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**Original Article**

# Towards the Application of Fuzzy Logic for Developing a Novel Indoor Air Quality Index (FIAQI)

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**Abstract**

**Background:** In the past few decades, Indoor Air Pollution (IAP) has become a primary concern to the point. It is increasingly believed to be of equal or greater importance to human health compared to ambient air. However, due to the lack of comprehensive indices for the integrated assessment of indoor air quality (IAQ), we aimed to develop a novel, Fuzzy-Based Indoor Air Quality Index (FIAQI) to bridge the existing gap in this area.

**Methods:** We based our index on fuzzy logic, which enables us to overcome the limitations of traditional methods applied to develop environmental quality indices. Fifteen parameters, including the criteria air pollutants, volatile organic compounds, and bioaerosols were included in the FIAQI due mainly to their significant health effects. Weighting factors were assigned to the parameters based on the medical evidence available in the literature on their health effects. The final FIAQI consisted of 108 rules. In order to demonstrate the performance of the index, data were intentionally generated to cover a variety of quality levels. In addition, a sensitivity analysis was conducted to assess the validity of the index.

**Results:** The FIAQI tends to be a comprehensive tool to classify IAQ and produce accurate results.

**Conclusion:** It seems useful and reliable to be considered by authorities to assess IAQ environments.

**Keywords:** Indoor air pollution (IAP), Fuzzy-based indoor air quality index (FIAQI), Indoor air quality (IAQ)

## Introduction

Indoor Air Pollution (IAP) has become a primary concern resulted from our awareness to the possible penetration of outdoor pollutants into the household environment and their production from various sources inside such areas. It is increasingly believed to be of equal or greater importance to human health compared to ambient air (1). People approximately spend 80% of their time indoors, depending on the geographical area, age, sex, job activities, season, etc. (2). This number for German children is about 75% (3), while it is above 90% for American adults (4). Although the concentrations of particles and some indoor parameters may be a fraction of those outdoors, this is only the case in the absence of indoor sources. When indoor sources are present, indoor concentrations can even exceed from their outdoors concentrations (5). For some pollutants,

such as $VOC_s$, indoor concentrations are noticeably higher than those of outdoors are which is possibly due to the wide range of indoor emission sources as well as the tightness of the buildings (6). According to USEPA (7), indoor air quality (IAQ) is among the top five environmental risks to human health. In addition, a high number of studies have associated exposure to indoor air pollutants with a wide range of health effects. For example, acute $O_3$ exposure adversely affects the pulmonary function; besides, it induces respiratory inflammation in both healthy individuals and those suffering from respiratory diseases such as asthma (8-10). Health effects of exposure to indoor PM have been size-dependent, with particles < 1μm having the strongest impact (11). A variety of respiratory health effects have been linked to other criteria pollutants, which could be found indoors (2, 4, 6, 12). $VOC_s$ is another critical category of indoor air pollutants with approximately 300 individual compounds, for which numerous health effects have been found (6). Formaldehyde, for instance, a ubiquitous organic pollutant frequently found indoors, has been human carcinogen (6, 13). Other non-cancer effects (mostly eye and respiratory irritation) have also been linked to this compound (13). The ultimate category of indoor air pollutants belongs to so-called "bioaerosols", such as airborne bacteria and fungi. Indoor fungi has been associated with Sick Building Syndrome (SBS), which comprises a variety of syndromes, including headache, fatigue, nausea, increased airway infection, etc. (14). Airborne bacteria and fungi can deeply penetrate into the human respiratory tract causing various health effects from allergic complaint to respiratory morbidity (15). Therefore, all of the aforementioned pollutants should be taken into consideration when assessing the IAQ.

An indicator with a single parameter of carbon dioxide ($CO_2$) concentration has being used as a useful tool for understanding of IAQ and ventilation effectiveness (16-18). Nonetheless, this index only indicates the probable occupant acceptance of IAQ (19). In addition, in spite of an adequate ACH, there might be some areas with stagnant air, in which higher concentrations of indoor air pollutants are present and can increase the total occupants' exposure. Ventilation effectiveness cannot be considered as a good indicator of occupants' exposure to coarse particles since they no longer strictly follow the air pattern. Therefore, a more accurate index is needed for assessing the IAQ, which included not all, but the most important indoor air pollutants with respect to human health. Recently, a new methodological approach, called "fuzz logic" (21), has been used to solve complex environmental issues. This approach has been quite appropriate for subjective environmental problems, mainly due to its ability to deal with the classification of environmental conditions, particularly near boundary values were conventional methods tend to fail. In addition, it can help us achieving a balance when different or even contradictory observation have been obtained (22, 23). Therefore, a number of studies have been conducted to develop environmental quality indices based on the fuzzy logic (24-26) and found it a suitable tool for assessing the environmental qualities. However, there has not been a study with the aim of developing an index for the IAQ assessment.

Hence, the present study was aimed to develop a novel, fuzzy-based index (FIAQ) for assessing the air quality in indoor environments. For this purpose, we took into account three important categories of indoor air pollutants, namely, criteria air pollutants, volatile organic compounds, and bioaerosols, in the body of the index. In addition, a case study of virtually generated indoor environments was also provided to indicate the index performance.

## Materials and Methods

### *A brief description of Fuzzy logic*

Fuzzy logic has being increasingly applied mainly due to its particular capability in efficiently handling the environmental complex issues. By applying fuzzy logic, qualitative elements such as expert's knowledge and experience can be added to the quantitative part of a problem. The traditional methods used to develop indices are not capable of handling the environmental problems.

Fuzzy-based systems consist of fundamental parts, including membership functions, fuzzy inference systems, fuzzy set operators, fuzzy inference rules, and defuzzification process. In previously conducted studies, the concept of fuzzy logic is explained in details (24, 27).

### *Criteria for the selection of weighting assignment to the parameters included in the FIAQI*

Considering the advantage of Mamdani inference system, selection of weighting factors to the parameters included in the FIQAI were performed according to the experts' knowledge and medical evidence about their human health effects existing in the literature (Fig. 1).

The top priority was given to the volatile organic compounds ($VOC_s$) group. Although criteria air pollutants are the most important air pollutants outdoors, the indoor concentrations of these compounds are 20-80% higher than their corresponding amount in the environment (12). In the case of $VOC_s$, the indoor concentrations of these parameters have been observed to be largely higher, compared to their corresponding amount in the environment, (28); this is mainly due to their large number of sources.

The medical evidences for each pollutant applied here are explained in details in previous literatures (29-40).

### *Development of the fuzzy-based indoor air quality index (FIAQI)*

Fig. 2 illustrates the algorithm of the proposed FIAQI. At the first step, we grouped the parameters in each category. Weighting factors were assigned to each parameter at this stage according to the effects of each one on human health. The sum of the weighting factors in each category is 1. Then, the parameters in each category were normalized between 0 and 500 by fuzzy inference system. At the second step, different weighting factors were assigned to each group according to their priority in terms of human health. The groups were then normalized between 0 and 500 by inference system, finally producing the global FIAQI.

In the FIAQI, we developed six rules for each parameter at the first step, and six rules for each group at the second step. In order to facilitate the weighting assignment, only one antecedent was assigned to each rule. The fuzzy rules developed here were in the form of one input one output. The 108-rule was extracted for this study.

The labeling of the final FIAQI values and the concentration breakpoints used for classifying each pollutant were done on the basis of the USEPA AQI methodology (41), since it is the most widely used air quality index with respect to human health. Mamdani inference system is the most applicable method for capturing experts' knowledge (24, 27, 42, 43).

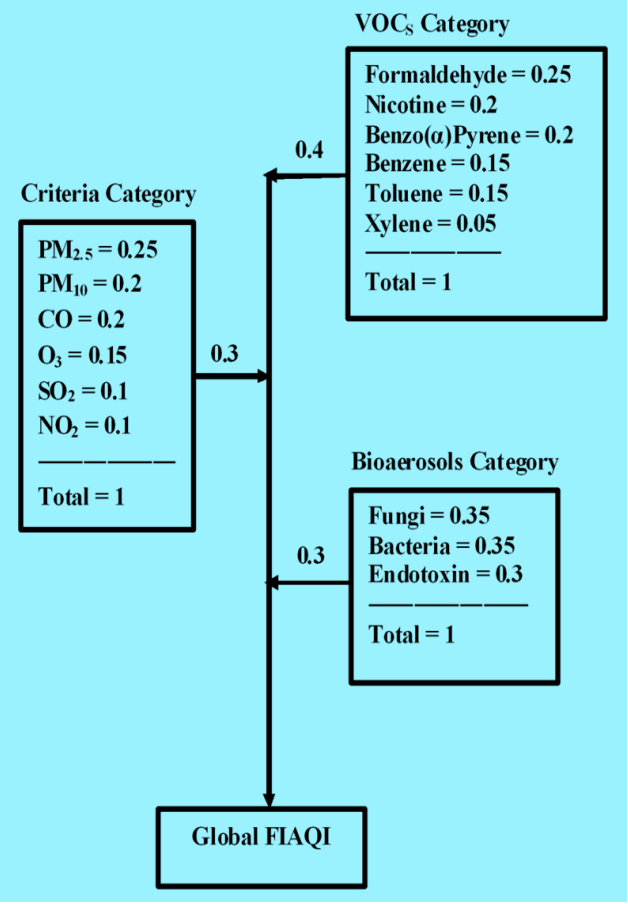


**Fig. 1:** Weighting assignment to different parameters and groups included in the FIAQI

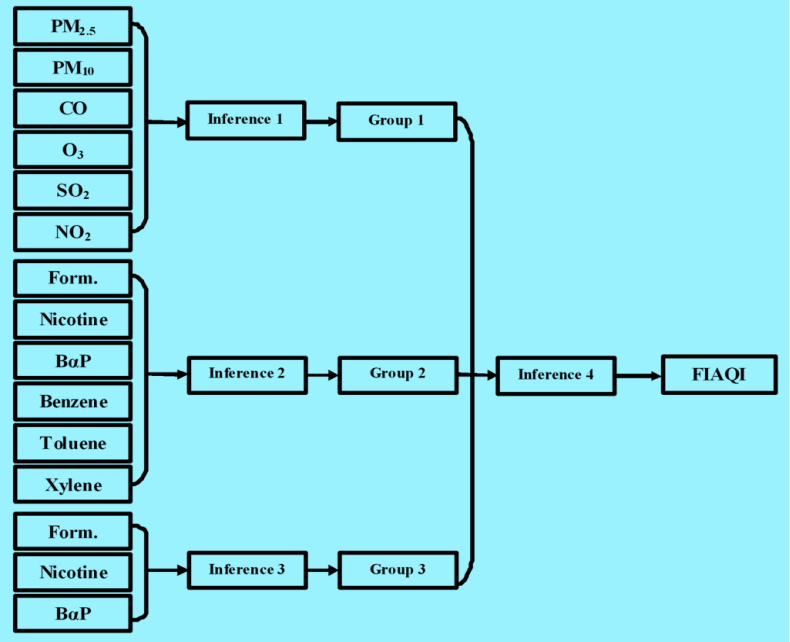


**Fig. 2:** Algorithm of the FIAQI index proposed by the present study

In the USEPA AQI, the standard levels for a specific pollutant is considered as a final index value of 100; and, the pollutant's concentrations below and above the standard level are classified into two and four groups, respectively.

We used trapezoidal membership functions in the body of the index to classify the concentration ranges of each parameter and the ranges of the final FIAQI index value. An example of the trapezoidal membership functions for classifying the concentrations of the pollutant $PM_{10}$ is illustrated in Fig. 3. Then, we assigned a linguistic term to each membership function, or set, in the value-based fuzzy system according to the terms used in the USEPA AQI (41) (Fig. 3).

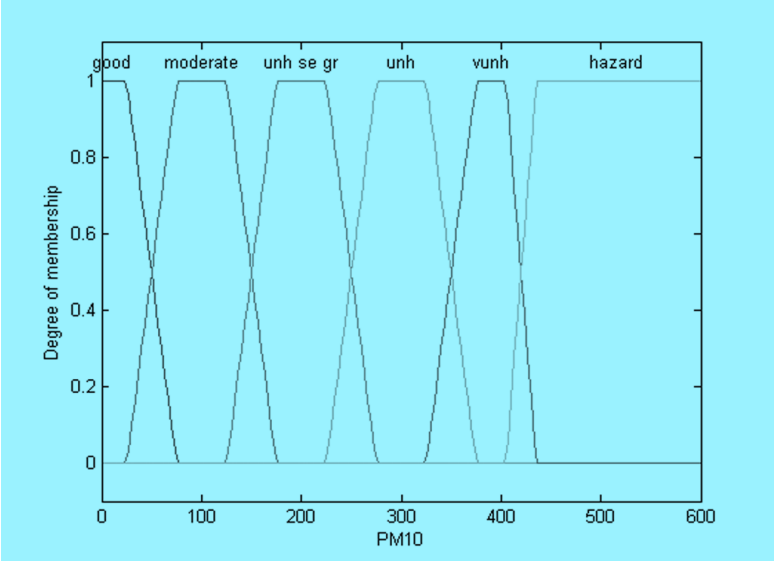


**Fig. 3:** An example of the trapezoidal membership functions for classifying $PM_{10}$ concentrations

The following equation was applied to create the fuzzy sets

$$\text{Trapezoidal}: f(x;a,b,c,d) = \begin{Bmatrix} 0 & x<a \text{ or } d<x \\ \frac{(a-x)}{(a-b)} & a \le x \le b \\ 1 & b \le x \le c \\ \frac{(d-x)}{(d-c)} & c \le x \le d \end{Bmatrix}$$

[2]

Three examples of rules extracted for this study are shown below:

Rule 8: *If $PM_{2.5}$ is "low" then FIAQI is "Moderate".*

Rule 42: *If Formaldehyde is "extremely high" then FIAQI is "Hazardous".*

Rule 87: *If Endotoxin is "moderate" then FIAQI is "Unhealthy for Sensitive Groups".*

The results of Mamdani inference system should be defuzzified into a crisp value. Various methods have been applied for defuzzification, including the mean of maxima method, the center-of-gravity method (COG), the weighted average method, and the max method. In the present study, the COG method was used, because it is considered as the most common and physically applicable method among the aforementioned defuzzification methods. The defuzzification process was carried out according to the following equation (27):

$$Z = \frac{\int \mu(z) z dz}{\int \mu(z) dz} \quad [3]$$

Fig. 4 indicates the surface graph of CO and Ozone as an example of the relationships and interactions among the parameters included in the FIAQI. The Fig. suggests how the changes in the concentrations of each input variable (CO and Ozone in this example) can affect the final FIAQI outputs.

Furthermore, MATLAB 7.9.0 (2009) was used to perform all of the computations.

Finally, in order to evaluate the performance of the index in classifying the concentrations of the indoor air pollutants, data were intentionally generated to cover a variety of quality levels.

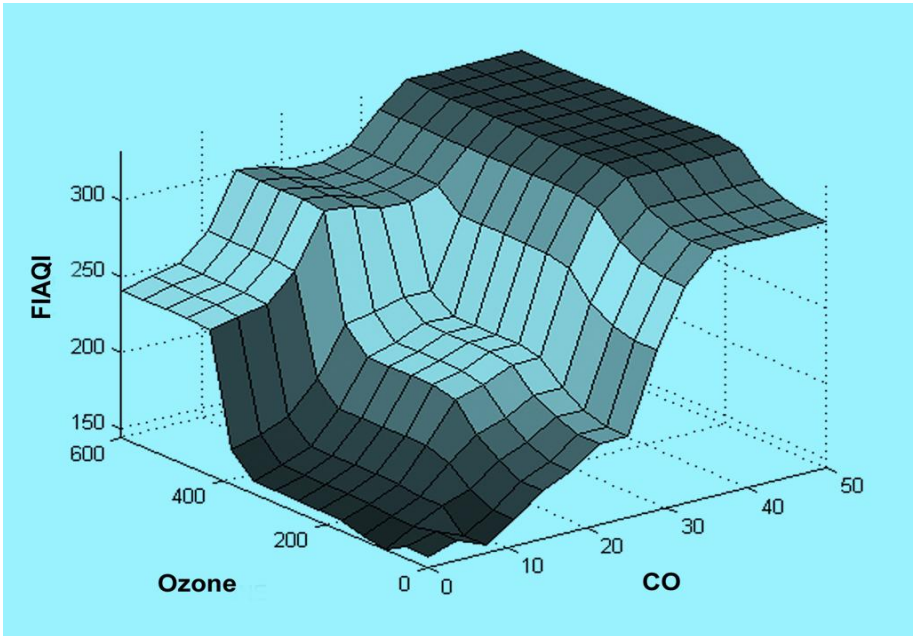


**Fig. 4:** The surface graph of CO and Ozone indicating the relationships and interactions among the parameters included in the FIAQI

### *The applied method in validating the proposed index (FIAQI)*

The internal validation of the FIAQI was assessed by conducting a sensitivity analysis. For this purpose, we changed the weighting factors on a systematic basis and evaluated the amount of changes that occurred in the FIAQI outputs. Table 1 presents the range of modifications we made in the weighting factors assigned to each parameter or group.

**Table 1:** Range of the changes made in the weighting factors

| Groups | Pollutants | Mean | Min | Max |
|---|---|---|---|---|
| Criteria group | $PM_{2.5}$ | 0.25 | 0.01 | 0.49 |
| | $O_3$ | 0.15 | 0.01 | 0.29 |
| | $SO_2$ | 0.1 | 0.01 | 0.19 |
| | $PM_{10}$ | 0.2 | 0.01 | 0.39 |
| | CO | 0.2 | 0.01 | 0.39 |
| | $NO_2$ | 0.1 | 0.01 | 0.19 |
| VOCs group | Formaldehyde | 0.25 | 0.01 | 0.49 |
| | Nicotine | 0.2 | 0.01 | 0.39 |
| | Xylene | 0.05 | 0.01 | 0.09 |
| | BαP | 0.2 | 0.01 | 0.39 |
| | Benzene | 0.15 | 0.01 | 0.29 |
| | Toluene | 0.15 | 0.01 | 0.29 |
| Bioaerosols Group | Fungi | 0.35 | 0.01 | 0.99 |
| | Bacteria | 0.35 | 0.01 | 0.5 |
| | Endotoxin | 0.3 | 0.01 | 0.49 |
| Final FAQI | Criteria group | 0.4 | 0.99 | 0.7 |
| | BTEX group | 0.6 | 0.01 | 0.3 |

## Results

### *Performance of the proposed fuzzy indoor air quality index*

Fig. 5 illustrates the outputs of the FIAQI for the data from our virtually generated case study. A good, very unhealthy, or hazardous IAQ was not seen in all the cases, since the FIAQI outputs were in the range of 51-200. In addition, the IAQ of the houses was poorer in winter and autumn, compared to that in spring and summer.

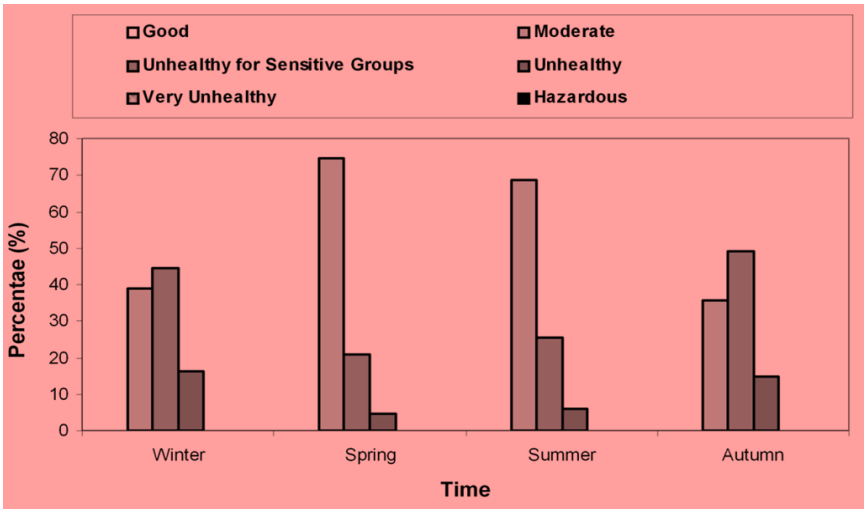


**Fig. 5:** The outputs of the FIAQI for the indoor air quality of the virtually generated data for the indoor environments

In winter, for example, only about 38% of the indoor environments had moderate IAQ, while above 60% had unhealthy IAQ; corresponding percentages for spring were 75% and 25%, respectively.

Fig. 6 indicates the outputs of the FIAQI against those of the USEPA AQI measured during the same days at the indoor and outdoor air, respectively. The FIAQI outputs generally well correlated with those of the USEPA AQI ($R^2$ = 0.87). This is consistent with our expectations. For example, in winter the ambient concentrations of the criteria pollutants were high, mainly due to undesirable meteorological conditions for dispersion of the pollutants, leading to high USEPA AQI values. The same result was observed for the indoor environments because of increased use of gas-fired stoves as well as the penetration of outdoor pollutants into the indoor environments in winter, leading to corresponding high FIAQI values.

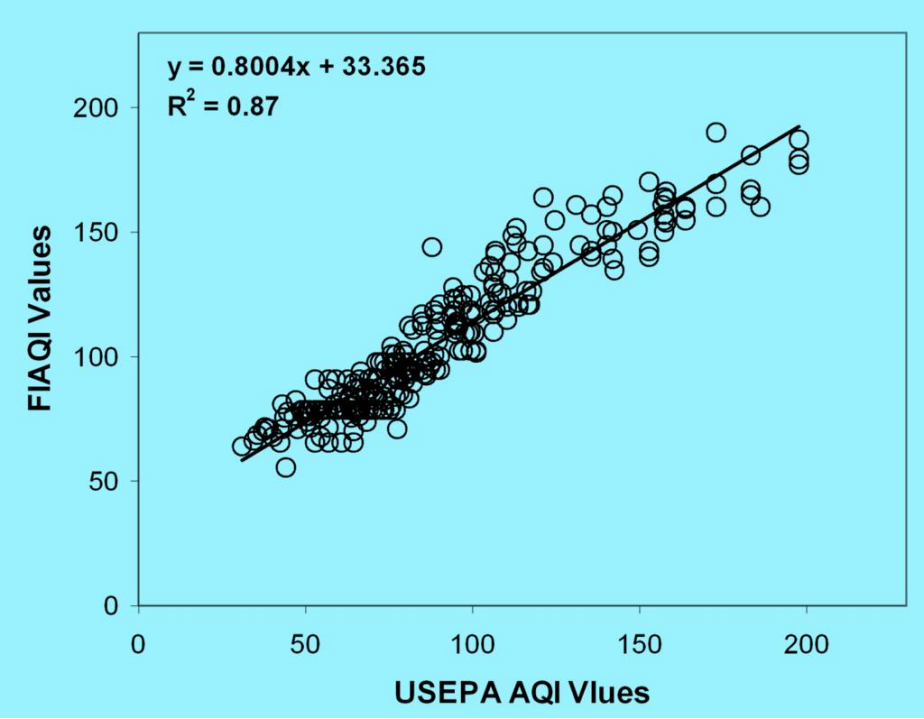


**Fig. 6**: Correlation between the outputs of the USEPA AQI and those of the FIAQI

## Discussion

### *Index performance*

These high FIAQI values can imply the potential impact of IAQ on the occupants in this city due to their exposure to the indoor air pollutants. UAEPA AQI is the most widely used index for assessing the ambient air quality (41). Since we applied the same standards and rationale as those used in the USEPA AQI to classify the pollutants concentrations, and the same terms as those used in the USEPA AQI to describe the indoor air quality, comparing the outputs of the two indices can shed some light into the performance of the FIAQI. However, since the USEPA AQI and the FIAQI include different pollutants, and that the former is developed for assessing ambient air quality while the latter is designed to assess indoor air quality, we believe the actual outputs cannot be compared.

In spite of the good correlation existing between the AQI and FIAQI outputs, it should be noted that the FIAQI values tend to be higher than those of the USEPA AQI. This can be attributed

to the fact that a higher number of pollutants have been included in the FIAQI, compared to those included in the USEPA AQI. In other words, even when the concentrations of criteria air pollutants are low at both indoors and outdoors, the AQI may indicate lower values; while the FIAQI values remain higher because of the presence of other types of indoor pollutants such as $VOC_s$ or bioaerosols. This is important with regard to the duty of the health system policy-makers. Nowadays, the impact of air pollution on human health is estimated only by the USEPA AQI, which is an index for assessing the ambient air, whereas people spent approximately 80% of their time at indoors (2). Therefore, it is probable that a single ambient air quality index may not be representative of the total exposure to air pollutants of people, suggesting the need for a complementary index for indoor air quality assessment.

The only question remaining unsolved is the points on the correlation graph at which the USEPA AQI values exceed those of the FIAQI (Fig. 6). This situation arises when the concentration of one of the criteria air pollutants is dramatically higher than those of other pollutants. In the USEPA AQI only the pollutants having the highest concentration is reported as the "responsible pollutant" and the concentrations of other pollutants do not have any impact on the final AQI value (41). In the FIAQI, however, all of the pollutants contribute to the final index value (based on their weighting factors), and therefore, high concentration of a single pollutant cannot significantly rise the index value. This was also observed in the previous studies concerning the application of fuzzy logic for the air quality assessment (24).

### *Novelty of the proposed index*

Nowadays, IAQ evaluations, which are not very common, are conducted either qualitatively or quantitatively (44). Quantitative assessment relies primarily on the visual observations of the investigators such as checking the indoor environment for the presence of visible mold and undesirable odor, which are the indicators of bioaerosols and $VOC_s$, respectively. Qualitative evaluations are limited to the measurements of a single parameter such as humidity, $CO_2$, temperature, etc. However, the FIAQI index proposed by the present study includes a variety of the most important indoor air pollutants, which are necessary if the index value has to represent well the IAQ with respect to human health. Therefore, it provides us with a quantitative and comprehensive understanding of IAQ. Another important advantage of the proposed index is its flexibility. Although a high number of pollutants have been included in the index, when the measurement of one pollutant is not technically or financially practical, the pollutant is automatically omitted from the index and its weighting factor is distributed among the remaining pollutants based on their priority, therefore, the final FIAQI value can be calculated in the absence of that pollutant.

### *Validating the index (FIAQI)*

The methodology we applied to develop the index can efficiently deal with the uncertainties and vagueness that have surrounded the air quality issues (23). This can be mainly done via the special type of classification that fuzzy logic applies. Additionally, we were able to include the experts' knowledge and expertise in the body of the FIAQI index (27); this was done through selecting critical parameters and assigning appropriate weighting factors to them. In this way, we could avoid the complexity and difficulty of designing traditional models, which are non-user-friendly for those who are not expert.

Another useful approach in justifying the validity of the FIAQI index lies on the selection of important indoor air quality parameters. According to the medical evidence currently available in the literature, all of the quality parameters included in the FIAQI have considerable effects on human health. Therefore, if an indoor air quality index is to represent well the air quality of an indoor environment in terms of human health, it should include all of aforementioned parameters. However, the effect of each parameter on the final index value should be delineated based on the significance of its influences on human health, as it was in the FIAQI.

The present study was conducted with the aim of developing a novel indoor air quality index based on fuzzy logic (FIAQI) for integrated assessment of IAQ with respect to human health. A broad range of air pollutants exist in indoor environments posing implications to human health. Therefore, the FIAQI included a variety of the most important indoor air pollutants, including criteria air pollutants and the most common $VOC_s$ and bioaerosols. According to the results from the present study, the FIAQI can be considered as a more useful, comprehensive tool to classify the IAQ compared to the current methods of IAQ assessment, which rely mainly on the evaluators' observations or quantitative measurement of a single quality parameter of the IAQ. In addition, since the USEPA AQI concerns people's exposure to the ambient air pollutants while people spend approximately 80% of their time indoors, the FIAQI can be used together with the USEPA AQI in order to estimate the total impact of both ambient and indoor air pollutants on human health. It should be noted that exploring the external validity of the FIAQI requires future epidemiologic studies, which enable us to predict accurately the health outcomes that can be attributed to each range of the proposed index.

## Conclusion

The FIAQI can be considered as a useful and comprehensive tool in classifying the IAQ. Therefore**,** this index can be used together with the USEPA AQI to estimate the impact of both ambient and indoor air pollutants on human health.

## Ethical considerations

Ethical issues (Including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the authors.

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