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Research Article

Developed Mathematical FQFD Approach for Enhancing Reliability of Solar Drying Systems

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Abstract

Saffron is the most expensive spice and is significantly valuable in non-oil export. Drying process of saffron is considered as a critical control point with major effects on quality and safety parameters. A suitable drying method covering standards and market requirements while it is costly beneficial and saves energy is desirable. Solar drying could be introduced as an appropriate procedure in rural and collecting sites of saffron since major microbial and chemical factors of saffron can be preserved and achieved by using a renewable energy source. So, a precise system taking advantage of management, engineering and food technology sciences could be developed. Since there was no published record of integrated methods of Analytical Hierarchy Process (AHP) and Fuzzy Quality Function Deployment (FQFD) applied to solar energy drying systems, in the present paper, FQFD as a quality management tool by emphasizing technical and customer requirements has been implemented in order to improve quality parameters, optimizing technological expenses and market expansion strategy. Subsequently, AHP based on survey from customers and logical pair-wise comparison is employed to decrease costs and increase the efficiency and the effectiveness of economic indicators. Using the integrated approach of AHP and FQFD in solar drying systems in saffron industry will result in cost benefit, quality improvement, the customer satisfaction enhancement, and the increase in saffron exports.

Keywords: Solar Energy Drying System; Saffron; Analytical Hierarchy Process; Fuzzy Quality Function Deployment.

Introduction

Saffron spice is dehydrated by stigmas of *Crocus sativus* L. and is the most expensive spice. Inappropriate post-harvest processes such as poor drying process will result in reduced quality parameters. During the long periods of traditional drying enzymatic activity will be high and microbial pollution occurs. Dehydration affects the content of compounds responsible for color, taste and aroma of saffron and also its microbial profile [1]. Not suitable drying may lead to scabbing, hardening of the surface, wrinkling, decline in rehydration ability, browning, surface burning and decreases in flavor and odor [2]. Therefore, a reduction in the post-harvest losses of food products should have a considerable effect on the economy of these countries [3].

It is interesting to note that a large variety of drying systems that are available in the world are based on solar systems and in general, solar drying systems could be designed in direct solar drying (DSD) or indirect solar drying (ISD) types. However, an improved design and adoption of the right solar dryer is a still needed [4]. In the current systems, sunlight collecting sheet, blower pump, drying chamber, side heating system and energy saving system are implemented. Parameters in designing such systems could be defined as relative moisture, the temperature of the drier, air flow rate, environment moisture and temperature, length and width of air tunnel, space and kind of trays and initial and final moisture of the product. Sun light is stored in solar collectors and then warm air flow is pumped to product chamber [5]. Drying a product over "critical moisture content"

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will defect significantly, however insufficient procedure will result in microbial and chemical spoilage [6]. There are lots of researches made on drying foods as an efficient system of utilizing solar energy. Sharma et al. [7] reported solar drying of tomatoes, chilies and mushrooms. Sethi and Arora [8] improved a conventional greenhouse solar dryer of 6 m2 ×4 m2 floor area (east–west orientation) for faster drying using inclined north wall reflection (INWR) under natural as well as forced convection mode. Similar temperature behavior for drying different crops in the greenhouse drying was also presented by Jain and Tiwari [9]. A fiber reinforced plastic (FRP) hybrid solar drying house was effectively used for brown rice drying by Rachmat et al. [10]. Feasibility studies of a solar chimney to dry agricultural products were also performed by Ferreira et al. [11]. Sreekumar [12] investigated the performance of a roof-integrated solar air heating system for drying fruit and vegetables in detail by three methods namely annualized cost, present worth of annual savings, and present worth of cumulative savings. A solar tunnel dryer was used for drying grapes by Muhlbauer [13]. It was reported that the dryer produced high quality dried grapes up to the desired moisture content level.

Many types of solar dryers have been developed during the last two decades; however, the applications of these dryers are still limited, mainly due to their unreliable performance and high investment cost relative to a production capacity [14]. Although Mamlook has used applied fuzzy sets programing to perform evaluation of solar systems in Jordan [15], there was no significant attempt to use integrated approach of AHP and FQFD in solar technology, specifically in solar drying systems for saffron. Thus, the aim of this study is to employ this integrated method to an indirect solar dryer used for saffron to enhance consumer satisfaction. AHP technique which is expanded by Saaty [16] considers a complex system into hierarchical system of elements. It has been used in enormous researches [17-19] for making decision about multi-criteria factors which considers problems in a real situation. In reality, by applying AHP, pair-wise comparisons are made of the elements of each hierarchy by means of a normal value.

Applied Fuzzy QFD technique in the present work, which is based on House of Quality (HOQ), includes CRs and TRs in the area of solar drying systems for saffron in order to find priority of TRs. Moreover, CRs represent customer requirements and appear as ‘’whats’’ in the HOQ, while TRs are listed as ‘’hows’’. Due to the need of prioritizing CRs by AHP to obtain CRs’ priority weight in the process of HOQ, AHP-Fuzzy-QFD as the useful developed method has been utilized to achieve the better status of design and customer satisfaction of solar drying systems for saffron. It is worth mentioning that Fuzzy logic [20] has been also employed to deal with linguistic judgments expressing the relative importance of CRs as well as the relationships and correlations required in the HOQ.

In the present paper, an indirect solar dryer was used for the purpose of this study as shown in Fig. 1. Climatic conditions such as temperature, humidity and solar intensity and nature of the product were some major factors in designing. Multi shelf cabinet dryer was coupled with flat plate solar air heater for air heating. An air collector with air inlet was considered to collect and store the thermal energy of sunlight. Hot air is supplied through related pipe at the bottom of drying chamber and air moved upward through wire mesh of the shelves by a fan; therefore, the system operates as a forced convection system since well-designed forced-convection distributed solar dryers are more effective and more controllable than natural-circulation types. The fan used for the system was a photovoltaic DC- fan. This led into having a warm air flow with a controllable temperature by a heat exchanger. The air flow reached to product chamber containing food drying trays and contact with the product. Finally, the air was exhausted from above the chamber. The dried sample was instantly transferred to laboratory for microbial and chemical tests. The solar dryer was also settled just near to laboratory towards sunlight and wind in summer season with acceptable sunlight during the day.

Methodology

Method of collecting data

In order to collect the data, analyze and evaluate the scientific information, customer surveys and interviewed experts in the area of energy, mechanical and food engineering have been considered in this article. In reality, two types of questionnaires have been utilized in this case, one for computing priority weights of customer requirements in AHP which was performed by customers and another for determining the relationships between CRs and TRs and the correlation between TRs in HOQ which was done by related experts. We have sent out these two distinct types of questionnaires for the purpose of doing a survey of both customers and related experts efficiently as many as possible.

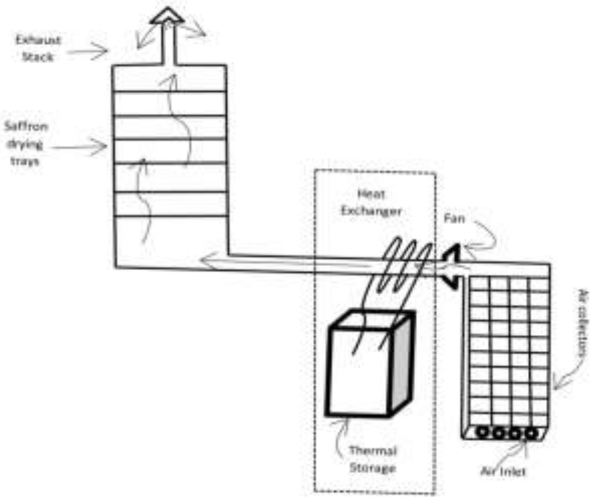


Fig. 1. Schematic of the indirect solar dryer used for saffron

Theoretically, the more effective experts' opinion and customers are, the more coherent and reliable the evaluation of crucial TRs in solar drying systems of saffron will be; as a result, we repeated this process for several times to reduce bias in the data and bias of one person or one voice. To facilitate the process of pair-wise comparison obtained from the survey, we designed out questionnaires with linguistic variables for both customers and experts to do the pair-wise comparison in the most adequate way. Accordingly, experts and costumers responses were summarized and the further comments were elicited. Consequently, two discrete deeds were applied. (i) Entering results of the customers' survey in Expert Choice Software in order to find priority weights of customer requirements in AHP method. (ii) Transforming the linguistic variables of a survey of experts to the form of fuzzy triangular numbers and analyzing them in HOQ. The transforming rules from the linguistic variables to the triangular fuzzy numbers are shown in tables 3 and 4.

AHP-fuzzy-QFD framework

The main framework of applying integrated AHP and FQFD approach to solar drying systems in saffron industry is shown in Fig. 2.

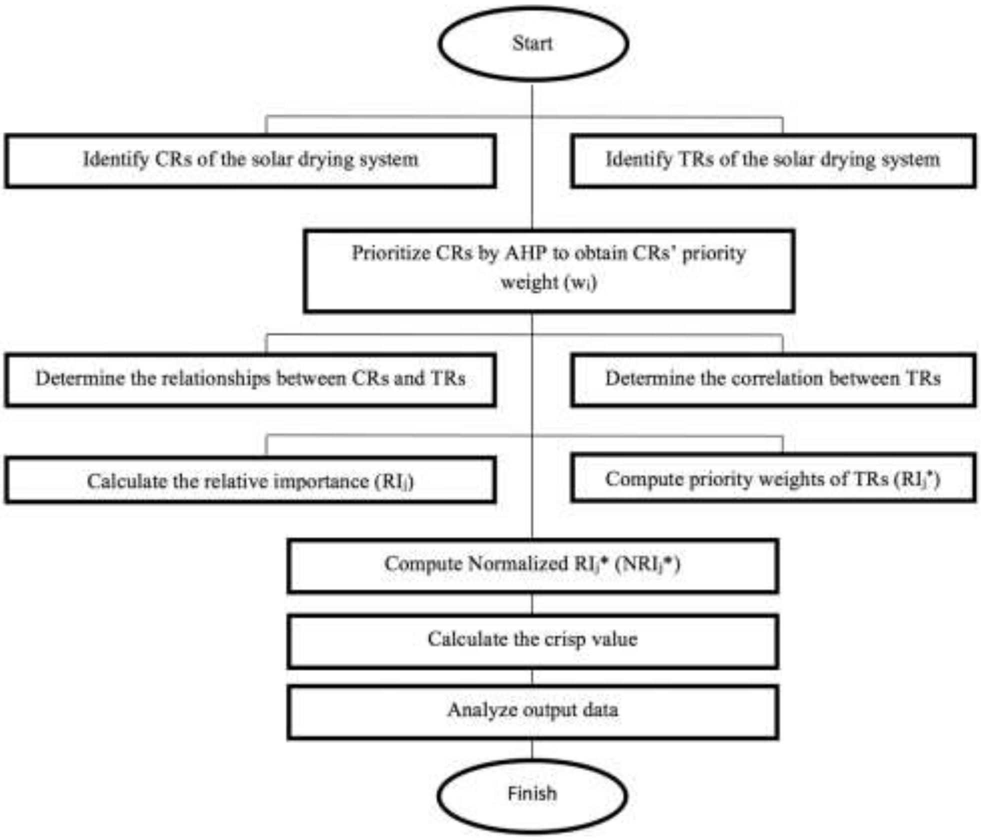


Fig. 2. Schematic representation of the algorithm

Identify CRs and TRs of the solar drying system in saffron industry

Basically, a great success of solar drying systems for saffron in a competitive market depends of course on identifying the customer requirements and providing their needs. By studying CRs and TRs gathered from the survey in the area of solar drying systems in saffron industry, fundamental requirements are considered to apply AHP-Fuzzy-QFD methodology to real cases. In actuality, CRs are defined as factors which present the underlying principles of initial steps for proceeding satisfaction of solar drying system of saffron consumers. Accordingly, TRs are crucial features of various technologies to successfully increase customers' satisfaction. CRs present a list of customer requirements and TRs are identified in order to achieve the CRs represented in Table 2.

Table 2. Customer requirements and technical requirements defined for developing solar drying systems in saffron industry

Code of CRs	Customer Requirements	Code of TRs	Technical Requirements
CR_1	Durability	TR_1	Controlled conditions of temperature, humidity and time
CR_2	Energy saving	TR_2	Materials used for the air collector
CR_3	Low required space	TR_3	Collector area
CR_4	High efficiency	TR_4	Absorber coating
CR_5	Cost-effectiveness	TR_5	The length and width of the air duct
CR_6	User-friendly	TR_6	Thermal energy gained from solar radiation
CR_7	Usable for different amount	TR_7	Photovoltaic cell as the power source of the fan(s)
CR_8	Useable for similar products	TR_8	Material of the trays and their distances
CR_9	Using alternative energy	TR_9	Complete gasket and no influence on air pollution and dust
CR_{10}	Hygiene	TR_{10}	Materials used for the cabinet dryer for the heat transfer enhancement
CR_{11}	Organoleptic properties	TR_{11}	Heat insulation to enhance heat transfer
CR_{12}	Easy Installation	TR_{12}	Air temperature and humidity
CR_{13}	Easy Portability	TR_{13}	Air flow rate & velocity
CR_{14}	Drying time	TR_{14}	Calibration of thermometers and timers

Prioritize CRs by AHP to obtain CRs' priority weight (wi)

In this step, after determining CRs, their priority weights were calculated by using Expert Choice 9.5 Software [21]. Expert Choice as decision-making software which is based on multi-criteria decision making, implements the AHP method efficiently [22]. Moreover, it has been used in fields such as manufacturing [18], environmental management [23,24] and agriculture [19]. For this aim, the pairwise evaluations were prepared to analyze fourteen CRs by nine scales with respect to experimental criterions such as cost, services, and improving product quality. Finally, the obtained priority weights are considered in HOQ to extract important TRs.

Determining the relationships between CRs and TRs, and the correlation between TRs

Due to the need of a translation of imprecise and vague linguistic terms of relative importance of CRs, relationships, and correlation matrices to numerical values, fuzzy logic is utilized. In this step, the degree of relationship between TRs was then expressed by Triangle Fuzzy Numbers (TFNs) in the fuzzy HOQ. Both of these correspondences are presented in tables 3 and 4.

As it is observed on Fig. 3, TFNs are considered which are denoted as a triplet (a, b, c) and non-fuzzy number [25,26]:

$$\mu_N(x):\begin{cases}(x-a)/(b-a), & x\in[a,b]\\ (c-x)/(c-b), & x\in[b,c]\\ 0 & otherwise\end{cases} \qquad (1)$$

Table 3. Degree of relationships, and corresponding fuzzy numbers (Adapted from [25])

Degree of relationships	Fuzzy number
Strong (S)	(0.7; 1; 1)
Medium (M)	(0.3; 0.5; 0.7)
Weak (W)	(0 ; 0; 0.3)

Table 4. Degree of correlations and corresponding fuzzy numbers (Adapted from [25])

Degree of correlation	Fuzzy number
Positive (★)	(0.5; 0.7; 1)
Negative (▲)	(0; 0.3; 0.5)

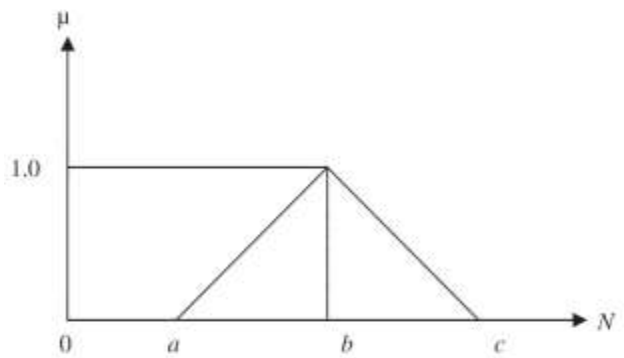


Fig. 3. Triangle fuzzy number

If M= (a_1, b_1, c_1) and N= (a_2, b_2, c_2) symbolize two Triangle Fuzzy Numbers, then the required fuzzy calculations are executed as shown in eq. (2) to (5) [25].

Fuzzy addition:

$$\mathrm{M}\otimes\mathrm{N}=(a_1+a_2, b_1+b_2, c_1+c_2) \qquad (2)$$

Fuzzy multiplication:

$$\mathrm{M}\otimes\mathrm{N}=(a_1\times a_2, b_1\times b_2, c_1\times c_2) \qquad (3)$$

$$\mathrm{M}\otimes 1/\mathrm{N}=(a_1/c_2, b_1/b_2, c_1/a_2) \qquad (4)$$

Fuzzy and natural number multiplication:

$$\mathrm{r}\otimes\mathrm{M}=(r.a, r.b, r.c) \qquad (5)$$

Calculating the relative importance (RIj) and priority weights of TRs (RIj*)

The aim of calculating these two parameters was to determine which TR has the most influence on developing solar drying systems in saffron industry RI_j was calculated by fuzzy multiplication of W_i to R_{ij}

$$RI_j=\sum_{i=1}^{n} W_i\otimes R_{ij} \qquad j=1,\ldots,m \qquad (6)$$

$$RI_j^*=RI_j\oplus\sum_{k=j} T_{kj}\otimes RI_K \qquad j=1,\ldots,m \qquad (7)$$

Calculating the normalized RIj* (NRIj*) and crisp value

Normalization is performed by dividing each RI^*_j by the highest one according to the fuzzy set algebra [26]. Then, in order to rank the TRs, the normalized scores of RI^*_j are de-fuzzified. Suppose M (a, b, c) is a Triangle Fuzzy Number; then, the crisp values are calculated using the eq. (8).

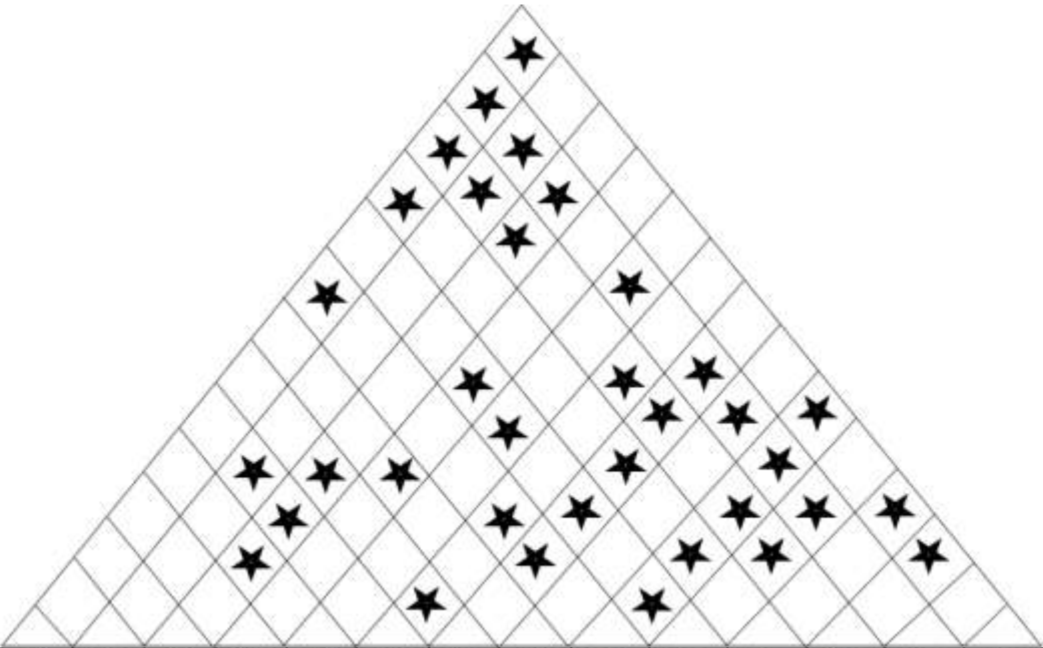
$$\frac{(a+4b+c)}{6} \qquad (8)$$

Results and discussion

According to the output of Fig. 4, TRs with high crisp values indicate that they can be usefully employed to enhance relevant CRs. Therefore, the priority of TRs must be considered for developing solar drying systems for saffron. Moreover, the analyzed output of AHP-Fuzzy-QFD process gives histograms recognizing priority of TRs in Fig. 5.

The drying behavior of agricultural crops during solar drying depends on different weather conditions including air temperature and humidity, air flow rate, and air velocity. As it can be seen in Fig. 5, after the rate of complete gasket and no influence on air pollution (1.22), the rate of air flow rate and velocity, air temperature and humidity, and photovoltaic cell as the power source of the fan (s) are virtually the same (1.18). The higher temperature, movement of the air, and lower humidity, increases the rate of drying process. If energy savings are considered, the best way to change the air flow rate of a fan is to vary the speed of rotation. To improve TRs shown on Fig. 5, there are different ways in accordance with the advancement of technology. Some of the solutions are noted in this paper. It is obvious that materials are really indispensable for having a complete gasket which has the highest rate of

TRs depicted in Fig. 5 and heat transfer enhancement.



CR_n	Weight	TR_1	TR_2	TR_3	TR_4	TR_5	TR_6	TR_7	TR_8	TR_9	TR_{10}	TR_{11}	TR_{12}	TR_{13}	TR_{14}
CR_1	0.009		M		W	W		M	M		M	M	M		
CR_2	0.106	S	S	S	M	M	S	S	M	M	S	S	S	M	S
CR_3	0.013			S		S		M	M						
CR_4	0.092	S	S	S	M	M	S	S	M	M	S	M	S	M	M
CR_5	0.104	S	S	S	M	M	S	S	M	M	M	M	M	M	S
CR_6	0.040														M
CR_7	0.035	M	M	S	M	S	S	M	M	M	M	M	M	M	M
CR_8	0.023	M	M	M	M	M	S	M	M	M	M	M	M	M	M
CR_9	0.038	M	W	M		W	M	W		M	M	M	M	W	W
CR_{10}	0.205				M				S	S	S	M			
CR_{11}	0.244	M		W	M		M	W	M	S	M	M	S	M	S
CR_{12}	0.012							M	M						
CR_{13}	0.010		M			M		M	M		M				
CR_{14}	0.069	S	S	S	M	M	S	M	M	M	S	S	S	S	S
R_{ij}		0.361	0.282	0.311	0.263	0.123	0.384	0.262	0.358	0.454	0.469	0.347	0.420	0.229	0.416
		0.541	0.409	0.449	0.439	0.198	0.57	0.387	0.563	0.682	0.703	0.55	0.615	0.371	0.606
		0.609	0.436	0.534	0.617	0.303	0.626	0.506	0.706	0.775	0.796	0.7	0.657	0.503	0.646
RI_j^*		1.086	0.798	1.02	0.676	0.627	0.905	1.569	0.604	1.717	1.344	1.093	1.697	1.539	1.207
		2.093	1.498	1.947	1.325	1.264	2.95	3.145	1.13	3.343	2.587	2.101	3.258	3.123	2.277
		3.244	2.222	3.129	2.119	2.136	3.979	5.097	1.826	5.209	4.157	3.236	4.777	5.168	3.205
Normalized RI_j^* ($N\ RI_j^*$)		0.208	0.153	0.195	0.129	0.120	0.173	0.301	0.115	0.329	1.344	0.209	0.325	0.295	0.231
		0.626	0.448	0.582	0.396	0.378	0.882	0.940	0.338	1	2.587	0.628	0.974	0.934	0.681
		1.889	1.294	1.822	1.234	1.244	2.317	2.968	1.063	3.033	4.157	1.884	2.782	3.009	1.866
Crisp Values		0.767	0.539	0.724	0.491	0.479	1.003	1.172	0.421	1.227	0.962	0.768	1.167	1.173	0.803

Fig. 4. Fuzzy-HOQ for solar drying systems in saffron industry

For instance, using nanocoating can be a useful method to enhance heat transfer in absorber coating which can have a positive effect on the drying process. Also, suitable materials used for the cabinet dryer, air duct, heat insulation, air collector and trays are really important to increase the solar dryer efficiency. Solar dryers can be constructed from locally available and low cost materials by considering different elements related to the rate of drying. Therefore, it should be noted that materials used in solar dryers play a crucial role in drying behavior. Besides, since photovoltaic cell is utilized as the power source of the fan, a suitable photovoltaic cell should be considered to convert the energy in light into electrical energy through the process of photovoltaic. There are many types of solar cell technologies which are in development, but some of them are most commonly used such as crystalline silicon, thin films concentrators, and thermo-photovoltaic solar cell technologies. The effect of the photovoltaic cell on the drying process as a useful factor should not be neglected.

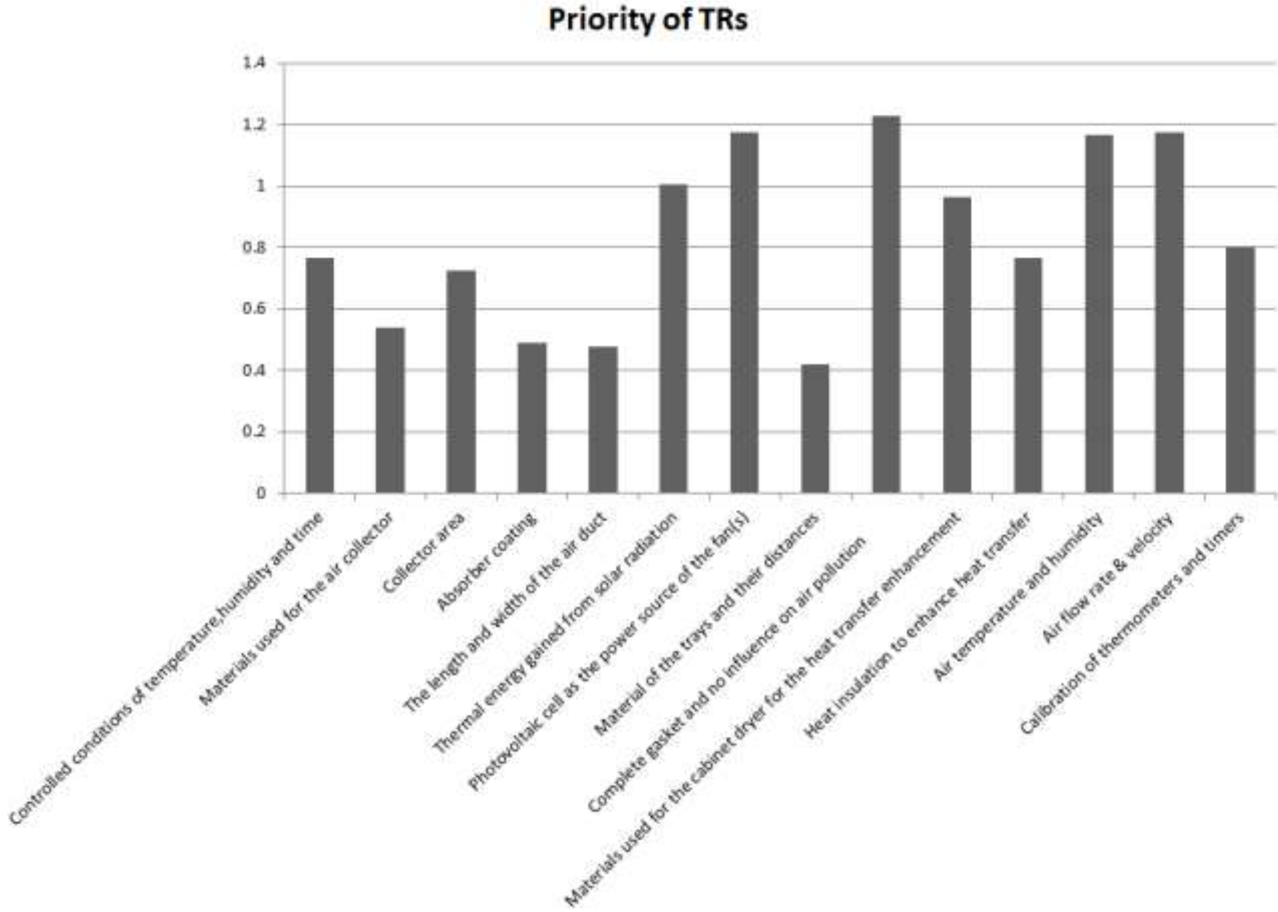


Fig. 5. Priority of TRs depending on crisp values

Conclusions

It is clear that drying process has major effects on the microbial profile and also the content of chemical compounds effective in color, taste and aroma of saffron. In this research, by linking CRs and TRs in fuzzy HOQ of mentioned systems, we achieved the priority of TRs which should be considered in the process of design to enhance quality level of solar drying systems in saffron. According to findings of the current study, the most important customer requirements such as organoleptic properties and hygiene with the weights of 0.244 and 0.205 are achieved respectively. Accordingly, the most crucial TR is the complete gasket and no influence on air pollution and dust with crisp value 1.227. Similarly, the lowest priority of TRs refers to material of the trays and their distances with crisp value 0.421. In this paper, using the integrated AHP and FQFD approach indicates some advantages such as; Economical method of drying, development and employment in rural and remote areas, the development of environmentally compatible methods, intensifying the level of competitive price of saffron in global market, and developing methods of using renewable energy systems in other areas of agricultural and horticultural industries.

Nomenclature

A Smallest possible value
B Most promising value
C Largest possible value
M and N Triangular fuzzy numbers
RI_j Relative importance of a TR
RI_j^* Priority weight of a TR
R_{ij} Relationship between the i-th CR and the j-th TR
RI_k Relative importance of the k-th TR
T_{kj} Degree of correlation between the k-th and j-th TRs
W_i Priority weight of a CR

Conflicts of interest

Authors declare no conflict of interest.

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