Genetic algorithms-based fuzzy analytical hierarchical process (GA-FAHP) for evaluating biofortified crop promotion strategies

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In developing nations such as India, malnutrition is a major nutritional and health challenge. Biofortification has the potential to be an effective instrument in India's attempts to combat malnutrition. Expert opinion must be used to evaluate the factors related to the promotion, distribution and adoption of biofortified crops. The analytical hierarchy process (AHP) is one of the most often employed decision-making methods. However, conventional AHP is incapable of identifying ambiguity in human judgements. Fuzzy AHP has already been devised to overcome this limitation. Fuzzy AHP necessitates information in pairwise comparisons, which is not always easy to gather. In this context, the Fuzzy AHP technique based on the genetic algorithm has been proposed, which can compute the priority weight without using a pairwise comparison matrix by directly dealing with expert-provided data. The proposed approach has been illustrated using the opinions of 1600 farmers from Odisha, India.

Keywords: Biofortified crops, fuzzy AHP, genetic algorithm, malnutrition.

MALNUTRITION is one of the most significant nutritional and health concerns in developing nations like India, resulting in poor health, stunted growth and lower mental capacity, all contributing to decreased productivity and lifetime earnings. In India's efforts to reduce malnutrition, biofortification has the potential to be a valuable strategy. The global community has acknowledged the importance of biofortified crops in treating micronutrient deficiency[1]. However, there have been concerns over the marketing, distribution and consumption of biofortified crops and commodities by vulnerable households. To rate the parameters associated with the promotion, distribution and adoption of biofortified crops, expert opinion must be utilized.

Expert opinion-based decision-making is a complicated process due to inherent differences. Multicriteria group decision-making (MCGDM) models are frequently constructed to quantify the choice of a group of experts. The purpose of the MCGDM model is to select the optimal option or to rank many alternatives. The analytical hierarchy process (AHP)[2] is among the most often utilized decision-making techniques. AHP is a utility-based MCGDM technique that deconstructs the problem from higher to lower levels of hierarchy to integrate the perspectives of decision-makers. After constructing the hierarchical structure, a pairwise comparison of two variables is performed. AHP can consider the intangible parts of any decision-making procedure. There are several captivating examples of AHP application in diverse domains, such as developing a knowledge asset value creation map for industry[3], selecting weapons for a defence system[4], assessing flood risk[5], landslide hazard assessment for disaster planning and management[6], identification of potentially important plant areas (IPAs)[7], etc.

Despite the obvious benefits, conventional AHP cannot detect ambivalence in human judgements. Several researchers have developed fuzzy AHP by combining fuzzy logic with AHP to avoid this shortcoming. The fuzzy AHP model was used to identify influential factors in building successful Internet of Things (IoT) systems for IoT-related enterprises[8], evaluating hospital service quality[9], mapping groundwater potential[10], developing a conceptual model for the software industry[11], identifying the location of a solid waste dumping site[12], etc. AHP and fuzzy AHP are constrained to require information in pairwise comparisons. For ease of usage, linguistic-ordinal data were collected instead of a pairwise comparison matrix. Consequently, techniques for constructing such matrices during the analysis phase are required so that ranking can still be executed.

Genetic algorithm (GA) is a stochastic search method that draws inspiration from the fundamental concepts of biological evolution and natural selection. By simulating the biological mechanisms of evolution, such as selection, crossover and mutation, GA replicates the evolution of living species, where the fittest individual dominates over the weaker ones. A good account of GA is given in Goldberg[13]. In this regard, the fuzzy AHP technique based on the GA has been proposed in this study, which may compute the priority weight by directly dealing with expert-provided data without using a pairwise comparison matrix.

The proposed method was used to rank the factors associated with the promotion, diffusion and adoption of biofortified crops based on feedback from farmers. The present article discusses materials and processes, empirical exemplification of the proposed GA-based fuzzy AHP to rank the factors related to the promotion, dissemination and uptake of biofortified crops, followed by pertinent conclusions.

Using the ideas of Wittkowski *et al.*[14], a pairwise comparison matrix was constructed. The approach is described in detail below.

Step 1: Assume that there are n factors ($c_1, c_2, ..., c_n$) for achieving a certain objective. If there are N experts in total, the table indicated (Table 1) must be constructed.

Thus according to Table 1, the n_{11} experts ranked c_1 as less important, n_{12} experts rated it as important, and n_{13} experts assessed it as more important.

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Step 2: The score is then computed in accordance with Table 2.

Step 3: The fuzzy comparison matrix is constructed per Table 3.

The following rule was employed to convert the relative score of the matrix into a fuzzy number.

Relative score	Fuzzy scale
Undermined or ≤ 0.10	(1, 1, 1)
0.11–0.20	(1, 2, 3)
0.21–0.30	(2, 3, 4)
0.31–0.40	(3, 4, 5)
0.41–0.50	(4, 5, 6)
0.51–0.60	(5, 6, 7)
0.61–0.70	(6, 7, 8)
0.71–0.80	(7, 8, 9)
≥0.80	(8, 9, 10)

Step 4: Using a fuzzy optimization approach, the weights parameters of the fuzzy comparison matrix were then computed. The following is a description of the approach.

The resulting fuzzy pairwise comparison matrix is displayed below

$$\tilde{A} = \{\widetilde{a_{ij}}\}_{n\times n} = \begin{bmatrix} (1,1,1) & (l_{12}, m_{12}, u_{12}) & \cdots & (l_{1n}, m_{1n}, u_{1n}) \\ (l_{21}, m_{21}, u_{21}) & (1,1,1) & \cdots & (l_{2n}, m_{2n}, u_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ (l_{n1}, m_{n1}, u_{n1}) & (l_{n2}, m_{n2}, u_{n2}) & \cdots & (1,1,1) \end{bmatrix}, \quad (1)$$

where $l_{ij} = 1/u_{ji}$, $m_{ij} = 1/m_{ji}$, $u_{ij} = 1/l_{ji}$ and $0 < l_{ij} \le m_{ij} \le u_{ij}$ for all $i, j = 1, 2, \ldots, n$; $j \ne i$. The following membership function can be used to generate a weight vector $\overline{W} = (w_1, w_2, \ldots, w_n)$

$$\mu_{ij}(w_i / w_j) = \begin{cases} \dfrac{(w_i / w_j) - l_{ij}}{m_{ij} - l_{ij}}, & \dfrac{w_i}{w_j} \le m_{ij} \\ \dfrac{u_{ij} - (w_i / w_j)}{u_{ij} - m_{ij}}, & \dfrac{w_i}{w_j} \ge m_{ij} \end{cases} \quad (2)$$

where $\mu_{ij}(w_i/w_j)$ is the membership degree of w_i/w_j belonging to the fuzzy judgement $\widetilde{a_{ij}} = (l_{ij}, m_{ij}, u_{ij})$.

Let

$\delta = \min(\mu_{ij}(w_i/w_j) | i = 1, 2, \ldots, n-1; j = 1, 2, \ldots, n+1\}$.

Then, δ is the minimum membership degree to which the crisp priority vector satisfies each fuzzy pairwise comparison. Crisp priority vector refers to a vector that contains a set of numerical weights assigned to a set of criteria in a decision-making process. The value of δ should be maximized to enhance the reliability of weight vector. Consequently, the subsequent nonlinear optimization model can be used to derive the weight vector.

Maximize δ subject to

$$\begin{cases} \mu\left(\dfrac{w_i}{w_j}\right) \ge \delta, i = 1, 2, \ldots, n-1; \; j = i+1, \ldots, n \\ \sum_{i=1}^{n} w_i = 1, \\ w_j \ge 0, i = 1, 2, \ldots, n \end{cases} . \quad (3)$$

Which can be represented equivalently as

Maximize δ subject to

$$\begin{cases} -w_i + l_{ij} w_j + \delta(m_{ij} - l_{ij}) w_j \le 0, i = 1, 2, \ldots, n-1; \\ \quad j = i+1, \ldots, n \\ w_i - u_{ij} w_j + \delta(u_{ij} - m_{ij}) w_j \le 0, i = 1, 2, \ldots, n-1; \\ \quad j = i+1, \ldots, n \\ \sum_{i=1}^{n} w_i = 1, \\ w_i \ge 0, i = 1, 2, \ldots, n \end{cases} . \quad (4)$$

In this study, weight parameters were computed using the GA approach by maximizing the δ for eq. (3) considering the constraints of eq. (4). The following is a summary of the GA approach.

Table 1. Information from experts

Factors	Less important	Important	More important	
c_1	n_{11}	n_{12}	n_{13}	$n_{11} + n_{12} + n_{13} = N$
c_2	n_{21}	n_{22}	n_{23}	$n_{21} + n_{22} + n_{23} = N$
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
c_n	n_{n1}	n_{n2}	n_{n3}	$n_{n1} + n_{n2} + n_{n3} = N$

Table 2. Computation of score

$N = a_1$	$N^2 = a_2$	$N^3 = a_3$	Score
$n_{11} \times a_1$	$n_{12} \times a_2$	$n_{13} \times a_3$	$z_1 = n_{11}a_1 + n_{12}a_2 + n_{13}a_3$
$n_{21} \times a_1$	$n_{22} \times a_2$	$n_{23} \times a_3$	$z_2 = n_{21}a_1 + n_{22}a_2 + n_{23}a_3$
.	.	.	.
.	.	.	.
.	.	.	.
$n_{n1} \times a_1$	$n_{n2} \times a_2$	$n_{n3} \times a_3$	$z_n = n_{n1}a_1 + n_{n2}a_2 + n_{n3}a_3$

Table 3. Construction of matrix

	c_1	c_2	.	.	.	c_n
c_1	1	z_2/z_1	.	.	.	z_n/z_1
c_2		1				z_n/z_2
.			.			.
.				.		.
.					.	.
c_n						1

Step 1: Set the fitness function. In this research, the fitness function maximised δ based on the constraints specified in eq. (4).

Step 2: Initialization. The GA approach generates a population of individuals for the parameters of the fuzzy AHP model, where each weight symbolizes an individual. In the population, distinct 'sets' of solutions exist. Each set of solutions accommodates (weights in our research) chromosomal individuals. The convergence of a GA towards an optimal solution relies on the population size.

Step 3: Selection. Preselected chromosomes from the current population are introduced into the mating pool to produce the following generation's offspring. If the fitness parameter is large, the probability that a chromosome will contribute one or more offspring to the next generation is high (i.e. higher the δ). After rating population fitness and associated chromosomes from highest to lowest, the best chromosomes are picked for continuation. A segment of the population is picked at random for the subsequent round of mating.

Step 4: Crossover rate and mutation rate. Crossover operation is utilized to produce new progeny. The crossover rate is the probability that a chromosome will undergo a crossover. The mutation operator is responsible for altering chromosomal genes. Mutation is accomplished by exchanging the locations of two groups of chromosomes. Moreover, it prevents the GA search from achieving local optima.

Step 5: Termination. The termination of GA relies on the convergence criterion, such as when the maximum number of generations has been reached or when the desired fitness value has been acquired.

Focus group discussions with subject area experts, research of the relevant literature, and brainstorming all led to a variety of strategies. The strategies were graded according to linguistic criteria (less important, important and more important). Based on the International Food Policy Research Institute's (IFPRI) District Nutritional Ranking, which evaluated 599 districts in India, five districts in Odisha state were chosen (four nutritionally poor districts and one nutritionally affluent district as a control district). Then, 1600 farmers were selected at random from the five districts to evaluate the strategies. Data collection took place in the year 2021. Table 4 displays the attributes of the food we consumed (biofortified crops).

According to farmers, pleasant, affordable and pleasurable food is more important than nutritious and healthy food from a consumer's perspective. Table 5 lists the factors that limit the adoption of biofortified crops.

From Table 5, it can be deduced that the lack of available seeds is not the greatest obstacle. However, the adoption of biofortified crops is hampered by a lack of farmers' understanding, uncertainty about market prices, and probable consumer resistance. Table 6 shows the decision-making factors for the cultivation of biofortified crops.

Table 4. Attributes of the food that is consumed (biofortified crops)

Attribute	Fuzzy AHP weight
Nutritious and healthy	17.57
Tasty	27.27
Affordable	26.94
Mood lifting and pleasurable	28.22

Table 5. Factor constraints for adoption of biofortified crops

Factor	Fuzzy AHP weight
Non availability of seeds	14.29
Lack of farmers' awareness	21.59
Non assurance of market prices	21.53
Not sure of consumer acceptance	21.07
Any other	21.53

Table 6. Factors for decision-making for cultivation of biofortified crops

Factors	Fuzzy AHP weight
Family support	9.35
Availability of seeds	11.67
Cost of inputs	11.21
Price in market	11.39
Can be used in traditional diet	11.43
No specific change in colour, texture, flavour	11.26
Sufficient knowledge of nutrition	11.19
Sufficient knowledge of package practices for biofortified varieties	11.30
Any other	11.19

Table 7. Biofortified foods promotional strategies

Factor	Fuzzy AHP weight
Yield	10.44
Pest resistance	12.91
Additional benefit of nutrition and health for self and family	12.40
Ease of use	13.01
Quality	12.40
Fits into existing farming system	10.44
Good health for self and family members	12.91
Utility/usefulness	12.40

Table 8. Consequences of important factors related to biofortified crops

Factor	Fuzzy AHP weight
Being up-to-date of new value added varieties	13.46
Saving money on deficiency diseases	16.96
Stimulation	17.72
Having common good in mind	16.79
Contributing to nutrition and health for all	16.79
Status, prestige	18.28

Table 9. Level of preference of biofortified crops by farmers

Crop	Fuzzy AHP weight
Rice	18.74
Wheat	26.13
Bajra	25.57
Sweet potato	29.56

Table 10. Willingness to grow biofortified crops

Condition	Fuzzy AHP weight
I will ONLY grow or consider growing biofortified crops if the seeds are cheaper than the conventional ones	18.59
I will ONLY grow or consider growing biofortified crops if the seeds are more or less the same price as conventional crops	26.85
I will grow or consider growing biofortified foods EVEN if they are slightly more expensive than conventional crops	28.98
I will grow or consider growing biofortified crops food EVEN if they are significantly more expensive than conventional crops	25.58

The factors listed in Table 6 impact pretty much equally the cultivation of biofortified crops. Table 7 lists the factors of biofortified food promotion strategies.

According to the viewpoint of farmers, the most important aspect of biofortified food-promoting techniques is their usability. In addition, pest resistance, additional nutritional and health benefits for the farmer and his family, quality, compatibility with the existing farming system, and utility/usefulness are essential factors. However, yield is the least significant factor among the promotional strategies for biofortified foods. Table 8 lists the consequences of important factors related to biofortified crops.

According to the farmers' perspective, status, prestige and stimulation are the most significant implications of biofortified crops. Table 9 classifies the biofortified crops based on the level of farmers' preference.

As per Table 9, the majority of farmers are inclined to cultivate biofortified wheat, bajra, and sweet potatoes. Whereas only a few are willing to cultivate biofortified rice. Table 10 outlines the conditions farmers are willing to cultivate biofortified crops.

From Table 10, it can be deduced that only a small proportion of farmers will consider cultivating biofortified crops if the seeds are cheaper than conventional seeds. The majority of farmers are willing to plant biofortified crops, provided the seed costs are comparable to or slightly higher than those of conventional crops. Even a substantial majority of farmers are willing to consider growing biofortified crops if they are much more expensive than conventional crops. Therefore, it can be safely assumed that the price of biofortified seed will not prohibit the farming community from embracing it.

To sum up, in developing countries like India, malnutrition is a main nutritional and health issue. Biofortification has the potential to be a useful tool in India's battle against malnutrition. In order to examine the aspects associated with the promotion, distribution and adoption of biofortified crops, farmers' inputs are required. However, identifying ambiguity in human judgements goes beyond the capability of conventional AHP. Fuzzy AHP can handle ambiguity in human judgements but requires information in pairwise comparisons, which is not always feasible. Hence, this research proposes a modified fuzzy AHP that can compute the priority weight without employing a pairwise comparison matrix by dealing directly with expert-provided data. In addition, a GA optimization approach has been used to estimate the weights of the proposed fuzzy AHP to increase the precision. The 1600 Indian farmers from Odisha were surveyed to illustrate the proposed method. The findings have important policy implications for the fight against malnutrition. In future studies, model precision can be enhanced by employing alternative optimization techniques, such as particle swarm optimization and the artificial bee colony algorithm.

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