** is G AND **gypsum content** is L **(*E* × gypsum)** is L THEN **Solonchak** is L, **Calcisol** is G, **Gypsisol** is L.

Rule 3: IF **EC_e** is M AND **($EC_e \times E$)** is M AND ***E*** is M AND **calcium carbonate equivalent** is G AND **SC** is G AND **gypsum content** is L **(*E* × gypsum)** is L THEN **Solonchak** is M, **Calcisol** is G, **Gypsisol** is L.

Rule 4: IF **EC_e** is L AND **($EC_e \times E$)** is L AND ***E*** is L AND **calcium carbonate equivalent** is M AND **SC** is M AND **gypsum content** is L **(*E* × gypsum)** is L THEN **Solonchak** is L, **Calcisol** is M, **Gypsisol** is L.

Rule 5: If **EC_e** is L AND **($EC_e \times E$)** is L AND ***E*** is L AND **calcium carbonate equivalent** is L AND **SC** is L AND **gypsum content** is G **(*E* × gypsum)**is G THEN **Solonchak** is L, **Calcisol** is L, **Gypsisol** is G.

The same procedure is used, as mentioned above, for the rest of the rules.

The method of min-max [25, 39, 40] was used to calculate the fuzzy inference. A weighting coefficient (Wi) is assigned to each inference rule. This coefficient depends on the structure of the rule, that is to say the combination of OR and AND. AND is used for the min operator and OR for the max operator. The weighting coefficient is used as a constant clipping of the output membership function.

Table 3: Statistical parameters of the indices of three soils.

Soils	Minimum	Maximum	Mean	SD
Is	0.15	0.53	0.31	0.12
Ic	0.13	0.50	0.25	0.1
Ig	0.14	0.51	0.19	0.06

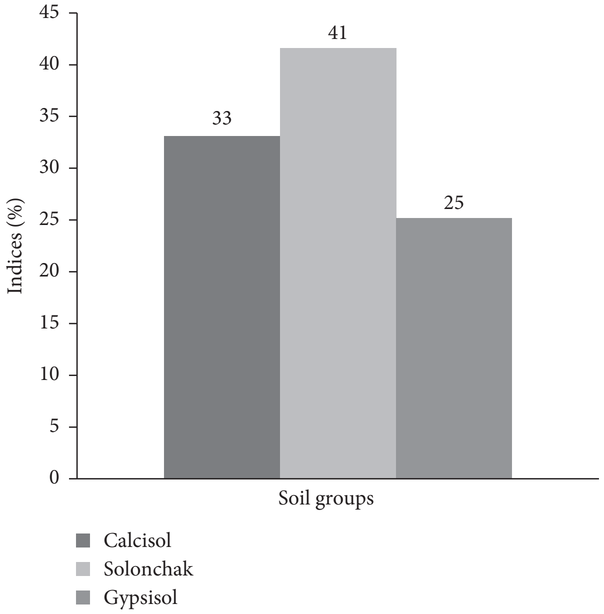

Figure 6: Histogram of frequency indices.

2.3. Interpretation of Indices. Classification by MFIS is in favor of the higher indices. However, when the indices have the same value, it means that soils have the same degree of membership. Therefore, the soil is considered intergrade. Thus, we can interpret the evidence as follows:

(i) If Is > Ic and Is > Ig, then the soil is classified Solonchak.

(ii) If Ic > Is and Ic > Ig, then the soil is classified Calcisol.

(iii) If Ig > Is and Ig > Ic, then the soil is classified Gypsisol.

(iv) If Is = Ic = Ig, then the soil is classified intergrade Solonchak-Calcisol-Gypsisol.

(v) If Is = Ic and Ig < Ic and Ig < Is, then the soil is classified as an intergrade Solonchak-Calcisol soil.

(vi) If Is = Ig and Ic < Gypsisol and Ic < Is, then the soil is classified as an intergrade Solonchak-Gypsisol soil.

(vii) If Ic = Ig and Is < Ic and Is < Ig, then the soil is classified as an intergrade Calcisol-Gypsisol soil.

3. Results and Discussion

Data analyses showed some differences between the three calculated indices. These data varied from 0.15 to 0.53 for Is, from 0.13 to 0.50 for Ic, and from 0.14 to 51 for Ig (Table 3). In general, Solonchaks under our study were more related to Calcisols (0.31 versus 0.25, resp.) than to Gypsisols (0.31 versus 0.19, resp.). These results suggest that the degree of membership of Solonchaks with Calcisols was more important compared to the degree of membership of Solonchaks with Gypsisols. 41% of the indices are assigned to Solonchaks, 33% to Calcisols, and 25% to Gypsisols as shown in Figure 6. This result revealed that the soils studied are dominated by Solonchaks.

The high similitude between Solonchaks and Calcisols suggests that soils studied could be classified as Calcisols. The results illustrated in Figures 6 and 7 show the following facts:

(i) Solonchaks are the most dominant followed by the Calcisols.

(ii) Solonchaks similar to Gypsisols are represented only by soil 89 with an index of 0.5. Soil 89 is qualified in WRB as Gypsic Solonchak.

(iii) Only soils 39, 107, and 138 simultaneously exhibit the same degree of similarity with Solonchaks, Calcisols, and Gypsisols because their indices are 0.21, 0.18, and 0.15, respectively. Therefore, soils 39, 107, and 138 are qualified in WRB as Gypsic Calcic Solonchak.

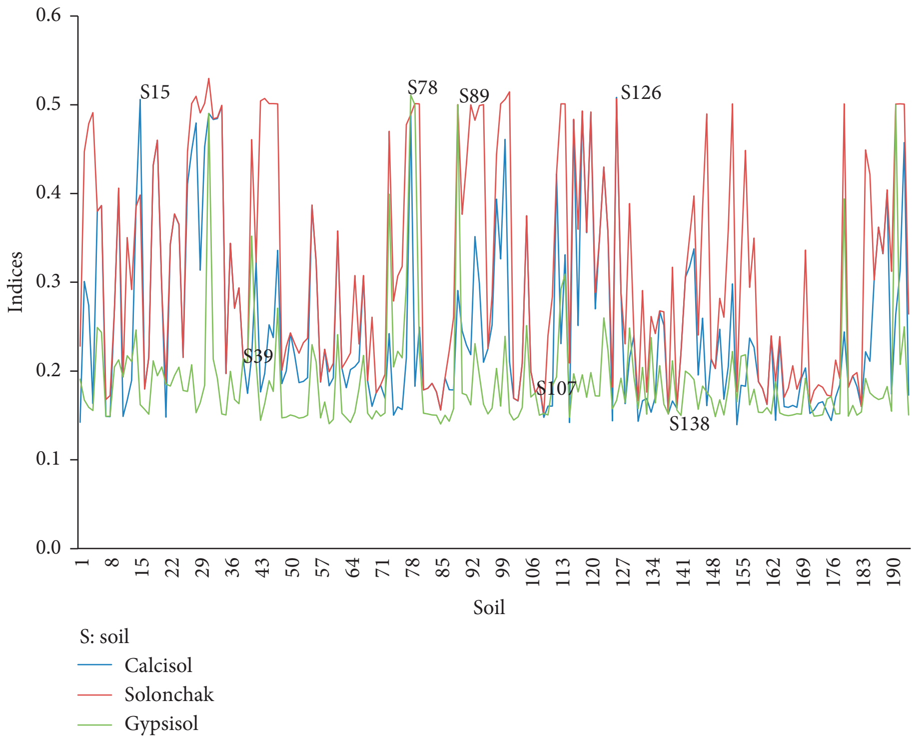

Figure 7: Classification of soils obtained by the MFIS.

(iv) In contrast, soil 78 is classified Gypsisol by the fuzzy classification unlike WRB. We explain this differences that the soil 78 is very rich in gypsum (58% by mass) (Table 4). This soil is qualified by WRB as Gypsic Solonchak.

Soils 15 and 126 have a higher degree of similarity to Calcisols than to Solonchaks (Figure 7). Therefore, these soils were classified by MFIS as Calcisols and not as Solonchaks. Moreover, the soils 15 and 126 are very rich in calcium carbonate equivalent (67%), rich in SC, with values ranging from 20% to 25% (by volume) for soils 15 and 126, respectively (Table 4). These 2 soils are qualified by WRB as Calcic Solonchak. The difference observed between the WRB and MFIS was due to fact that the threshold values and priority order of classification were not considered by MFIS.

According to the overall trend of the three curves (Figure 7), we concluded that the majority of Gypsisols was affected by values below 0.2. The indices between 0.2 and 0.4 affect soils that have almost the same dominance between Solonchaks and Calcisols. These reveal the presence of a dominant overlap between Solonchaks and Calcisols compared to Solonchaks and Gypsisol. Index values above 0.4 represent essentially Solonchaks. Therefore, we can allocate indices (I) obtained by MFIS into three groups to determine the frequency of the level of soil membership studied within each group, as shown in the following breakdown:

(i) Group 1 (low indices): $I < 0.2$

(ii) Group 2 (average indices): $0.2 < I \leq 0.4$

(iii) Group 3 (high indices): $I > 0.4$

Table 4: Characteristics of Solonchaks 15, 126, and 78.

Parameters	Soil 15	Soil 126	Soil 78
pH	8.6	7.5	7.6
ECe (dS/m)	23	15	15
Calcium carbonate equivalent (%)	67	67	22
Secondary carbonate (%) by volume	20	25	1
Gypsum (%) by mass	5	8	58
E (cm)	70	40	100

Note. E: thickness of the diagnostic horizons; EC_e: electrical conductivity.

3.1. Membership Degree between the Soils Studied. Figure 8 showed that 50% of Gypsisols, 32% of Calcisols, and 19% of Solonchaks in the study area shared the group of low indices ($I < 0.2$). This result means that in this group, studied Solonchaks have a low degree of membership with Gypsisols and a relatively higher degree of membership with Calcisols. Similarly, some Solonchaks of this group have simultaneously the same degree of membership with Calcisols and Gypsisols. The Majority of the soils of group 1 are qualified by WRB as Gypsic Solonchak, and a small proportion of these soils are qualified as Gypsic Calcic Solonchak. In group 2 ($0.2 < I \leq 0.4$), 43% of the average indices are assigned to Solonchaks, 39% to Calcisols, and 18% to Gypsisols. According to WRB, the qualifier Calcic is predominant for this group comparing the qualifier Gypsic.

This result suggests that Solonchaks, which are also dominant in this group, have a higher degree of membership with Calcisols than with Gypsisols. In group 3 ($I > 0.4$), 67% of the indices are assigned to Solonchaks against 26% and 6% to Calcisols and Gypsisols, respectively. This result means

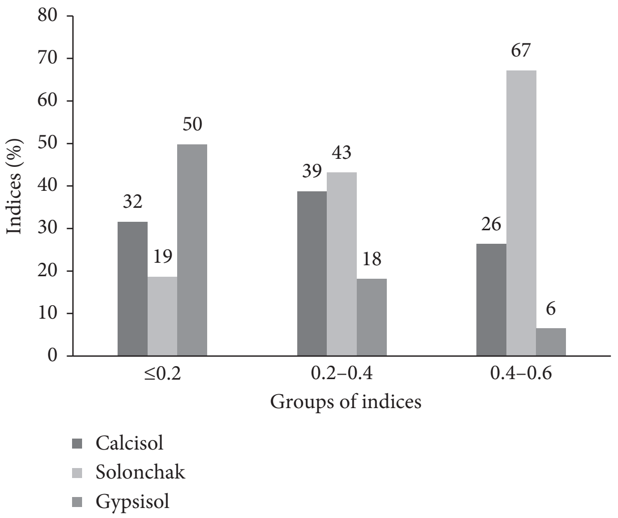

Figure 8: Histogram of frequencies of groups of indices.

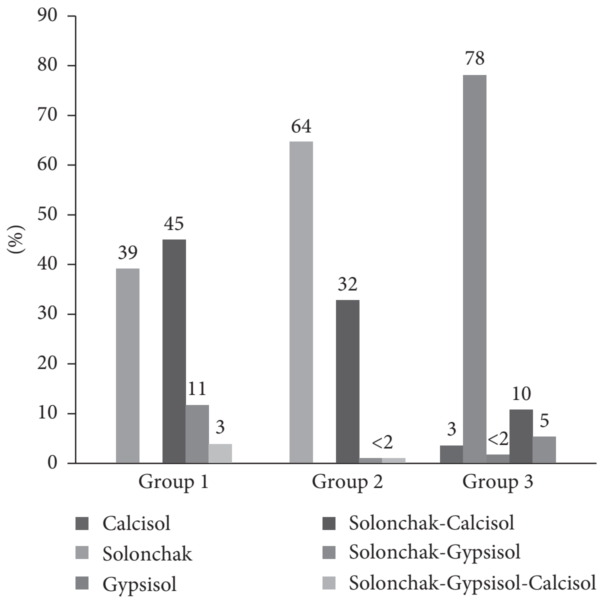

Figure 9: Histogram of soil group frequencies and their intergrades.

that Solonchaks clearly dominate this group. It also suggests that, compared to groups 1 and 2, the degrees of membership between soils (Solonchaks with both Calcisols and Gypsisols) in group 3 were low, and there are some Solonchaks that have no membership with either Calcisols or with Gypsisols. On the other hand, the proportions of the soil qualifiers in group 3 are distributed in the following way: Calcic (80%), Gypsic (12%), Gypsic Calcic Solonchak (3%), and 5% of Solonchaks, which are neither Calcic nor Gypsic.

Overall, these results showed that the studied soils were dominated by Solonchaks; 74% of these Solonchaks are Calcic Solonchak. The degree of membership of Solonchaks to Calcisols or Gypsisols was different depending on the group considered. The degree of membership between Solonchaks and Calcisols is stronger than that between Solonchaks and Gypsisols. Thus, Solonchaks with a higher degree of membership with Calcisols are qualified by WRB as Calcic Solonchaks.

The data analysis of each group of indices (Figure 8) was computed to determine Solonchaks, Calcisols, and Gypsisols frequencies and all possible intergrade soils. Figure 9 shows that Solonchak frequency increased from 39% in group 1 to 64% in group 2 and to 78% in group 3. Both Calcisols and Gypsisols were only detected in group 3 (3% and less than 2%, resp.). In each group, the soils which are neither Solonchaks, nor Gypsisols, nor Calcisols may be considered as intergrade soils with Solonchaks. As conclusion, the MFIS-based algorithms could estimate the number of soil intergrades and the degree of membership values (indices) of these soils with more precision [12–25] compared to WRB soil classification.

Figure 9 shows three types of intergrade soils, Solonchaks-Calcisols, Solonchaks-Gypsisols, and Solonchaks-Calcisols-Gypsisols. These intergrade soils represent 60% of Solonchaks in group 1 with a clear predominance of Solonchaks-Calcisols (45%) followed by Solonchaks-Gypsisols (11%) and Solonchaks-Calcisols-Gypsisols (3%). These intergrade soils represent only 34% of soils in group 2 and 16% in group 3. The use of MFIS revealed that Solonchaks previously classified by WRB have strong similarities with Calcisols and Gypsisols.

According to MFIS, Solonchaks have a higher degree of membership with Calcisols (29%) (Figure 10) than with Gypsisols (5%), and only 1% was Solonchaks-Calcisols-Gypsisols. Consequently, the classification of Solonchaks intergrades will be Solonchaks-Calcisols, Solonchaks-Gypsisols, and Solonchaks-Calcisols-Gypsisols. MFIS also showed that 61% of soils were strictly Solonchaks and only 1% and 0.5% were strictly Calcisols and Gypsisols, respectively. Based on WRB, from the 61% Solonchaks detected by MFIS, only 26% were classified as Solonchaks, 43% as Calcic Solonchaks, 3% as Gypsic Solonchaks, and 1% as Gypsic Calcic Solonchaks.

3.2. Correlation between the Indices of Soil Obtained by MFIS and Diagnostic Criteria of WRB.

The correlation data analyses were conducted to determine the relationship between the indices obtained by MFIS, and its diagnostic criteria are defined by WRB (EC_e, calcium carbonate equivalent, SC, gypsum, thickness of horizon (E), ($E \times EC_e$), ($E \times$ gypsum)). The statistical parameters of these relationships presented in Table 5 showed that all correlations were positive and significant ($0.49 < r < 0.77$; $P < 0.05$) except for (E) ($0.01 < r < 0.06$; $P > 0.05$). Solonchaks indices (Is) presented significant and positive correlation with EC_e (0.76), and Gypsisols indices (Ig) showed high correlation with gypsum content (0.70), while Calcisols indices (Ic) soil presented significant correlation with calcium carbonate equivalent and SC (0.77 and 0.70, resp.). The majority of WRB diagnostic criteria were highly correlated with the indices obtained by MFIS. These results suggest that MFIS gives the same soil classification as WBR; however, its application provides more precision concerning the degree of membership values between soils (reference group soil).

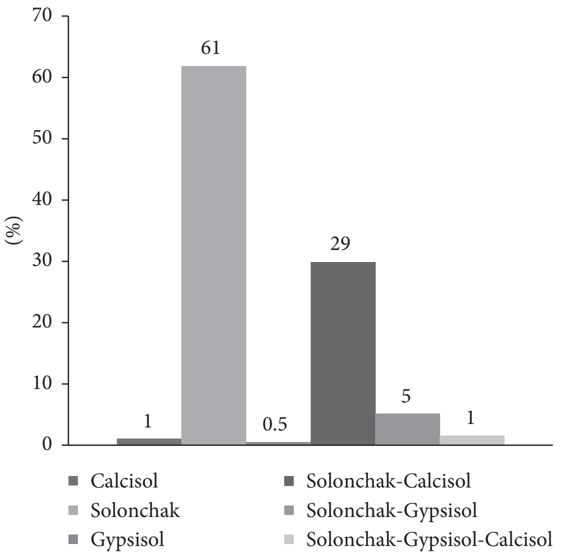

Figure 10: Histogram of soil group frequencies and their intergrades.

Table 5: Correlations between indices of Solonchaks (Is), Calcisols (Ic), and Gypsisols (Ig) and different diagnostic criteria.

Relations	*df*	*r*	R^2
Is, $\mathrm{EC_e}$	192	0.76^*	0.58
Is, *E*	192	0.01	0.0001
Is, $(E \times \mathrm{EC_e})$	192	0.49^*	0.24
Ig, gypsum	192	0.7^*	0.49
Ig, *E*	192	0.06	0.04
Ig, $(E \times \text{gypsum})$	192	0.6^*	0.36
Ic, *E*	192	0.04	0.002
Ic, SC	192	0.7^*	0.5
Ic, calcium carbonate equivalent (CE)	192	0.77^*	0.6

Note. *Significant at probability $P < 0.05$; *r*: coefficient of correlation; *R*: coefficient of determination; *df*: degree of freedom.

Table 6: Relations between indices of Solonchaks, Calcisols, and Gypsisols

Relations	*df*	*r*	R^2
Is, Ic	192	0.7^*	0.46
Is, Ig	192	0.52^*	0.27
Ig, Ic	192	0.32^*	0.1

Note. *Significant at probability $P < 0.05$.

Data analyses showed that the relationships between the three soil indices were positive and significant ($P < 0.05$) (Table 6). The relationship $\mathrm{Is} \times \mathrm{Ic}$ ($r = 0.7$) is stronger than $\mathrm{Is} \times \mathrm{Ig}$ ($r = 0.52$) and $\mathrm{Ic} \times \mathrm{Ig}$ ($r = 0.32$). The high correlation between Is and both Ic and Ig suggests the presence of some intergrade soils under our conditions (Solonchak-Calcisol, Solonchak-Gypsisol, and Solonchak-Calcisol-Gypsisol) (Figure 10).

Therefore, Solonchaks studied are actually a mixture of Solonchaks, Calcisols, and Gypsisols. However, the results showed that the indices assigned to Solonchaks were the most dominant (about 41%) followed by those assigned to Calcisols (33%) and Gypsisols (25%). In general, Solonchaks presented the highest indices, followed by Calcisols and Gypsisols.

In total, Solonchaks have a higher degree of membership with Calcisols (29% of soil or Solonchak-Calcisol) than with Gypsisols (5%). Data analyses also confirmed these results by the high correlation between Solonchaks and Calcisols ($r = 0.7$; $P < 0.05$) and between Solonchaks and Gypsisols ($r = 0.52$; $P < 0.05$). Solonchaks-Calcisols (29%) intergrade soils were the most important in the north of Algeria compared to Solonchaks-Gypsisols (5%). These results confirm the conclusion of Hughes et al. [26] who showed that fuzzy logic allows the determination of intergrade groups. Also, Viscarra Rossel et al. [41] use the fuzzy approach to provide information on the group of soil overlaps. MFIS showed that the degree of overlapping membership of these Solonchaks-Gypsisols-Calcisols intergrades was poorly represented (<2%). Similarly, it was found that 1% and 0.5% of 194 Solonchaks classified by WRB are respectively recognized as Calcisols and Gypsisols by MFIS. This small difference between the two classification systems is due to the fact that the threshold values of diagnostic criteria defined by conventional classifications would not be suitable for soil that is considered as a continuum system [9]. Consequently, significant information is lost [42], especially for both taxonomic fragmentation and soil mapping. However, fuzzy classification is continuous and numerical [12] that use the linguistic variables and Gaussian membership functions.

These results revealed that the two used systems (WRB and MFIS) provide the same classification (predominance of the Solonchak group). Based on fuzzy logic, the soil previously classified by WRB as Calcic Solonchak has high degree of membership to Calcisols, and some of these Calcic Solonchaks are now classified by MFIS as Calcisol. Solonchaks qualified previously by WRB as Gypsic Solonchak has a high degree of membership to Gypsisol, and some of these soils were classified by MFIS as Gypsisol. The differences noted between the two soil system classifications are attributed to the fact that the WRB depends on the order of priority and weights attributed to diagnostic criteria. MFIS exhibited more precision concerning intergrade soils and degree of membership compared to WRB. This precision is very useful in soil management practices and land evaluation systems [23–43].

4. Conclusion

The soil classification by MFIS of 194 profiles previously classified as Solonchaks (Calcic Solonchak, Gypsic Solonchak, and Gypsic Calcic Solonchak) by WRB revealed 6 different soil groups represented by Solonchaks, Solonchaks-Calcisols intergrades, Solonchaks-Gypsisols intergrades, Solonchaks-Calcisols-Gypsisols intergrades, Calcisols, and Gypsisols. In addition, this study showed that Is, Ic, and Ig were highly correlated with almost diagnostic criteria established by WRB except for horizon thicknesses. Moreover, the correlation between Is and Ic ($r = 0.7$) was more important than Is and Ig ($r = 0.52$) and Ic and Ig ($r = 0.32$).

These relationships between indices suggest the presence of intergrade soils. On the other hand, these results confirm that Solonchaks-Calcisols intergrade is more dominant than Solonchaks-Gypsisols intergrade, as previously reported by Halitim [44] and Djili [30]. Our results showed that soil groups determined by WRB are analogous to those determined by MFIS. However, the application of MFIS provides us the degree of membership between all these soils and their intergrades and takes into account the continuous complex nature of soil. As general conclusion, MFIS improved soil classification by using the degree of membership. Therefore, fuzzy logic could be considered as the basic tool for both classification and soil mapping and an undeniable support in precision agriculture. The application of the MFIS to other soils of the world is possible because of the flexibility of inference rules.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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