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Development of indoor work environmental air quality index for a dyeing and printing industry

Dharmendra Jariwala*, Robin Christian

Department of Civil Engineering, Sardar Vallabhbhai National Institute of Technology, Surat, Gujarat, India

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CORRESPONDING AUTHOR:

dv_ jariwala@yahoo.com
Tel: (+91 261) 2227334
Fax: (+91 261) 2227334

ABSTRACT

Introduction: Due to various components, materials, and processes, industrial indoor air quality differs from building indoor air. Air quality and the working environment impact health, performance, and comfort. This study developed an Indoor Work Environmental Air Quality Index (IWEAQI) to assess and characterize industrial work environments.

Materials and methods: Surat "Textile city" is situated in the western part of India in Gujarat state. The small-scale dyeing and printing industry has been selected as a study area. The industry locations like Jet dyeing machine area, stenter machine area, printing machine area, looping machine area and washing basin area has been selected. Various chemicals, adhesives, solvents, dyes, and varied temperature and humidity conditions are used to transform the raw cloth into the finished product. CO, CO_2, SO_2, NO_2, O_3, Total Volatile Organic compounds (TVOC), Formaldehyde, Particulate Matters (PM_{10}, $PM_{2.5}$), WBGT index, humidity, noise, and light were considered to construct IWEAQI. Continuous observations were recorded at minute intervals with a real-time monitoring system. To account for all contributing aspects, United States Environmental Protection Agency (USEPA) air quality index technique was updated for index formulation. IWEAQI was validated using the Pollution Index approach.

Results: The proposed approach calculated IWEAQI from results. Both approaches gave an index value of 46-80. The developed approach and pollution index method were compared using regression analysis. All study locations had regression values between 0.93 and 0.99.

Conclusion: The technique classifies IWEAQI as excellent (0-20), good (21-40), moderate (41-60), poor (61-80), and very poor (81-100). From the developed index value, which parameters are influencing the most can be judged.

Introduction

With the rapid development of industrialization, air pollution has become a public concern problem in modern societies [1]. The air quality affect the human being in terms of health, performance

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and comfort [2]. At present indoor air pollution has been given prime attention to investigate air pollution as people spent about 80-90% of their daily time in an indoor space like a home, office, shop or workplace [3]. Indoor Air Quality (IAQ) affects everyone, especially the most vulnerable to children, elder people and people with health conditions like asthma and heart disease. IAQ is dynamic, as it varies from place to place, depending upon the activities carried out inside the building. IAQ is influenced by large numbers of parameters like the number of occupants, indoor activities, ventilation conditions, temperatures, humidity and various contaminants inside the building. In an industrial environment, IAQ will be varied with respect to the type of material used, chemical reactivity, pollutants emission, suspension and re-suspension phenomena, air velocity, temperature and humidity [4]. Some countries in the world had developed their IAQ standards for buildings, schools, hospitals and public places, but a guideline of IAQ is not available for industrial environments. At present India is lacking in IAQ standards for any type of building [5].

Good IAQ is critically important for safeguarding health since people spent most of their time indoors. There are challenges in monitoring IAQ due to the presence of so many influencing parameters. The following literature reflects the monitoring of IAQ in different types of buildings worldwide. IAQ of an office building with respect to visual, acoustic and hygrometric aspects had been assessed as per EU directive in European countries. It has been used to assess the comfort condition of employees. Environmental Quality Index (EQI) and Building Quality Index (BQI) have been calculated. The researcher also classified the building into seven quality classes, A to G [6]. Researcher developed an integrated approach to provide a systematic method for the assessment of buildings using IAQ and energy audit. Objective measurements of IAQ parameters and subjective measurements regarding occupant perception of environmental conditions were studied in five air-conditioned office buildings in Singapore. The study reveals that occupant perception of environmental acceptability is quite distinct from the empirical measuring of IAQ, reflecting the complex nature of IAQ [7]. A systematic approach towards IAQ audit for four types of public buildings mainly offices, hostels, schools and libraries in Portugal. A comprehensive IAQ audit methodology was developed considering physical, chemical and biological parameters. The developed methodology was suitable for short-term assessment and preparation of an action plan to solve IAQ problems [8].

A study in Europe investigated 56 office buildings IAQ in the summer season. This was done with objective measurement, physical symptoms and air quality perception among occupants. Results showed that 27% of occupants did not accept the air quality [9]. Researchers developed the environmental indoor air quality index (EIAQI) using the concept of Indoor Air Quality Index (IAQI) and thermal comfort index (TCI). The IAQI developed in this research work was modified using outdoor AQI designed by the USEPA. The developed index showed that the system is able to justify the indoor environmental setting like smoking, operation of air condition and window positioning [10]. Most of the researchers investigated indoor Environmental Quality (IEQ) considering indoor air, thermal comfort, acoustic and illumination aspects, in various types of buildings like offices, mechanically ventilated buildings, elderly daycare centers, sports centers and commercial complexes. The prime objective of all research was to obtain the most influencing factors on IAQ. Further, many researchers developed indexes to correlate it with the health, satisfaction and performance of occupants [11-16].

It is always easy to understand the quality of air in the form of an index, known as Air Quality Index (AQI) which is of numerical values and developed by considering the main criteria pollutants. The majority of countries worldwide had formulated AQI to evaluate ambient air quality. Various methodologies developed for air quality index determination are the AQI system of the US EPA, Revised Air Quality Index, Common Air Quality Index, Oak Ridge Air Quality Index, New Air Quality Index, Pollution Index, Air Quality Depreciation Index, Integral Air Pollution Index, Aggregate Air Quality Index, Aggregate Risk Index, PCA Neural Network AQI model, Fuzzy Air Quality Index, Air Quality Health Index [17]. IAQ standards and indexes are yet to be developed in most of the countries.

Very few countries have established their IAQ standards for controlling indoor air., which may be used as a safeguard of human health. These may be referred to as the Indoor Environmental Index (IEI) proposed by the USA, CLIM 2000 and BILGA developed by the Laboratory of Hygiene of Paris (LHVP) for France, Indoor Environment Index (IEITW) developed by Taiwan and Indoor Air Quality Certification (IAQC) for Hongkong [4].

India is on the path of developing IAQ standards for various types of buildings. India is the most industrialized country, outdoor and indoor air pollution is a major threat to the environment. Though stringent standards are available for ambient air quality, it is crucial to identify the most influencing pollution sources. Urban air quality is critically influenced by various industries and transportation sources. At the same time, the IAQ of various types of buildings also becoming part of the outdoor air quality deterioration. So, it is necessary to find the IAQ of various types of buildings with respect to the utility of a building. The IAQ standards available from the different countries may be adopted as a guideline. However, the number of occupants, ventilation, temperature, humidity, and utility of the building may be varied as per the Indian condition.

Indian industrial environment may be varied as most of the industries are falling under the medium and small scale. Compare to large-scale industries they may have a constraint of funds, space and technical knowledge. The geographical locations of the industries are highly influenced by meteorological parameters. This makes the standardization of work environmental conditions difficult. Considering this here an attempt has been made to develop, a simple arithmetical comprehensive Indoor Work Environmental Air Quality Index (IWEAQI), in the Indian context of industries. The methodology developed here uses the framework of USEPA. The concept to determine the outdoor air quality by the USEPA is modified and used in the present methodology.

Materials and methods

For the development of IWEAQI, the method introduced by US EPA for outdoor air was considered and modified to accommodate more variables. In the US EPA method average concentration of each pollutant had been considered for index calculation using Eq. 1 [17].

$$\mathrm{Ip} = (\mathrm{Cp} - \mathrm{BPLo}) \times \frac{\mathrm{IHi} - \mathrm{ILo}}{\mathrm{BPHi} - \mathrm{BPLo}} + \mathrm{ILo} \quad (1)$$

Where,

I_p = Index value for pollutant p, C_p = Rounded concentration of pollutant p, BP_{Hi} = Higher Breakpoint value of Cp, BP_{Lo} = Lower Breakpoint value of Cp, I_{Hi} = Index Breakpoint value of BP_{Hi}, I_{Lo} = Index Breakpoint value of BP_{Lo}

Once the individual index value of each

parameter is obtained, the highest index value among them was considered for the final AQI. In this methodology effects of significant pollutants are indirectly neglected and the obtained highest numerical value is finally considered. Thus, the pollutant which has a minimum value may be considered as a good, might have no influence on AQI value. So, in this present study for developing the model, the equal weightage of all parameters is considered to determine the IWEAQI. To validate the developed model, the Pollution Index (PI) method, developed by Cannistraro [18] was considered. In the PI method, the two most critical pollutants were considered and sub-indices were calculated using Equation 2. Sub-indices are the ratio of the weighted mean of the pollutant for the observation period to the limiting value for the protection of health, further, the average of sub-indices was obtained to arrive at the index value. Here in this, the same rationale was taken, where sub-indices of the pollutants were calculated by mean observed value to limiting reference value. Further, these calculated sub-indices were considered to obtain subsequent related sub-indices and final values.

$$\mathrm{Ix} = \frac{\mathrm{Vmax}}{\mathrm{Vrif}} \times 100 \quad (2)$$

where,

Ix represents the sub-index of x^{th} pollutant, Vmax represents the average concentration of the x^{th} pollutant, Vrif represents the maximum permissible value of the x^{th} pollutant

Development of the model

Work environmental condition is largely influenced by air quality, thermal comfort, acoustic comfort and visual comfort aspects of the work area. It is necessary to identify, the most influencing parameters, which have been carried out by referring available literature. The available index and methodologies developed by various researchers have been studied. To these various influencing parameters have been selected and disintegrated into 6 subgroups like inorganic gas pollutants, organic gas pollutants, particulate matter, thermal comfort, noise and visual comforts. Inorganic gaseous pollutants included in the study were CO, CO_2, SO_2, NO_2 and O_3. Organic pollutants such as Total Volatile Organic Compounds (TVOC) and formaldehyde (HCHO) were taken into consideration. Particulate matter in the form of PM_{10} and $PM_{2.5}$ were contributing to the study. Indoor temperature is different as per the geography and function of the buildings; to overcome this wet bulb globe temperature index recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) was taken into consideration. Acoustic comfort and visual comfort were the parameters that influence the comfortable working conditions of the worker, as they largely depends on the intensity and duration for which workers were working in the area.

The model of IWEAQI was divided into four levels, the first level calculates the sub-indices of the selected pollutants, the second level is the simple arithmetical mean of the parameters taken in that group, the third level calculates two indexes namely indoor air pollution index and work comfort index, finally, in the level four IWEAQI was obtained by the average of indexes obtained in the level three. The tree structure diagram of the IWEAQI is shown in Figure 1. Sub-indices of the level 1 pollutant were calculated using Eq. 1, while indexes in levels 2, 3 and 4 are obtained by the arithmetic mean of the former indices. Final IWEAQI will obtain in the range between 0-100 and has been classified into 5 categories from excellent to very poor shown in Table 1.

Table 1. Index value and a class of IWEAQI

Index Value	IWEAQI class
0–20	Excellent
21– 40	Good
41–60	Moderate
61–80	Poor
81-100	Very Poor

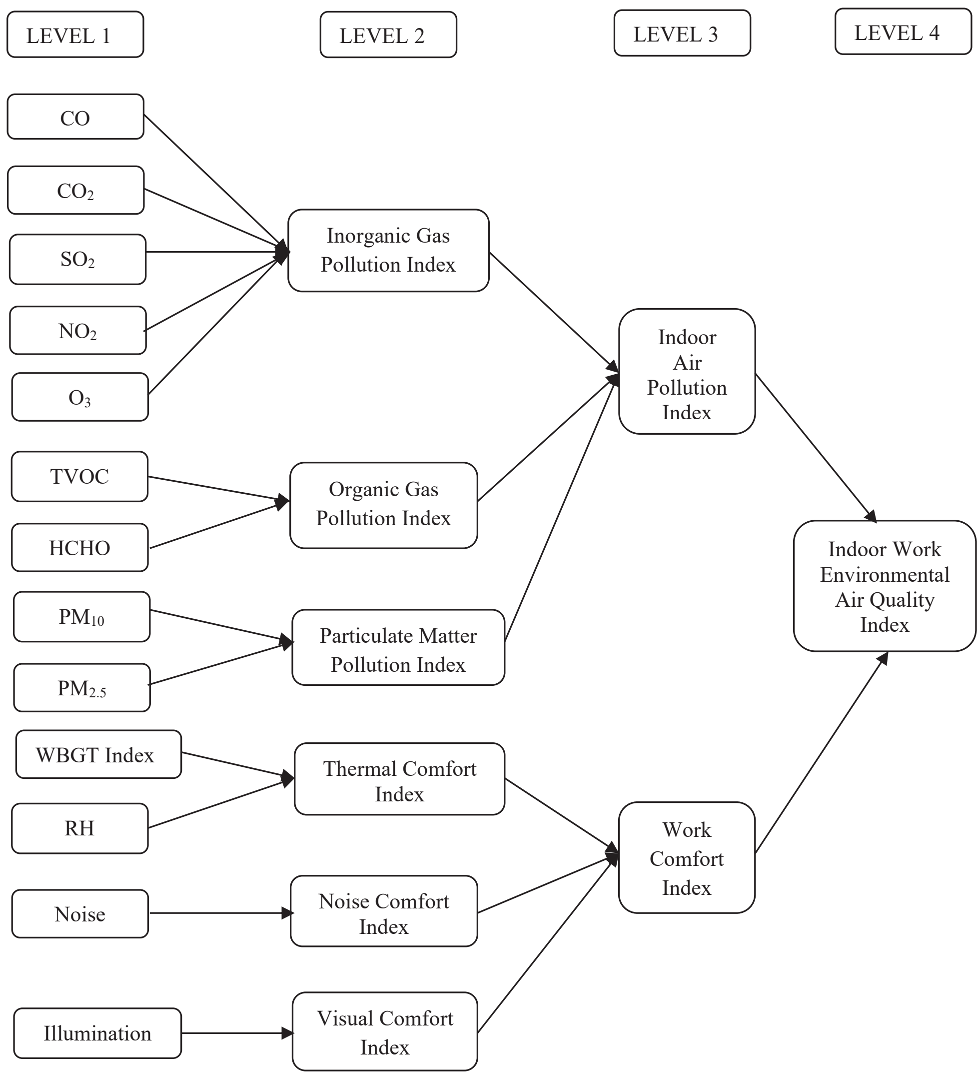


Fig. 1. Tree structure diagram of the IWEAQI

Selection of threshold limiting value

To calculate the index, it is necessary to set the maximum permissible limiting value and breakpoint value of each variable. In India, no guidelines and standards on IAQ are available to till date. So, to select maximum permissible limiting values for suggested influencing parameters, guidelines and standards of different countries and agencies like China, Hongkong, Japan, Korea, Kuwait, Malaysia, Singapore, Australia, Canada, Finland, Germany, United Kingdom (UK), Occupational Health and Safety Administration (OSHA), National Institute for Occupational Safety and Health (NIOSH), US EPA (United States Environmental Protection Agency), ACGIH has been considered in the present model, which is summarized in Table 2 [19].

Table 2. Maximum Permissible Limiting Value of influencing parameters

Agencies/ Country	CO (ppm)	CO_2 (ppm)	SO_2 (ppm)	NO_2 (ppm)	O_3 (ppm)	TVOC (ppm)	HCHO (ppm)	PM_{10} ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)	WBGT Index (^oC)	RH (%)
OSHA	50*	5000*	5*	5*	0.1*	--	0.75*	--	5000*	--	30-70
NIOSH	35*	5000*	2*	--	0.1*	--	0.016*	--	--	--	30-70
US EPA	9*	--	--	0.053*	0.08*	--	0.027*	150**	65**	--	--
ACGIH	--	5000*	2*	3*	0.1*	--	0.3*	10000*	3000*	33	--
China	8.7*	1000**	0.19#	0.13#	0.08#	0.15*	--	150**	--	--	--
Hongkong	6*	1000*	--	3*	0.061*	0.15*	0.081*	180*	--	--	40-70
Japan	10**	1000*	--	--	---	--	--	--	--	--	--
Korea	8.7*	1000*	--	0.05**	0.06*	---	0.1*	150*	--	--	--
Kuwait	8.7*	--	--	0.11#	0.1*	3*	0.12*	--	--	--	--
Malaysia	10*	1000*	--	--	0.05*	3*	--	150*	--	--	40-70
Singapore	9*	1000*	--	--	0.05*	3*	0.1*	150*	--	--	40-70
Australia	30*	5000*	0.20#	3*	--	0.12#	1*	90#	--	--	--
Canada	11*	3500*	0.02*	0.05**	0.12#	0.05*	0.04*	--	40*	--	--
Finland	1.7*	1200*	--	--	0.04*	0.087*	0.04*	20*	--	--	--
Germany	--	5000*	0.5*	0.19*	--	--	0.3*	4000*	---	--	--
UK	--	5000*	--	0.11#	0.05*	0.07*	--	--	--	--	--
WHO	8.7*	1000*	0.05**	0.1#	0.05*	--	0.081##	50**	25**	--	--

1 h average,   * 8 h average, ** 24 h average, ## 30 min average

Central Pollution Control Board (CPCB), a regulatory authority of the Government of India has formulated guidelines on allowable noise limits, which are used and presented in Table 3, in any case, it should not be more than 90dB [20]. According to IS 6665:1972 code of practice for industrial lighting recommended values of illumination should not be less than 500 lux [21]. It is a fact that some countries have derived IAQ standards considering comforts, health, concentration and regulations. From Table 2, it is seen that there is a wide variation in the guideline value set by various countries. The indoor environment of the industrial premises is highly varied compared to other indoor environments. Considering this, the highest value of the gaseous pollutant, set by various countries is considered as an acceptable maximum permissible value. WHO standards are mostly derived, considering the criteria of health and comfort. So, the reference value of PM_{10} and $PM_{2.5}$ as 50 µg/m^3 and 25 µg/m^3 (WHO standard), which was seen to be stringent to achieve, even in ambient environments. At the same time, the majority of the countries have suggested 150 µg/m^3 as a reference value for PM_{10}. So, in the present study reference value of 150 µg/m^3 is considered in place of the WHO value of PM_{10} 50 µg/m^3. Only a few countries/agencies have their permissible value of $PM_{2.5}$ for indoor air environments. So, the USEPA reference value of $PM_{2.5}$ (65 µg/m^3) has been considered in this study. Most of the countries considered the reference value as an 8-hour average value of the pollutants. So, in the present study, an 8-hour average value is considered for the further development of a breakpoint value for each class of index. The maximum allowable permissible limiting values of each pollutant selected in the study are summarized in Table 4.

Table 3. Noise standard as per CPCB

Category of area/zone	Limits in dB(A) Leq	
	Day time	Night time
Industrial	75	70
Commercial	65	55
Residential	55	45
Silence	50	40

Table 4. Maximum allowable permissible limiting value for various parameters

Parameters	Maximum allowable permissible limit	Specifying Agencies
CO	50 ppm	OSHA
CO_2	5000 ppm	OSHA
SO_2	2 ppm	OSHA
NO_2	5 ppm	OSHA
O_3	0.1ppm	OSHA
TVOC	3 ppm	DOSH, SIAQG
HCHO	0.75 ppm	OSHA
PM_{10}	150 $\mu g.m^{-3}$	USEPA
$PM_{2.5}$	65 $\mu g.m^{-3}$	USEPA
WBGT Index	33ºC	ACGIH
RH	30-70%	OSHA
Noise	90	CPCB
Illumination	500 lux (Minimum permissible value)	IS 6665

Development of breakpoints for various parameters

The IWEAQI index was evaluated in the range of 0 to 100 and further classified into five equal classes: Excellent (0-20), Good (21-40), Moderate (41-60), Poor (61-80), and Very Poor (81-100). Lower and higher breakpoint values in terms of concentration had been formulated for each class of AQI in the USEPA method. In this study, the maximum permissible value of each parameter is represented in Table 4. It is further split into lower and upper breakpoint values for each class. In general, there is no concrete mechanism available for selecting a breakpoint or class for the most influencing parameters. The equal class might cause unevenness in significant output generation. Hence to determine upper and lower breakpoints of influencing parameters were determined based on the expert's opinion and judgment. Academicians, researchers and consultants working in the field of air quality were considered as an expert. Experts were contacted through email and asked to define breakpoints for each index class as per their perceptions and experience. The opinion was obtained in terms of the range of the class. The reported value of the class given by various experts is averaged out. The breakpoint value obtained from experts for each influencing parameter has been summarized in Table 5.

Table 5. Breakpoint table for indoor environment parameters

Index Class	Excellent	Good	Moderate	Poor	Very Poor
Index Value	0-20	21-40	41-60	61-80	81-100
CO (ppm)	0-9.00	9.1-15.0	15.1-25.0	25.1-35.0	35.1-50.0
CO_2 (ppm)	0-1000	1001-2000	2001-3000	3001-4000	4001-5000
SO_2 (ppm)	0-0.30	0.31-0.70	0.71-1.10	1.11-1.50	1.51-2.00
NO_2 (ppm)	0-0.75	0.76-1.50	1.51-2.50	2.51-3.50	3.51-5.00
O_3 (ppm)	0-0.02	0.03-0.04	0.05-0.06	0.07-0.08	0.09-0.1
TVOC (ppm)	0-0.50	0.51-1.10	1.11-1.70	1.71-2.40	2.41-3.00
HCHO (ppm)	0-0.10	0.11-0.20	0.21-0.45	0.46-0.60	0.61-0.75
PM_{10} (µg/m^3)	0-25	25.1-50	50.1-80	80.1-110	110.1-150
$PM_{2.5}$ (µg/m^3)	0-10	10.1-20	20.1-30	30.1-45	45.1-65
WBGT (°C)	0-10.0	10.1-20.0	20.1-25.0	25.1-28.0	28.1-33.0
Humidity (%)	30-50	50.01-70	70.01-80	80.01-90	90.01-100
Noise (dB)	0-30	31-60	61-70	71-80	81-90
Illumination (Lux)	701-1000	501-700	301-500	151-300	0-150

Study area and data collection

In the present study, an attempt had been made to evaluate the IWEAQI for the textile dyeing and printing processing house of the textile city Surat of India. The decision to focus on this sector was made because Surat is a major centre for the production of synthetic fabrics, where 20–25% of the city's population is engaged in this sector. About 400 dyeing and printing processing units are operated in the various industrial estate of the city. The dyeing and printing industry is a labour-intensive small-scale industry. The majority of units are utilizing poor-quality of fuel like coal, which is used to generate steam. A variety of pollutants like PM, SOx and NOx are emitted as the coal utilized in the boiler. At the same time, typical adhesives are used in the dyeing process for making dyeing and printing operations more effective. Limited space of the units and poor ventilation facilities make the dispersion of the pollutants more complicated. Finally, it deteriorates the indoor as well as outdoor air quality. The instruments used to monitor the influencing parameters are summarized in Table 6.

Table 6. Instruments used for the monitoring

Parameter	Instrument used	Name of the Manufacturer	QA/QC
NBT, DBT, GT, RH	QuestTemp36	TSI Incorporated, USA	ISO 7243 and ISO 7726
NBT, DBT, GT, RH	Tenmars 188D	Tenmars. Taiwan	ISO 7243 and ISO 7726
Air velocity	KM 732 (Hot wire anemometer)	Kusam-Meco, India	Resolution 0.01m/s
Formaldehyde	CAIR monitor	Parna air, India	Resolution 0.01 ppm, record observation at a 5 s interval
CO, CO_2, SO_2, NO_2, O_3, PM_{10}, $PM_{2.5}$	Sensor-based Indoor air quality analyzer	Parna air, India	Resolution 0.01 ppm, record observation at a 5 s interval
Noise	Sound level meter KM 8080MK-1	Kusam-Meco, India	Resolution 0.1 dB, accuracy ±1.5dB
Illumination	Lux meter KM-203	Kusam-Meco, India	Resolution 0.01 lux, accuracy ±3%

Considering the manufacturing process, data on the selected parameters were recorded at five locations namely the Jet dyeing Machine area (JM), Stenter Machine area (SM), Looping Machine area (LM), Printing Machine area (PM) and Washing Basin area (WB) for all three seasons. The monsoon period was considered from August to September, winter from December to January and summer from April to May. Observations of selected parameters were recorded at an interval of one minute. Instruments were placed at a height of 1.2 m, which is the average height above the abdominal level in humans. Monitoring was carried out for the day shift (8 AM to 8 PM) and night shift (8 PM to 8 AM). Data had been recorded at minute intervals for continuous five days in each season at every location. Total 3600 observations were available in each season per shift at selected locations. The average and standard deviation of observed parameters at all five locations is presented in Table 7. For illumination, observations were taken only during the daytime, as during night time all the activities were performed in the availability of an artificial light source.

Table 7. Statistical analysis of observed data

Variable	Location	Monsoon		Winter		Summer	
		Day (N= 3600)	Night (N=3600)	Day (N=3600)	Night (N=3600)	Day (N=3600)	Night (N=3600)
$PM_{2.5}$ (μg/m^3)	JM	86.88±44.04	138.16±48.04	202.82±76.39	273.58±116.89	79.97±65.08	76.34±43.32
	LM	318.7±196.6	289.7±168.2	172.0±113.2	186.6±102.4	174.6±143.3	157.0±101.3
	SM	188.1±165.2	214.1±102.9	193.4±173.5	197.5±98.9	618.8±262.9	535.9±245.9
	PM	268.0±248.8	305.1±272.5	208.8±130.6	282.7±128.9	143.3±73.5	139.9±79.3
	WB	172.2±144.0	215.9±146.3	173.2±80.6	165.4±63.6	105.4±89.6	144.6±117.2
PM_{10} (μg/m^3)	JM	100.14±51.93	160.19±56.13	233.85±88.30	315.14±131.39	95.35±85.04	89.57±53.01
	LM	348.3±209.9	309.8±167.3	201.2±136.4	215.8±115.8	202.4±162.3	188.0±127.6
	SM	215.5±187.4	248.0±121.3	222.3±188.2	229.3±114.4	675.6±260.4	596.3±249.5
	PM	299.3±262.7	337.8±283.3	244.7±160.3	331.9±154	166.5±86.20	161.9±89.70
	WB	204.5±169.8	259.7±179.9	200.2±94.3	192.3±75.9	123.7±105.4	168.7±135.9
CO_2 (ppm)	JM	458.28±43.21	518.47±89.74	375.03±165.83	224.06±222.60	522.16±195.29	625.39±295.16
	LM	258.00±66.18	269.49±63.48	501.6±99.7	529.3±72.7	499.2±60.1	501.4±49.9
	SM	447.5±32.8	454.0±29.1	505.0±87.1	561.5±71.8	339.6±111.4	564.8±135.5
	PM	556.6±139.0	558.8±135.20	490.1±164.4	524.3±160.8	510.5±99.2	495.2±62.0
	WB	471.4±49.6	525.6±67.2	528.3±58.0	535.2±56.4	541.2±266.1	517.2±170.2
SO_2 (ppm)	JM	0.03±0.13	0.19±0.38	1.67±3.49	0.30±0.52	0.00±0.03	0.01±0.20
	LM	1.07±1.60	1.37±1.59	0.10±0.36	0.18±0.32	2.34±1.14	2.31±1.31
	SM	0.26±1.52	0.09±0.59	0.22±0.70	0.31±0.45	0.00±0.00	0.00±0.00
	PM	1.01±3.40	1.64±4.48	0.01±0.06	0.07±0.18	0.96±2.93	2.85±6.64
	WB	0.06±0.98	0.11±0.86	0.27±0.51	0.58±0.50	0.25±1.56	0.00±0.06
NO_2 (ppm)	JM	1.32±0.04	1.31±0.03	15.77±12.53	21.59±11.45	1.50±0.52	1.46±0.15
	LM	25.19±2.84	24.80±2.99	1.30±0.59	1.25±0.06	4.71±7.04	3.54±5.46
	SM	2.13±0.86	1.85±0.16	1.36±0.90	1.31±0.05	22.23±5.01	23.88±4.33
	PM	16.41±11.54	14.23±11.98	1.34±0.03	1.34±0.05	2.03±2.48	4.17±6.79
	WB	1.41±0.80	1.33±0.21	1.48±0.18	1.44±0.20	2.22±1.85	4.29±6.96
CO (ppm)	JM	0.00±0.05	0.01±0.05	0.30±0.69	0.24±0.46	0.00±0.01	0.00±0.03
	LM	0.08±0.25	0.09±0.26	0.14±0.42	0.52±0.76	0.00±0.00	0.00±0.04
	SM	0.14±0.41	0.30±0.72	0.18±0.46	0.27±0.56	0.00±0.01	0.00±0.03
	PM	0.31±1.42	0.38±1.58	0.02±0.11	0.05±0.19	0.03±0.36	0.11±1.03
	WB	0.02±0.13	0.09±0.32	0.32±0.68	0.88±0.82	0.00±0.02	0.01±0.17

Table 7. Statistical analysis of observed data

Variable	Location	Monsoon		Winter		Summer	
		Day (N= 3600)	Night (N=3600)	Day (N=3600)	Night (N=3600)	Day (N=3600)	Night (N=3600)
O_3 (ppm)	JM	0.13±0.01	0.13±0.02	11.36±11.13	17.19±9.86	0.07±0.31	0.07±0.12
	LM	20.16±2.61	19.78±2.74	0.12±0.04	0.10±0.02	2.60±5.79	1.60±4.42
	SM	0.08±0.03	0.07±0.03	0.14±0.05	0.13±0.01	17.39±4.58	18.95±3.96
	PM	12.14±10.10	10.38±10.30	0.12±0.02	0.13±0.02	0.91±0.67	0.24±1.63
	WB	0.06±0.48	0.05±0.17	0.12±0.03	0.11±0.03	0.08±0.08	2.19±5.85
TVOC (ppm)	JM	0.60±0.90	0.41±0.74	0.75±0.63	0.77±0.63	1.49±0.88	1.50±0.87
	LM	2.77±1.59	2.76±1.57	1.17±2.03	1.71±2.56	1.82±1.11	1.75±1.07
	SM	0.43±0.64	0.39±0.67	0.82±1.52	2.42±3.37	1.84±1.25	1.64±1.16
	PM	1.07±2.44	1.52±2.80	1.34±2.34	2.10±3.07	5.67±3.48	5.67±3.49
	WB	1.52±1.99	0.72±1.09	1.19±2.01	0.77±1.27	0.68±1.06	0.56±0.89
HCHO (ppm)	JM	0.02±0.02	0.03±0.06	0.02±0.04	0.02±0.00	0.47±0.32	0.15±0.09
	LM	0.12±0.23	0.09±0.14	0.05±0.08	0.06±0.06	0.11±0.41	0.04±0.06
	SM	0.18±0.18	0.20±0.18	0.15±0.19	0.27±0.39	0.62±.0.36	0.46±0.26
	PM	0.80±0.95	0.69±0.89	0.06±0.32	0.11±0.52	0.40±0.83	0.38±1.19
	WB	0.06±0.21	0.05±0.13	0.03±0.07	0.02±0.02	0.04±0.13	0.03±0.02
WBGT (ºC)	JM	28.80±1.45	27.18±1.46	25.17±1.11	22.61±0.81	29.91±1.67	29.71±1.36
	LM	31.45±0.77	30.3±1.00	27.1±2.3	26.8±1.5	36.6±1.7	36.9±1.8
	SM	32.3±5.2	31.4±4.2	25.3±2.3	23.9±1.9	35.0±1.3	34.6±1.8
	PM	37.7±2.6	37.2±3.1	28.0±2.0	25.0±1.3	35.1±0.8	33.8±0.7
	WB	32.6±3.2	30.7±2.8	25.1±2.2	23.0±1.9	32.6±2.1	29.5±1.6
RH (%)	JM	41.94±8.54	50.95±7.94	60.67±11.49	64.12±11.73	79.36±11.24	79.04±12.70
	LM	37.70±5.20	36.3±4.6	47.2±5.4	51.1±6.6	57.4±8.1	55.3±9.4
	SM	53.2±5.3	60.0±4.1	43.5±5.2	46.4±6.1	54.8±10.0	59.6±7.1
	PM	43.7±3.7	45.8±3.2	43.3±4.7	50.5±1.8	61.0±6.0	68.4±3.5
	WB	48.3±8.4	56.9±7.4	46.8±5.1	48.9±6.6	42.1±8.1	50.7±11.8
Noise (dB)	JM	82.3±2.95	79.8±1.67	85.7±3.91	83.9±3.63	83.8±2.22	83.0±2.56
	LM	76.9±1.96	74.3±1.21	78.2±1.82	78.6±1.30	77.4±1.32	77.0±1.09
	SM	86.8±4.34	82.4±3.76	88.1±3.39	88.6±2.95	84.9±2.15	83.8±2.68
	PM	85.8±5.04	84.6±3.96	87.8±2.48	87.5±2.09	86.2±2.47	86.3±1.79
	WB	75.4±2.55	73.2±1.78	81.1±2.76	78.4±6.12	80.2±2.70	79.5±2.55

Table 7. Statistical analysis of observed data

Variable	Location	Monsoon		Winter		Summer	
		Day (N= 3600)	Night (N=3600)	Day (N=3600)	Night (N=3600)	Day (N=3600)	Night (N=3600)
Illumination (Lux)	JM	56±10.76	--	40±9.6	--	73±18.72	--
	LM	92±5.98	--	83±3.27	--	98±10.77	--
	SM	98±7.32	--	86±5.76	--	109±12.09	--
	PM	105±15.07	--	90±13.09	--	123±20.39	--
	WB	77±18.07	--	67±11.23	--	96±19.48	--
Air Velocity (m/s)	JM	0.32±0.31	0.28±0.19	0.27±0.19	0.30±0.19	0.54±0.41	0.49±0.36
	LM	0.19±0.24	0.13±0.19	0.36±0.24	0.35±0.26	0.25±0.18	0.25±0.19
	SM	0.71±0.35	0.82±0.27	0.24±0.26	0.26±0.28	0.56±0.33	0.59±0.35
	PM	0.55±0.33	0.57±0.33	0.50±0.4	0.65±0.56	0.95±0.57	0.94±0.56
	WB	0.31±0.29	0.33±0.29	0.25±0.24	0.24±0.26	0.54±0.31	0.54±0.33

Results and discussion

In the present study, parameters influencing IAQ were monitored at a one-minute interval using a real-time monitoring system. This is because the change and nature of the pollutants varied drastically in indoor space, at selected locations in the dyeing and printing industry. The obtained results of all influencing parameters were used to determine sub-indices in level 1 for IWEAQI, with the proposed methodology considering the USEPA formula referring to Eq. 1.

Here it is noted that for all influencing parameters, the higher value of parameters is related to the higher class of index value, which has been categorized as poor work environmental conditions. But in the case of illumination, a higher class value is related to better work environmental conditions, so a higher value of illumination has been related to a lower index value. While calculating the final index value, illumination sub-indices obtained using Eq. 1 were deducted from the IHi of that index class. Further, it is added to the ILo of the same index class to get the correct sub-indices value. Sub-indices obtain in level 2 to 4 in both methods is the arithmetical mean of the former sub-indices. A sample calculation for the final IWEAQI value for a set of observations, obtained with the USEPA formula is represented in Table 8.

It has been observed that monitoring parameters considered for the calculation of index value may exceed the maximum permissible limit of parameters. In such cases, the sub-indices value in level 1 is considered as 100 (i.e. maximum index value) for calculation as considered in Table 8 (sub-index level 1 of O_3 and $PM_{2.5}$. Sample calculation for a set of observations with the PI method is shown in Table 9. For the calculation of level 1 sub-indices equation 2 was used. For the calculation of illumination sub-indices obtained by dividing the observed value with maximum permissible value was deducted from 100%, to obtain the correct sub-indices.

Table 8. Sample calculation IWEAQI using the USEPA method

Parameters	Observed Value	Sub Index Level-1	Sub Index Level-2	Sub Index Level-3	IWEAQI Level-4
CO (ppm)	1.93	4.28	36.83	48.77	57.50
CO_2 (ppm)	485.32	9.71			
SO_2 (ppm)	0.60	35.03			
NO_2 (ppm)	1.32	35.15			
O_3 (ppm)	0.13	100.00			
TVOC (ppm)	0.57	22.27	13.79		
HCHO (ppm)	0.03	5.31			
PM_{10} (μg m^{-3})	132.76	91.38	95.69		
$PM_{2.5}$ (μg m^{-3})	114.69	100.00			
WBGT (°C)	27.80	87.00	51.17	66.22	
RH (%)	45.34	15.34			
Noise (dB)	82	84.00	84.00		
Illumination (Lux)	315	63.50	63.50		

Table 9.Sample calculation IWEAQI using the PI method

Parameters	Observed Value	Sub Index Level-1	Sub Index Level-2	Sub Index Level-3	IWEAQI Level-4
CO (ppm)	1.93	3.85	33.99	46.49	62.26
CO_2 (ppm)	485.32	9.71			
SO_2 (ppm)	0.60	30.03			
NO_2 (ppm)	1.32	26.36			
O_3 (ppm)	0.13	100.00			
TVOC (ppm)	0.57	18.94	11.24		
HCHO (ppm)	0.03	3.54			
PM_{10} (μg/m^3)	132.76	88.50	94.25		
$PM_{2.5}$ (μg/m^3)	114.69	100.00			
WBGT (°C)	27.80	84.24	74.50	78.04	
RH (%)	45.34	64.77			
Noise (dB)	82	91.11	91.11		
Illumination (Lux)	315	68.50	68.50		

The index value obtained by both methods is finally in the range of 0-100. So, both methods were appropriate for the development and calculation of IWEAQI. The index value obtained by both methods was compared and represented graphically. Fig. 2 to 6 represents the graphical variation of index value obtained by the developed model and PI method at various locations in the industry.

IWEAQI obtained with modified USEPA methods was ranging between 47.78-60.92, while it was ranging between 47.28-62.32 with the PI method. So, work environmental condition at the jet dyeing machine area was observed moderate to poor.

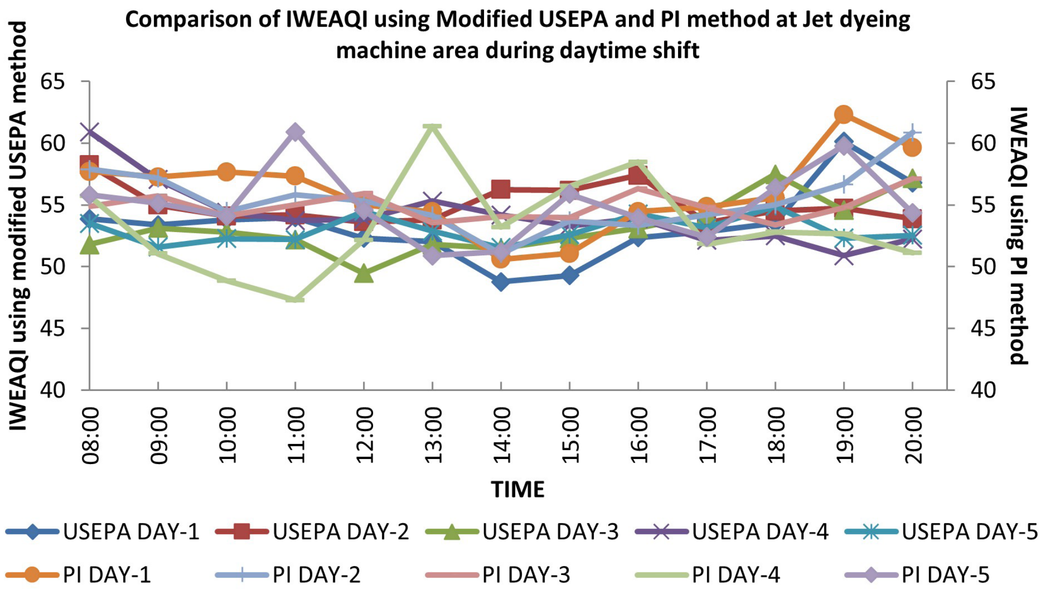


Fig. 2. Comparison of IWEAQI obtained using modified USEPA and PI methods at jet dyeing machine area

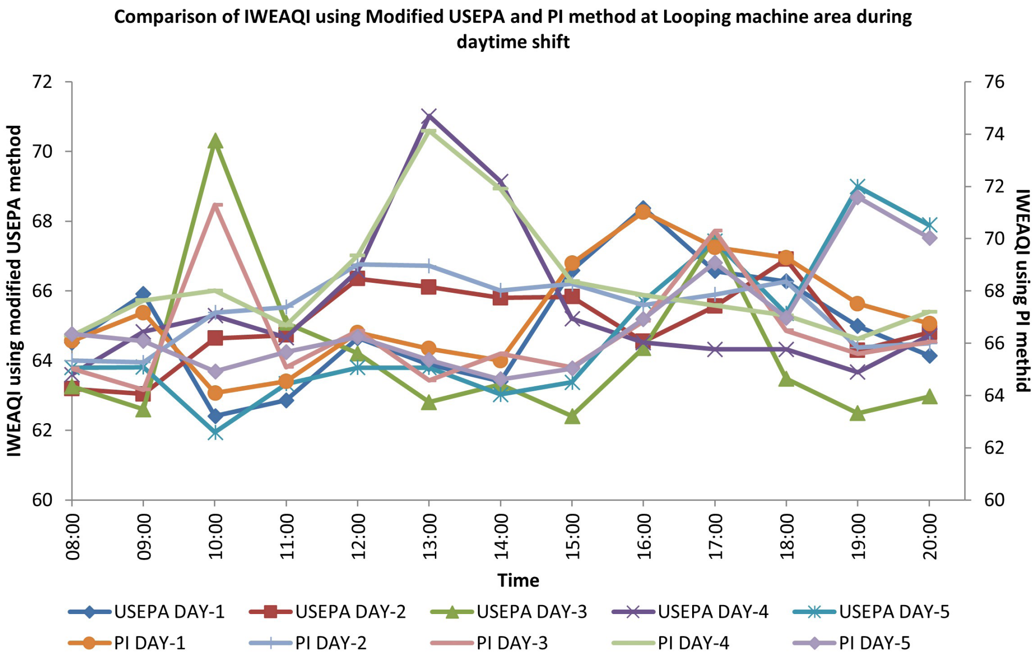


Fig. 3. Comparison of IWEAQI obtained using modified USEPA and PI methods at looping machine area

IWEAQI obtained with modified USEPA methods was in the range of 57.02-71.02, and with the PI method it was in the range of 59.54-74.12. It reflected that work environmental condition at the looping machine area was also moderate to poor.

IWEAQI obtained with modified USEPA methods was in the range of 47.63-64.09, and with the PI method it was in the range of 48.82-66.34. It reflected that work environmental condition at the stenter machine area was also observed moderate to poor.

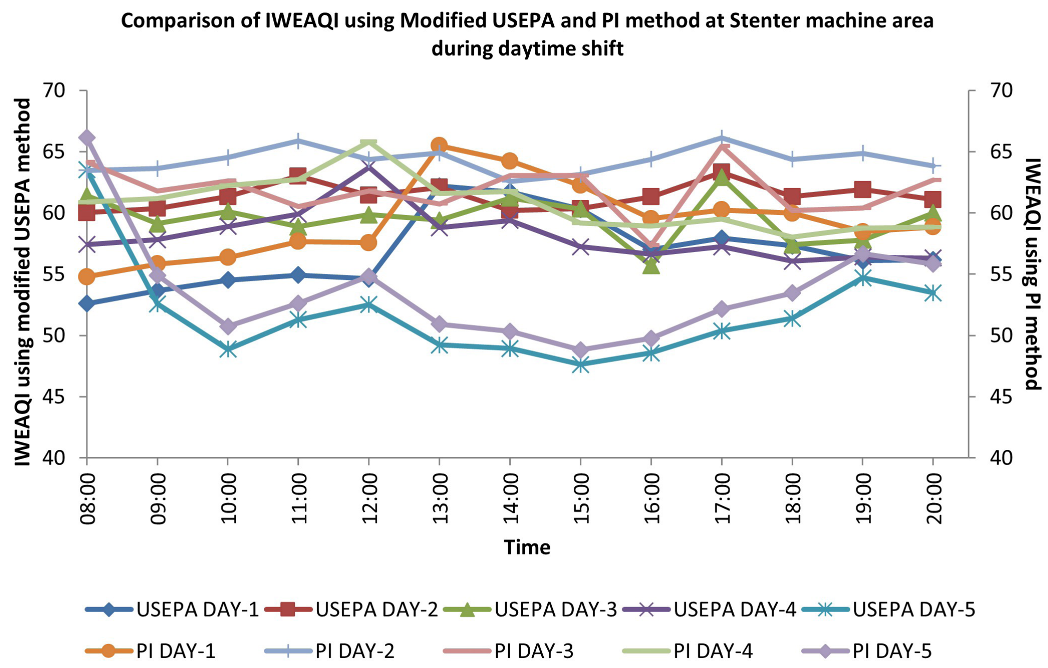


Fig.4. Comparison of IWEAQI obtained using modified USEPA and PI methods at the stenter machine area

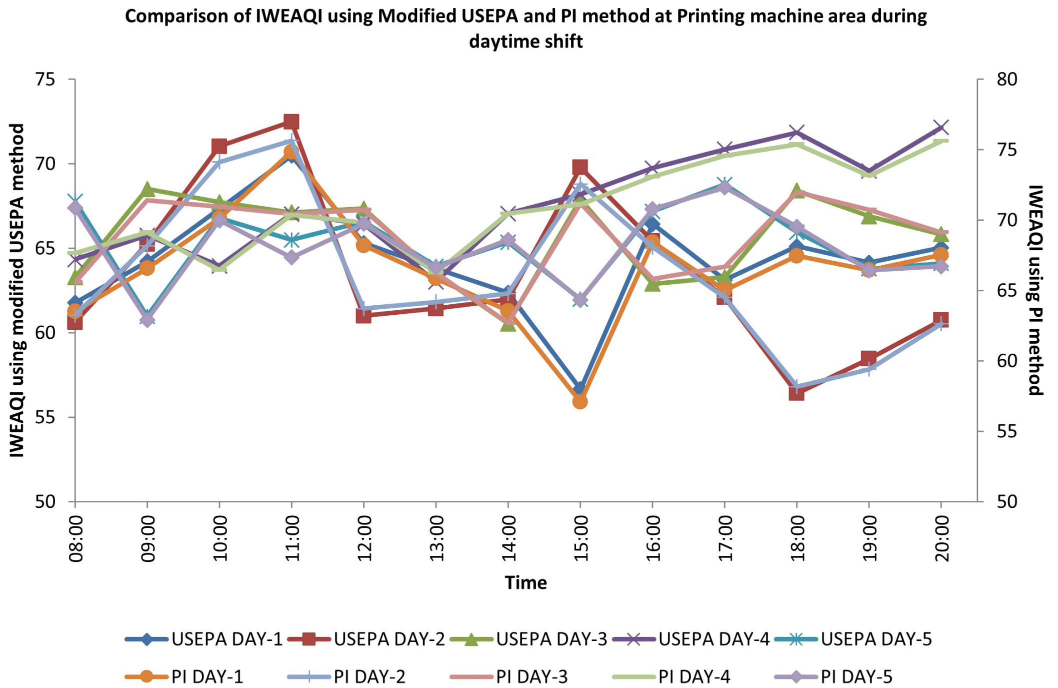


Fig. 5. Comparison of IWEAQI obtained using modified USEPA and PI methods at printing machine area

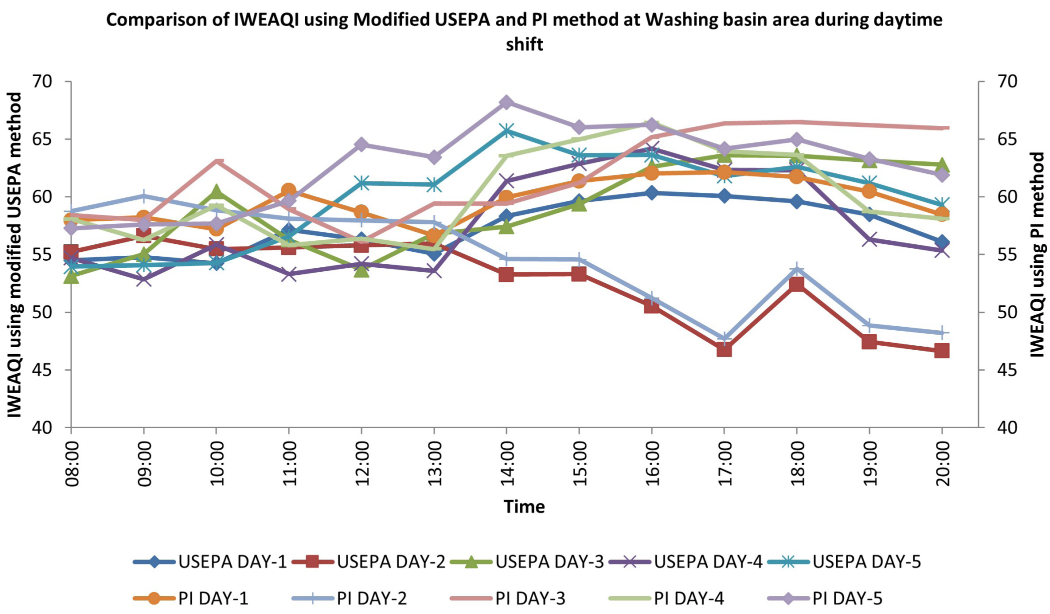


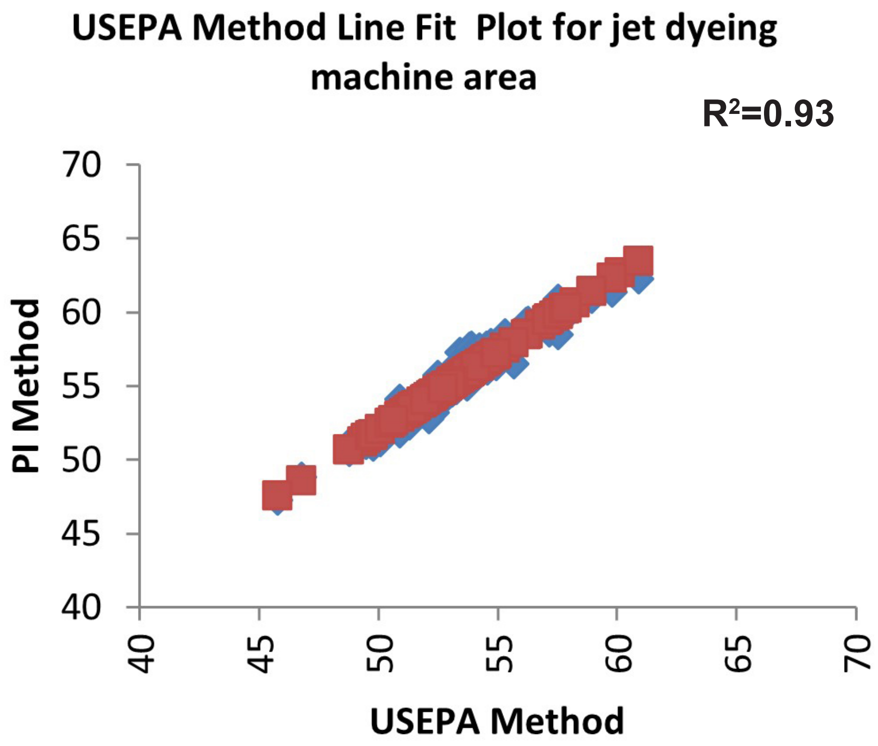
Fig. 6. Comparison of IWEAQI obtained using modified USEPA and PI methods at washing basin area

IWEAQI obtained with modified USEPA methods was in the range of 56.42-76.17, and with the PI method it was in the range of 57.09-80. It reflected that work environmental condition in the printing machine area was also observed moderate to poor.

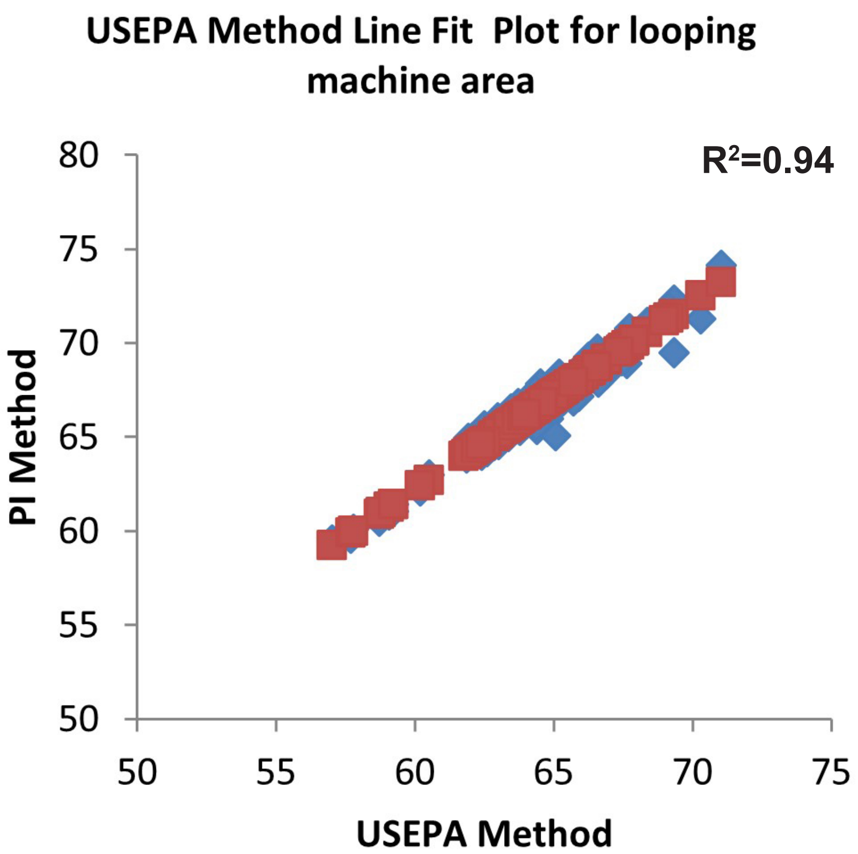
IWEAQI obtained with modified USEPA methods was in the range of 46.52-65.71, and with the PI method it was in the range of 47.70-68.20. It reflected that work environmental condition at the washing basin area was also observed moderate to poor.

It has been observed that IWEAQI is significantly influenced by temperature, humidity and various types of chemicals used in the process. The temperature variation at various locations in the dyeing and printing industries was observed in the sequence of looping machine area > printing machine area > stenter machine area > washing basin area > jet dyeing machine area. Dyeing and printing is a chemical-dominating process, where a maximum amount of chemicals, solvents, adhesives and dyes has been used, whereas, in the looping machine process, no chemicals were used. At the same time in a washing area during the process, chemicals are used in a hot water bath to remove the excess chemicals and dyes. So, the volatilization of chemicals has been reported in the sequence of trend as looping machine area > printing machine area > washing basin area. Due to the combined effects of temperature and volatilization looping machine area has been determined with a high IWEAQI value. From the observed IWEAQI value, it has been analyzed that a good working environment was observed in the sequence of jet dyeing machine area < stenter machine area < washing basin area < looping machine area < printing machine area.

Referring to Figs. 2 to 6, it has been observed that the index value obtain by both methods follows the same trend. Further to check whether both methods follow a similar trend and to verify the closeness of both methods, regression analysis was also done, which is represented in Figs. 7a to 7e. The obtained R^2 value was in the range of 0.93 to 0.99 indicating the strong association between both methods.

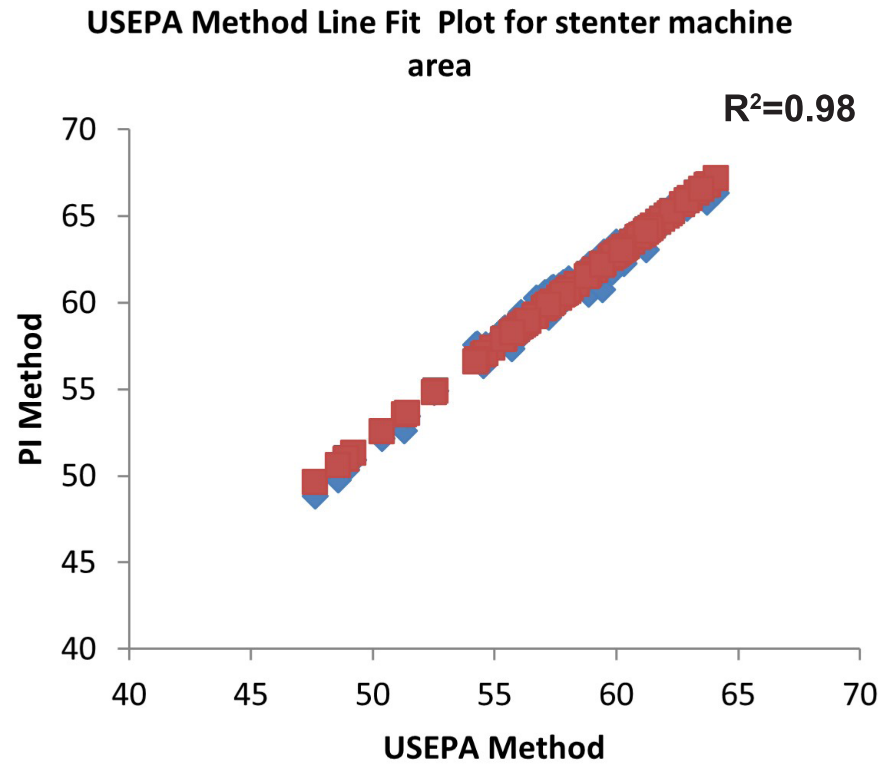


a) Best fit curve at jet dyeing machine area

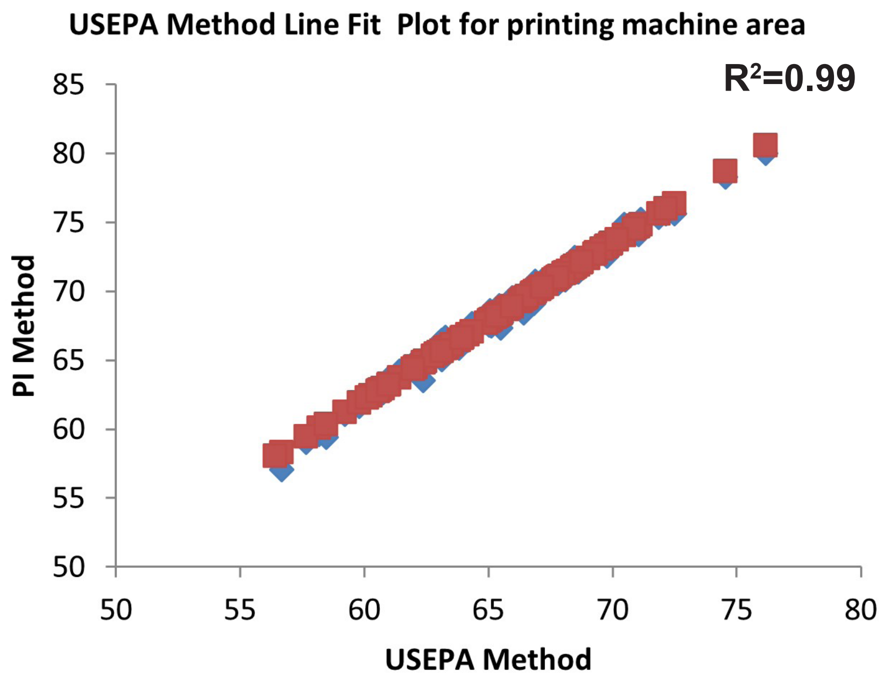


b) Best fit curve at looping machine area

Fig. 7. Regression analysis plot between USEPA and PI method

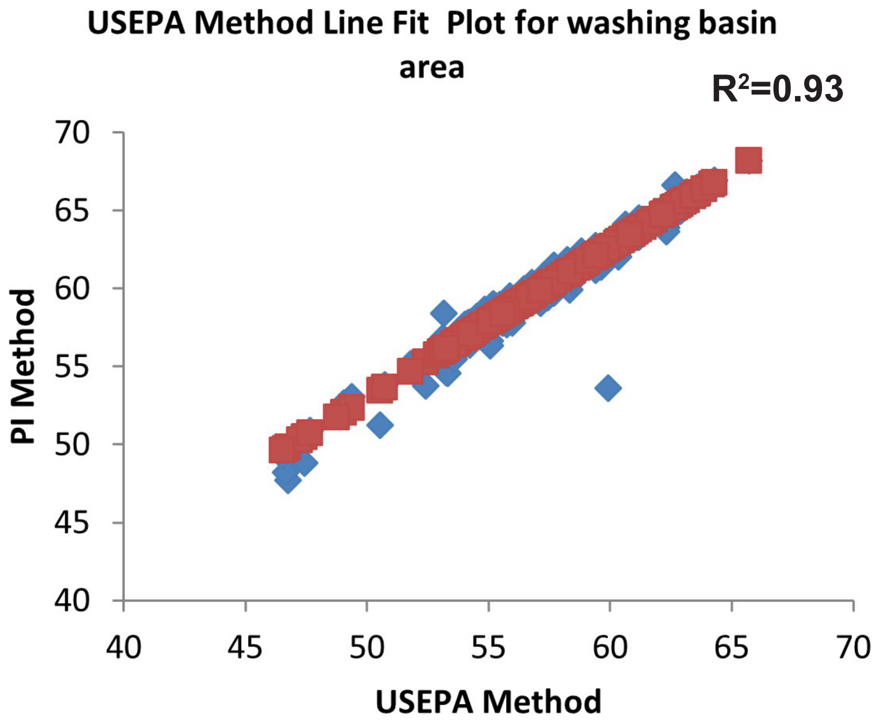


c) Best fit curve at stenter machine area



d) Best fit curve at printing machine area

Fig. 7. Regression analysis plot between USEPA and PI method



e) Best fit curve at washing basin area

Fig. 7. Regression analysis plot between USEPA and PI method

It is worth noting that the majority of the countries are still on the path of developing IAQ guidelines. Still, it will take a long time to prepare the regulatory guidelines for an industrial environment. In the present study, significant influencing parameters for indoor work environments have been considered by referring to available literature and methodology worldwide. Thus, the present study fulfils the criteria to conceptualize the guidelines for work environmental conditions in an industrial environment.

Conclusion

In the present work, an attempt has been made, to develop IWEAQI for the dyeing and printing industry in a small-scale industrial cluster in a developing nation context. To develop the IWEAQI framework, the USEPA AQI method was taken into consideration, which was slightly modified to accommodate indoor air quality influencing parameters and comfort parameters. The developed framework was used to calculate index values in the range of 0-100. The obtained index value was further validated with the PI method. By both methods, IWEAQI was obtained in the range of 46–80, which was falling under the class of moderate to poor. Both methods show a close association in terms of the index value, which indicates various parameters selected in the present research work are significantly influencing the IWEAQI. The obtained regression values in the range of 0.93-0.99, indicates strong cohesion between the two methods. The index value from the present study strongly reveals that indoor air quality, thermal comfort, acoustic level and visual aspect affect the work environmental condition in an industrial environment. Sub-indices calculation reflects the area where the major focus is required to take effective steps for further improvement. Thus, the developed methodology can be used as a strong and effective tool for managing overall work environmental conditions for industries.

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Competing interests

The authors declare no conflicts of interest concern with this study.

Author's contributions

All authors equally contributed to the study's conception and design. Manuscript preparation, data collection, and analysis were performed by D.V. Jariwala. The first draft of the manuscript was written by D. V. Jariwala. Dr R. A. Christian gave critical comments and revised the manuscript. Both authors read and approved the final manuscript.

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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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