

**EVALUATION OF INDOOR AIR QUALITY IN UNDERGROUND
METRO STATION PLATFORMS IN DELHI CITY**

PRAVEEN B.



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
AUGUST 2018**

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EVALUATION OF INDOOR AIR QUALITY IN UNDERGROUND METRO STATION PLATFORMS IN DELHI CITY

by

PRAVEEN B.

Department of Civil Engineering

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

AUGUST 2018

THIRUKKURAL

Thiruvalluvar, between the 300 and 100 BCE

கற்க கசடறக் கற்பவை கற்றபின்
நிற்க அதற்குத் தக.

**karka kasadarak karpavai kattrapin
nirkka adharkuth thaga.**

கல்வி கற்க நல்ல நூல்களைக் குற்றமறக் கற்க வேண்டும்,
அவ்வாறு கற்றபிறகு, கற்ற கல்விக்கு தக்கவாறு நெறியில்
நிற்க வேண்டும்.

**So learn that you may full and faultless learning gain,
Then in obedience meet to lessons learnt remain.**

Thirukkural, 391

Dedicated to

My Beloved Family

and

My Teachers

CERTIFICATE

This is to certify that the thesis entitled “**Evaluation of Indoor Air Quality in Underground Metro Station Platforms in Delhi City**”, being submitted by **Mr. Praveen B.**, has been prepared under our supervision in conformity with the rules and regulations of the Indian Institute of Technology Delhi We further certify that the thesis has attained a standard required for the award of the degree of **Doctor of Philosophy** of the institute. The work, or any part thereof, has not been submitted elsewhere for the award of any other degree or diploma.

Dr. MUKESH KHARE

Professor

Department of Civil Engineering

Indian Institute of Technology Delhi

New Delhi-110016

INDIA

Dr. RADHA GOYAL

Deputy Director

Indian Pollution Control Association

Delhi-110092

INDIA

ACKNOWLEDGEMENTS

The completion of this thesis represents the realization of a closely held dream. I am grateful for the support and assistance freely given to me by so many people during the course of the research.

First of all, I am deeply grateful to my supervisor, Prof. Mukesh Khare, for his supervision and for sharing his special expertise throughout my entire PhD study, not only in my study, but also in my life. His constant encouragement and patience has been a source of inspiration and motivation, his dedication to excellence and precise attitude in science and education sets a good example for my future career. Without his guidance and advice, the completion of this thesis is unachievable.

Thank you very much Sir!

I would also like to thank my co-supervisor, Dr. Radha Goyal, for her invaluable assistance and constant encouragement with data collection during field work, as well as her input into analysis and modeling discussion. Thank you Ma'am!

I extend my sincere thanks to Dr. E. Sreedharan (Former Managing Director), Mr. Mangu Singh, Managing Director, Mr. Satheesh Kumar (Former Director (Electrical)), Mr. A.K. Gupta, Director (Electrical), Delhi Metro Rail Corporation Limited (DMRC), New Delhi, for showing their deep enthusiasm in my research work and allowing me to field sampling/monitoring at selected underground metro stations in Delhi cities. I would also like to extend my thanks to Chandni Chowk and Patel Chowk station managers/maintenance engineers/basic staffs for providing logistic facilities and cooperating with me during the course of my field data collection.

I would like to express my gratitude to SRC members Prof. A.K. Gupta, Dr. Gazala Habib (Department of Civil Engineering) and Prof. Manju Mohan, Centre for Atmospheric Sciences, IIT Delhi for their invaluable suggestions and advice throughout my research work.

I would like to thank Dr. Sanjay Gupta, Mr. Ishwar Singh, Mr. S. Shukla, Mr. Ramesh (Environmental Engineering Laboratory), for their help and cooperation in conduction my experiments in the laboratory and Mr. Rajeev Sharma (Survey Laboratory), Mr. Vikram, Mr. Rajive Aggarwal, Ms. Pooja, Mr. Amit Bundela and Mr. Ghelot (Civil Engineering Department Administration Staff) for their help during my research period.

Sincerely thank all the PhD students (especially, Dr. Sunil Gulia, Dr. Baranidharan S., Dr. Ramamoorthy, Dr. Sumanth, Dr. Jaiprakash, Mr. Gaurav Singh, Ms. Richa G. John, Ms. Agnes Shiji Joy, Dr. Pooja Srivastava, Ms. Komal Shukla, Ms. Swati Rani, Ms. Aparna Sharma, Mr. Shiva Kumar, and Mr. Sasi) and other colleagues from Department of Civil Engineering, IIT Delhi, it was a great honour to study their company, and the days spent with them have given me unforgettable memories of IIT Delhi life. Thanks all of my friends (Mr. Satish Kumar, Mr. Karthikeyan, Mr. Satish and Mr. Sathyaseelan) for their constant support and encouragement. It is my great fortune to have their friendship.

And last but certainly not least, thanks to my family and Ms. Archana Chawla, for their constant love, support and unwavering confidence in me.

PRAVEEN B.

AUGUST, 2018

ABSTRACT

Indoor air quality (IAQ) has become a global health issue due to rapid urbanization resulting into construction of air tight high rise buildings affecting the indoor environment. People spend 80-90% of their time inside the buildings compared to ambient environment making IAQ assessment a *sin qua non*. The underground metro stations (UMS) represent a unique microenvironment because of their closed character and restricted ventilation, specific emission sources, and micro-meteorological conditions. The deterioration in the IAQ in UMS has been associated with energy conservation mechanisms such as reduced and increased insulation, use of synthetic materials in construction and interiors and also unplanned orientation of the underground metro system that cause increased infiltration of outdoor air pollutants. The underground metro system is a confined space that may promote the concentration of contaminants either from the ambient atmosphere or generated internally. However, indoor air pollutants which result from heavy use of the facility, overcrowding, and inadequate ventilation systems, remain accumulated in underground environment systems itself.

In order to address these scientific gaps in knowledge, this research work conducted, for the first time in UMS in Delhi city, India. A comprehensive statistical analysis of experimental data, along with multi-parameter assessment, exposure evaluation and its standard limit comparison, and evaluation of IAQ model and simulation of indoor air in UMS platforms. An extensive indoor air quality (IAQ) monitoring campaign was conducted during December 2012 to February 2014 (which includes four different seasons) in the Delhi metro rail system. The study has been investigated the level of PM₁₀, PM_{2.5} and PM_{1.0}, gaseous, ventilation parameter and bioaerosol along with thermal comfort parameter's (i.e. temperature and relative humidity) and

meteorological parameters (i.e. wind speed and directions) in one of the selected mechanically ventilated UMS platform in Delhi city, India.

The indoor and outdoor hourly average concentrations of PM₁₀, PM_{2.5} and PM_{1.0} for winter, summer, monsoon and post-monsoon seasons have been monitored in this study. The average PM₁₀ concentrations in UMS are observed to be 318.5 µg/m³, 223.2 µg/m³, 247.2 µg/m³ and 220.5 µg/m³ in winter, summer, monsoon and post-monsoon seasons, respectively. These values for PM_{2.5} are 151.8 µg/m³, 104.4 µg/m³, 119.7 µg/m³ and 110.2 µg/m³, respectively and for PM_{1.0}, 115.6 µg/m³, 83.3 µg/m³, 90.4 µg/m³ and 84.4 µg/m³, respectively. It is observed that the overall PM concentrations are higher in winter season followed by monsoon, summer and post-monsoon seasons. Indoor/outdoor (I/O) ratio for PM₁₀, PM_{2.5} and PM_{1.0} for winter (1.2, 0.9 and 0.8), summer (1.3, 0.9 and 0.9), monsoon (1.2, 0.9 and 0.8) and post-monsoon (1.1, 0.9 and 0.9) indicating that the PM₁₀ concentration are generated internally within the UMS, but PM_{2.5} and PM_{1.0} are infiltrated from outdoor environment. The indoor and outdoor gaseous pollutants such as SO₂ and NO₂ has been monitored. Both SO₂ and NO₂ I/O ratio analysis shows the sources of these gaseous pollutants are mainly from outdoor environment. The detailed statistics analysis of CO concentration data for all four seasons, it has been observed that outdoor CO concentrations for winter and summer are exceeding the standards during night time and during monsoon and post-monsoon seasons outdoor CO concentrations are exceeding the standards as laid down by NAAQS/USEPA and CPCB, India. The CO₂ concentration as a ventilation parameter in UMS platform were closely associated with the ridership in all four seasons. The mean CO₂ measurement are mostly below ASHRAE guideline of 1000 ppm. Further, mass balanced based IAQ model has been evaluated and validated for PM₁₀, PM_{2.5} and PM_{1.0}. The computational fluid dynamics based VENTCLIM model has also

been used to simulate indoor air flow in the UMS platform of Chandni Chowk metro station. The results show a satisfactory agreement with observed data at selected UMS platform.

The results presented here have relevance for both public health and for policies aimed at reducing human exposures to indoor air pollution. It is imperative to incorporate policies which ensure that such built environments are as safe as possible in terms of keeping exposure levels at a minimum.

सार

भीतरी वायु की गुणवत्ता (IAQ) एक वैश्विक स्वास्थ्य का मुद्दा है, शहरीकरण के परिणामस्वरूप तेजी से हवा तंग उच्च वृद्धि इमारतों का निर्माण किया जा रहा है जो की भीतरी वातावरण को प्रभावित कर रही है। लोग बाहर के वातावरण की तुलना में अपने पुरे दिन का लगभग ८०-९० प्रतिशत भाग इमारतों के अंदर व्यतीत करते हैं, जो IAQ के आकलन को अनिवार्य बनता है। भूमिगत मेट्रो स्टेशनों (UMS) एक अद्वितीय सूक्ष्म पर्यावरण का प्रतिनिधित्व करते हैं, जिसका प्रमुख कारण है उसका बंद प्रकृति, प्रतिबंधित वेंटिलेशन, विशिष्ट उत्सर्जन स्रोत और सूक्ष्म मौसमविज्ञान-संबंधी परिस्थितियां। UMS के IAQ में गिरावट की वजह ऊर्जा संरक्षण तंत्र के साथ जुड़ी हुई समस्याएं जैसे की, कम और बढ़ा हुआ इंसुलेशन, निर्माण और अंदरूनी जगहों पर सिंथेटिक सामग्री का उपयोग तथा भूमिगत मेट्रो प्रणाली के अनियोजित दिशानिर्देश हैं, जिसके कारण बाहरी वायु प्रदूषकों के भीतर घुसने में वृद्धि हुयी है। भूमिगत मेट्रो प्रणाली एक सीमित जगह है, जो या तो परिवेश वातावरण से या आंतरिक रूप से उत्पन्न दूषित पदार्थों की एकाग्रता को बढ़ा सकती है। हालांकि, भीतरी वायु प्रदूषक जो की परिणाम है, सुविधा के भारी उपयोग, भीड़, और अपर्याप्त वेंटिलेशन सिस्टम का, भूमिगत पर्यावरण प्रणालियों में ही संचित रहते हैं।

ज्ञान में इन वैज्ञानिक अंतरालों को संबोधित करने के लिए, यह शोध कार्य, UMS में पहली बार दिल्ली शहर, भारत में आयोजित किया गया। जिसमें प्रयोगात्मक डेटा का एक व्यापक सांख्यिकीय विश्लेषण, साथ में एकाधिक-पैरामीटर मूल्यांकन, अनावृत्ति मूल्यांकन और उसके मानक सीमा की तुलना, तथा IAQ मॉडल और UMS प्लेटफार्मों में भीतरी हवा के अनुकरण का मूल्यांकन सम्मिलित किया गया है। व्यापक भीतरी वायु की गुणवत्ता (IAQ) कि जांच का काम सन 2012 दिसंबर से सन 2014 फरवरी (जिसमें चार अलग मौसम भी शामिल है) के दौरान दिल्ली मेट्रो रेल प्रणाली में आयोजित किया गया, इस अध्ययन में PM_{10} , $PM_{2.5}$ और $PM_{1.0}$, गैसीय, वेंटिलेशन पैरामीटर के साथ थर्मल कम्फर्ट पैरामीटर (यानी तापमान और सापेक्षिक आर्द्रता) और मौसम विज्ञान के मापदंडों (यानी हवा की गति और दिशाओं) के स्तर की जांच दिल्ली शहर भारत में एक चयनित, यांत्रिक रूप से हवादार UMS प्लेटफार्म में की गई है।

इस अध्ययन में PM₁₀, PM_{2.5} और PM_{1.0} की भीतरी और बाहरी सांद्रता का सर्दी, गर्मी, मॉनसून और मानसून के पश्चात के मौसम में प्रति घंटा औसत अध्ययन किया गया है। UMS में औसत PM₁₀ की सांद्रता सर्दी, गर्मी, मानसून और मानसून के पश्चात के मौसम में क्रमशः 318.5 µg/m³, 223.2 µg/m³, 247.2 µg/m³ और 220.5 µg/m³ पायी गयी। उसी प्रकार PM_{2.5} के लिए यह मान क्रमशः 151.8 µg/m³, 104.4 µg/m³, 119.7 µg/m³ और 110.2 µg/m³ पाए गए तथा PM_{1.0} के लिए क्रमशः 115.6 µg/m³, 83.3 µg/m³, 90.4 µg/m³ और 84.4 µg/m³ पाए गए। यह देखा गया कि कुल PM सांद्रता सबसे अधिक सर्दियों में और उसके बाद क्रमशः मानसून, ग्रीष्म और मानसून के पश्चात के मौसम में अधिक होती है। भीतरी-बाहरी वायु (I/O) का अनुपात PM₁₀, PM_{2.5} और PM_{1.0} के लिए क्रमशः सर्दियों में (1.2, 0.9 और 0.8), ग्रीष्म ऋतु में (1.3, 0.9 और 0.9), मानसून में (1.2, 0.9 और 0.8) और मानसून के पश्चात (1.1, 0.9 और 0.9) मापा गया, जो की यह दर्शाता है कि PM₁₀ की सांद्रता UMS के भीतर आंतरिक रूप से उत्पन्न होती है, लेकिन PM_{2.5} और PM_{1.0} बाहरी वातावरण से अंदर आती है। भीतरी और बाहरी गैसीय प्रदूषक जैसे SO₂ और NO₂ की सांद्रता का भी आकलन किया गया। दोनों SO₂ और NO₂ के I/O अनुपात विश्लेषण से पता चलता है इन गैसीय प्रदूषक के स्रोतों मुख्य रूप से बाहरी वातावरण से आ रहे हैं। CO की सांद्रता का भी चारो सत्रों के लिए एकाग्रता डेटा का विस्तृत विश्लेषण किया गया और यह देखा गया है कि सर्दियों और गर्मियों के लिए CO की बाहरी सांद्रता रात के समय मानकों से अधिक है तथा मानसून के दौरान और मानसून के पश्चात यह सांद्रता भारत द्वारा निर्धारित मानकों जैसे NAAQS/USEPA और CPCB, से अधिक है। CO₂ की सांद्रता एक वेंटिलेशन पैरामीटर के रूप में UMS के मंच में बारीकी से सभी चार सत्रों में मेट्रो की सवारी के साथ जुड़ी हुयी है। CO₂ का औसत माप ASHRAE के दिशानिर्देश के स्तर जो की 1000 PPM है, से ज्यादातर कम है। इसके अलावा, द्रव्यमान संतुलित आधारित मॉडल IAQ का मूल्यांकन किया गया है जो की PM₁₀, PM_{2.5} और PM_{1.0} के लिए मान्य पाए गए है। अभिकलन द्रव गतिशीलता आधारित मॉडल VENTCLIM का उपयोग चांदनी चौक मेट्रो स्टेशन के UMS प्लेटफार्म में भीतरी हवा प्रवाह का अनुकरण करने के लिए भी किया गया है। इस अध्ययन में चयनित UMS प्लेटफॉर्म पर मापे गए मान का परिणाम संतोषजनक पाया गया।

यहां प्रस्तुत परिणाम दोनों सार्वजनिक स्वास्थ्य के लिए और भीतरी वायु प्रदूषण से मानव जोखिम को कम करने के उद्देश्य से नीतियों के लिए प्रासंगिकता है। यह सुनिश्चित करें कि ऐसे निर्मित वातावरण में ऐसी नीतियों को आवश्यक रूप से शामिल किया जाये जिससे एक कम से कम जोखिम का स्तर बना रहे।

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NOMENCLATURE

AAQ	-	Ambient air quality
ACH	-	Air change per hour
AHU	-	Air handling unit
ASHRAE	-	American society of heating, refrigerating, and air-conditioning engineering
ASTM	-	American standard testing materials
cc	-	Cubic capacity
CDS	-	Central difference scheme
CFD	-	Computational fluid dynamics
cfm	-	Cubic feet per minute
CFU	-	Colony forming units
CNG	-	Compressed natural gas
CO	-	Carbon monoxide
CO ₂	-	Carbon dioxide
COHb	-	Carboxyhaemoglobin
CPCB	-	Central pollution control board
DALY	-	Disability adjusted life years
DMRC	-	Delhi metro rail corporation
DNS	-	Direct numerical simulation
EDM	-	Environmental dust monitor
EPA	-	Environmental protecting agency
ETS	-	Environmental tobacco smoking
ft ²	-	Square feet
HCHO	-	Formaldehyde
HCV	-	High capacity vehicle
HVAC	-	Heating, ventilation, and air-conditioning
I/O	-	Indoor-outdoor
IAP	-	Indoor air pollution
IAQ	-	Indoor air quality

L/s	-	Liter per second
LCV	-	Light capacity vehicle
LES	-	Large eddy simulation
LPG	-	Liquefied petroleum gas
M	-	Meter
m ²	-	Square meter
m ³	-	Cubic meter
m ³ /hr	-	Cubic meter per hour
MVAC	-	Mechanical ventilation and air conditioning
NBD	-	National burden of disease
NO ₂	-	Nitrogen dioxide
NO _x	-	Nitrogen oxides
O ₃	-	Ozone
pCi/L	-	Picocuries per liter
PM	-	Particulate matter
ppm	-	Parts per million
PSD	-	Platform screen door
RANS	-	Reynolds averaged Navier-Stokes
RPM	-	Respirable particulate matter
RSPM	-	Respirable suspended particulate matter
SBS	-	Sick building syndrome
SD	-	Standard deviation
SES	-	Subway environment simulation
SIMPLEC	-	Semi-implicit method for pressure linked equations consistent
SO ₂	-	Sulfur dioxide
SO _x	-	Sulfur oxides
SVOC	-	Semi-volatile organic compound
TOC	-	Total organic carbon
TSP	-	Total suspended particulate
TSPM	-	Total suspended particulate matter
TVOC	-	Total volatile organic compound

UDS	-	Upwind differencing scheme
UFP	-	Ultra fine particle
UPE	-	Under platform exhaust
VOC	-	Volatile organic compound
VVOC	-	Very volatile organic compound
WHO	-	World health organization
%	-	Percentage
°C	-	Degree celsius
$\mu\text{g}/\text{m}^3$	-	Microgram per cubic meter
mg/m^3	-	Milligram per cubic meter
mg/ft	-	Milligram per feet