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Research Article

Multicriteria Methodology for the Efficient Programming of Agricultural Cultivation Activities in a Colombian Region

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The potato is one of the main agricultural products in Colombia and is the second most important crop in the country. The production of this tuber represents 3.3% of the country's agricultural gross domestic product (GDP). More than 100,000 producer families subsist on cultivation at the national level, the vast majority of which are smallholdings. However, smallholders are not able to exploit the full potential of this activity, and one of the main factors that does not allow for improving productivity is the inefficient use of land in agricultural activities. This leads to issues such as erosion, overexploitation of soil resources, reduced productivity, and, depending on the time of year, even an excess of potato supply. Therefore, a multicriteria methodology is proposed based on the key elements of the potato crop production cycle and its environment, made up of farmers from the municipality of Ventaquemada, located in Boyacá, where potato cultivation is a traditional practice. This department is the second-largest potato-producing department in the country. A review of the literature was carried out to determine and characterise the area of the selected department, and based on the above, the relevant criteria were defined and the alternatives to be evaluated were identified. Second, the proposed model is evaluated with its respective prioritisation process of both the criteria and the alternatives according to the analytic hierarchy process (AHP) methodology. Finally, the results of the model are presented, prioritizing the type of tillage, irrigation method, seed type, and its disinfection process for potato cultivation. This takes into account topographic and climatic conditions, the ecosystem, soil type, implementation costs, among other factors specific to the case study.

1. Introduction

Colombia is a country with favorable geographical and climatic conditions for agricultural production. This facilitates the development of projects to generate products that are essential for human consumption according to the basic family basket, which represents approximately 6% of the value added to national GDP [1]. Its share of GDP began to increase in 1990 until 2016, during which there was an increase in the area planted with permanent crops, from 2,333,471 hectares to 3,339,278 hectares, representing a 43.10% increase [2]. However, the same cannot be said in terms of productivity, as the country has significant deficits in agricultural productivity yields. For example, in maize and potatoes, the country's average production is 3.6 t/ha and 19.3 t/ha, respectively, while in the United States, the average yield is 11 t/ha in maize and 49 t/ha in potatoes [3].

The Colombian departments of Boyacá and Cundinamarca are the main producers of tubers such as potatoes, and Boyacá is the second-highest producing department of this product at the national level [4]. However, there have been problems in the planning of primary producers overusing the available land [5], resulting in a negative impact on the land due to overexploitation, where 686,000 ha have an agricultural vocation (30%) and 1,073,303 ha (47%) are in agricultural production, where 44% is in conflict of overuse and 10% is in subuse. Seventy-five percent of the total departmental area presents erosive processes, of which 8% have severe erosion [6].

A peasant economy with a low impact on the competitiveness of the region still predominates and partially contributes to reducing the high rates of poverty that characterise daily life in the department. The farms that are currently being developed by small-scale farmers lack technology, technical assistance, planting planning, and adequate phytosanitary controls, all of which have an impact on high production costs. In addition, the lack of economic resources and the precarious presence of the State in many areas are reflected in an insufficient irrigation and drainage infrastructure, as well as in the lack of implementation of technological packages that improve yields, profitability, and competitiveness of the department of Boyacá. Finally, the overexploitation of land use and the heavy deforestation of watersheds for the establishment of crops have led to the deterioration of natural resources and low social development of the peasant.

For the case study, it was conducted in the municipality of Ventaquemada, Boyacá, where the main economic activity is agriculture, particularly the cultivation of potatoes. The area not only serves as a source of the tuber but also as a seed supplier at the regional and national levels. However, the municipality encompasses 15% of the "Rabanal" paramo, where its extensive use for potato cultivation, indiscriminate use of chemicals, and mechanized ploughing impact water resources and soil. In addition, these practices generate high costs for their recovery. Therefore, it is important to develop tools that allow for the sustainable integration of this economic activity with the ecosystem.

To address this problem, a multicriteria tool is proposed that allows prioritizing relevant alternatives in the production process of potato cultivation, assessing several criteria previously selected for their relevance in this agricultural process, and taking into account the geographical, environmental, and resource availability conditions of the area under study.

2. Literature Review

The literature review focused on identifying support tools for decision-making in the different stages of agricultural crops, where comprehensive models were found [7]. During land use planning, the identification and selection of suitable sites for the development of such economic activities are required, taking into account available resources and their limitations.

Due to the complexity of these activities and the synergy of the different factors that were interrelated to properly use the available natural resources, according to soil suitability [8], applications were found to different production chains using multicriteria models (MCDA).

The results obtained with the application of multicriteria analysis models have mainly allowed the determination of the suitability of soil for different production chains [8] such as areas suitable for pistachio cultivation [9], barley cultivation [7], crops such as corn, rapeseed, and soybeans in land units, respectively, and maize cultivation was preferred to other plants [10], citrus crops [11], and energy crops [12].

Other results were identified such as the definition of potential zones for rainwater harvesting, agricultural ponds, and control dams [13–15], identifying areas at risk of drought [16], and the evaluation of fertilization and irrigation alternatives in an agricultural system considering environmental indicators.

In Colombia, one of the main applications carried out at the national level was the methodology developed by UPRA (Rural Agricultural Planning Unit) and the Universidad Nacional of Colombia, which is used for the evaluation of land at the national level with a scale of 1 : 25000, proposing an AHP model [17]. Indicators and data sources were taken into account for the selection of sociocultural, environmental, and economic criteria.

Subsequently, this information was integrated with geographic information systems. This allowed us to determine the suitability of land use for agricultural activities in terms of high, medium, low, or not suitable for 18 agricultural production chains [18].

According to the literature review, the application of multicriteria methods in agricultural production chains took into account the criteria and variables identified in Table 1.

3. Methodology

Under the literature review and considering the complexity of the problem in defining a domain order among the alternatives based on different decision criteria [20, 21], the Analytic Hierarchy Process (AHP) method is selected, which was proposed by Thomas Saaty in the 1970s. This choice is made taking into account that it is perceived as a simple method with reliable results [22], considering its use of paired comparisons of criteria and alternatives [23]. This comparison is carried out by experts aiming to solve a planning and resource allocation problem, among others [24]. Subsequently, it is verified with a consistency coefficient [25].

Figure 1 shows a typical schematic of the AHP analysis.

Then, a measurement methodology is used to prioritize among the elements of each level by consulting or asking a population of respondents to evaluate each set of elements based on a higher-level criterion. Each pair of elements is evaluated separately, for which a 9-point scale known as the Saaty scale (Table 2) is used to determine the importance of one item over the other.

Based on the information collected, a comparison matrix (MCC) is constructed, with its values indicating the "strength" with which each element dominates the other concerning an established criterion. This forms a matrix A of dimensions $m \times n$ (equation (1)), where a_{ij} represents the priority between factor i and factor j, and the values of the

Table 1: The objective, criteria, and variables in MCDA models agricultural application.

Location	Objective	Criteria*	Variables
Ardebil, Irán	Determine the suitability of the land for agriculture [7] Establish crop priority planning policies in 66 separate land units in the study area [10]	NR	(i) Soil depth (ii) Earrings (iii) pH (iv) Electrical conductivity (v) Percentage of exchangeable sodium (vi) Calcium carbonate equivalent (vii) Plaster content
		PHR	(i) Climatic characteristics
Sídney, Australia	Develop spatial modelling procedures for the suitability analysis of agricultural land with the use of geographic information systems (GIS) [8]	NR	(i) Soil suitability index, considering soil productivity; (ii) Erosion tolerance index to minimise erosion risk (iii) Runoff curve to regulate the discharge of water resources; (iv) Proximity to the body of water (minimise pollution to the water resource)
		CI	Soil access measure (maximise)
Golfo of Edremit–NW Turquía	Determine the right site for cultivation [9]	NR	(i) Land use capacity classes (ii) Soil depth; (iii) Soil limiting factors (drainage and salinity)
		PHR	(i) Average temperature and minimum temperature in critical periods
Italia-Campania and Molise	Landscape planning tool [12]	NR	(i) Changes in land use with energy crops over a period of time (ii) Ecological and environmental indicators; (iii) Analysis of environmental fragmentation with landscape metrics
		CI	(i) Economic benefits for farmers
Bundelkhand, India	Assess socioeconomic sustainability from drought vulnerability using an AHP methodology [16]	CI	(i) Agricultural work
		SC	(i) Population density (ii) Marginalised population (iii) Farmers (iv) Literacy rate
Northern Ghana	Strategic planning of agricultural land use [19]	NR	(i) Resource (ii) Efficiency (RUE) (iii) Sustainability in maize production systems (iv) Environmental costs of producing maize, use measured as total energy
		QY	(i) Benefits of maize, measured in food supply from grain kcal/year and potential electricity (bioenergy)
Ramsar, Irán	Determine the suitability of the land for agriculture [11]	NR	(i) Elevation (ii) Tilt angle (iii) Rainfall
		PHR	(i) Maximum and minimum temperature

Table 1: Continued.

Location	Objective	Criteria*	Variables
California	Assess the use of water for irrigation on agricultural land [14]	NR	(i) Water policies (ii) Irrigation status
		PHR	(i) Weather conditions
		CI	(i) Wastewater treatment plants (volume of decarding and adequate treatment processes)
		QY	(i) Type of harvest
Ebenat, Ethiopía	Identification of suitable sites for rainwater harvesting [13]	NR	(i) Land use/land cover (ii) Soil texture (iii) Rainfall volume measurement (iv) Slope of the ground (v) Runoff density (vi) Topography
		CI	(i) Distance between settlements and roads
Jaipur district and Bhadrak, India	Identify a tool to manage water resources and make decisions to mitigate threats of flooding, drought, soil erosion, improve soil moisture, and crop intensity using [15]	NR	(i) Land use/land cover Geomorphology (i) Earrings (ii) Stream density-soil type (iii) Surface runoff
Colombia	Development of a tool for the zoning and definition of soil suitability of agricultural production chains (crops, livestock, poultry, and livestock) [17]	NR	(i) Soil criteria (depth, texture, moisture, nutrients, and pH) (ii) Relief (slope) (iii) Ecological integrity and water availability
		PHR	(i) Climate (temperature, thermal floor, and rainfall) (ii) Threats from natural phenomena and risk of erosion
		CI	(i) Labour (availability) and connectivity according to access roads and proximity to urban areas (ii) Technological infrastructure and technological balance in primary production
		SC	(i) The participation of organisations and the distribution of land

*NR: natural resources: soil and water, PHR: plant health risk, CI: cost of implementation, SC: socio-cultural, QY: quality and the yield of the crop. Source: the authors.

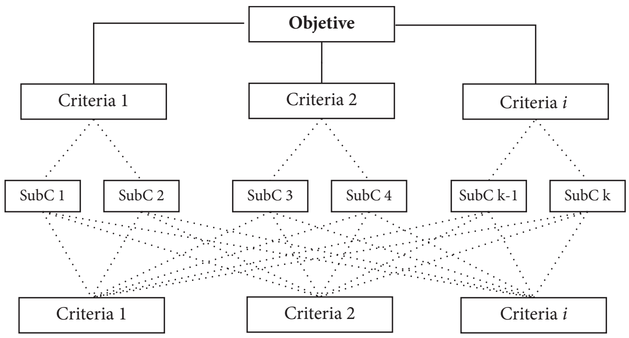

Figure 1: Schematic of an AHP [24].

lower half concerning the diagonal (reciprocal values) correspond to the inverse values of the upper half ($a_{ji} = 1/a_{ij}$), where $a_{ij} = 1$ when $i = j$.

$$A = a_{ij} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & 1 \end{bmatrix}. \quad (1)$$

In the comparison matrix A, the columns represent the relative weights of each factor with respect to the others. To determine the factor of highest preference, for a certain criterion, the values are normalized by dividing each element of column j by the sum of all the elements of that column (equation (2)), and then weights vector called a "priority vector" is estimated by averaging each row of the normalized matrix (equation (3)). This vector indicates the relative importance of each factor in a range between 0 and 1.

$$\mathbf{X_{ij}} = \frac{\mathbf{a_{ij}}}{\sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{a_{ij}}}, \quad (2)$$

$$\mathbf{W_i} = \frac{\sum_{\mathbf{j=1}}^{\mathbf{n}} \mathbf{X_{ij}}}{\mathbf{n}}. \quad (3)$$

The next step is to calculate all consistency coefficients. The original preference matrix of the 139 criterion is multiplied by the respective criterion priority vector in the following equation:

$$\begin{bmatrix} 1 & a_{12} & a_{13} \\ a_{21} & 1 & a_{23} \\ a_{31} & a_{23} & 1 \end{bmatrix} \times \begin{bmatrix} W_1 \\ W_2 \\ W_3 \end{bmatrix} = \begin{bmatrix} Cv_1 \\ Cv_2 \\ Cv_3 \end{bmatrix}. \quad (4)$$

Each element of the vector obtained above is divided by its corresponding value (at the same position) in the priority vector of the criterion under analysis. As a result of the operation, the λmax is obtained as the average of the terms of the previous vector in the following equation:

$$\boldsymbol{\lambda}_{\mathbf{max}} = \frac{\sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{Cv_i/W_i}}{\mathbf{n}}. \quad (5)$$

Next, the consistency index (CI), which reflects the consistency of a decision-maker's judgments, is calculated using the following equation:

$$\mathbf{CI} = \frac{\boldsymbol{\lambda}_{\mathbf{max}} - \mathbf{n}}{\mathbf{n-1}}. \quad (6)$$

The consistency ratio (CR) is then calculated with equation (7), indicating the consistency of each matrix: if CR = 0, the matrix is consistent; if CR ≤ 0.1, the matrix has an acceptable inconsistency; if CR > 0.1, the matrix has an unacceptable inconsistency, and paired comparisons must be reevaluated. The consistency index (IA) of a random matrix of order n is obtained depending on the size of the matrix (n) (Table 3) [24].

$$\mathbf{CR} = \frac{\mathbf{CI}}{\mathrm{IA}}. \quad (7)$$

Finally, the global weight vector (equation (8)) is obtained, which indicates the overall priority of each alternative, by multiplying the vector matrix of local weights by the vector of weights of each criterion. This vector indicates the relative priority of all alternatives from the worst evaluated (lowest value) to the best evaluated (highest score).

$$\text{Vector global weights} = (\text{vector matrix global weight}) \times (\text{vector weights criteria}). \quad (8)$$

3.1. Consolidation of Responses. Since the AHP technique allows for multiple valuations, it is necessary to create a consolidated valuation matrix. Often, reaching a consensus among the experts involved is challenging, requiring the synthesis or resolution of conflicting judgments. This process involves comparing pairs of alternatives based on specific criteria. Each expert provides individual judgments by comparing one alternative (e.g., A) with another (e.g., B) according to the given criteria. These individual judgments must then be synthesized into a single judgment.

When experts make comparisons between two components, they assign ratios as values. If an individual compares the second object (B) to the first (A), this ratio must be replaced with its reciprocal. It is logical to assume that this reciprocal should also be used in the synthesized judgment. Therefore, a method is needed to establish a rule for group judgment that maintains this reciprocal property.

Based on the aforementioned explanation, a new response matrix is calculated as the geometric mean of the original matrices [26] provided by the experts (Figure 2).

Table 2: The Saaty scale.

Saaty's scale	Definition	Explanation
1	Equally important	Two activities that contribute equally to the objective
3	Weakly important	Experience and judgment slightly favor one element over the other
5	Something important	Experience and judgment strongly favor one element over the other
7	Strongly important	One element is very dominant over the other
9	Absolutely important	The evidence favoring one element over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between two adjacent scales	They are used as a compromise between two judgments

Table 3: Consistency index scale.

n	IA
1	0
2	0
3	0.525
4	0.882
5	1.115
6	1.252
7	1.341
8	1.404
9	1.452
10	1.484
11	1.513
12	1.535
13	1.555
14	1.570
15	1.583
16	1.595

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{mn} \end{bmatrix} \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{m1} & c_{m2} & \cdots & c_{mn} \end{bmatrix}$$

$$\begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ d_{m1} & d_{m2} & \cdots & d_{mn} \end{bmatrix}$$

$$d_{11} = \sqrt[3]{a_{11} \times b_{11} \times c_{11}}$$

Figure 2: Response matrix consolidation process.

With this consolidated comparison matrix, the entire process, starting from equation (1), is carried out in a similar manner. The final result will be a vector referred to as the priority vector of the alternatives, which constitutes the solution to the problem.

4. Materials and Methods

Considering the complexity of decision-making and the numerous factors involved in agricultural production processes, the aim was to identify the optimal alternative among various activities involved in potato preparation and cultivation. This study focused on an agricultural production unit comprising small farmers, taking into account the land's agricultural potential to ensure long-term stability and sustainability. Figure 3 illustrates the proposed methodology.

4.1. Identification and Selection of the Study Area. The problem of Boyacá lies in the rural sector, where most of its population is categorised as smallholders who present difficulties in access to productive factors since they depend entirely on the income of their productive units, such as self-consumption and the supply of competitive local and regional markets, to cover markets at the national and international levels. Although there are some products that have high production volumes, the lack of specialisation and planning of this activity is evident; furthermore, there is a shortage of labour and abandonment of the countryside by the young population.

In Boyacá, there are multiple variables by which the price of the potato in the market can vary, resulting in minimum profit margins or even losses at the end of operations for the peasant producers.

Another factor involved in this problem is linked to potato imports in Colombia, which show an annual growth trend [27]. Colombian farmers have a great disadvantage with respect to foreign producers because most smallholders and small producers do not possess sufficient training and technical assistance, and their products often do not comply with plant health requirements.

Having a low quality of land, in turn, generates a low quality of crop, which is one of the factors that produce constant variation in the price of the potato [28].

The lands can be grouped into eight agrological classes according to their characteristics. Class number one groups land with ideal conditions for agricultural production, and as land presents fewer conditions for cultivation, its class number increases to be grouped into class eight, which is considered only suitable for the preservation of wildlife and natural resources [29].

There are no lands with agricultural classes 1 and 2 in Boyacá, which means that the production process of agriculture must be carried out with practices that conserve the condition of the soils to avoid degrading or eroding them and losing its fertility to produce the crop. It should be noted that the department of Boyacá is 70% mountainous, with the rest of the territory composed of soft reliefs [29].

Agriculture is the activity that generates most employment in the department of Boyacá; however, agriculture is carried out in a traditional way that does not allow farmers to obtain all the potential that the land of this area can provide; therefore, this leads to decreased yields, affects the quality of the land, and makes the crops more prone to pests and diseases. One of the main causes of this is the smallholder model of land tenure that is managed in the area, since these small producers rely on their empirical and traditional knowledge to produce their crops/smallholders represent the largest population of farmers in the department [5].

Based on the above, it is important to focus the problem on this category of producers, the smallholders, because this is where the problems regarding potato prices, soil erosion, and low productivity lie and where, therefore, there is great possibility for improvement. As this is an important issue for Boyacá, this paper seeks to generate improvement in the area that represents greater production of this crop and falls under this category of farmers. The area chosen in this grade work that meets the guidelines of the problem and with the facility to obtain information is the municipality of Ventaquemada.

4.1.1. General. Ventaquemada is a Colombian municipality located in the Province of Centro, in the department of Boyacá. The territorial extension of the Municipality of Ventaquemada is 159.32 km^2, of which 99.68%, or

Objective:
To determine the set of alternatives that, according to the selected experts, best align with the decision criteria, which emphasize enhancing crop productivity, improving the quality of the harvested product, and addressing soil overuse in the municipality of Ventaquemada, Boyacá.

Steps	Activities
Identification and selection of the study area:	• Characterization of the study area • Identify land use aptitude in the study area
Identification and selection of alternatives:	• Determine agroclimatic conditions • Definition and characterization of possible alternatives
Identification and Selection of Criteria:	• Definition of criteria and sub-criteria • Characterize the criteria and sub-criteria • Validation of selected criteria with experts
Expert judgment:	• Identification and location of experts • Application of surveys
Multi-criteria decision analysis – AHP:	• Processing of results • Test with the coefficient of consistency. • Allocation of weights to criteria and sub-criteria

Outputs:
Define alternatives to improve crop productivity, the quality of the harvested product, and reduce the impact on land use in the municipality of Ventaquemada, Boyacá

Figure 3: Methodological strategy for the implementation of AHP.

158.82 km^2, corresponds to rural areas, and 0.32%, equivalent to 0.50 km^2, corresponds to urban areas [30]. Ventaquemada is determined in areas where the soils (sandy loam) have high organic properties, on flat and/or gently sloping terrain (0–12%), with conditions suitable for agricultural activities.

4.1.2. Temperature. The temperature in the region, considering the data of Nuevo Colón station, fluctuates by 12.0°C in the minimum annual average monthly temperature, with an average annual value of 14.4°C and a maximum of 16.5°C per year. The municipality is located between the cold thermal floors and the paramo [30].

4.1.3. Precipitation. The precipitation in Ventaquemada shows great heterogeneity despite the altitudinal location of the seasons; in the area, the unimodal regime includes rainy periods in the months of June and July, followed by a significant drop in rainfall in August and September that increases slightly in October, and, finally, a low rainfall season between the months of November and March [30].

4.1.4. Agriculture Sector. The municipality of Ventaquemada stands out for its agricultural vocation, where most production systems are traditional. The potato is the main agricultural product and economic source, occupying second place at the national level. Other crops that stand out in the municipality are carrots, peas, bulb onions, beans, traditional corn, and uchuva. In addition, the municipality has microenterprises dedicated to the processing of precooked potato production and dairy processing [30].

The municipality has a coverage associated with agricultural production, mainly based on the presence of transitional crops whose vegetative cycle is usually less than one year, even only a few months, and permanent arable crops. Potato cultivation is the main source of rural employment in the municipality. Approximately 2,800 farmers live from this product, and approximately 5,000 hectares are planted with potato with a production close to 100,000 tons per year [30].

The planting seasons are framed by the rainy season. The two large sowings are performed in two periods, the first in the months of February and March, called the big year, and the second in the month of June. Other sowings are performed on a smaller scale throughout the year. The two varieties that are most cultivated are the "pastusa superior" for fresh consumption and the "Diacol Capiro (R12)" for industrial processes. This crop is rotated with pastures or carrots in their great majority in the high areas of the municipality and in the lower part with pastures, corn, beans, peas, and arracacha [30].

4.1.5. Hydrography. The water basins corresponding to the municipality of Ventaquemada are the subbasin of the Ventaquemada River, the microbasin of the Albarracín River, the subbasin of the Teatinos River, and the microbasin of the Cortadera Ravine [30].

4.1.6. Land Use. The lack of regulation of land use at the municipal level is a problem with serious complications that negatively affects the ecosystem and soils (e.g., expansion of the agricultural belt, sown in inadequate heights, and deterioration of the moors, quarries, and others).

With regard to the agricultural frontier, one evident problem is that they are planted according to particular needs. This situation continues affecting water cover sites and altering environmental factors specific to the municipality, given that the paramo soils are susceptible to degradation by overuse. Ventaquemada presents soil loss due to erosion and mass removal processes, reduction of arable areas, contamination of the landscape, and impoverishment of the inhabitants [31].

4.2. Identification and Selection of Alternatives. Cultivation was carried out, taking as a focus the activities or procedures that entail a choice of possible alternatives. Assistance was obtained from an expert in the field to validate the group of selected alternatives and their importance.

The resulting activities were as follows:

(1) Choice of seed type
(2) Selection of type of tuber disinfection
(3) Selection of tuber weight
(4) Choice of tuber size
(5) Selection of irrigation system
(6) Selection of seeding depth
(7) Type selection of tillage

4.3. Selection of Type of Tillage. Tillage is the operation of agriculture that consists of drawing furrows moderately deep in the ground with a hand tool or with a plough. Among the functions of tillage, we consider facilitating the circulation of water for proper irrigation, destroying weeds, making the soil less compact, improving the structure and texture of the soil, and avoiding stagnation.

The alternatives for this activity are as follows:

(1) Conventional tillage: Involves the intensive use of disc attachments such as rakes, rakes, and polishers that seek to remove the surface from the ground. The number of passes ranges from 4 to 8, which can cause annual soil losses of 10 t/ha, compaction, and soil degradation [32].
(2) Reduced tillage: This consists of reducing the work of preparing the soil for sowing a crop or pasture [32].
(3) No-till or no-till seeding: No-till means seeding that is done directly in soils, without the need to remove it or remove the stubble that covers it. It is important to eliminate weeds [33].
(4) Manual tillage: In this technique, only the manual tool "azadón" is used to form crop rows with minimal soil disturbance [34].

4.4. Selection of Irrigation System. Through an irrigation system, water is supplied to a cultivated area; this resource meets the water needs of plants that are not solely covered by precipitation.

The alternatives for this activity are as follows:

(1) Drip: In the drip irrigation system, the water is distributed in a localised manner by droplets through droppers installed in drip hoses, small reservoirs (gallons, bamboo, etc.), or distribution pipes [35].
(2) Microsprinkling: The microsprinkling irrigation system is a modification of the traditional sprinkling system that allows water to be sprayed within walking distance of the plant and localised [35].
(3) Spraying: In the sprinkler system, water is distributed through sprinklers, which produce water droplets of different sizes, imitating natural rainfall [35].

4.5. Selection Type of Tuber Disinfection. The disinfection system consists of applying treatments to the potato seed to eliminate pathogens, mainly fungi and bacteria, that can affect its germination and development capacity.

The alternatives for this activity are as follows:

(1) Dusting: This consists of the application of powdered products on the tubers. Several application techniques have been adapted to potato cultivation [36].
(2) Spraying: Application of a product in liquid form to the planting path [36].
(3) Immersion: This involves immersing the seed in a solution or suspension for a time that depends on the type of seed and the product used [37].

4.6. Choice of the Tuber's Physical Appearance. This activity consists of the choice of the seed to be sown concerning its physical appearance, that is, the size and weight of the tuber, which is understood as the size or the diameter of the seed.

The alternatives for this activity are as follows:

(1) Small: Includes tubers measuring between 30 and 60 millimetres in diameter and 20 to 59 grams in weight [38].
(2) Large: Includes tubers measuring more than 60 mm in diameter and weighing more than 59 grams [38].

4.7. Identification and Selection of Criteria. In the same way, the identification of alternatives was started by understanding the stages involved in the production of potato cultivation or what is called the productive cycle of potato cultivation. This cycle is divided into six stages that range from the planning of the crop to its respective commercialisation in the market as shown in Figure 4.

According to the literature review and the steps mentioned above, the factors identified at the social, technical, economic, and environmental levels have considered 56 variables that are grouped into 13 subcriteria and 6 criteria as shown in Table 4.

Considering the stages of the crop production chain, the characteristics of the selected criteria are presented in Table 5.

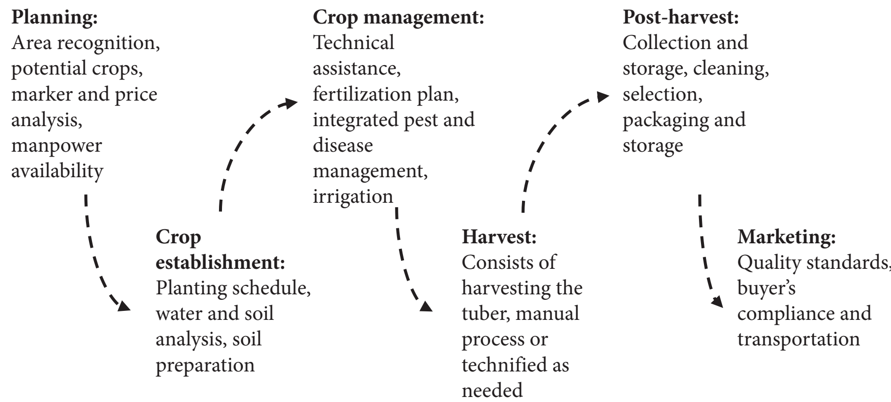

Figure 4: Stages of the potato crop production cycle, adapted from [39].

4.8. Selection of Experts. Most of the authors agree that in multicriteria techniques, a decisive point of the process that takes place in this type of methodology is the correct selection of the panel of experts. For example, Goluchowicz and Blind [40] state that the process of selecting experts is more important than other aspects when applying a Delphi method (a quality decision-making technique based on the opinion of a group of experts) since the quality of the results of the process depends to a large extent on the expertise of its participants.

Understanding the great importance of a correct selection of the panel of experts, a group of three people was selected who have experience as potato growers in the municipality of the study, have university degrees related to the agricultural field, belong to or have been part of groups or associations associated with potato cultivation and have participated in projects related to the agricultural sector of the department.

5. Results and Discussion

5.1. Criteria Results. Following the implementation of the AHP, the ranking of preferences by the experts involved is extracted from the priority vector of the standard criteria matrix. Group 1 is associated with AHP for tillage and irrigation, while Group 2 is associated with physical appearance and disinfection. The latter contains four criteria because the alternatives of these AHPs do not apply to be evaluated against the total selected criteria.

For the criteria of Group 1, the water resource criterion was prioritised with 46.63%, which is the highest score over the second criterion, soils, with 17.21%, indicating a clear preference of the group of experts towards environmental aspects, leaving little priority to the criteria directly involved with the crop.

For Group 2 criteria, a preference was obtained for the criterion "phytosanitary risk" with a value of 36.64%, followed by the criteria "implementation costs" and "crop quality," which presented fairly similar results. This suggests that experts do not perceive a clear preference between one and the other; finally, the fourth position was the criterion "Crop yield," with a preference value of 14%.

5.2. Alternative Results. For farming alternatives, the winning result was the conventional tillage method with a 38.68% priority, followed by reduced tillage with 31.41%, then no-till with 19.94%, and finally manual tillage with 9.97%. In conclusion, there is a clear preference for less invasive tillage methodologies for the soil.

For the alternatives of physical appearance, the winning result was the large seed tuber with 56.53% priority over the small seed tuber, which obtained a result of 43.47%. Regarding disinfection alternatives, it is noted that experts do not have a clear preference between the alternatives of immersion and dusting, which obtained priority levels of 38.15% and 37.27%, respectively. Finally, there was the alternative of sprinkling with a 24.58% priority.

For irrigation alternatives, the winning result was the drip method with a 70.53% priority, which reflects a very strong preference on the part of the experts consulted, followed by microsprinkling with 17.60%, and finally spraying with 11.80%.

Finally, based on the knowledge of the experts and the results obtained, it can be concluded that applying a reduced tillage technique, the immersion method for the disinfection of the seed, drip as an irrigation system for cultivation, and making use of large seed size is conducive towards efficient programming of potato cultivation in the area of Ventaquemada, Boyacá. These techniques will improve crop productivity, the quality of the harvested product, and the problem of overuse of the soil, which were the aspects identified as the objectives of the criteria involved in the selection of the AHP tool.

6. Discussion

An extremely important aspect of developing the methodology successfully with effective results in studies of this type is the characterisation of the area and the context in which the research is carried out, which helps to correctly determine the most relevant criteria and variables to be treated and generates greater reliability in the study since the results obtained will be more accurate.

The success of implementation and the correct results in ranking methodologies will also depend to a large extent on the human resources involved, which is why special attention

Table 4: Identification and selection of criteria.

Variables		Preliminary criteria	Selected criteria
(i) Relative humidity-Hibert (ii) Temperature-Hibert (iii) Andean weevil, Premnotrypes vorax (Hustache) (iv) Guatemalan moth (*Tecia solanivora*) (v) Precipitation-Hibert (vi) Precipitation-moth (vii) Hibert (*Phytophthora infestans*)		(i) Exposure to pests and diseases (ii) Transmission of pests and diseases	Soils
(i) Soil type (ii) Soil depth (iii) Soil texture (iv) Soil fertility (v) Temperature control (vi) Lighting control (vii) Control of hygrometric degree (viii) Stony (ix) Natural drainage (x) Elevation	(i) Pending (ii) Precipitation (iii) Altitude (iv) Soil organic carbon (v) Total soil nitrogen (vi) Acidity-pH (vii) Salinity and sodicity (viii) Cation exchange capacity (ix) Base saturation (x) Aluminium saturation	(i) Land erosion (ii) Nutrient conservation	Plant health risk
(i) Financial capacity of the family (ii) Accessibility to agricultural equipment (iii) Working income (iv) Ability to sell the product (v) Poverty rate (vi) Availability of labour force	(i) Access to information (ii) Agricultural skills (iii) Seed (iv) Use of plant regulators and special substances (v) Fertilisers (vi) Fuel	(i) Inputs (ii) Workmanship (iii) Machinery	Cost of implementation
(i) Price of municipal rural land (ii) Size of the rural land (iii) Districts of land adaptation (iv) Crop existence (v) Distance between seeds (vi) Distance between grooves		(i) Amount of land used (ii) Quantity of potatoes harvested	The yield of the crop
(i) Resistance to climatic conditions (ii) Nutrient absorption (iii) Tuberculous shape (iv) Tuberculous size (v) Tuberculous colour (vi) Tuberculous weight		(i) Potato quality (ii) Plant quality	Quality of the crop
(i) Consumption use (ii) Index of water use (iii) Water accessibility (iv) Number of nearby water sources (v) Use of chemicals		(i) Water consumption (ii) Water pollution	Water resource

Table 5: Characteristics of the criteria selected.

Criterion	Nature	Description	Objective
Soils	Technical	This refers to soil care, relevant aspects such as the erosion that directly affects the soil by decreasing the yield of the crop and conservation	To mitigate the overuse of the soil
Plant health risk	Technical	This refers to the risk of transmitting and/or transporting pests in the crop	To reduce the risk of transmitting and/or transporting pests in the crop
Cost of implementation	Economic	This refers to the cost generated in the production process of potato cultivation, factors such as inputs, labour, and machinery used are considered	To reduce the costs generated in the production process
The yield of the crop	Technical	This refers to the ratio of the total production of the crop harvested per hectare of land used. It is usually measured in metric tonnes per hectare (t/ha)	To evaluate the alternative that generates a greater yield in the crop
Quality of the crop	Technical	This refers to characteristics of the tuber such as its shape, size, depth of eyes, and resistance to pests or pathogens inhabiting the soil, among others. In addition, the content of reducing sugars, starch, and protein in tubers	To improve the quality of the crop harvested
Water resource	The environment	This refers to the amount of water used in the production process of potato cultivation	To reduce the amount of water used in the production process of potato cultivation

should be given to the process of introducing and training the staff who will be involved in this process. This process should be able to motivate staff and generate the necessary commitment to implement hierarchy methodologies efficiently.

In addition, according to what has been observed in the literature and in practice itself on the development of this type of methodology, for future research, it may be advisable to have a greater number of experts who maintain the profile and a level of expertise as presented in the development of this work and with the willingness to collaborate with the study to prevent and/or deal with various inconveniences that may arise.

In this model, agronomic factors such as fertilization, the variety of potato crops (taking into account that there are up to 25 types in the region), and the quality of irrigation water were not considered. However, these factors could be taken into account in future work by complementing the model with the specific characteristics of each of these criteria. This could even involve integration with quantitative variables, not relying solely on expert judgments.

7. Conclusions

The proposed methodology provides a feasible solution to the problem of the soil used in potato cultivation in the department of Boyacá. This valuable tool determines alternative solutions, considering the complexity of the problem and the associated context.

On this occasion, the approach was used to select alternative solutions that could apply to the region under assessment, which implies adhering to the possibilities and traditions of the research segment, taking into account those alternatives that would probably be applied by the micro-units, which are preestablished by their planting culture.

The AHP is a fairly flexible tool. Considering the scope of the research, it can be extended as much as there are resources to develop it; it can be synthesized as well, if necessary. However, it is important to make clear that a larger study should be carried out that envisages many more alternatives and provides a more complete result that promotes a cultural change in planting for better cultivation and soil conservation.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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