



**AN INTEGRATED INDOOR AIR QUALITY  
MONITORING SYSTEM WITH POLLUTANTS  
RECOGNITION AND ENHANCED INDOOR AIR  
QUALITY INDEX**

by

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My parents and my wife.

This is for you.

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## TABLE OF CONTENTS

	<b>PAGE</b>
<b>THESIS DECLARATION</b>	<b>i</b>
<b>ACKNOWLEDGEMENT</b>	<b>ii</b>
<b>TABLE OF CONTENTS</b>	<b>iv</b>
<b>LIST OF FIGURES</b>	<b>ix</b>
<b>LIST OF TABLES</b>	<b>xii</b>
<b>LIST OF ABBREVIATIONS</b>	<b>xiv</b>
<b>ABSTRAK</b>	<b>xviii</b>
<b>ABSTRACT</b>	<b>xix</b>
<b>CHAPTER 1 INTRODUCTION</b>	
1.1 Introduction	1
1.2 Problem Statement	3
1.3 Research Objectives	7
1.4 Research Scopes	7
1.5 Research Contributions	9
1.6 Thesis Outline	10
<b>CHAPTER 2 BACKGROUND AND LITERATURE REVIEW</b>	
2.1 Introduction	12
2.2 IAQ Authorities and Standards	13
2.2.1 IAQ in Malaysia	15
2.2.2 IAQ in Hong Kong	17

2.3	Factors Affecting IAQ	18
2.3.1	Physical Conditions	19
2.3.1.1	Temperature	19
2.3.1.2	Relative Humidity	20
2.3.1.3	Air Movement	20
2.3.2	Poor Ventilation System	21
2.3.3	Radiation	21
2.3.4	Other Common Indoor Air Contaminants	22
2.3.4.1	Chemical Contaminants	22
	➤ Second-Hand Tobacco Smoke	22
	➤ Ozone	23
	➤ Volatile Organic Compounds	23
	➤ Formaldehyde	23
	➤ Combustion Gases	24
	➤ Carbon Monoxide	24
	➤ Nitrogen Dioxide	24
	➤ Carbon Dioxide	24
	➤ Oxygen	25
2.3.4.2	Biological Contaminants	25
2.3.4.3	Dust Particle	26
2.4	Health Effects Due to Poor IAQ	27
2.5	Related Research in IAQMS Development	29
2.5.1	Single vs. Multiple Sensors	29
2.5.2	Size and Cost	31
2.5.3	Wireless Monitoring Devices	32

2.5.4	Air Quality Index	35
2.5.5	Other Features	39
2.5.6	Summary	43

## **CHAPTER 3 SYSTEM ARCHITECTURE**

3.1	Introduction	44
3.2	Selection of IAQ Parameters	46
3.3	Overview on System Architecture	48
3.4	Sensor Module	49
3.4.1	Sensor Components	51
3.4.1.1	Sensors Selection	54
3.4.2	Microcontroller	61
3.4.3	Wireless Transceiver	63
3.5	Base Station	65
3.6	Service-Oriented Client	67
3.7	Calibration and Validation	69
3.8	Cost Analysis	73
3.9	Summary	75

## **CHAPTER 4 RECOGNITION OF SOURCES INFLUENCING INDOOR AIR POLLUTION BASED ON SUPERVISED MACHINE LEARNING**

4.1	Introduction	76
4.2	Sources of Indoor Air Pollution	77
4.3	Experiment Setup and Data Collection	79
4.4	Sensor Response	81

4.5	Steps in Pattern Recognition	84
4.6	Data Pre-processing	85
4.6.1	Baseline Manipulation	86
4.6.2	Normalization	87
4.6.3	Compression	88
4.6.4	Selection of Data Pre-processing Techniques	88
4.7	Dimensionality Reduction Stage	89
4.7.1	Dimensionality Reduction for RW Feature	92
4.7.2	Dimensionality Reduction for All Features	93
4.7.3	PCA Visualisation	94
4.8	Supervised Machine Learning Analysis for Pattern Recognition	98
4.8.1	Multilayer Perceptron	99
4.8.1.1	MLP Classifier	102
4.8.2	K-Nearest Neighbour	108
4.8.2.1	KNN Classifier	110
4.8.3	Linear Discriminant Analysis	114
4.8.3.1	LDA Classifier	117
4.9	Overall Result of MLP, KNN and LDA	119
4.10	Classification on Multiple Sources of IAP	123
4.11	Summary	127

## **CHAPTER 5 DEVELOPMENT OF PROPOSED ENHANCED INDOOR AIR QUALITY INDEX**

5.1	Introduction	128
5.2	Air Quality Index	129



5.2.1	IAQI – EPA based Calculation	131
5.3	Thermal Comfort Index	134
5.4	Proposed Breakpoint Table	134
5.5	Smell Index	139
5.5.1	Category of Smell	139
5.5.2	Smell Sample	140
5.5.3	Smell Classification Based on IAQ Sensors	141
5.6	Enhanced Indoor Air Quality Index	144
5.6.1	Application of EIAQI in Controlled Environment	146
5.6.2	Application of EIAQI in Real Environment	152
5.7	Summary	154
<b>CHAPTER 6 CONCLUSION AND FUTURE WORKS</b>		
6.1	Conclusion	155
6.2	Limitation and Future Research	158
<b>REFERENCES</b>		160
<b>APPENDIX A</b>		168
<b>APPENDIX B</b>		170
<b>APPENDIX C</b>		171
<b>APPENDIX D</b>		179
<b>APPENDIX E</b>		184
<b>LIST OF PUBLICATIONS</b>		189

## LIST OF FIGURES

NO		PAGE
1.1	Research laboratory that similar to standard office environment	8
2.1	Overview of literature review	13
3.1	Research methodology	45
3.2	Proposed system configuration for real-time IAQ monitoring	48
3.3	Block diagram of the sensor module	49
3.4	Flow chart of microcontroller algorithm	50
3.5	Prototype of sensor module	51
3.6	Sensor structure of MOX sensor	53
3.7	Sensor structure of electrochemical gas sensor	54
3.8	CDM4161A module	56
3.9	MiCS-2610 sensor with basic measuring circuit	57
3.10	TGS2602 sensor with basic measuring circuit	58
3.11	KE-50 sensor	59
3.12	Dust sensor with internal schematic	60
3.13	HSM-20G module	60
3.14	Block diagram of STC12C5A60S2	61
3.15	IRIS mote	63
3.16	Flow chart of the transceiver algorithm	65
3.17	Block diagram of base station	66
3.18	Software structure of service-oriented client	67
3.19	GUI front-end for of proposed IAQMS	68
3.20	Calibration setup	69

3.21	Scatterplot of CO <sub>2</sub> sensor calibration	70
3.22	NO <sub>2</sub> data	71
3.23	Temperature data	72
3.24	RH data	72
4.1	Room setup for the experiment	79
4.2	Data collection procedures	80
4.3	Sensors response for ambient air	82
4.4	Sensors response for presence of chemical cleaning product	82
4.5	Sensors response for rotten cooked fish	83
4.6	Sensors response for presence of air freshener	83
4.7	Sensors response for presence of cigarette smoke	84
4.8	Steps in pattern recognition	85
4.9	Typical sensors response	86
4.10	PCA plot of RW feature	94
4.11	PCA plot of VAN feature	95
4.12	PCA plot of DIFF feature	96
4.13	PCA plot of REL feature	96
4.14	PCA plot of FRACT feature	97
4.15	PCA plot of SN feature	97
4.16	MLP network architecture	100
4.17	Network architecture of MLP model	103
4.18	MLP classification rate for each feature	107
4.19	KNN classification rate for each feature	112
4.20	LDA classification rate for each feature	118
4.21	Classification performance before-PCA dataset	120

4.22	Classification performance after-PCA dataset	120
4.23	3-D PCA visualization for VAN feature	122
4.24	Data collection procedures for multiple sources present	124
4.25	Sensor's response when additional sources of IAP present	125
5.1	Process of enhanced IAQI	129
5.2	Process of air quality index calculation	130
5.3	E-nose based on biological olfactory system	141
5.4	Network architecture for smell perception	143
5.5	Calculation procedures for enhanced IAQI	144
5.6	Overall index for ambient air for 3 hour duration	146
5.7	Overall index for presence of air freshener	147
5.8	Overall index for presence of cigarette smoke	148
5.9	Overall index for presence of rotten cooked food	149
5.10	Overall index for presence of chemical product	150

## LIST OF TABLES

NO		PAGE
2.1	IAQ parameters, its sources and health effects to human	28
2.2	Previous IAQMS	35
2.3	Summary of previous literatures on added value features	42
3.1	Summary of previous research of IAQ parameters	47
3.2	List of sensors used in the system	52
3.3	Summary of sensors used in previous research	55
3.4	Technical specifications of the STC12C5A60S2 microcontroller	62
3.5	Technical specifications of the IRIS mote	64
3.6	Means and standard deviations for three parameters	73
3.7	Total cost of the system	73
3.8	Price comparison with professional IAQ monitoring device	74
4.1	Sources of indoor air pollutants	79
4.2	Data pre-processing techniques selected	89
4.3	Total variance explained for RW feature	92
4.4	Total variance explained for all features	93
4.5	Methods for supervised machine learning	98
4.6	Parameters for MLP training	104
4.7	Performance of MLP for RW feature	105
4.8	Classification rate for each feature	106
4.9	Confusion matrix of MLP for SN after PCA	108
4.10	Confusion matrix of MLP for VAN before PCA	108
4.11	Performance of KNN for RW feature	111

4.12	The best performance of KNN for each feature	111
4.13	Confusion matrix of KNN for SN after PCA	113
4.14	Confusion matrix of KNN for VAN before PCA	113
4.15	Performance of LDA for each feature	117
4.16	Confusion matrix of LDA for SN after PCA	119
4.17	Confusion matrix of LDA for VAN before PCA	119
4.18	Result of classifier based on mixed sources	126
5.1	EPA's breakpoint table and AQI Index	132
5.2	Indoor air pollutants for different countries	133
5.3	Breakpoint table for IAQI and TCI	136
5.4	Parameter cover by IAQ authorities and this study	138
5.5	Smell Categories	140
5.6	Smells samples	141
5.7	Performance of MLP for VAN feature	144
5.8	Result of the EIAQI when multiple sources present	151
5.9	Maximum, minimum and average value for each index for all three rooms	152
5.10	Average value for each index for all three rooms	153

## LIST OF ABBREVIATIONS

ADC	Analog-To-Digital Converter
ANN	Artificial Neural Network
ANOVA	Analysis Of Variance
API	Air Pollution Index
AQI	Air Quality Index
ARIMA	Autoregressive Integrated Moving Average
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BRI	Building related illnesses
CO	Carbon Monoxide
CO <sub>2</sub>	Carbon Dioxide
CPU	Central Processor Unit
DOSH	Department of Occupational Safety and Health
DIFF	Differential
DPM	Data Processing Module
EIAQI	Enhanced Indoor Air Quality Index
ETS	Environmental Tobacco Smoke
ETS	Health effects due to environmental tobacco smoke
FDA	Fisher Discriminant Analysis
MLP	Multilayer Perceptron
FLASH	Procedure Memory
FRACT	Fractional
FTDI	Future Technology Devices International

FTS	Fuzzy Time-Series
GN	Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places
GUI	Graphical User Interface
H <sub>2</sub>	Hydrogen
H <sub>2</sub> S	Hydrogen Sulfate
HKEPD	Hong Kong Environmental Protection Department
HVAC	Heating, Ventilation, And Conditioning
IAP	Indoor Air Pollution
IAQ	Indoor Air Quality
IAQI	Indoor Air Quality Index
IAQMG	Indoor Air Quality Management Group
IAQMS	Indoor Air Quality Monitoring System
ICP-IAQ	Industry Code of Practice on IAQ
KNN	K-Nearest Neighbor
LDA	Linear Discriminant Analysis
MCU	Microcontroller Unit
MoHR	Ministry of Human Resources
MOX	Metal Oxide
MVAC	Mechanical Ventilating And Air Conditioning
MSE	Mean Square Error
NO <sub>2</sub>	Nitrogen Dioxide
O <sub>2</sub>	Oxygen
O <sub>3</sub>	Ozone
OAP	Outdoor air pollution



OS	Operating System
OSH	Occupational Safety and Healthy
PC	Principal Component
PC1	First Principal Component
PC2	Second Principal Component
PCA	Principle Component Analysis
PDA	Personal Digital Assistant
PIR	Pyroelectric InfraRed
PM	Particulate Matter
PWM	Pulse Width Modulation
RF	Radio Frequency
RH	Relative Humidity
RW	Raw
REL	Relative
SAW	Surface Acoustic Wave
SBS	Sick Building Syndrome
SD	Standard Deviation
SI	Smell Index
SIAQG	Singapore Indoor Air Quality Guideline
SIDS	Sudden Infant Death Syndrome
SMC	Sensor Module Cloud
SN	Sensor Normalization
SO <sub>2</sub>	Tin Dioxide
SPI	Serial Peripheral Interface
SRAM	Static Random Access Memory

TCI	Thermal Comfort Index
TCP	Thermal Comfort Problems
Temp	Temperature
UART	Universal Asynchronous Receiver and Transmitter
US EPA	United States Environmental Protection Agency
VOCs	Volatile Organic Compounds
VAN	Vector Array Normalization
WHO	World Health Organization
WSN	Wireless Sensor Networks

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# **Sistem Pemantauan Kualiti Udara Dalam Bersepadu yang Dapat Mengenalpasti Sumber Pencemaran Serta Indeks Pencemaran Udara Dalam yang Ditambahbaikkan**

## **ABSTRAK**

Kualiti udara dalaman (IAQ) yang buruk boleh menjejaskan kesihatan manusia. Udara dalaman yang tercemar mempunyai tahap kepekatan gas yang berbahaya sehingga lima kali lebih tinggi dari udara dalaman biasa. Bagi memastikan kita dapat bernafas dengan udara dalaman yang selamat dan selesa, pemantauan IAQ yang berterusan adalah penting. Objektif utama kajian ini adalah untuk membangunkan sebuah sistem pemantauan udara dalaman (IAQMS) bersepadu yang dapat mengenalpasti sumber pencemaran serta indeks pencemaran udara dalaman yang ditambahbaikkan (EIAQI). Sistem IAQMS tanpa wayar ini menggunakan pelbagai pengesan termasuk pengesan gas, pengesan zarah dan pengesan haba untuk mengesan sumber-sumber pencemaran udara dalaman dan sistem ini adalah lebih murah berbanding sistem pemantauan yang profesional. Secara keseluruhan, kajian ini menggunakan lapan pengesan untuk mengukur sembilan gas dan bahan pencemar udara dalaman seperti Oksigen ( $O_2$ ), Karbon Dioksida ( $CO_2$ ), Karbon Monoksida (CO), Ozon ( $O_3$ ), Nitrogen Dioksida ( $NO_2$ ), Sebatian Organik Meruap (VOCs), Habuk (PM), Suhu (Temp) dan Kelembapan Relatif (RH). IAQMS ini telah berjaya mengenalpasti lima punca pencemaran udara dalaman dengan kadar pengkelasan 100%. Punca-punca pencemaran tersebut adalah: udara persekitaran, aktiviti manusia, kehadiran bahan kimia, kehadiran wangian dan kehadiran makanan dan minuman, berjaya dikenalpasti menggunakan 'Multilayer Perceptron' (MLP) dan 'K-Nearest Neighbor' (KNN) menggunakan data 'Vector Array Normalization' (VAN) yang tidak melalui 'Principal Component Analysis' (PCA). Akhir sekali, objektif terakhir kajian ini adalah untuk mengintegrasikan IAQMS dengan EIAQI. Kajian ini mencadangkan EIAQI yang terdiri daripada tiga indeks yang berbeza: Indeks Kualiti Udara Dalaman (IAQI), Indeks Keselesaan Terma (TCI) dan Indeks Bau (SI). IAQI menggunakan tujuh gas dan bahan pencemar udara dalaman untuk mengukur kualiti udara dalaman dan menunjukkan status IAQ sama ada ia adalah "Baik", "Sederhana", "Tidak Sihat" ataupun "Berbahaya". IAQI ini dibangunkan dengan menggunakan index kualiti udara (AQI) yang diterbitkan oleh Agensi Perlindungan Persekitaran Amerika (US EPA) sebagai sumber rujukan utama. TCI menggunakan prinsip yang sama dengan IAQI. TCI menggunakan Temp dan RH untuk menunjukkan tahap keselesaan terma sama ada "Sangat Selesa", "Selesa", "Kurang Selesa" ataupun "Sangat Kurang Selesa". Berbeza dengan IAQI dan TCI yang menjana indeks mereka berdasarkan bahan pencemar tunggal, SI dihasilkan berdasarkan pelbagai parameter pencemar. Sebagai contoh, IAQI ditentukan berdasarkan pencemar tunggal yang memberikan kadar kualiti yang paling rendah. SI sebaliknya, menjana persepsi bau berdasarkan semua sembilan bahan pencemar. SI akan mengelaskan bau tersebut sama ada "Neutral", "Menyenangkan" atau "Tidak Menyenangkan". Akhir sekali, EIAQI dirumuskan dengan menggabungkan ketiga-tiga indeks yang diperolehi sebelum ini. EIAQI memberitahu pengguna mengenai status keselesaan keseluruhan di dalam bilik.

## **An Integrated Indoor Air Quality Monitoring System with Pollutants Recognition and Enhanced Indoor Air Quality Index**

### **ABSTRACT**

Poor indoor air quality (IAQ) may pose threats to human's health. The concentration level of harmful gases and contaminants in polluted indoor air is up to five times higher than in normal indoor air. In order to ensure that people breathe-in safe air comfortably in the indoor air environments, continuous IAQ monitoring is deemed important. The main objective of this study is to develop an integrated indoor air quality monitoring system (IAQMS) with pollutants recognition and Enhanced Indoor Air Quality Index (EIAQI). The wireless IAQMS adopts an array of sensors including gas sensors, particle sensors and thermal sensors to detect multiple pollutant parameters at a relatively low cost as compared to the professional sensing devices. Overall, this study uses eight sensors to measure nine indoor air pollutants which are Oxygen (O<sub>2</sub>), Carbon Dioxide (CO<sub>2</sub>), Carbon Monoxide (CO), Ozone (O<sub>3</sub>), Nitrogen Dioxide (NO<sub>2</sub>), Volatile Organic Compounds (VOCs), Particulate Matter (PM), Temperature (Temp) and Relative Humidity (RH). This IAQMS has successfully recognized five sources of indoor air pollution with classification rate of 100%. These five sources of indoor air pollution are: ambient air, human activity, presence of chemical, presence of fragrance and presence of food and beverage, are successfully classified by Multilayer Perceptron (MLP) and K-Nearest Neighbour (KNN) using Vector Array Normalization (VAN) before Principle Component Analysis (PCA) feature. Finally, the last objective of this study is to integrate the IAQMS with EIAQI. This study proposes an EIAQI which comprises of three different indices: Indoor Air Quality Index (IAQI), Thermal Comfort Index (TCI) and Smell Index (SI). IAQI utilized the seven air parameters to measure the quality of indoor air and shows the status of IAQ whether it is "Good", "Moderate", "Unhealthy" or "Hazardous". This IAQI is developed using Air Quality Index (AQI) from the United States Environmental Protection Agency (US EPA) as its main reference. TCI applied the same principle with IAQI. The TCI used Temp and RH to indicate the thermal comfort level of a room. Therefore, TCI status is shown either as "Most Comfort", "Comfort", "Less Comfort" or "Least Comfort". In contrast with the IAQI and TCI which generate their index based on single pollutant parameter, SI is generated based on an array of pollutant parameters. For example, IAQI is determined based on single pollutant that gives the lowest rate. SI on the other hand, generates the smell perceptions based on all nine pollutants input. The final result would be classified as either the smell is "Neutral", "Pleasant" or "Unpleasant". After all individual index has been obtained, an EIAQI is formulated which combines all the previous three indices. This EIAQI informs the users about the overall comfort status in the room.

## CHAPTER 1

### INTRODUCTION

#### 1.1 Introduction

The issue of outdoor air pollution (OAP) such as haze is well known to the public due to the attentions given by the media. On the contrary, the issue of indoor air pollution (IAP) is less known to the public although IAP poses similar threats towards humans' health as compared to OAP. In fact, more attentions should be given to the issue of IAP because people normally spend 90 percent of their time in indoor environments (EPA, 2009). IAP, which undermines indoor air quality (IAQ), is found to contain indoor air pollutants such as harmful gases and contaminants at a concentration level up to five times higher than the concentration of these pollutants in normal air. In severe cases, the concentration level of the pollutants could rise up to 100 times than normal concentration level which lead to hazardous condition for human's health (EPA, 2009).

IAP can be defined as the disturbance of any gases, materials or human activities on the state of ambient air in indoor environment (Reffat & Harkness, 2001). In other words, IAP does not need the presence of disease or infirmity. As long as the concentration in the normal ambient air is disturbed either by gases, other materials or human activity, it is already considered as pollution. The most common sources of IAP is contributed by human activity such as the emission of carbon dioxide through breathing, combustion products from cigarette smoking and emission of volatile organic

compounds (VOCs) from excessive usage of cosmetic products such as perfumes and deodorants (Batterman & Burge, 1995). Other materials such as chemical products, building materials and office materials are also major sources of IAP. Chemical products such as air fresheners and cleaning products contribute to IAP by emitting VOCs while building and office materials like printers and carpets also release air contaminants such as dust into indoor air atmosphere (Borkar, 2012; CDC, 2014; Mumyakmaz & Karabacak, 2015; Sait, 2001; & Wasana, 2007). IAP may also emerge as a result of variations of gas concentration in the indoor air as well as from variations in thermal conditions such as temperature and humidity (DOSH, 2010; & Postolache, Pereira, & Girao, 2009). Finally, odour or smell also contributes to IAP (Capelli, Sironi, & Rosso, 2014). Therefore, anything that emits odour such as rotten food and strong smell of coffee are considered as part of sources of IAP. These sources of IAP might not look harmful, but to a certain extent (based on the concentration level) they may be hazardous to human health.

The health effects from IAP may be experienced soon after exposure, or possibly, years later depending on the individuals and type of pollutants they have been exposed to (EPA, 2014). The common health conditions that may show up immediately include irritation of the eyes, nose, and throats, headaches, dizziness, fatigue, asthma and humidifier fever. The health effects of years of exposure to IAP are more dangerous and can be fatal, which include some respiratory-related diseases, heart disease, and cancer (Maroni, Seifert, & Lindwall, 1995; & Mohave, 2000). The health effects relating to poor indoor air quality have been divided into four categories: Environmental Tobacco Smoke (ETS), Sick Building Syndrome (SBS), Building Related Illness (BRI), and Thermal Comfort Problems (TCP) (DOSH, 2010; EPA, 2008; & IAQMG, 2003).

Hence, meticulous attention should be given to make sure the indoor air is safe and comfortable.

In order to ensure that people breathe-in safe air comfortably in the indoor environments, continuous monitoring of IAQ is deemed important. Real-time and continuous IAQ monitoring allows people to be alert of any pollution that might happen in indoor environment right on time when it happens. Furthermore, the concentration level of gases and contaminants in the indoor air easily vary and can be impacted by various situations (J. Kim, Chu, & Shin, 2014). The changes in the indoor air concentration might not be noticeable by humans' senses because most of the gases and contaminants in indoor air are odourless and colourless. By having continuous IAQ monitoring system in real time, any pollution can be detected and users can be notified immediately, thus, necessary actions could be taken to prevent any unwanted events.

## **1.2 Problem Statement**

Many researchers have come out with various versions of indoor air quality monitoring systems (IAQMS) to monitor the quality of air in indoor environment. The early development of IAQMS started with the introduction of electronic nose or e-nose which is composed of an array of sensors for classifications of oils and alcohol odours in 1982 by Persaud and Dodd (Persaud & Dodd, 1982). Since then, there have been numerous attempts to develop a monitoring system to be used in indoor environment, for example Borkar, (2012), Bhattacharya, Sridevi, & Pitchiah (2012), J. Kim et al. (2014), Postolache et al. (2009) and S. Choi, Kim, Cha, & Ha (2009). Their objectives vary from assessment of IAQ in certain targeted indoor spaces, development of index

for application in indoor environments, predicting IAQ levels during certain conditions to a more sophisticated objective of recognizing certain types of indoor air pollutants.

Nevertheless, most of these systems are impaired by some flaws, either due to high costs, incomprehensive coverage of gas sensors, problems in collecting data using portable devices, or lacking in data processing application. A comprehensive system which can overcome the flaws in the previous IAQMS and further enhanced with smart application that could process the air quality data quickly and economically is needed for better IAQ monitoring.

The main problem with the existing IAQMS is that the researchers need to choose between comprehensive coverage of gas sensors but very costly and a low cost system with less accurate gas sensors. Sometimes, the researchers need to sacrifice the comprehensiveness of gas sensors by using less gas sensors in order to produce a low cost IAQMS. A professional gas sensor units or devices which cover a wide variety of gases and measure them to a very sensitive concentration are usually very expensive. Hence, not everyone could afford such devices (Borkar, 2012; Cheng, 2014; & Mamat et al., 2011). Normally, these professional gas sensors are used only when a problem of IAQ is reported. This cost constraint has resulted in insufficient data being made available to the researchers in the studies of IAQ and IAP. As a result, many researchers have tried to propose low cost IAQMS such as J. Kim et al. (2014), Borkar (2012) and Bhattacharya et al. (2012). However, this type of IAQMS usually could not detect multiple pollutants; rather they can only detect single pollutant (i.e. carbon dioxide or carbon monoxide alone) as reported by previous research such as Cheng (2014), Yingjie (2012) and Yu et al. (2011). Hence, they cannot give comprehensive result for IAQ assessment. Comprehensive IAQ result usually requires monitoring of more than 8 pollutants including carbon monoxide, ozone, particulates matter and VOCs (DOSHS,