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ADDIS ABABA UNIVERSITY SCHOOL OF GRADUATE STUDIES
Ethiopian Institute of Architecture Building Construction and City Development (EiABC)

INDOOR AIR POLLUTION:
PRAGMATIC SMOKE MITIGATING INTERVENTIONS FOR
REDUCING CO AND PM2.5 IN TRADITIONAL TUKUL HOUSES
The case of Butajira area

DAGMAWIT KIDANE BELIHU

ADVISOR: ASS. PROF. DENAMO ADDISSIE NURAMO (PHD)

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the Degree of Master of Science in Architecture
(Advanced Architectural Design)**

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DAGMAWIT KIDANE BELIHU

OCTOBER 2023,

ADDIS ABEBA, ETHIOPIA

Approved by board of adjudication

ASS. PROF. DENAMO A. NURAMO _____

Advisor

Signature

Date

ASS. PROF. NEBYOU YONAS _____

Internal examiner

Signature

Date

ASS. PROF. ALAZAR ASSEFA _____

External examiner

Signature

Date

ASS. PROF. DAGNACHEW ADUGNA _____

Chairperson

Signature

Date

ASS. PROF. DAGNACHEW ADUGNA _____

Post graduate program director

Signature

Date



Indoor air pollution: Pragmatic smoke mitigating interventions for reducing CO and PM_{2.5} in traditional tukul houses. The case of Butajira area

DECLARATION

I declare that this research is an original work that previously haven't been submitted to any degree or diploma programs. The materials and sources used in this research have been properly cited and acknowledged to the best of my knowledge.

SIGNATURE: _____



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LIST OF ABBREVIATIONS

AAU	Addis Ababa University
AQI	Air Quality Index
CDC	Central Disease Control
CO	Carbon monoxide
COPD	Chronic Obstructive Pulmonary Disease
EPA	United States Environmental Protection Agency
HAP	House Hold Air Pollution
HH	House Hold
HHID	House Hold Identification
HVAC	Heating, Ventilation, and Air Conditioning
IAP	Indoor air pollution
IC	Improved Cook Stove
PATS+	Particle and Temperature Sensor
PICA	Platform for Integrated Cook stove Assessment
PPM	Parts per million
PM	Particulate matter
SOP	Standard operating procedure
SSA	Sub-Saharan Africa
VOC	Volatile Organic Compounds Sensor
WHO	World Health Organization
µg/m ³	Microgram per cubic meter



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ABSTRACT

A considerable number of people are residing in substandard spaces that fall below the WHO recommended air quality limits which includes exposure to indoor air pollution. The wide use of solid biomass coupled with indoor cooking are major contributing factors for high concentration of indoor air pollutants in Ethiopia. Over 95% of the Ethiopian population relies on solid biomass for household energy consumption and majority of them reside in rural vernacular houses where multiple functional spaces are overlapped in a single space. The lack of ventilation in these spaces and the amount of time spent indoors from cooking to sleeping etc. makes the occupants vulnerable to multiple health problems. The common health problems in the study area are recognized as side effects of prolonged exposure to indoor air pollutants. This research investigates the relationship between indoor air pollution in rural tukul houses and architectural modifications that can decrease selected indoor air pollutant concentrations in Butajira, Southern part of Ethiopia. The aim was to measure the 24hr PM_{2.5} and CO concentrations, study the architectural features of the tukuls and experiment with ventilation by providing multiple openings and altering the interior layout to study the indoor air pollution level reduction. A controlled experimental study was conducted in three selected households. The experiment had four phases where the first one measured the initial pollutant concentration levels, the second one introduced a window in the south-west orientation, the third one provided a second opening to control the air path and the final phase altered the location of the cook stove to achieve maximum efficiency. The results of the experiment confirmed the current pollutant concentrations profoundly exceed ideal WHO limits. The lowest before intervention CO concentrations were over two times higher than homes without indoor cooking and WHO recommended limits. Similarly, the lowest initial PM_{2.5} limits were 13 times higher than the maximum WHO limits. In two of the study houses the intervention successfully decreased both CO and PM_{2.5} concentrations. The best results were recorded in the fourth phase where PM_{2.5} dropped by 49.6% and CO showed an 87.6% decrease. The combined intervention where both openings and interior layout were altered showed the most positive results. In one study house the impact of context, activity pattern and existing architectural elements resulted in increased measurements. It was concluded that the contextual influence at an urban scale, interior layout/partition, cooking pattern and complete detachment of cooking spaces have the best potential for improving indoor air quality in existing tukul houses.

Keywords: INDOOR AIR POLLUTION, VENTILATION, OPENING DESIGN, CONTROLLED EXPERIMENT, TUKUL HOUSES



CHAPTER ONE

1. INTRODUCTION

1.1. BACKGROUND OF THE STUDY

Indoor air quality is considered as an important aspect of the general public’s quality of life. It is concerned with the quality of air in buildings in relation to the health and comfort of occupants. Studying indoor air quality is imperative since people spend majority of their time indoors. Previous studies infer more than 80% of the sub-Saharan African (SSA) population relies on solid biomass for daily cooking and lighting consumption; such as fire wood, charcoal, agricultural by-products, and animal waste (Benti et al ., 2021). Above 90% of the population in Ethiopia relies on traditional energy sources (biofuel) for domestic energy consumptions (Benti et al., 2021). Hence, it can be induced that majority of the rural areas in Ethiopia use fire wood for cooking and other household energy/heat source requirements.

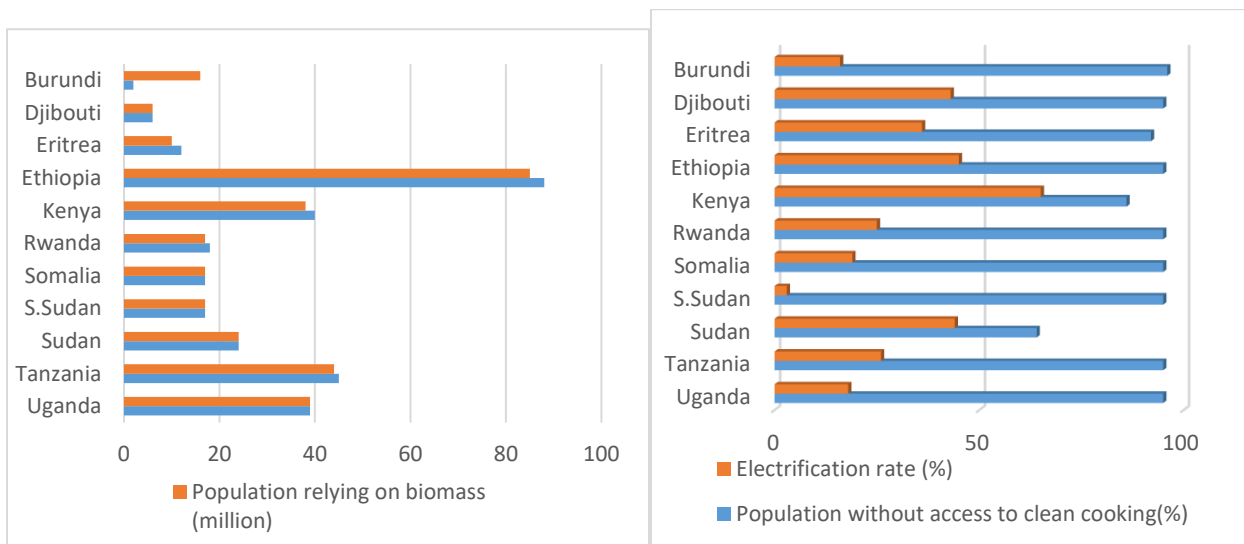


Figure 1: Ethiopian population with access to electricity and clean cooking; Energy supply in Ethiopia by type and energy consumption by sector

(Benti et al ., 2021)



The release of toxic aerosols in an indoor or outdoor environment results in air pollution if the quantity of the released toxin exceeds the fresh air supply. The release of such toxins indoors is responsible for various respiratory diseases.

Women and children who spend majority of their time around traditional open stoves which is one of the main sources of indoor air pollution suffer the most from its health consequences. An estimated 50,000 deaths occur annually as a result of indoor air pollution, this makes indoor air pollution accountable for 5% of the total load of disease in Ethiopia (Balidemaj et al., 2021).

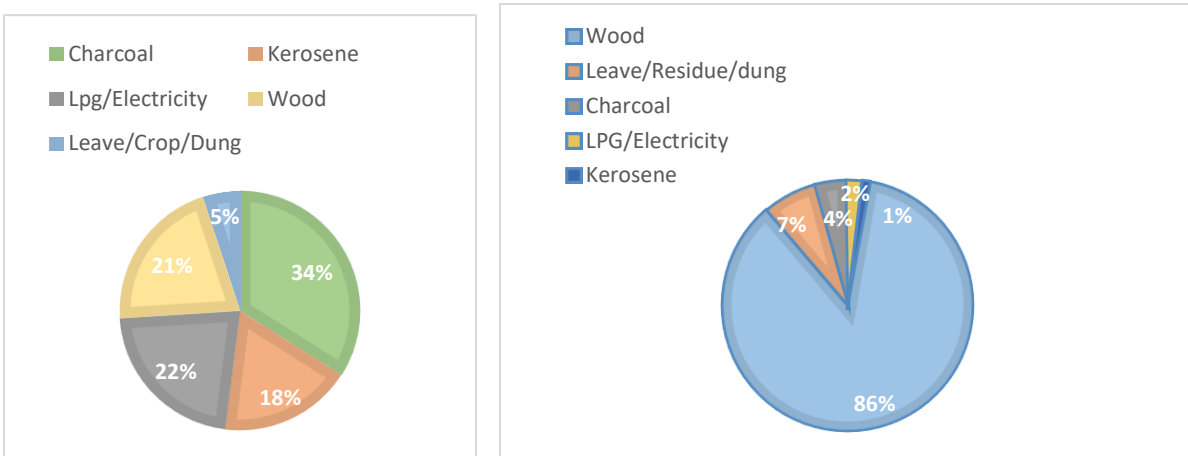


Figure 2: Household energy use in Addis Ababa (left) and Household energy use rural in Ethiopia (right)

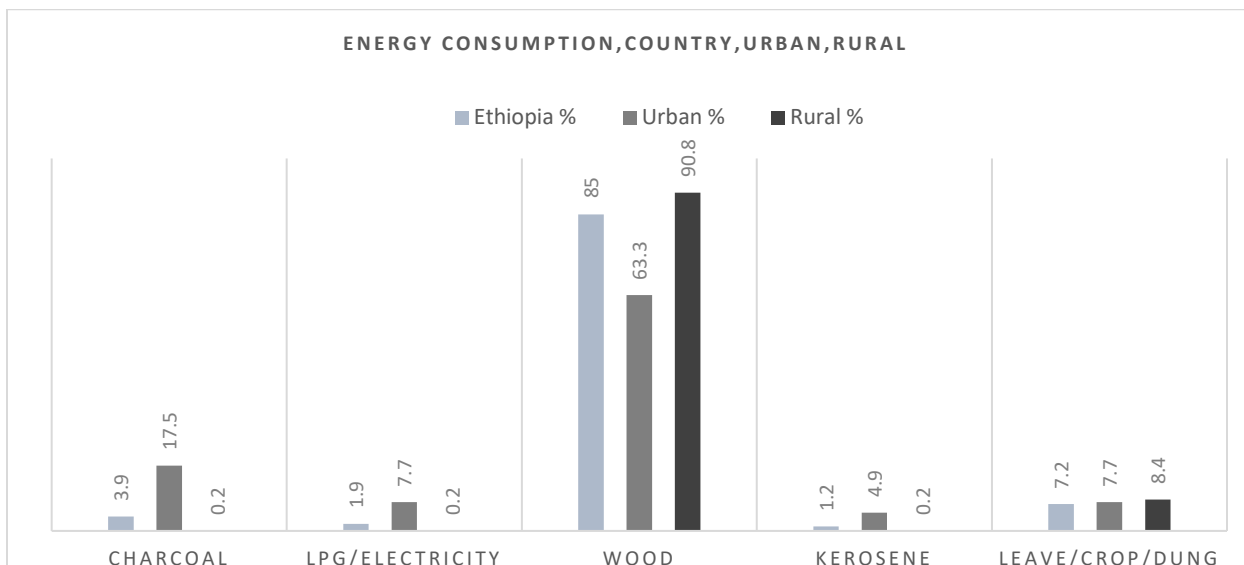


Figure 3: National household energy use in Ethiopia, urban and rural regions

(Tefera et al., 2016)



Sub Saharan Africa is among the highest consumers of solid biomass, it accounts for 70% of the continent's total energy consumption (Benti et al ., 2021). In order to achieve the collective global aspiration of doubling renewable energy consumption by 2030, studying the reason behind consumers selecting biomass for daily energy needs and providing local renewable energy options in the region is crucial. "Bioenergy accounted for 12% of the world's total final energy consumption, with 9% coming from traditional sources and 3% from modern bioenergy. Approximately 280 million tons of oil equivalents of solid biomass are now utilized in Sub-Saharan Africa, accounting for 90% of household energy. Almost all of this is wood, straw, charcoal, or dried animal and human waste, which is largely used as cooking fuel. Of the approximately 915 million inhabitants in SSA in 2012, an estimated 730 million (about 80%) have no access to clean cooking facilities" (Benti et al ., 2021).

Although biomass has several benefits, inefficient use of it has gravely costed the African continent. Aside from a major loss of the forest ecosystem, serious setbacks were recorded in the climate, the wellbeing of all inhabitants and overall economic development. The availability of biomass in rural area makes is an easy energy choice, hence finding an alternative energy source or introducing systematic improvements to minimize the negative health effects is important.



1.2.PROBLEM STATEMENT

The fuel used in rural Ethiopian households originates mainly from fire wood collected from surrounding plants and from dried animal waste. In addition to threatening the forest ecosystem, the combustion of firewood will generate heat energy which also releases major air pollutants such as particulate matter and CO₂. Daily household activities that require energy such as cooking are conducted indoors which exposes the residents of the house to harmful pollutants emitted during the process. The exposure of occupants to indoor air pollution caused by biomass consumption is a major health threat. The rural population which comprises around 80% of the total population (César&Ekbon, 2013) is housed in substandard units that mandate major improvements. At a global scale 93% of the world's children are residing in substandard environments that exhibit air quality measurements beyond the recommended WHO guidelines (Admasie&Amha, 2019). Ethiopia's nationwide biomass fuel consumption is close to 95% where nearly 99% of rural inhabitants use biomass as fuel (Addisu, 2021).

Several literatures have recounted concentration of PM_{2.5}, PM₁₀, SO₂, NO₂, O₃, CO and PB are 280µg/m³, 285µg/m³, 20µg/m³, 97ppm, <45ppb, < 0.10µg/m³ and 2.8ppm correspondingly (Tarekegn&Gulilat, 2018). The existing levels of pollutants such as carbon monoxide and particulate matter show considerable measurements well above the maximum limits set by WHO (Bluffstone et al., 2019). This high concentration of pollutants is directly associated with severe health concerns such as acute respiratory infections including phenomena which is the third leading cause of disease in Ethiopia; It has also been proven that low birth rate is highly associated with prolonged exposure to high pollutant cooking fuels (Admasie&Amha, 2019).

A considerably high concentration of pollutants such as carbon monoxide and particulate matter can be mitigated through architectural interventions. Options revolving around the construction of houses have great potential in improving indoor air quality. The consideration given to orientation of buildings, the number/size of openings and the wind angels compared to the openings play a role in controlling the quality of air inside spaces. In rural Ethiopian households, these important aspects that should be an integral part of housing development are heavily neglected. Hence, the residents' health and wellbeing is significantly compromised over time. In order to find a solution for existing houses that have limited to no ventilation, studying the suitable design layout, orientation and other air flow facilitating solutions is necessary (Tamire et al., 2021).



1.3. RESEARCH QUESTIONS

The study attempts to answer the following research questions:

- What is the current concentration level of selected air pollutants in rural Ethiopian households (with a specific emphasis to rural houses in Butajira area)?
- What is the current state of housing design in relation to ventilation, openings and architectural layout (with a specific emphasis to rural houses in Butajira area)?
- What are the potential architectural interventions that can be introduced to ensure indoor air quality in traditional tukul houses?
- Can the impact of the interventions be qualified to confirm the outcomes are operative enough to attain acceptable indoor air quality levels under WHO standards?

1.4.OBJECTIVE OF THE RESEARCH

1.4.1. GENERAL OBJECTIVES

The main objective of this research is to investigate into suitability/effectiveness of selected architectural interventions to reduce indoor air pollution in rural houses by improving air ventilation.

1.4.2. SPECIFIC OBJECTIVES

The following are specific objectives of the research devised from the main objective:

- Measure the concentration of selected pollutants for a minimum of 24hrs in traditional tukul houses in southern Ethiopia around Butajira area.
- Asses the current state of the tukul houses and study their architectural layouts.
- Propose mitigating solutions that improve the positive impact of ventilation on traditional tukul houses and improve indoor air quality.
- Perform a controlled experiment in the traditional tukul houses to test the effectiveness of the architectural interventions and record any improvement in indoor air quality.



1.5. SCOPE OF THE STUDY

The scope of this study is appraising IAQ from building science perspective. The study is limited to recording a 24hr indoor air quality data of three traditional rural dwelling units in rural Butajira area. This empirical study measured the HAP concentrations of tukul houses in Wurib Woreda of butajira. The experiment measured the HAP concentrations in each household before and after specific architectural modifications. All the measurements were taken on the dry (bega) season hence a detailed wind study was not conducted. The focus of the study is not indoor air pollution sources.

1.6.LIMITATIONS OF THE STUDY

Indoor air change and onsite indoor air pollutant measurements need a long time to gather reliable data. The rural location of the study area limits the researcher's ability to visit the site frequently and collect multiple data in various seasons/days. The focus on one seasons wind data limits the accuracy of the data for various seasonal wind effects. Availability of space, funding and similar building materials for the construction is among other notable limitations.

1.7. SIGNIFICANCE OF THE STUDY

This research studied the gaps in indoor air quality and the impact of rural housing typologies on indoor air pollution. Improved housing units, which can help the government update the rural housing regulations accordingly are proposed by the study. Additionally, the research has introduced improved vernacular housing options that consider key community concerns. The residents have an easy and familiar typology that requires minimal adaptation. The data gathered for this research can trigger further related studies that target new gaps in indoor air quality. Different perspectives are prompted further analyzing the gaps. Aside from future researchers the study will benefit the rural community, policy makers and local building professionals.



CHAPTER TWO

2. LITERATURE REVIEW

2.1. INTRODUCTION

This literature review comprises of the information collected regarding the architectural scientific health and technological sources and resolutions related to indoor air pollution. This chapter is focused on the effect of indoor air pollution on building occupants and the architectural intervention options that could minimize indoor air pollution. In addition to knowledge that relates to indoor air pollution and controlled ventilation experiments various findings of renowned scholars have been critically reviewed and reported.

2.2. THEORETICAL REVIEW

2.2.1. DEFINITION OF TERMS AND CONCEPTS

- **Indoor air pollution** is “dust, dirt, or gases in the air inside buildings such as home or workplace that could be harmful to breathe in. Poor indoor air quality has been linked to lung diseases like asthma, chronic obstructive pulmonary disease and lung cancer. It has also been linked to increased risk of heart disease and stroke” (BritishLungFoundation, 2021).
- **Vernacular architecture** is “the term used to categorize method of construction using traditional knowledge and ingenious locally available resources to address local needs” (Addissie et al., 2019).
- **Controlled experiment** is researching a subject by isolating the variable factors from the constant conditions and analyzing how they affect or alter the said conditions (Kothari, 2004).
- **Architectural intervention** is defined as a physical intervention that is a result of a project, proposes an architectural space generated on the basis of human intervention (quaderns, 2021).



2.3. AIR POLLUTION

Environmental pollution arises once the physical, chemical, or biological elements of the air masses, temperature, climate, etc. are changed. Pollutants damage the environment in two ways, by accumulating toxic compounds above the accepted extent and by adding new and harmful toxic elements. Primary air pollutants are directly produced by the sources (such as fossil fuel and biofuel), while secondary pollutants are a consequence or byproduct of the primary pollutants (Kampa et al., 2008).

Air pollution is a multidimensional scourge of our time and a major contributor for climate change. A significant effect of air pollution on an individual level is its impact on health. Air pollutants affect human health when they are concentrated above a certain acceptable level. Miniature pollutants like Particulate Matter (PM) can penetrate the respiratory system and cause cardiovascular and respiratory problems. Similarly, high concentration of ground level ozone can negatively affect the respiratory system and cause chronic health problems. Direct and prolonged exposure to pollutants such as carbon monoxide and lead can go as far as provoking direct poisoning and prolonged inebriation. Additional air compounds that are harmful to humans includes Volatile Organic Compounds (VOCs), nitrogen oxide, sulfur dioxide, dioxins and polycyclic aromatic hydrocarbons (PAHs) which are among the major recognized air pollutants. An excess concentration of these compounds can cause Chronic Obstructive Pulmonary Disease (COPD), bronchiolitis, asthma, lung cancer, central nervous system dysfunctions, and cutaneous diseases (Ioannis et al., 2020).

Another pressing issue caused by air pollution is climate change. Similar to other natural disasters, climate change affects the geographical distribution and transmission of infectious diseases. The global health care system that is already overstrained will be at grave risk if climate-sensitive infectious diseases keep emerging and re-emerging. To avoid such issues, formulating a multidisciplinary approach that involves experts from a scientific background, various organizations and the general public is crucial. Creating public awareness and encouraging researches that address the issue and propose durable solutions at an individual and institutional levels is equally important.



2.4. PRIMARY AIR POLLUTANTS

The use of biomass results in the release of multiple harmful pollutants. The released pollutants can be categorized into, gaseous, particulate matter and volatile substances. The pollutants are mainly carbon monoxide, nitrogen dioxide, sulfur dioxide, particulate matter and volatile organics. Both WHO and CDC recognize six primary air pollutants for setting permissible levels of pollution. The gases are carbon monoxide, lead, nitrogen oxides, ground-level ozone and particulate matter (PM) (CDC, 2021).

2.4.1. PARTICULATE MATTER (PM)

Particulate matter contains extremely small solid and liquid particles that can penetrate deep in to the lungs through inhalation. Incomplete combustion, environmental emission and open stove cooking are the primary sources of Particulate matter (PM). Particulate matter (PM) is a prominent health hazard and it is the cause of various acute and chronic cardiovascular and respiratory diseases. The penetration of particles in to the respiratory system depends on the size, smaller particles with diameter 2.5 micrometers (μm) and under are called PM_{2.5} (D'Amato et al., 2015). A positive relation was shown between both short-term and long-term exposures of PM_{2.5} and acute respiratory infections, cardiovascular diseases, infant mortality, low birth weight, asthma and other diseases. The same positive connection can be made between PM_{2.5} exposure and mortality/morbidity (Lall et al., 2004).

A cross sectional study focusing on PM_{2.5} concentration was conducted in five Woredas in Butajira SNNP region, 147 households were equipped with PATS+ devices to measure a 24hr mean and median concentration. The respective mean and median results were 410 g/m^3 and 340 g/m^3 , this result is around 16 times higher than the 24hr limit of 25 g/m^3 set in the WHO guideline (Tamire et al., 2021). WHO guidelines set the PM_{2.5} indoor air quality standard below 10 $\mu\text{g}/\text{m}^3$ annual mean and 25 $\mu\text{g}/\text{m}^3$ 24-h mean for lower income countries (Tamire et al., 2021) however, the Ethiopian environmental protection authority specified the standard concentration of PM_{2.5} as 65 $\mu\text{g}/\text{m}^3$ (EPA(ethiopian), 2004)



2.4.2. CARBON MONOXIDE (CO₂)

Incomplete combustion of any carbonaceous fossil fuel results in the release of carbon monoxide which is a colorless and odorless gas. It's been the leading cause of poisoning mortality in various countries. Carbon monoxide poisoning symptoms such as dizziness, fatigue, nausea, loss of consciousness, and vomiting can lead to short and long-term health complications. Direct and prolonged exposure to carbon monoxide leads to serious poisoning which can cause hypoxia, ischemia, and cardiovascular chronic diseases (Abelsohn et al., 2002). The duration of exposure, ventilation, and carbon monoxide concentration influence the severity of these health issues. Making sure our interior spaces get continuous fresh air supply is ideal. Ensuring automobile exhaust, home fires, and indoor home products like heaters and stoves are properly contained can also limit the amount of carbon monoxide in our immediate environment.

2.4.3. NITROGEN OXIDE (NO₂)

Nitrogen oxide is a mixture of two naturally produced gases (nitric oxide and nitrogen dioxide). Pollution from vehicles and the fuel burning process is the primary source of nitrogen oxide, but it is mainly produced from automotive engines. Stoves and gas can produce significant amounts of nitrogen oxide in insufficiently ventilated indoor spaces. Nitrogen oxide can penetrate the lung and cause respiratory irritation; when inhaled at high levels it can result in respiratory diseases, coughing, bronchospasm and pulmonary edema. Nitrogen oxide's components nitric oxide which is known for its colorlessness and nitrogen dioxide known for its odor, acidity and high corrosive nature have properties that affect human health and environment. Long term exposure can cause chronic lung disease and impaired sense of smell these health effects are caused when NO₂ concentrations are above 0.2 ppm, when the concentration is above 2 ppm our T-lymphocytes or NK cells that produce our immune response get compromised (Ioannis et al., 2020).

High levels of nitrogen dioxide can also be harmful to plants as it been known to damage foliage which limits plant growth. A cross sectional study conducted in Butajira zone measured the NO₂ concentrations with 17,995 samples collected from local households in which “The mean level of 97 lg/m³ exceeded the annual WHO air quality guideline of 40 lg/m³ by almost 2.5 times. The exceedance is consistent for all months of the survey. Close to 70% of the samples exhibited NO₂ levels over this guideline” (Tamire et al., 2021).



2.4.4. LEAD

Lead poisoning is mainly caused by industrial pollution and piston-engine aircraft. Although lead is a heavy metal mostly used in industrial plants it poses a huge health risk to the general public. Lead can be inhaled, absorbed and digested in to our organs which can cause loss of memory (mental retardation), muscle and joint pain. Lead affects the nervous system and accumulate in the blood, lung, liver, soft tissue, and cardiovascular, nervous, and reproductive systems (Iqba, 2012). Similar to Nitrogen oxide it also affects plants and crop growth.

2.4.5. GROUND-LEVEL OZONE (O₃)

Ground level ozone is a result of chemical reaction between naturally emitted oxides of nitrogen and volatile compounds. Ozone has low water-solubility which allows it to get inhaled deep in to the lungs and cause severe respiratory issues. “An increase in ozone concentration was associated with an increase in the daily number of deaths (0.33%), in the number of respiratory deaths (1.13%), and in the number of cardiovascular deaths (0.45%). No effect was observed during wintertime.” (Ioannis et al., 2020).



It's possible to assess indoor air quality by directly measuring the level of indoor pollutants such as Carbon monoxide (CO), Radon, Nitrogen dioxide (NO₂), secondhand smoke, lead particles, asbestos, and mold. Aside from measuring these pollutants it is possible to measure pollutant sources such as fuel and stove. The second option allows for a more simple and accurate measurement. Table 1 demonstrates the major sources of indoor air pollution and multiple air pollutants released during the combustion of these resources.

Table 1: Major health-damaging pollutants generated from indoor sources

(Smith et al., 2003)

Pollutant	Major indoor sources
Fine particles	Fuel/tobacco combustion, cleaning operations, cooking
Carbon monoxide	Fuel/tobacco combustion
Nitrogen oxides	Fuel combustion
Sulfur oxides	Coal combustion
Arsenic and fluorine	Coal combustion
Volatile and semi-volatile organic compounds	Fuel/tobacco combustion, consumer products, furnishings, construction materials, cooking
Aldehydes	Furnishing, construction materials, cooking
Asbestos, Lead	Remodeling/demolition of construction materials
Biological pollutants	Moist areas, ventilation systems, furnishings
Radon	Soil under building, construction materials



Key pollutants affecting the quality of indoor air quality along with their associated health risk and common source of emission is summarized in the table below.

Table 2: Source and effects of key indoor and outdoor air pollutants

(Saini et al., 2020)

Pollutants	Major Sources of Emission	Associated Medical Health Consequences
SO₂	Fossil fuel combustion such as oil, coal and natural gas, outdoor air	Acute exposure leads to bronchial activity.
CO	Tobacco smoke, stoves, boilers, kerosene or gas heaters, fuel burning	Low birth weight, Increase in perinatal deaths
CO₂	Combustion activities, metabolic activity and motor vehicle in garages	Headaches, sleepiness, Poor concentration, Loss of attention
Fungal Spores	Internal surfaces, foodstuffs, plants and soil	Asthma episodes, Allergic reactions, Eye, throat and nose irritation, Sinus and other respiratory problems
Radon	Soil Building concentration materials such as stone and concrete	Risk of lung cancer, Breathing problems
Asbestos	Insulation, fire retardant materials	Cancers such as mesothelioma, Pleural thickening, Pleural plaques and asbestosis
NO₂	Motor vehicles in garages, fuel burning and outdoor air	Exacerbation of asthma and wheezing, Reduced lung function in kids, Respiratory infections
Pollens and allergens	Outdoor air, plants, weeds, grass, trees, insects, domestic animals, and house dust	Trigger symptoms of allergy
Particles (PM_{2.5})	Tobacco smoke, re-suspension, combustion products	Exacerbation of Asthma, Wheezing, Respiratory infections, Exacerbation of COPD, Chronic bronchitis and COPD
Ozone	Photochemical reactions	Airway irritation, Permanent lung damage, Pneumonia and bronchitis, Aggravate asthma
Lead	Paints, firearms, lead bullets, dust, soil, radiators, consumer products	Memory loss, Hearing loss, Damage to the nervous system in new-borns, High blood pressure, Kidney & heart disease, Reduced fertility, Hyperactivity or loss of consciousness
VOCs	Burning of gas, wood, and kerosene, cleaning agents, paints, hair spray, perfumes and tobacco smoke	Allergic skin reactions, Visual disorders and memory impairments, Damage to the central nervous system, kidney, and liver, Decline in serum, cholinesterase levels, SBS



The EPA has set standard National Ambient Air Quality Standards (NAAQS) under the clean air act which identifies two NAAQS “Primary standards provide public health protection, including protecting the health of "sensitive" populations such as asthmatics, children, and the elderly. Secondary standards provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings.” (EPA, United States environmental protection agency, 2022)

Table 3: USA National Ambient Air Quality Standards

(EPA, United States environmental protection agency, 2022)

Pollutant	Primary/ Secondary	Averaging Time	Level		Form
Carbon Monoxide (CO)	primary	8 hours	9 ppm		Not to be exceeded more than once per year
		1 hour	35 ppm		
Lead (Pb)	primary and secondary	Rolling 3month average	0.15 µg/m ³		Not to be exceeded
Nitrogen Dioxide (NO₂)	primary	1 hour	100 ppb		98th percentile of 1-hour daily maximum concentrations, averaged over 3 years
	primary and secondary	1 year	53 ppb		Annual Mean
Ozone (O₃)	primary and secondary	8 hours	0.070 ppm		Annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years
Particle Pollution (PM)	PM _{2.5}	primary	1 year	12.0 µg/m ³	annual mean, averaged over 3 years
		secondary	1 year	15.0 µg/m ³	annual mean, averaged over 3 years
		primary and secondary	24 hours	35 µg/m ³	
	PM ₁₀	primary and secondary	24 hours	150 µg/m ³	
Sulfur Dioxide (SO₂)	primary	1 hour	75 ppb		99th percentile of 1-hour daily maximum concentrations, averaged over 3 years
	secondary	3 hours	0.5 ppm		Not to be exceeded more than once per year



2.5. MEASURING INDOOR AIR POLLUTION

Partial combustion of biomass results in the presence of harmful compounds indoors. Open fire stoves used for meal preparation and household energy consumption result in the release of air pollutants. The concentration of pollutants is magnified if the process takes place in an indoor area with low supply of air/oxygen and inadequate fresh air exchange rate. Inorganic and organic compounds such as carbon monoxide and Polycyclic aromatic hydrocarbon (PAH) groups are among the main pollutants released during incomplete biomass combustion (Tadesse, 2015).

Types of air pollution include gases (such as nitrogen oxide, Sulphur, carbon monoxide, etc.) and particulate matter (which includes dust, dirt and other miniature air particles). Measuring the concentration and exposure of such pollutants is a complex matter that requires technology and manual timely measurement. The amount of toxic particles is usually determined by the concentration of black smoke which determines the level of air pollution (NRC, 1981).

Traditional methods of sampling where air is sampled by bag or cylinder and taken to the lab plus advanced techniques that measure the pollutant levels on site can be used to measure indoor air pollution. Air quality index is the main indicator for increase and decrease of air pollutants. The status of the study building, the sampling date and time, the activities carried out in the building and the climate affect the measurement of air pollutants (Villanueva et al., 2021).

PCE-MPC10 is designed to assist indoor air quality assessments; it measures particulate matter concentrations, humidity and temperature. PCE-MPC 10 is ideal for indoor air quality studies because it's easy to use and transport. Additional devices that can be used for indoor pollution measurement include; VOC sensor, HOBO CO data Logger, UCB particles monitor, particle counter, PCE MPC, sensors, portable air, AQI, pollution meter and PATS+. The indoor air pollution measuring devices are systematically placed inside the research area. Typically, the device is placed away from direct sunlight, openings, HIVAC units and at a specified distance from the main source of pollution. Thorough consideration should be given to the height the device is placed upon, preferably it is placed at height-level in common areas and lower than height-level in seating and sleeping spaces (iotacommunications, 2021).



Indoor air pollution: Pragmatic smoke mitigating interventions for reducing CO and PM_{2.5} in traditional tukul houses. The case of Butajira area

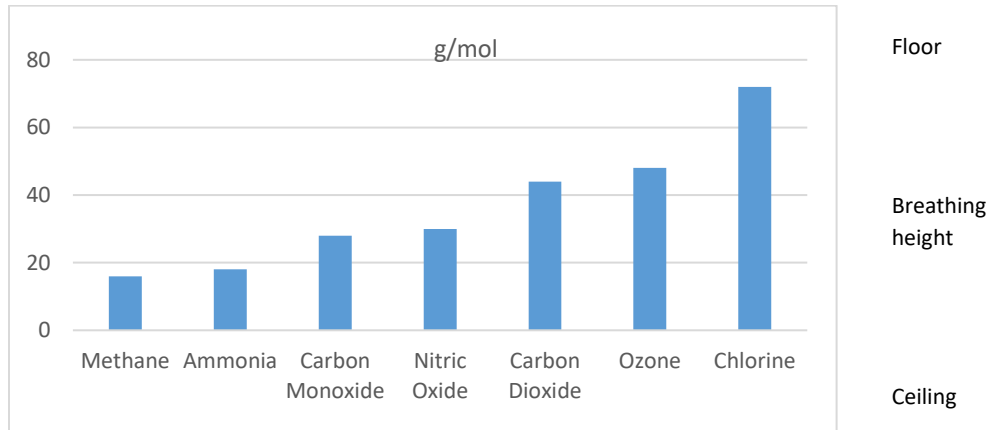


Figure 4: IOQ sensor placement

(iotacommunications, 2021)

Monitoring indoor air quality includes assessing the effectiveness of fresh air exchange in attaining the ideal indoor environment, ensuring the toxins are controlled and making sure the thermal comfort including temperature and humidity are within the acceptable comfort zone levels. Once the data is collected its crucial to cross check the measurement with the suggested parameters for each pollutant and determine the level and severity of pollution. Indoor air quality is also monitored in order to alert occupants when pollutants reach critical concentration points. This helps occupants take proper measures to rectify the indoor air pollution by opening windows, turning artificial air conditioning on or removing the source of pollution such as open stoves and other fires.

CHARACTERISTIC	CONDITIONS TO BE MET
Particulate Matter	10 micrometers or less in diameter: 50 ug/m ³ ; 2.5 micrometers or less in diameter: 15 ug/m ³
Carbon Monoxide	Less than 9 ppm
VOCs	Less than 500 ug/m ³
Formaldehyde	Less than 27 ppb
Carbon Dioxide	About 700 ppm above outdoor air levels (usually about 1,000 to 1200 ppm) (ASHRAE)
Humidity	Below 60%, ideally between 30% and 50% (EPA)
Temperature	68.5°F to 74°F (winter); 75°F to 80.5°F (summer) (ASHRAE)

Figure 5: Recommended parameters for indoor air quality as noted by the International Well Building Institute

(iotacommunications, 2021)



2.6. CLIMATIC CONDITION AND INDOOR AIR QUALITY

Weather is the atmospheric condition recorded in a specified place and time. The average long-term weather of a certain area or the mean and variability data of a specific area characterizes climate. There are four seasons in Ethiopia, Meher from June to August with heavy rainfalls; Tseday from September to November; Bega from December to February with the dry season; Belg from March to May with occasional rain. The geographical location of the structure is very crucial to the level of indoor air quality. Location determines the climatic context of the building which outlines the main natural elements that influence air quality (Hagos, 2018).

Basic factors that signify the air quality and indoor comfort level of a certain location can be induced from natural climatic elements such as the wind, sun and water (rainfall). These three natural phenomena are deduced to different numerical values by different measurement tools unique to all three. Each element has more than one measurable component that will define and determine the boundaries of envelop design in response to the environment. By referring to the three main elements, other climatic elements such as air temperature, solar radiation, humidity, precipitation, clouds, wind speed and direction could be documented (Hailu et al., 2021).

The air quality, thermal comfort and energy efficiency in a building is directly influenced by the microclimate of the site. Architecture tackles climatic issues of a building by considering the site-specific conditions including orientation, building fenestration, building material and technology. Climate-responsive architectural design practice is a diverse way designers can explore solutions for climate issues that threaten the comfort of building occupants. Climate responsive architecture aims to achieve the ideal indoor environment with minimal artificial interventions (Malekafzali&Aho, 2017). Similar to the occupant's energy choice, the climate and how the architect chooses to design around it affect the comfort of a building.

The ideal indoor climate ranges from 23°C to 29.5°C temperature and a relative humidity between 18% and 50%. Humidity up to 78% is tolerable when temperature is lower than 23°C (Olgyay, 1963). The three prominent elements that are affected by climate are ventilation rate, airflow direction and air distribution (airflow pattern), the ventilation rate of an indoor space is predominantly controlled through these three basic elements.



2.7. BUILDING ENVELOP VS. INDOOR AIR QUALITY

Building envelop physically separates the exterior and interior environments, the enclosure of a building protects and modifies the intended space to achieve the ideal indoor atmosphere. The building envelop has various functions that can roughly be categorized in to these three categories:

- Support: to resist different external loads and forces and assure strength and rigidity.
- Control: to control the exchange and flow of wind, temperature, humidity, and radiation between the interior and exterior of the building.
- Finish: the look of the building, this is the aesthetics and overall appearance of the building.

The enclosure of a building is exposed to both external and internal environmental loadings. The external loads on a building fenestration are a result of climate (including natural disasters) and manmade effects (including fire and global warming). The internal loads on a building originate from human activity (including ventilation, indoor fire, smoke), conditioning and natural occurrences (Straube, 2012).

When designing to achieve the ideal indoor environment especially air quality, it's important to consider the control function of the building as it controls the air exchange through openings. The design, size and orientation of openings determine the comfort and safety of the interior space. The fabric of the building enclosure is another important element that includes thickness (layers), surface character and other material properties. Insufficient air exchange through the fabric will lead to congestion of air pollutants which results in unfavorable indoor air quality. The fabric or material used to construct the building (brick, stone, wood, aluminum or others) has an impact on how quickly changes in weather conditions are felt in the enclosed space (fekadu, 2021).



2.8.BUILDING FENESTRATION

“Fenestration refers to the openings in the building envelope, including the installation of windows, doors, and skylights” (Afework et al., 2021). The fenestration pattern, its size and orientation especially in relation to wind direction are design elements that can be manipulated to attain ideal indoor air quality. The inclusion of openings in the building envelope is necessary to achieve optimal indoor comfort through ventilation, heat exchange, natural light radiation and access to the inside and outside. Openings such as windows can promote passive solar heating and cooling; as well as providing natural points of ventilation, air circulation and fire exits.

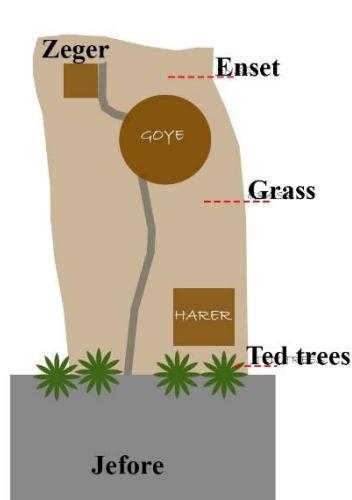
The relationship between fenestration and improved indoor air pollution and health of occupants is closely related. Increased number of well-designed openings is known to decrease the pollutant concentration levels. A study focusing on ventilation interventions to achieve improved household air quality found a decrease in PM_{2.5} concentrations with increased number of fenestration. Although the study didn't conclusively state the extent to which the decrease of PM_{2.5} concentrations resulting from improved ventilation are beneficial to the occupant's health (Weaver et al., 2017).

2.9.VERNACULAR ARCHITECTURE

Architectural practice employed to solve a specific regions housing problem based on local knowledge and native resources is identified as vernacular architecture. Vernacular architecture is known for its sustainability and adoptability. It is unique to the original location; the climate and available materials in the area have a big impact on the design. Vernacular architecture is a reflection of the culture, tradition and social practices of a region, distinctive architectural programs are designed to accommodate the unique social practices. Since vernacular architecture is based on locally available materials and the climate of that specific region it may be hard to replicate the same design in a different region (Salman, 2018).

2.9.1. VERNACULAR HOUSES IN SNNP REGION

Traditional houses in south share three similar spatial features; the main residence, the traditional kitchen and the cattle and crop storage space. These spaces can be found under the same roof or in various houses depending on the region and culture.



The traditional houses around Butajira share similar spatial features. The most common settlement in south region specifically gurage zone is called ‘Qaya’ which is based on a main avenue. The main avenue is called ‘Jefore’ which has multiple households along the road. Single settlement on each sides of the road may hold up to 80 people within 13 households on each side of the road. (Teku, 2017) The road is wide enough to accommodate communal gatherings and children activities.

Figure 6: Typical Gurage house layout

The ‘Goye’ is the main house that is supported by a central structural column called ‘Echeba’ that is commonly surrounded by a fire place called ‘Gurdet’. The interior of the ‘Goye’ is separated with timber partitions to separate the living/sleeping space (which is bigger than the rest), the barn called ‘Gadar’ and the storage space. The remaining buildings in the compound are for cooking and children bedrooms. The ‘Harar’ is the children room while the ‘Zeger’ is the kitchen. The ‘Zeger’ is usually constructed with mud and steel roof.

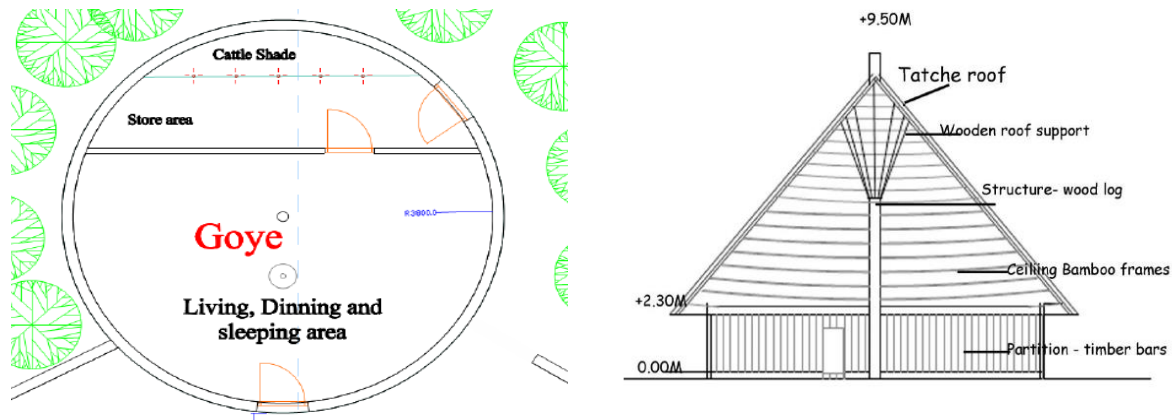


Figure 7: Traditional Gurage houses (common interior layout and structure)

(Teku, 2017)



There are multiple houses in a single compound. Two dominant types of housing styles can be observed around the study region; the traditional circular house made of wood plastered with mud covered in thatched grass roofs and modern houses with iron sheet roofs and concrete block Walls (Nilsson, 2016). The traditional tukul houses have vertical supports made of wood pieces mounted in the ground. The woods are stalked on top of each other to achieve the desired height. Relatively thinner wood pieces are integrated horizontally, both elements are joined by mud-straw mix and cow dung plastering. The traditional houses lack internal partitions that separate the various functions in the house including the kitchen. There is only one opening in most of the traditional houses around the study area, aside from the door all other surfaces lack openings. Both houses are susceptible to pest infestation especially rats. The main construction material in the tukul houses is wood which contributes to deforestation; it also exposes the house to accidents related to fire.

Most of the rectangular houses have multiple internal partitions and a moderately better spatial layout. Depending on the economical capacity the rectangular houses have various openings, the walls are built similar to traditional tukul houses except the rectangular form and the corrugated iron sheets. The high roof levels lack indoor ceiling and insulation so the indoor thermal comfort is achieved through above average room height. Most traditional tukul houses don't have foundations and the structure is reliant on one central support connected with radiating vertical wood supports holding up the roof and walls. The rectangular houses don't have a distinct foundation system either, in some cases a stone and concrete foundation is constructed without steel reinforcement. The floors of the traditional houses are made of rammed earth while the rectangular houses use either rammed earth floor or a thin layer of concrete. For insulation and decoration, the floor is covered with a plastic or a woven straw carpet in both houses. (Nilsson, 2016)

The commonly observed lack of windows in traditional tukul houses is intentional as they use the smoke from the cook stoves to fight against insects, the furniture is often made of straw and mud. The lack of ventilation space leads to accommodation of smoke in the high roof level. In the contrary recent rectangular house types have multiple rooms designed for specific functions with one or more openings. The lack of control in the houses around Butajira is a major challenge affecting indoor air quality, the interior functions are rarely separated which exposes all residents to the pollutants exerted from the kitchen.



2.10. ARCHITECTURAL INTERVENTIONS TO FACILITATE INDOOR VENTILATION

One of the best architectural interventions for ensuring indoor air quality is providing effective openings that provide adequate ventilation throughout the space. Ventilation is the exchange of air inside and outside the building commonly defined as the process of intentionally introducing clean air into a space. It can be introduced by natural or mechanical options depending on the climate of the site and with the use of windows, doors, atriums and other form of building fenestrations. These openings on the building envelop need to consider various aspects of the building and the climate. Under favorable climatic conditions natural ventilation methods are the ideal choice, natural ventilation can save 10% to 30% of total energy consumption (Walker, 2016). There are two common types of natural ventilation methods:

- Wind-driven ventilation (cross ventilation) is the exchange of air through the use of wind movement from one opening to another. When openings are placed on opposite sides it becomes cross ventilation; for maximum results wind direction and wind speed should be considered. “The inlet opening should face within 45° of the wind direction dominant during the most overheated periods. The inlet opening will define the direction of the air stream entering. To get the maximum localized air velocity, the inlet opening should be much smaller than the outlet” (Szokolay, 2004).

Buoyance-driven ventilation (stack effect ventilation) takes advantage of the stack effect or the weight difference between hot and cold air, the stack effect concept is further elaborated by fluid dynamics which states low pressure air moves faster allowing fresh cold air to push up high pressure warm air. Openings are strategically placed at lower and higher levels to accommodate the hot air that is being pushed up by the cold air (Manimegalai, 2021).

While designing a naturally ventilated space, it's important to set the edge of the structure perpendicular to south-west direction as it is the origin of warm and dry summer winds. Our design should be narrow since the maximum width that can be naturally ventilated is only 13.8m. (Walker, 2016) Incorporating clerestories, ridges, and attic vents can assist in both buoyancy and wind driven ventilation; one should also ensure internal air flow between interior partitions. Before taking any ventilation measures its best to determine what kind of ventilation method the design will benefit from. For hot and dry climates, a closed building ventilation approach is preferable while an open building approach works best for warm and humid areas.



2.11. WIND INDUCED NATURAL VENTILATION

Natural ventilation is heavily reliant on the surrounding microclimate and the building parameters that result from its orientation to effectively provide and remove air from interior spaces. Architectural elements such as opening design, natural forces and the ventilation principles are the major aspects that guide the natural ventilation design. The wind gain in a building is determined by negative and positive pressure points that push hot and cold air across each other. “When wind strikes a building, a region of higher pressure is created on windward wall and a negative pressure on the leeward side of the building façade. A pressure gradient is thereby created across the building in the direction of the incident wind. This pressure gradient around a building in turn creates a negative pressure area inside the building that encourages air to move through the building and via its openings. The air moves through from the opening in the positive pressure façade to the opening in the negative pressure one” (Bhatia, 2021).

The movement of wind in and around a building is heavily influenced by the architectural design of the house. Indoor air quality is specifically connected to the type and layout of the kitchen in relation to wind pressure which is expedited through openings. The design of architectural characteristics especially the common sources of pollution such as the kitchen has a big influence in the personal and environmental pollutant exposure measurements. “Personal concentrations of PM_{2.5} were not associated with kitchen type and were not predicted by kitchen area samples; rather they were driven by spikes in PM_{2.5} concentrations during cooking” (VanVliet et al., 2013).

The importance of effective natural ventilation is evidenced by findings of prior studies in this area “Ventilating the cooking area by having the door or any windows open during the active cooking period showed a statistically significant reduction of the 24-h mean concentration of PM_{2.5}. Optimizing ventilation has been considered as an important practice for reducing the health risks. The practice of not opening a window or if there are no windows is due to the cultural perception related to security or a fear of theft in the area as reported in our previous study and might also be related with the weather conditions” (Tamire et al., 2021). The role of natural ventilation and fenestration is crucial to reduce indoor air pollution levels.



2.12. EFFECTS OF COOKING PRACTICES ON INDOOR AIR QUALITY

Cooking behaviors and types of cooking stoves are among the major indoor air pollution sources. Aside from improved thermal efficiency; improved cook stoves (IC) show a notable reduction in HAP and a less significant release of black carbon (BC) (Pratiti et al., 2021). Local studies recorded a 60% reduction of HAP when improved cook stoves (Mirt) was used in traditional tukul households (Bluffstone et al., 2019).

‘Chowdhury et al aerosol and air quality research’ conducted a pilot project in forty households located around rural Bangladesh, half of the selected households use a traditional mud stove and the other half use improvised mud stove with chimney ducts that emit outside. The findings of the study show a high concentration of pollution during the combined cooking period of breakfast and lunch. The extensive sampling and monitoring showed high PM and CO concentrations (mg/m³) measured by UCB, duplicate UCB, and DustTrak, and CO concentrations (mg/m³). The recorded concentrations are so high they can potentially penetrate very deep in to the respiratory and cardiovascular system. They found cooking with an improvised stove instead of traditional mud stoves lowered CO and PM concentrations by 23% and 59% respectively. (Chowdhury et al., 2012)

2.13. INDOOR POLLUTION SIMULATION AND CONTROLLED EXPERIMENTS

Various alternative simulation software’s are available for natural ventilation analysis including CFD, AIRPAK, FLOVENT, STAR-CD, EnergyPlus™ and DOE-2. The most convenient simulation software is Computational Fluid Dynamics (CFD) which is a common simulation method for indoor air quality research that is labor demanding but gives accurate air flow understanding (Walker, 2016).

In a study entitled ‘CFD Simulation Analysis on Make-up Air Supply by Distance from Cook stove for Cooking-Generated Particle’; the controlled study set out to understand the effects of PM and CO on modern ventilation systems. The changes can be monitored through Computational Fluid Dynamics (CFD) which generates data for the whole area. The concentration of PM and CO were measured in varying distance from the cook stove up to two-and-a-half-meter distance. The CO was measured directly while PM concentration during cooking was accrued to be divided by time and converted into PM emission rate. The study showed the ideal location of diffuser location to be one and a half meter away from the cook stove (H.Kim et al., 2020).



To ensure the reliability of CFD, the results were compared with a manual measurement conducted every 15s. Carbon dioxide is one the components measured at three points for comparison, the measured concentrations of p1, p2 and p3 are 582,561 and 567 ppm. The data from the CFD is 576, 564 and 567 ppm. The measured concentrations vary by up to 6ppm which is insignificant for indoor air quality analysis (H.Kim et al., 2020). CFD can be simulated using ‘simscale’ simulation software, the cloud-based simulation software is used to conduct computational fluid dynamics and computer aided engineering demands in an interactive and accurate manner. Since the focus of this study is on traditional circular houses with nominal internal partitions. Studying the boundary elements along with existing arrangements of cook stove and furniture placements will result in a varying CFD results (Mateus et al., 2023).

The results of control room experiments are generally dependent on the following factors: “The intended use of the room and thus the exercise of specific actions by the inhabitants, which are part of everyday life; The presence of equipment elements and stored items whose type is determined by the specific purpose of the room; The lifestyle of the inhabitants, their social status (cultural factors) and The intensity of air exchange rate” (Maré et al., 2017).

Related studies suggest various indoor air pollution control options including eradicating the source of pollution, ventilating the room to lower the concentration of pollutants and filtering the air to eliminate the pollutants. The ideal option would be to improve or eliminate the source of pollution but in existing structures where switching to sustainable energy is not an option, working on the spatial properties and ventilation is the preeminent option.

A 2004 study conducted in India by Balakrishnan concludes “Modeling indoor air pollution concentrations provides valuable insights into the key determinants of exposure: fuel type, kitchen type, and/or kitchen ventilation. The models developed in this study offer results that can provide definite improvement for epidemiological and intervention studies” (Balakrishnan et al., 2004). The most significant factors during a controlled indoor air pollution study are primary fuel type and the kitchen ventilation condition. For a more accurate modeling exercise extended measurement periods that last over 24 hours is recommended since the human activity variable is reduced. (Balakrishnan et al., 2004) Came to this conclusion after experimenting with three types of kitchen layouts. The controlled experiment considers the location of doors and windows, stove location and the presence and absence of partitions.

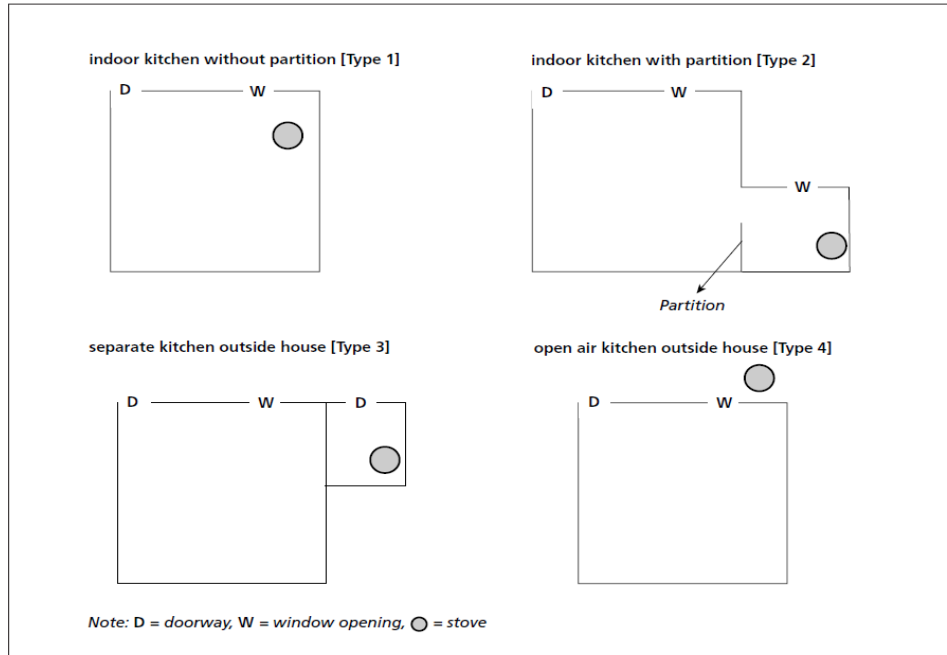


Figure 8: Control experiment in an indoor kitchen

(Balakrishnan et al., 2004)

In a controlled case study (Ram et al., 2014) conducted in rural kamalapur households with and without cross ventilation were compared. Households with cross ventilation showed a significantly lower PM_{2.5} concentration than households without cross ventilation (Ram et al., 2014). The study used qualitative and quantitative methods to measure the difference in PM_{2.5} concentration during the structural change (opening various number of doors and windows and adding low cost fans) and test the behavioral factors that resulted in PM_{2.5} decrease. Finally, (Ram et al., 2014) analyzes the acceptability of structural and behavioral changes by the occupants.



2.14. MATERIAL INTERVENTION

Another contributing element to indoor air pollution is building material related emission. Construction materials especially finishing materials such as paint, flooring and other interior decorative elements emit various pollutants including Volatile organic compounds, ammonia, PM_{2.5} and radon. In addition to efficient ventilation and improving the interior layout, carefully selected construction materials can significantly improve indoor air quality (Wagdi, 2015).

A good representation for modified building materials that target indoor air pollution is a new type of brick introduced by Carman Trudell titled ‘pollution absorbing bricks’ or ‘breathe bricks’ (Trudell, 2020). The bricks are designed in a faceted manner to direct airflow inwards, they are molded in the form of porous concrete block. “Shafts are provided for structural reinforcement. A coupler made of recycled plastic is provided between two bricks and a hopper is provided at the base for the collection of particles” (Yadav, Civil Wale, 2020).

The results of filtration capacity test on the bricks show, it filters 30% of particles spanning up to 2.5 microns or smaller in diameter, which is equal to smoke or haze, and it filters 100% of coarse particles with diameter more than and equal to 10 microns (Yadav, Civil Wale, 2020). Such improvement coupled with other interventions can transform the air quality assurance sector. Another emerging technology that can advance indoor air flow is ‘Development of a compact ventilation system for facade integration’ this technology introduces compact ventilation units that measure 15cm with 19cm diameter (Kolarik et al., 2020). The achieved flow rates, with an external pressure drop of 50 Pa at each in-/outlet and a rotational speed of 900 rpm, is in the range of 25 to 35 m³/h and changes linearly with the rotational speed (Kolarik et al., 2020).



2.15. INDOOR AIR QUALITY POLICY AND LEGAL FRAMEWORK

Many international and local building codes and standards related to indoor air pollution are explored as data sources in this research. The codes and standards are a specified set of rules that are used to ensure public health and safety. Widely accepted standards are discussed below.

- **ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), ASHRAE 55**

ASHRAE recommends for spaces to receive no less than 15 cubic feet of air in one minute and 0.35 air change in an hour (ASHRAE, 2019) in its standard 62.2-2019, “**Ventilation and Acceptable Indoor Air Quality in Residential Buildings**”. Further suggestions from ASHRAE include providing ventilation for tightly enclosed spaces that are used for cooking and fire related activities.

- **CEN (European Committee for Standardization)**

The CEN sets minimum ventilation requirements on CEN 15251, a unique feature of CEN is its separate set of standard targeting mechanically and naturally ventilated systems.

- **ISO (International Organization for Standardization), ISO 7730**

ISO 16814:2008 specifies the appropriate indoor air quality for human occupancy with due consideration to local limitations and ideal air quality.

- **ES-EBCS (Ethiopian Standard, Ethiopian Building Code Standard)**

EBCS 11 covers the collective guidelines for natural and artificial ventilation design, installation, construction, maintenance and related activities.

- **CES (Compulsory Ethiopian Standards)**

Compulsory Ethiopian standard section 8 that focuses on building ventilation has general guidelines based on EBCS.

- **EPA (Ethiopian environmental protection authority standards)**

Sets the local guidelines of ambient environment standards for Ethiopia.

Other building standards and regulations also cover building aspects that affect indoor air quality. Similar local standards include, Ethiopian Building Directives, Addis Ababa building proclamation and Addis Ababa building regulation.



2.16. RESEARCH GAP IDENTIFICATION

Currently very limited local research data targeting architectural interventions for indoor air pollution is available. Architectural aspects of indoor air pollution have not been studied as much as the health, technological and other related indoor air pollution aspects. Conducting a specific study on architectural interventions targeting ventilation measures in a detailed controlled experiment will contribute new and up to date air quality data, explore possible solutions and offers other similar advantageous outcomes.

Similar studies reviewed during the literature study show lack of consideration to the vernacularism and social values in the community; this can be evidenced by the communities' restraint to widely integrate most housing related pilot projects in their traditional construction techniques. Hence a research that targets existing structures with small but essential changes that can improve indoor air quality without disrupting the vernacular aspects of traditional tukul houses will benefit the public in numerous ways.

Ethiopia is the second most populous country in the African continent fortunately, the country has shown prompt urbanization rates. Conversely this urban growth largely fails to benefit majority of the population as it is unpredicted and overwhelming. The resulting side effects from this rapid urbanization include scattered settlements that require large scale urban planning to access basic facilities including road networks, electricity and telecommunication and similar urban components. The rapid urbanization rate will fail to keep up with the limited economical capacity of the country, forcing majority of the rural community to continue living with currently existing living conditions. As a result, modifying existing living conditions is the best option to combat the immediate threats faced by the population. The severity of health conditions resulting from indoor air pollution require immediate modifications in the form of architectural (improved building designs), mechanical (improved ventilation systems) or electrical (improved cook stoves) interventions. Considering the current accessibility of electrical and mechanical options by the rural community, architectural modifications are the best intervening measures.



Although various health professionals have published papers (reviewed in the previous chapter) indicating air pollution as a cause of multiple respiratory, visual and other chronic diseases especially in women and children. Previous concentration measurements in Ethiopia show increased PM_{2.5} concentrations compared to similar study results from Ghana, Nepal and India (Tamire et al., 2021). They also indicate a prominent need to provide alternative housing designs that target effective ventilation and quality air flow, fire resistance, indoor light gain and thermal comfort especially (Addissie et al., 2019), (Teku, 2017) and (Nilsson, 2016) (Tamire et al., 2021). To provide a typology that can be widely adopted by the rural society the major environmental elements that influence the occupant's health and comfort need to be tested to achieve the ideal indoor atmosphere. The lack of abundant resource, knowledge and recent technique in the rural housing development is the main obstacle that results in substandard indoor spaces. The effect of wind in relation to opening size and location with consideration to the vernacular values of the society are yet to be perfected. This study will explore the effects of natural elements such as orientation and wind in relation to ventilation and indoor air quality whilst maintaining the positive aspects of the traditional tukuls.

The existing living conditions, the indoor air pollution related disease load in the area and the economic incapability of the residents to switch to improved housing typology calls for a transitional intervention. The current structure of the tukuls is incapable of accommodating indoor cooking without affecting the IAQ. A study that is conducted on existing structures with minimal cost and lifestyle change could fill the gap created in the integration of previous research outcomes with pure scientific and socioeconomic changes.



2.17. CONCLUSION

Various studies and organizations including the US Environmental Protection Agency (EPA, United States environmental protection agency, 2022) categorized indoor air pollution as one of the top five environmental threats to public health. EPA specified source control as the most effective and cost-efficient approach to “eliminate individual sources of pollutants or reduce their emission” (EPA, United States environmental protection agency, 2022). While various researches have been done on this area, the impact of indoor air pollution continues to affect the health and wellbeing of the rural Ethiopian community.

The current technological advancements in the energy sector including renewable energy sources are inaccessible to most rural areas. The readily available energy options pose multiple side effects especially to the wellbeing of its users. The gas released during the processing of these energy sources including biofuel and other locally processes sources such as animal waste cause major health issues. These issues can range from minor headache to chronic illnesses that lead to death. Women and children who spend majority of their time near the source of fire are impacted the most by its severe consequences. Although various studies have been done to provide a lasting solution, the issue is still prominent especially in rural areas such as Butajira.

It's evident from the reviewed literatures that architectural interventions focusing on existing housing typologies have a promising potential to improve the indoor air quality of spaces with minor adjustments to the spatial, structural, material and other architectural characteristics. Hence, conducting a detailed experimental study on the effect of openings and orientation and its corresponding side effect on indoor air quality can help preserve traditional tukul houses by eliminating the main side effects that are pushing the residents to shift to relatively modern houses. If the change towards modern tin houses is still largely observed the results of this study will ease the indoor air pollution related challenges faced by the occupants during this transitional period and target the majority of the tukul house owners that can't afford to make the transition.

CHAPTER THREE

3. RESEARCH METHODOLOGY

3.1.INTRODUCTION

There are three research methodology types, qualitative, quantitative and experimental.

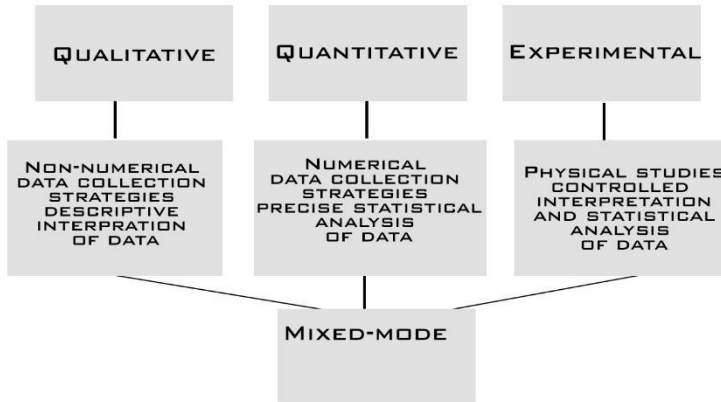


Figure 9:Characteristics of research methods

(Akšamija&Ajla, 2021)

The research methodology applied here is an experimental approach. Such that one specific case in the study area was selected and experimented on to justify the absence of indoor air quality and explore possible architectural interventions. The constant parameters and the variable parameters were identified. Different computer and on-site measurements of common pollutants, architectural measurements and supportive site analysis were taken. Since the research questions require onsite measurements, modifications and the researcher’s active intervention; the experimental research approach was found ideal. Experimental research methods are organized procedures used to explore the study subject by manipulating constant and variable parameters in order to measure its effects on desired aspects of the subject (Ross, 2004).

The advantage of experimental research methodology is its capacity to govern independent variables and eradicate irrelevant variables. This methodology can determine the chain of events between variables and it is easily replicable which makes it an ideal choice however, it requires more time and money than other research methodologies. Experimental research methods are ideal for determining the effects of specific variables in a field or laboratory test; in architectural research this can be used to study behavioral, environmental or performance related outcomes by prototyping, testing and experiments (Akšamija&Ajla, 2021).

3.2. EXPERIMENT BASED RESEARCH METHODOLOGY

The selected site for the experiment is chosen for its vernacular characteristics, its concentration of measurable data or severity of the study issue in the region, the aspired integrity of the local ambiance and the intricacy of the local social practices. In an experiment-based research methodology, the researcher actively intervenes with the variables in order to produce and measure the difference in the collected data. Experimental data can be expensive but it allows for a reproducible and casual technique.

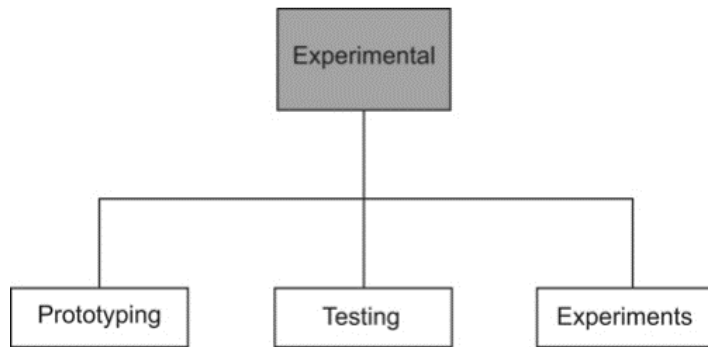


Figure 10: Experimental research methods in architecture

(Akšamija&Ajla, 2021)

3.3. IDENTIFYING CONSTANT AND VARIABLE PARAMETERS

To identify the level of discomfort and factors affecting IAP; constant and variable parameters were set. These parameters were recognized as constant and variable based on the level of pollution in the house, the resulting change in measurements and rise of discomfort inside the house according to the indoor air quality standards. The constant variables include the size, location, construction material of the house and the local climate. Additionally, the measurement location, device and time were kept similar throughout the experiment. The variable parameters include the opening locations in the house, the spatial arrangement, the size and number of the openings, and the height of the structure.

3.4. STUDY CONTEXT

The study was conducted from May 2022 to May 2023 in SNNP region, gurage zone Wurib Woreda. The research area is found in southern part of the gurage zone in Wurib Woreda which is one of the ten Woredas recognized by the Butajira rural health program. The chosen site has main access roads to welkite and Addis Ababa (through Butajira).

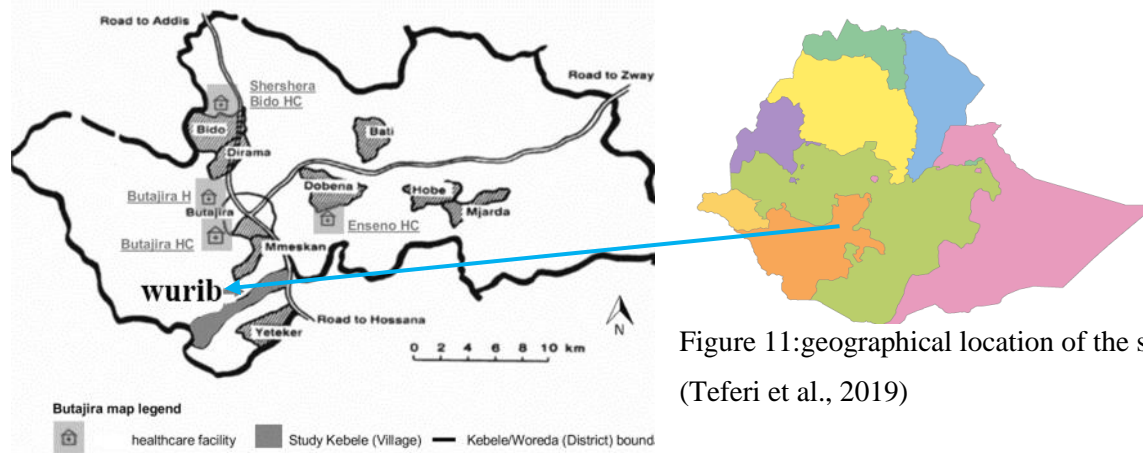


Figure 11: geographical location of the study area (Teferi et al., 2019)

The control experimental study which was conducted in Rural Butajira (Wurib Village) by collecting data for four consecutive measurements in three selected households has given original results that were synthesized in a qualitative format. The methods of opening and re-construction of windows and measuring the 24hr PM_{2.5} (in $\mu\text{g}/\text{m}^3$) and CO (in PPM) concentrations using PATS+ sensor was conducted four times in all households.

- First reading before intervention
- Second reading after introducing the first window
- Third reading after introducing a second window
- Fourth reading was taken after changing the previous stove location and opening all available windows in the house.

The Standard Operation Protocol suggesting measuring 1.5 meter above the ground level of the households was taken from WHO guidelines along with the construction of multiple standard windows in each household. The results showed a mixed outcome that differed from the conventionally expected outcomes. Majority of the intervention showed success in decreasing the PM_{2.5} and CO concentrations while various success levels were achieved in different intervention types across all sample houses.



3.5. STUDY LOCATION “BUTAJIRA”

Butajira is located around 150Km south of Addis Ababa. The district represents all the three agro-ecology sites of Ethiopia: kola/warm, woyina dega/temperate, and dega/cold. Butajira has a population of 89,824 covering 16.13 km² (Brinkhoff&Thomas, 2022). The area is mainly inhabited by ethnic Gurages speaking varying dialects of Guragigna languages including six varying languages: Inor, Sebat Bet Gurage, Wolane, Kistane, Messqan and Silt’e. Islam is mostly practiced in east parts of the region while orthodox Christianity dominates in the western region. The population spread in the region is more than double the national average at 216 people per km². (Nilsson, 2016) The rural population usually lives in traditional ‘Tukul’ houses typically characterized by thatched roof and circular mud walls with small and rare openings.

3.6. STUDY DESIGN

A controlled experimental study was used to measure the link between ventilation and indoor air pollution in three houses in rural Butajira zone. Experimental houses in lower lands of Wurib Woreda were chosen to be part of the study. The houses were selected based on size, proximity and weather data. The selection parameters were used to specify three experimental tukul houses with varying size and pollution level in order to make the research inclusive. The number of experimental houses will be limited to three to thoroughly experiment with the design interventions and measure the pollution level of each house. The precise number allowed the researcher to implement various interventions repeatedly and select the best outcome.

Size: the size of the houses varies including the number of partitions, clear usable space and the overall size in design and materials. The experimental houses had varying sizes to ensure the pollutant concentration isn’t affected by congestion due to size.

Proximity: the second parameter is proximity to public facilities. The consideration given to proximity accounts for the level of development of that specific area. The awareness about pollution and indoor air quality decreases in places with limited access.

Weather data: the final selection parameter is the weather data which can affect the houses with varying weather data during the experiment taking this into consideration will produce a holistic research that won’t be influenced by the seasonal weather-related energy usage.



3.7.DATA COLLECTION PROCEDURES AND TOOLS

The houses were chosen using purposive sampling method. Population and housing data were collected from the local AAU campus situated in Butajira which is a local institute that records the housing, social, population, and other socioeconomic changes of the area. The data gathered from the AAU campus was be used to choose ideal locations/houses from the 10 Woreda's in Butajira region. The research data was collected twice, the first data collection session was used to identify the experimental houses, gather the owners' information and take a 24hr measurement of selected indoor air pollutants. Additionally, the existing context of the site including weather, orientation, number/size of openings, cooking patterns and related information were gathered. Professional data collectors were employed to mount PATS+ devices in each house and record the indoor air data.

PATS+ devices were used to measure personal exposure to PM_{2.5} concentrations. The device is Berkly air's unique HAP data logger. The PATS+ device is portable, small and easy to work with. To analyze the data collected by the device it was operated on PICA allowing users to download, review and display the information in graphic and excel formats.

The collected data was interpreted by the researcher. There were two site visits; the first visit was used to select the study houses, take onsite measurements of the selected houses, collect the socio-economic data and collect initial pollution in the houses. During the second site visit air pollution mitigating interventions were designed and constructed in each sample house while recording the effect of the architectural change on the pollutant concentrations.

3.7.1. TYPE OF DATA COLLECTED FOR THE STUDY

The study is focused on measuring and retracting the effects of air pollutants in indoor spaces. In addition to measuring the indoor air pollutants, architectural data is gathered by focusing on the existing condition and physical measurements of the house. Two of the internationally recognized primary pollutants; PM_{2.5} and carbon monoxide were the primary pollutants measured while the physical measurements of the house included openings, partitions and interior layout of functions and furniture's. The socio-economic background of the occupants was gathered as well as their activity patterns, their medical history and any previous experience they have with indoor air pollution.



3.7.2. PARTICULATE MATTER_{2.5} AND CARBON MONOXIDE MONITORING

Data collectors clarified their responsibility inside the research protocol before starting the measurement. Data collectors informed the details and scopes of the measurement protocol (i.e. duration to be monitored, safety or precaution, starting time, ending time, sounds and lighting of equipment etc.). Meanwhile, an observational check list was used to observe and monitor activity pattern of the cook and other family members, the structure of house and spatial arrangement, ventilation and other related activities in the kitchen. The monitoring duration was 24 hours in accordance with WHO's minimum requirement.

After 24 hours of measurement, the devices were unmounted and the second interview containing post measurement questions was conducted by the researcher. The questions were mainly focused on the cooking and other activity patterns recorded by the device.

Following the berkeleyair PATS+ standard protocol, the data was downloaded from the device and properly labeled. The researcher oversaw and cross checked the survey, cooking pattern, choice of energy source, activities conducted by all residents during the data collection and data monitoring.

The face to face interviews were conducted in four steps. First the researcher distributed the sample questionnaire to the data collectors to form a common understanding of the target data. The house tour was the second step which gave the researcher a detailed understanding of the housing typology and activity pattern of the residents. The third step took place during the placement of the measurement devices by conducting the pre-recording investigation. The final step was the detailed investigation conducted after the 24hr recording period. The questions were personalized where it's relevant for the specific housing typology and family background.

3.8.SETTING

The study was conducted in three rural households around butajira region, the data was collected in person including interviews. The data was continuously recorded for 24hrs inside the house. The internal and external measurements were taken on each house. The activity pattern of the residents was observed through the onsite interview and the researcher's observational checklist.



3.9. DATA COLLECTORS

The data was collected by the researcher with the support of trained public health officers who is specialized in data collection, interpretation and analytics. The data collectors were under the strict observation of the researcher.

3.10. DATA QUALITY ASSURANCE

The houses were properly identified and labeled by their local code numbers gathered from the AAU campus database. Regular supervision was conducted by the researcher and data collectors to ensure the device wasn't altered by the occupants. The data collection process was supported by the use of questioners on a daily basis. The measurement device was tested for accuracy in addition to monitoring the proper installation and validating the continuity of the recorded data. Aside from the strict hourly and daily follow ups, the vast experience data collectors had with PATS+ devices and added direction from the researcher ensured the data quality.

3.11. DATA COLLECTION TOOLS AND TECHNIQUES

3.11.1. HOUSEHOLD BACKGROUND DATA COLLECTION

The household data collection was conducted by using a well-thought-out questionnaire designed to assess the socioeconomic data and the occupant's daily household activity pattern. The questionnaire was conducted after the 24hr data collection period was complete. The subjects questioned during the process were the elderly (the women) as they usually spend majority of their time indoors making it easier for them to identify the type of fuel used, the cooking patterns including peak cooking hours and type of food cooked. The architectural dimensions were taken simultaneously including the interior partition walls, the location of cooking stove and internal height of the structure.

3.11.2. MORAL AND ETHICAL CONSIDERATIONS

The objective of the study along with the purpose of the measurements and the importance of their active and honest participation was verbally communicated to the subjects. Their verbal consent was recorded. All necessary legal and cultural protocols were followed and the findings of the study were shared with the local authorities to help improve IAP.



3.12. DATA ANALYSIS APPROACH

The fixed number of experimental houses and the specific pollutants that are targeted by the study resulted in a large but manageable amount of information. The data was sorted by the researcher into the proper architectural drawing formats and the necessary charts and graphs to illustrate the desired scientific data. The data was analyzed and categorized according to internationally accepted standards. The interventions were designed using the architectural data produced from the analysis. The architectural measurements collected onsite were converted to universally readable drawings by Revit software. Similarly, the PATS+ data was simplified to excel charts and graphs. All architectural data was converted to metric system measurements while all CO and PM_{2.5} was converted to PPM and $\mu\text{g}/\text{m}^3$ respectively.

3.13. CLIMATIC DATA OF BUTAJIRA

This research studies indoor air quality in traditional houses and the relationship between ventilation and indoor air quality. Accordingly, the climatic data of Butajira region has been collected from Addis Ababa University local research office that is found in Butajira city. The study was conducted in three households sharing similar climatic conditions.

3.14. DATA COLLECTION

3.14.1. PRIMARY DATA COLLECTION

The primary housing data collected by the researcher has been modeled in Revit software to further analyze existing site conditions, to study the best orientation, the best interior layout and overall architectural features. Onsite indoor air measurement has been recorded in each experimental houses PATS+ device for a minimum of 24 hours. Data including pm_{2.5} concentration, CO concentration, Humidity, temperature was carefully measured by PATS+.

3.14.2. ON SITE MEASUREMENT

PATS+ device was used to measure PM_{2.5}, CO, Humidity and air temperature in the selected experimental houses. The measurement was taken for 24 hours in each house where the device was mounted 1.5 meters above the floor and one meter away from the source of fire in accordance with the sop adopted from WHO guidelines. Each house had a unique household identification number. All PATS+ data was simultaneously collected across all houses in ten consecutive days.



Table 4: Measurement details in experimental houses

House ID	Start Date	End Date	Device	Device location	Duration
HHID770.1	02-12-2022	11-12-2022	PATS+	1.5m above the central support	24hrs
HHID818.2	02-12-2022	11-12-2022	PATS+	1.5m above the central support	24hrs
HHID 724	02-12-2022	11-12-2022	PATS+	1.5m above & 1m away from the source of fire	24hrs

Diagrams taken from Platform for Integrated Cook stove Assessment (PICA) software which is used to present a simplified field data collected with PATS+ devices are included in the appendix section. Additional charts are also included in the results to compare the success of each intervention in the same sample house and across all houses. Architectural diagrams showing the existing measurements of the house are prepared in location plan, floor plan and sectional views. The synthesized data is discussed in the results, the figures show the concentration of CO and PM_{2.5}. A minimum of 24hr data was collected in each house. The figures show the maximum, minimum and median concentration of each pollutant in ppm (for CO) and µg/m² (for PM_{2.5}).

3.15. STUDY OF THE EXPERIMENTAL SUBJECTS (TUKUL HOUSES)

Three houses were carefully selected as the subjects of this controlled experiment, the houses were chosen based on their location, energy consumption and their vernacular characteristics. Each house was measured for a minimum of twelve hours, the measurement was taken by PATS+ device mounted at two meters height and at least one meter away from the energy source. Three traditional tukul houses of different sizes were chosen as study subjects. The design, recorded pollution data and social environment of each house is encompassed below.



3.16. DATA COLLECTION PROTOCOL

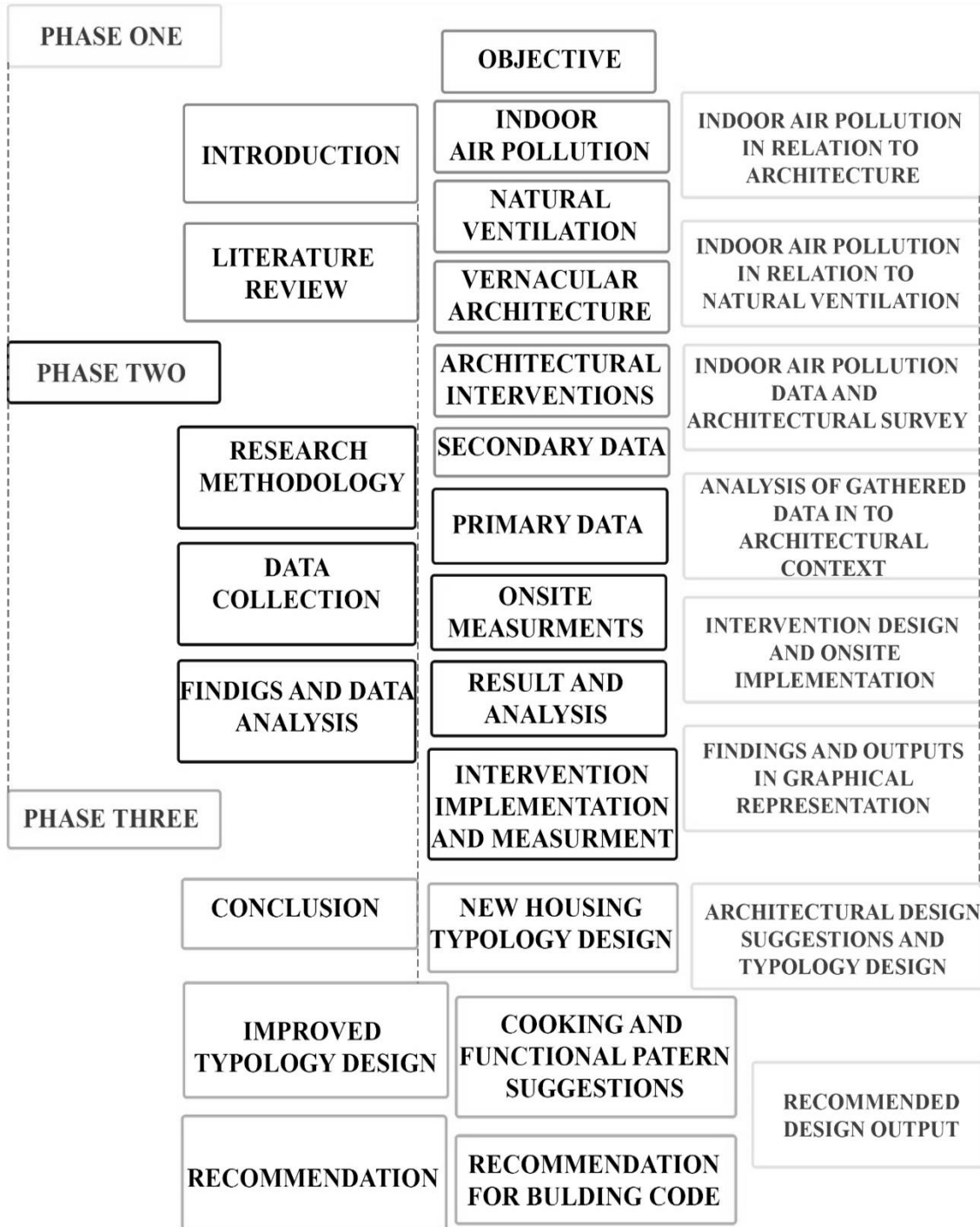


Figure 12: data collection procedure

CHAPTER FOUR

4. RESULTS

The individual architectural and HAP results of all three study houses are discussed under their corresponding house hold identifications.

4.5.1. EXPERIMENTAL TUKUL HHID770.1

4.5.1.1.INTRODUCTION

The first experimental house is found in rural Wurib Woreda where the house doesn't have direct access from the vehicular road. The house has been in use for over Ten years, it is showing significant signs of structural failure especially on the roof and walls. There are six permanent residents in the house, two women aged 58 and 28, a 32 year old man, and three young children all under the age of 13. The 28yr old female resident is currently six months pregnant. The female residents and children spend over eight hours in the house. The residents cook food in the house twice a day, they typically use wood and animal waste for cooking. They own two cows and three sheep that are kept in the house all day and night except for a few hours of the morning. The animals are kept in the house to avoid the sun and indoor fire is always kept going to keep the animals warm and exterminate flies and rats. The house had only one small door and no windows. The residents have experienced breathing related side effects and eye problems especially during peak cooking time where there is a lot of smoke.

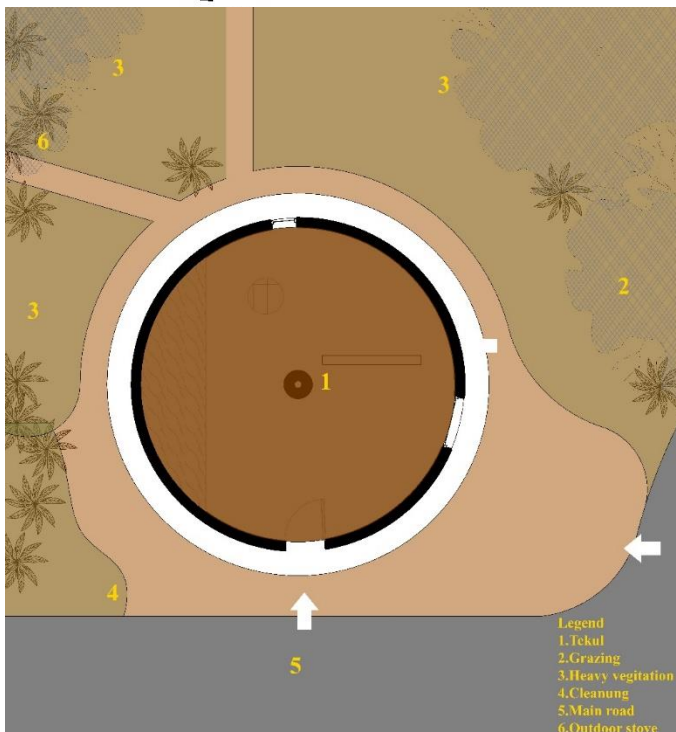
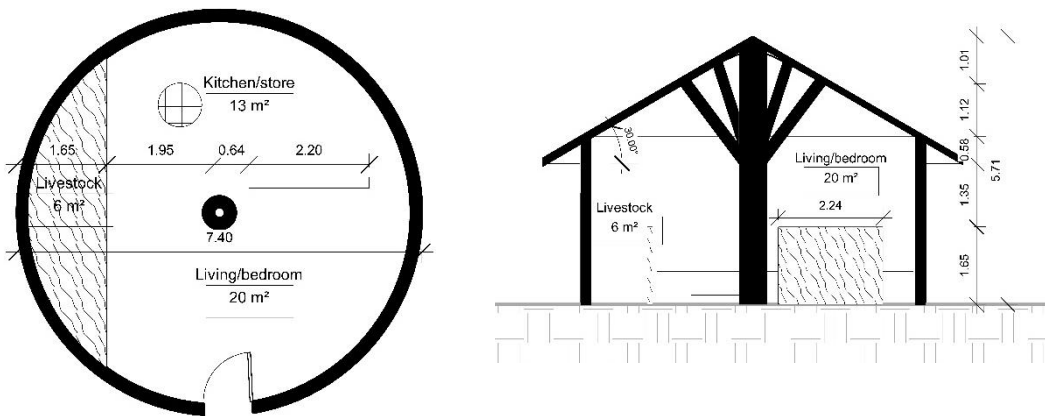


Figure 13: Site pictures of the house (exterior, cookstove and interior view)

4.5.1.2.ARCHITECTURAL FEATURES OF THE HOUSE

The house is a traditional tukul house made of wood, mud and straw; the roof is tacked with straw and wood. A central support made of a single tree is placed in the center of the structure. A traditional three stone fire stove is placed at the back end of the house along the storage area. The storage area on the far back side of the house is separated from the rest of the house with standing pieces of wood measuring 1.60m long, the partition is covered by cloth and other house hold items. The left side of the house is reserved for the livestock while the remaining space serves as a living/sleeping space.

4.5.1.3.ON-SITE HOUSE MEASUREMENTS AND DRAWINGS



HHID 770.1 INTERVENTION

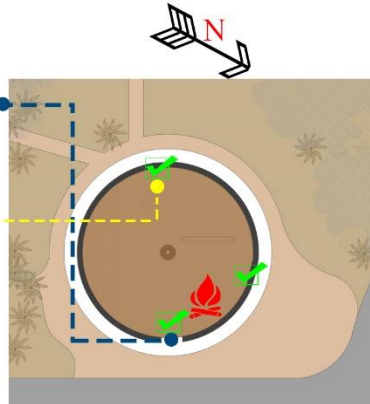
EXISTING SITE CONDITIONS

Existing opening:

- *A single door on N-E side
- *No cross ventilation

Stove location:

S-W side of the house



IDEAL SITE CONDITIONS

Ideal opening:

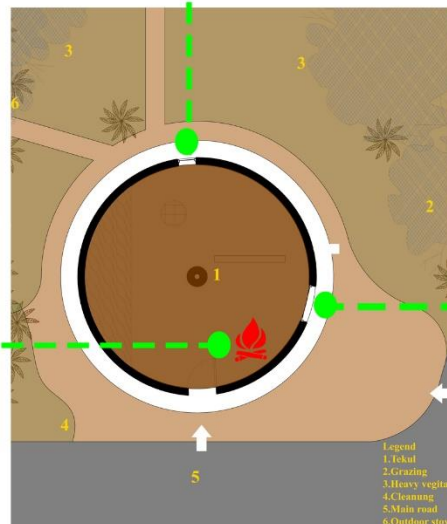
- *Multiple openings especially on S-W side. ✓
- *cross ventilation

Stove location:

Service areas on Norther side of the house. 🔥

1. INTERVENTION ONE:

Window one opened on S-W side of the house.



3. INTERVENTION THREE:

Stove moved to the N side of the house.

2. INTERVENTION TWO:

Window Two opened on N-W side of the house.

Figure 14: Experimental House No.1 Site plan, floor plan and section view with pre and post intervention diagrams



4.5.1.4.CO AND PM_{2.5} CONCENTRATION (24HR)

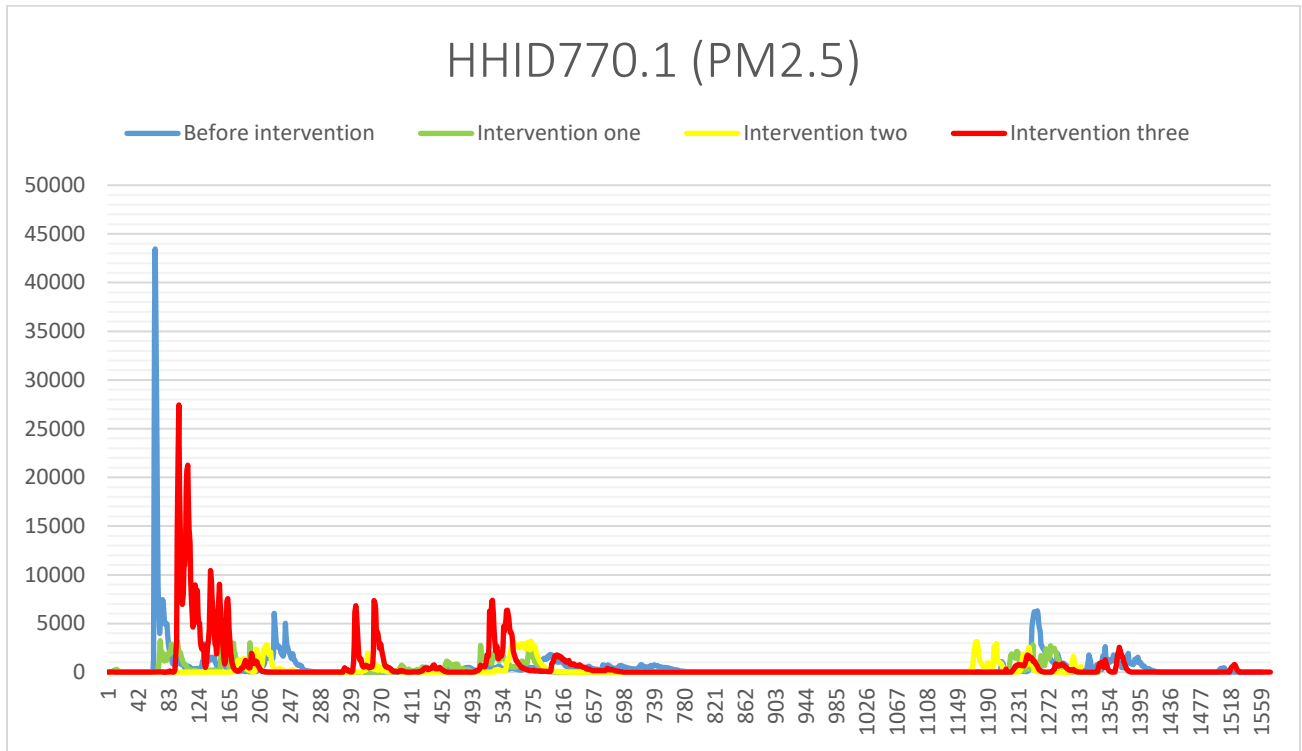


Figure 15:PM_{2.5} 24hr measurements in ppm (before and after intervention comparative chart)

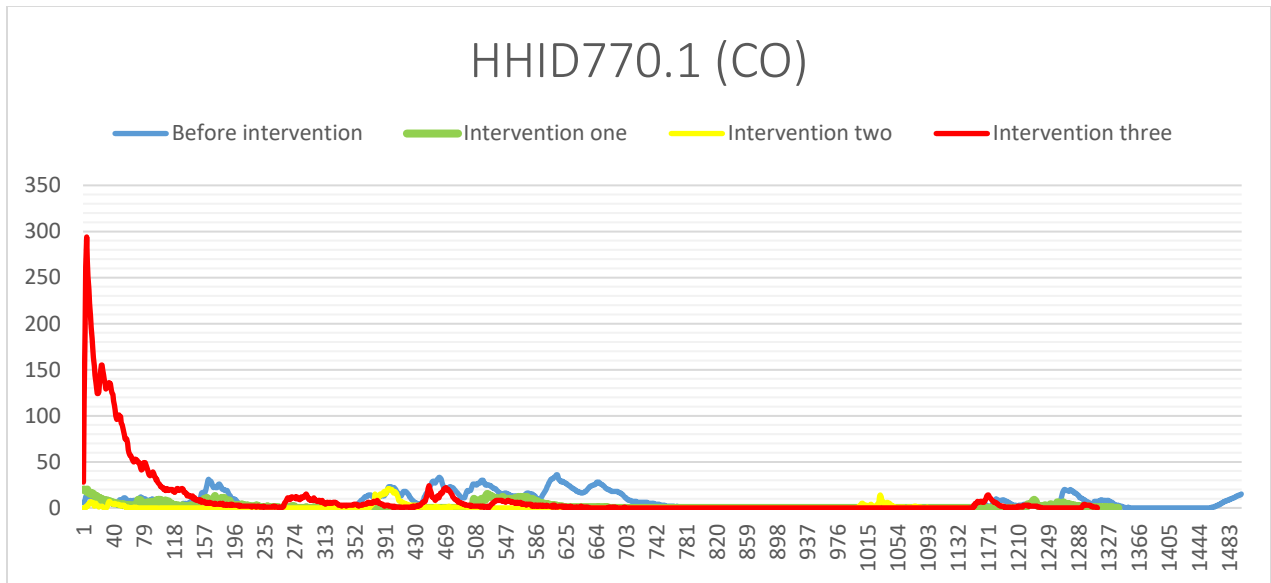
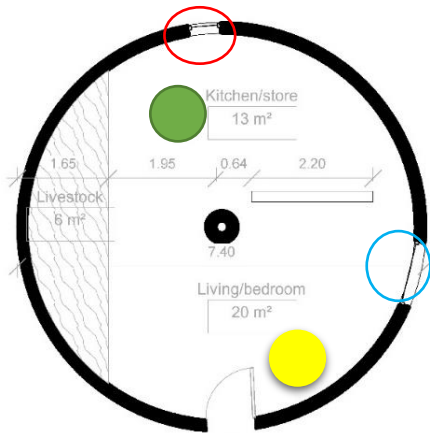


Figure 16: CO 24hr measurements in µg/m³ (before and after intervention comparative chart)

The findings in HHID770.1 show the most positive overall improvement. The house had only one opening (a door) prior to the intervention. The occupant size and cooking pattern is comparatively smaller than the rest of the sample houses. During the day, the occupants don't perform activities other than cooking inside the house. There is no heavy vegetation in the immediate surroundings of the house. Compared to the other study houses this house is small in size. Intervention two where two openings were provided in the existing layout showed the best result with 88.48% (5.84 ppm) decrease in CO and a 49.6% (222.78 µg/m³) decrease in PM_{2.5}, the change in the stove location showed an increase in the concentrations although both windows were open. The female resident consistently used crop residue to cook food during the study period. Compared to the remaining study houses she also kept a very clutter free and clean house.



The first intervention where a 60cm*60cm window was opened is circled in red while the second intervention where a 80cm*90cm window was opened is highlighted in a blue circle. The original location of the stove is circled in green while the position it was moved to in the third intervention is highlighted in yellow.

Figure 17: Intervention locations

The first intervention consists of introducing a single 60cm by 60cm wooden window to the southwest side of house (circled in red) where the wind is prevalent. The size of the window is decreased by 20cm*30cm in this intervention to avoid structural failure due to the delicate existing state of the intervention area. The intervention is successful in reducing CO by 70.1% (4.67 ppm) and reducing PM_{2.5} by 36.42% (163.51 µg/m³). Aside from the pollutant level improvement a significant increase in daylight gain was recorded.

The second intervention consists of adding a second window in the northeastern side of the house (circled in blue) where the occupants spend majority of their time including sleeping, eating and other indoor activities. The results lowered by 87.6% (5.84 ppm) for CO levels and showed a 49.6% (222.78 µg/m³) decrease in PM_{2.5} levels. The second intervention where an additional 90cm*80cm window was added and only the second window was kept open throughout the day showed the lowest pollutant levels from all three interventions.

In the third intervention both windows were kept open and the cooking stove was moved to an architecturally appropriate spot (due north, where the ideal location for service areas is recommended). The northern side of the house is adjacent to the door where the air coming through the door was observed forcing the smoke back in to the house. Although both windows were kept open the pollution levels showed very little improvement compared to the first two interventions. CO only decreased by 10.6% (0.71 ppm) while the PM_{2.5} showed a 44.7% (200.83 µg/m³) decrease. The PM_{2.5} measurements showed better result than the first intervention.

The intervention that was believed to succeed prior to the experiment was intervention three but the most successful intervention was intervention two. The lack of heavy vegetation in the immediate surroundings of the house contributed to the comparative success of HHID770.1 since the wind was unobstructed and reached the interior with higher pressure. Additionally, this household showed the most improved interior lighting after the interventions.

4.5.2. EXPERIMENTAL TUKUL HHID 818.2

4.5.2.1. INTRODUCTION

The second experimental house is also in rural Wurib Woreda around 200m from the main road. This house is along the secondary main road with direct vehicular access. The house is considerably larger than other tukul houses in the neighborhood, it was built around 30 years ago. The owners have built a modern tin house in their compound but they still cook, eat and sleep in the tukul house. There are seven residents in the house, an elderly women who suffers from asthma and eye problems aged over 65 years, her son who is around 35 years old, his wife who is around 30 and their child aged 1 and 3. Additionally there are one male and female residents aged 19 and 25 respectively. The residents of the house except the two adult males suffer from breathing related and eye irritation symptoms.



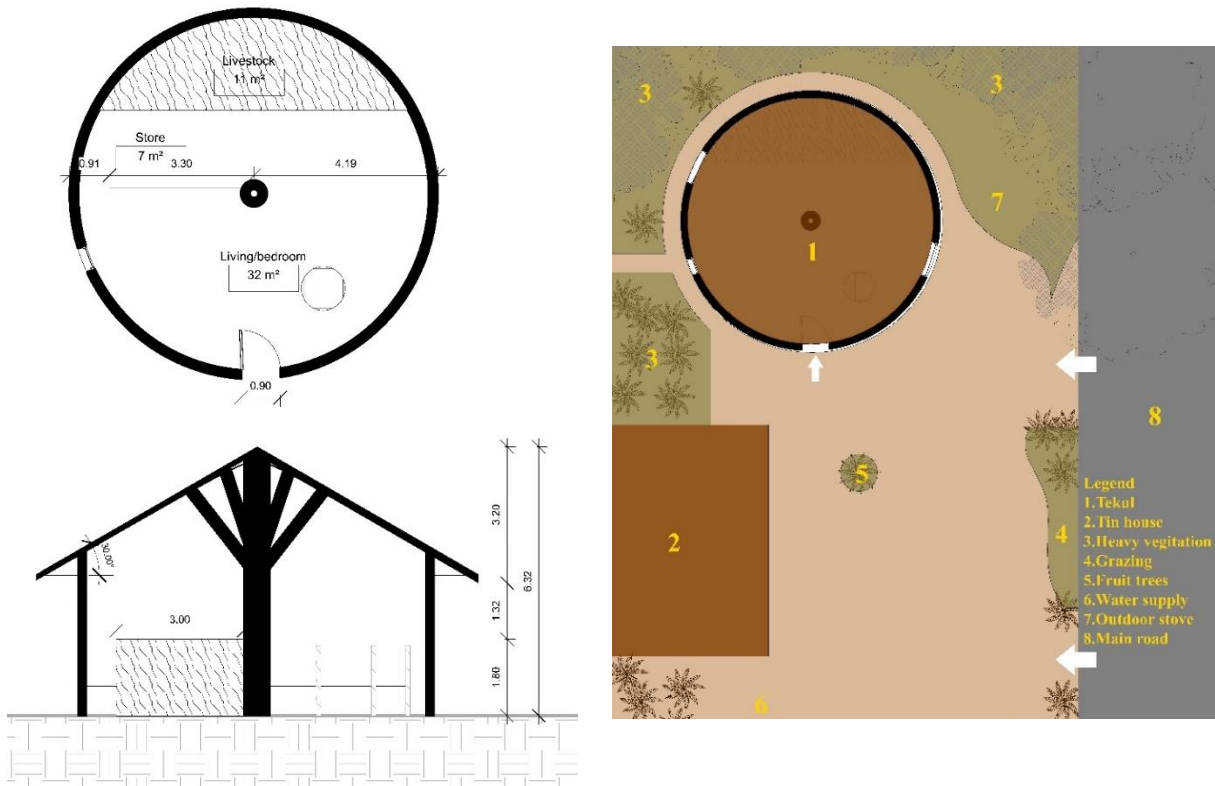
Figure 18: site pictures of the house (exterior, interior and cookstove views)

The residents cook twice a day and keep the fire going for an extended coffee ceremony. They use wood and animal waste to run the fire. The smoldering fire and its smoke is used to keep the livestock warm and it also serves as a pesticide. The family owns four cows and three sheep that are kept in the house except for a few hours in the morning, the animals are kept warm by a continuously run small fire which exerts a lot of smoke.

4.5.2.2. ARCHITECTURAL FEATURES OF THE HOUSE

It's a traditional tukul house made of wood, straw and mud. The house has similar structural and spatial features to the first experimental house. There is only one door and one window in the house. The house is considerably bigger including the central structural support, its roof and the usable interior space. The livestock is kept in the back of the house separated by a few free-standing wood pieces. There is a small storage area on the right side of the central support. The remaining space is reserved for living and sleeping areas.

4.5.2.3. ON-SITE HOUSE MEASUREMENTS AND DRAWINGS



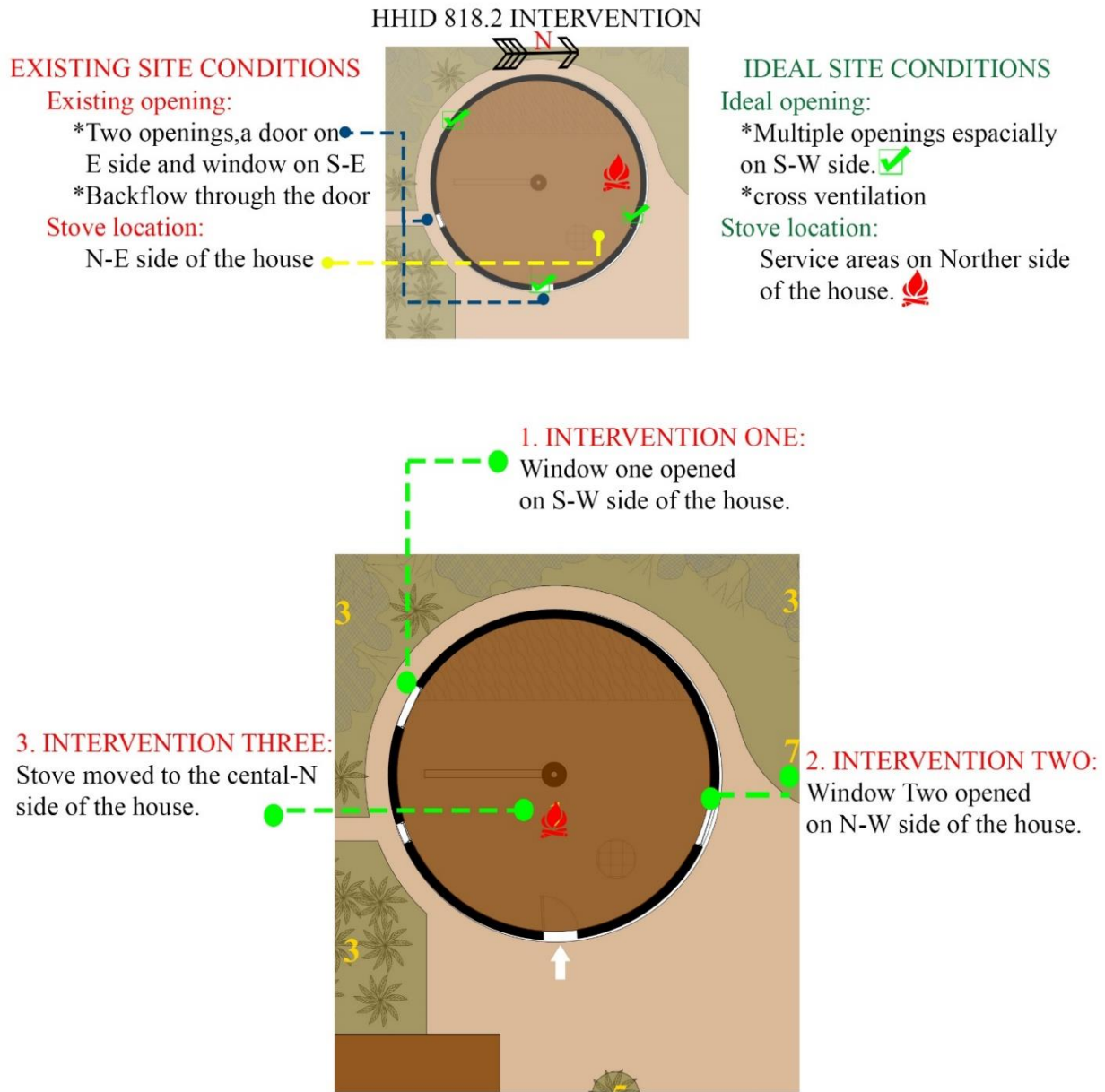


Figure 19: Experimental House No.3 Site plan, Floor plan and section view with pre and post intervention diagrams



4.5.2.4.CO AND PM_{2.5} CONCENTRATION (24HR)

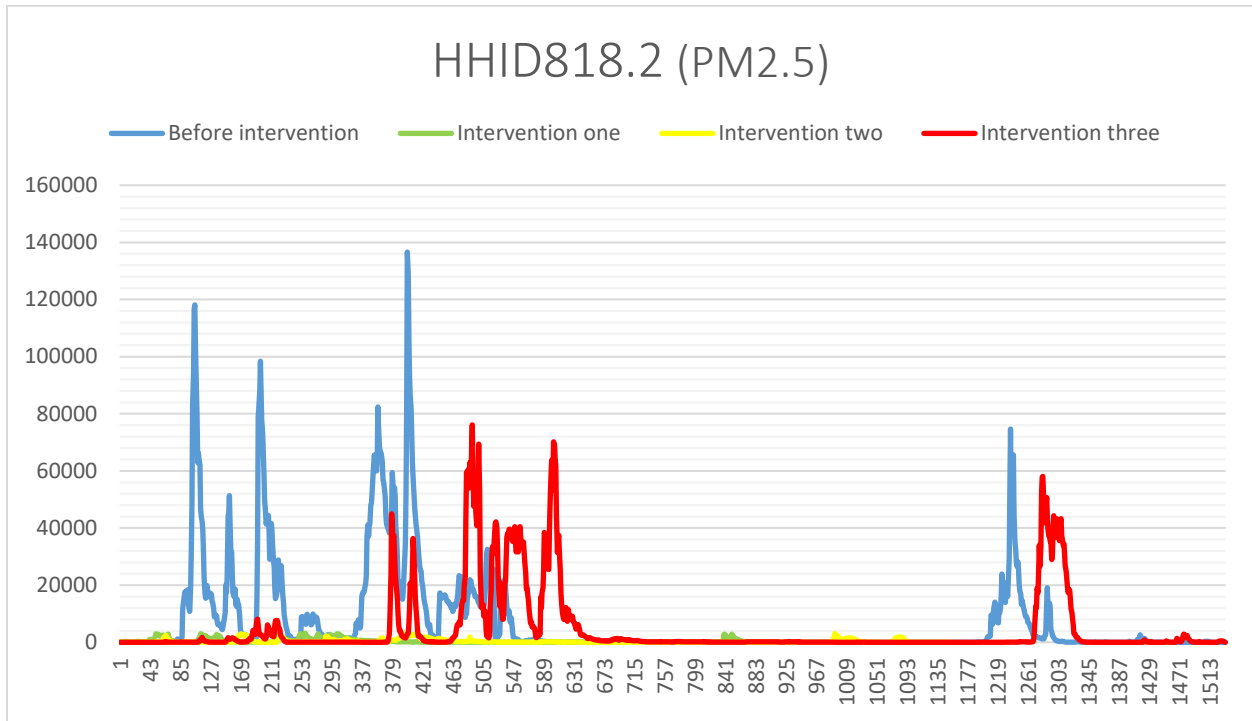


Figure 20:PM_{2.5} 24hr measurements in ppm (before and after intervention comparative chart)

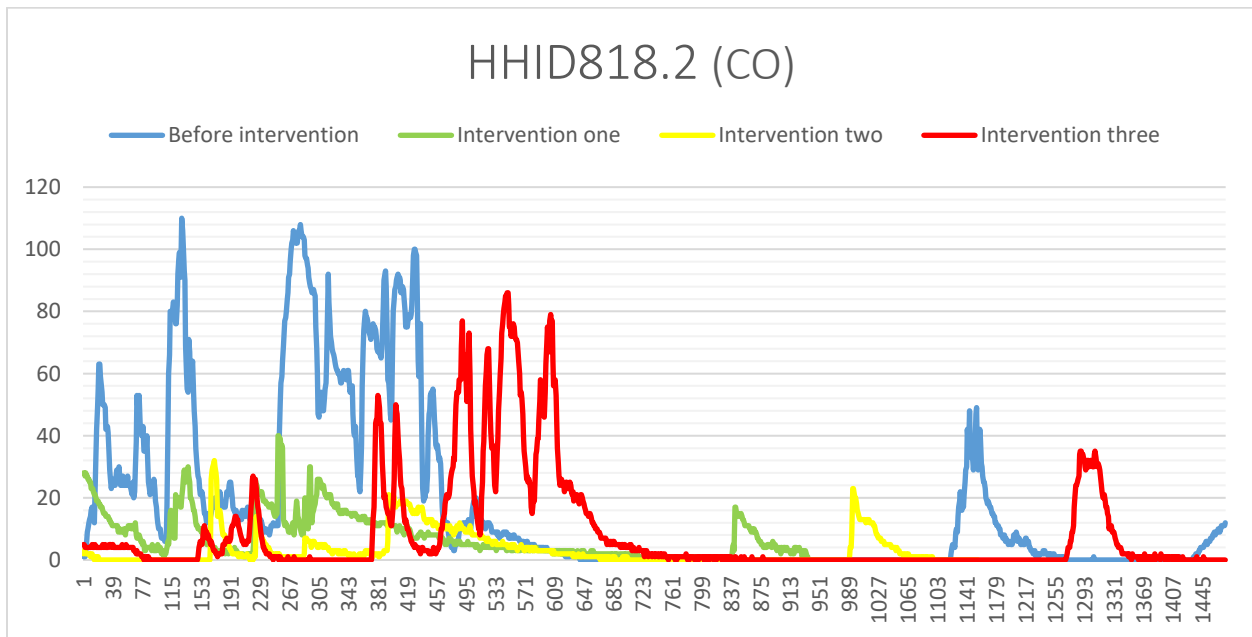
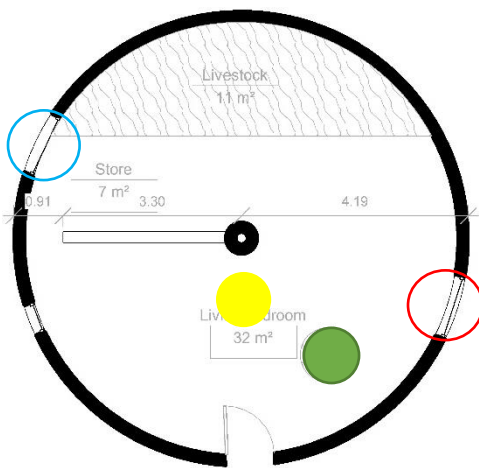


Figure 21:CO 24hr measurements in µg/m3 (before and after intervention comparative chart)

The findings in HHID818.2 show positive improvement especially in intervention three where the interior layout was altered. This is the biggest and most well-kept house (structurally), the best result showed a 49.9% (1.61 ppm) decrease in CO and a 10.8% (36.38 µg/m³) decrease in PM_{2.5}. The house had two openings prior to the study, it had one well oriented 60cm*80cm window on the southwest side. The high pollution concentration is a result of larger family size that resulted in repetitive cooking, the use of animal waste as fuel (which exerts more smoke) and the location of the stove which is directly next to the door allowing the wind coming through the door to push the smoke back into the house. Adding two more windows for a better air movement coupled with proper placement of the stove to the northern side of the house showed great improvement. The existence of large vegetation on the southwestern side of the house may limit the fresh air gain of the house as it lacks the proper distance between the window and the plants this was countered by adding additional window on the windward side of the house.



The first intervention where a 80cm*90cm window was opened is circled in red while the second intervention where a 80cm*90cm window was opened is highlighted in a blue circle. The original location of the stove is circled in green while the position it was moved to in the third intervention is highlighted in yellow.

Figure 22: Intervention locations

The first intervention consists of introducing a single 80cm*90cm wooden window to the northeastern side of house (circled in red) where the cross ventilation can be achieved with the existing window. The intervention increased CO by 124% (4.27 ppm) and PM_{2.5} by 26.9% (90.75 µg/m³). Aside from the increase in pollutant levels a prominent increase in daylight gain was recorded. The increase in pollution is directly related to the outdoor cooking location. The residents perform heavy cooking (bread and injera) outdoor close to the newly introduced window, the additional smoke from the outdoor fire contributed to the increase in pollutant measurements.



The second intervention consists of adding a second window in the southwestern side of the house (circled in blue) to facilitate the fresh air gain by increasing openings in the windward side. The results lowered by 6.1% (0.21 ppm) for CO levels and showed a 0.71% (0.58 $\mu\text{g}/\text{m}^3$) decrease in PM_{2.5} levels. In the second intervention a second 90cm*80cm window was added and only the second window was kept open throughout the day. Although the results improved it didn't show a vast decrease.

The third intervention is where both windows were kept open and the cooking stove was moved to the northern side of the house. In the previous interventions minor improvements were recorded because of the existing stove location, the stove was next to the door where the smoke is re-entering the house when it is pushed by the air coming through the door. The pollution levels showed vast improvement compared to the first two interventions. CO decreased by 46.9% (1.61 ppm) while the PM_{2.5} showed a 10.8% (36.38 $\mu\text{g}/\text{m}^3$) decrease. The third intervention showed better results than the first two interventions.

The intervention with the top result was expected to be intervention three which was later proved to be correct. The heavy vegetation in the immediate surroundings of the house especially on the southwestern side contributed to a reduced supply of fresh air leading to the limited success of HHID818.2.

4.5.3. EXPERIMENTAL TUKUL HHID 724

4.5.3.1. INTRODUCTION

The third experimental house is a traditional tukul house with similar characteristics to the first house. This is a considerably older house built around thirty years ago. There are Seven residents in the house; a women aged over 50, her husband who is over 60 and their children aged 15, 12, 9, 6 and 1. They cook meals at least twice a day, their extended family and neighbors visit during the evenings so they usually have a coffee ceremony which exerts a lot of smoke. They mostly use wood and animal waste as energy sources. The women suffers from pneumonia and asthma.

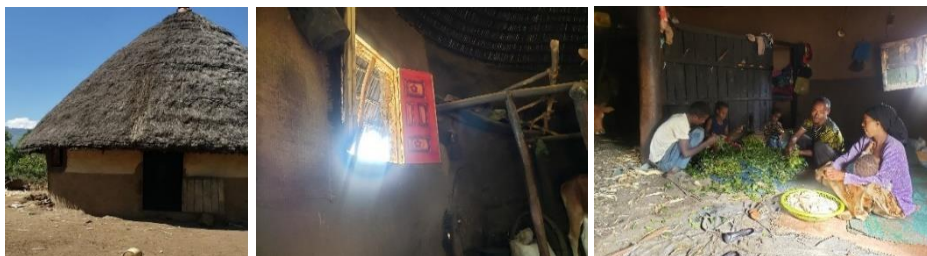


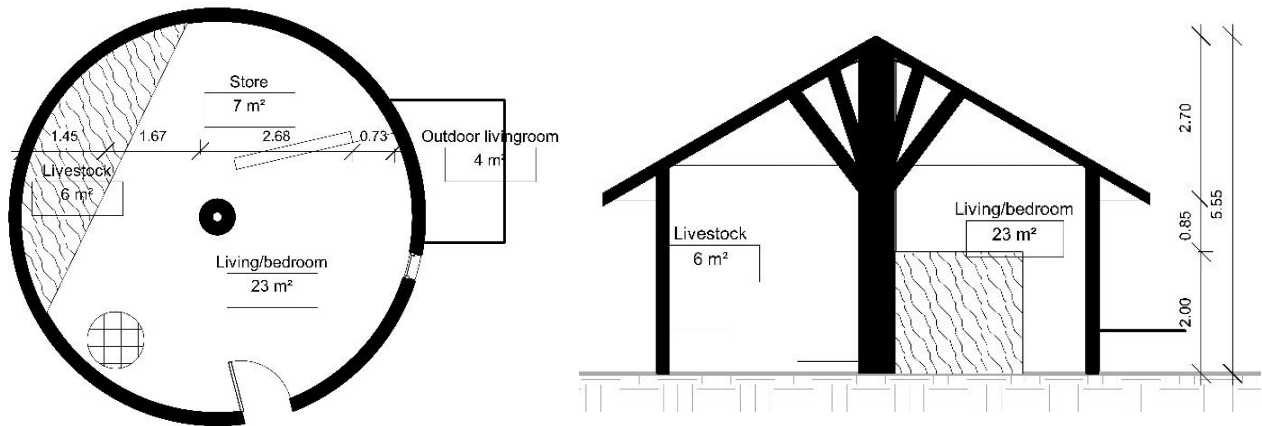
Figure 23: site pictures of the house (exterior and interior views)

4.5.3.2.ARCHITECTURAL FEATURES OF THE HOUSE

The house has three rooms separated by mud walls and curtain door covers, the rooms serve as a living room, bedroom and kitchen. The kitchen is an extended addition to the original structure that has a separate opening connected to the main house. The house has doors and windows in all rooms except the kitchen which only has one door.

Although the windows are operable the residents barely open them, the lack of open windows combined with curtain doors that barely separate the air movement the house has limited air movement. The storage area is separated by a traditional mat unique to gurage culture.

4.5.3.3.ON-SITE HOUSE MEASUREMENTS AND DRAWINGS



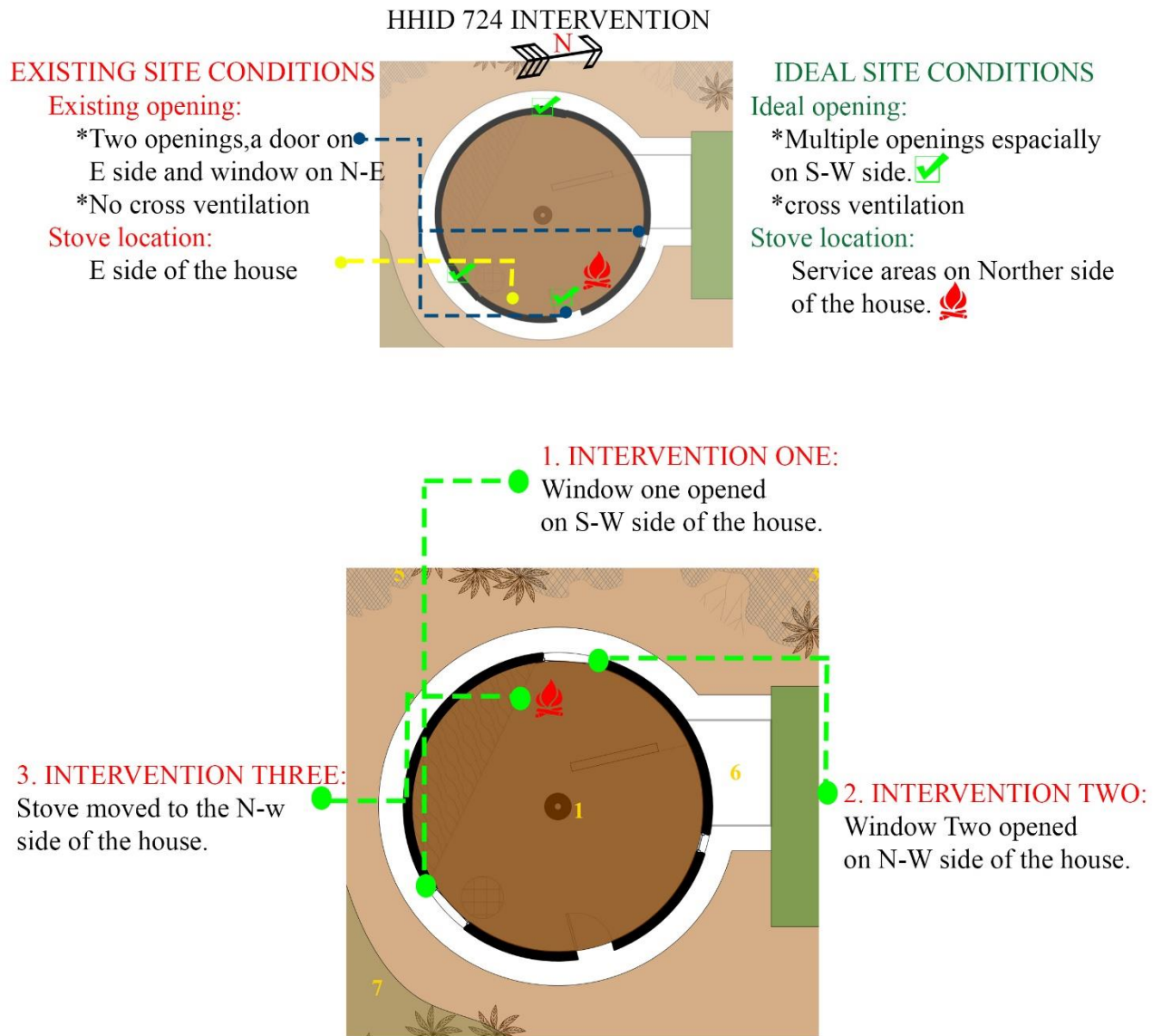


Figure 24: Experimental House No.2 Floor plan and section view with pre and post intervention diagrams



4.5.3.4.CO AND PM_{2.5} CONCENTRATION (24HR)

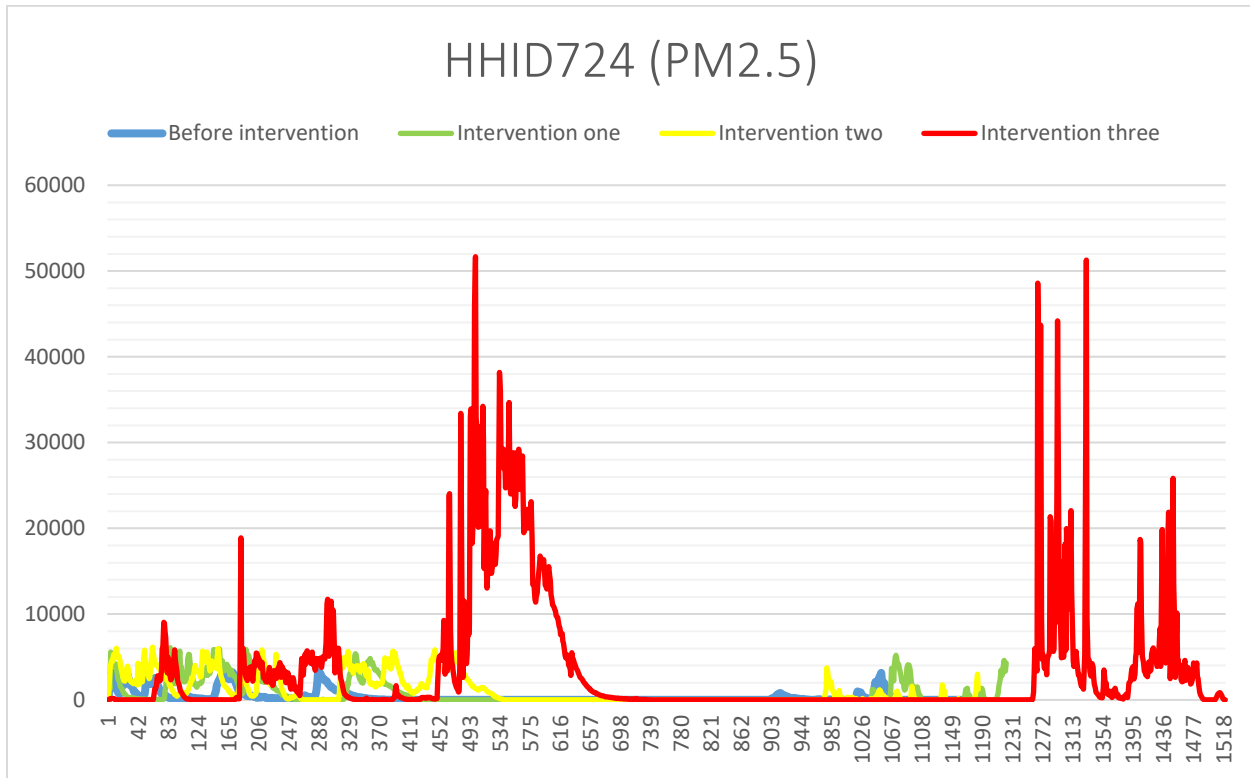


Figure 25:PM_{2.5} 24hr measurements in ppm (before and after intervention comparative chart)

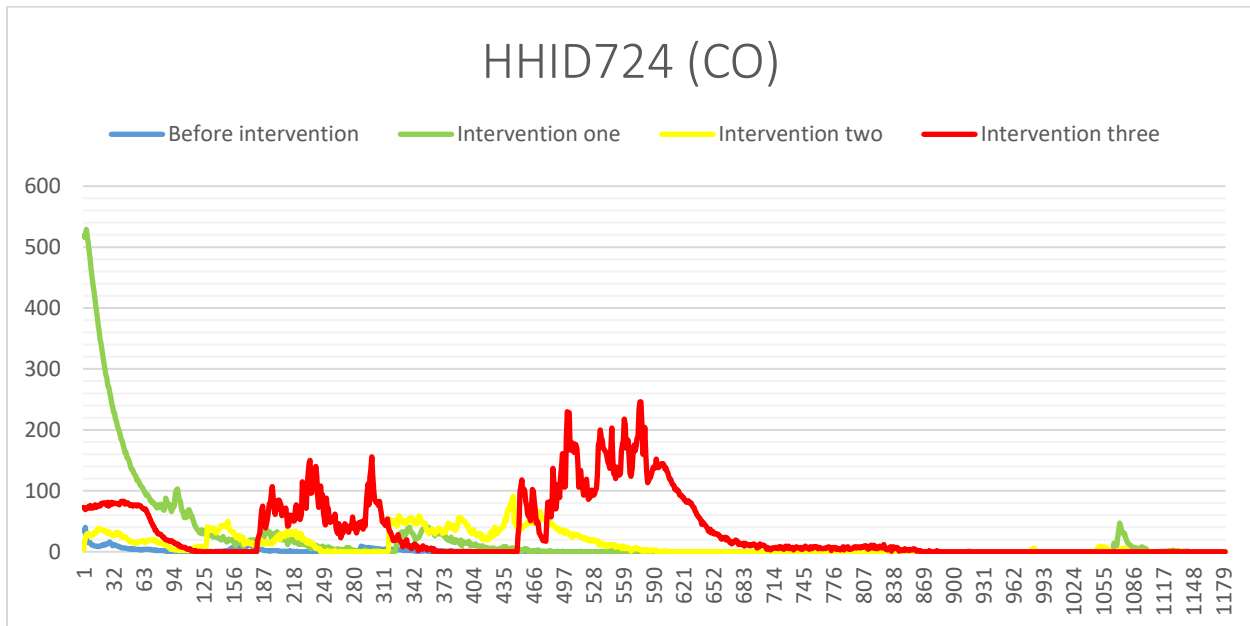
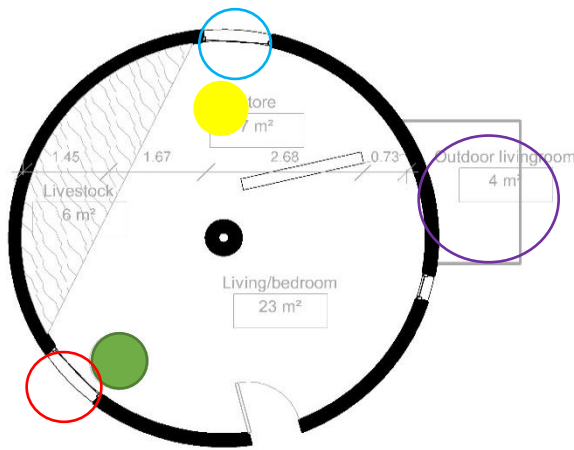


Figure 26:CO 24hr measurements in µg/m³ (before and after intervention comparative chart)

The findings in HHID724 show differing results, this is the oldest house with the largest number of occupants additionally the occupants performed multiple activities in the house throughout the day. The structural state of the house doesn't allow for the release of smoke through the roof which shows visible amount of smoke, dust and similar substance buildup.

Similarly surrounding dust particles and smoke (they typically cook outside to avoid the heavy smoke) can enter through the cracks on the lower parts of the wall which show small openings. The pollution concentration in the house is so bad the occupants only cook specific foods inside and keep all openings open day and night. There were two openings in the house prior to the study, the existing window was too small (50cm*70cm) and in the wrong orientation.



The first intervention where a 80cm*90cm window was opened is circled in red while the second intervention where a 80cm*90cm window was opened is highlighted in a blue circle. The original location of the stove is circled in green while the position it was moved to in the third intervention is highlighted in yellow. The outdoor living space is outlined in purple.

Figure 27: Intervention locations

The first intervention consists of introducing a single 80cm*90cm wooden window to the southwest side of house (circled in red) where the wind is prevalent. The intervention showed increased pollution levels where CO increased by 1755% (20.54 ppm) and PM_{2.5} increased by 128.6% (432.06 µg/m³). Aside from the increase in pollutant levels a significant enhancement in daylight gain was recorded. The first intervention showed the lowest PM_{2.5} concentrations from all three interventions.

The second intervention consists of adding a second window in the southern side of the house (circled in blue) where the occupants have a long partition blocking air movement in addition to a full storage area. Similar to the first intervention results the pollution level showed an increase. CO increased by 932.4% (10.91 ppm) and PM_{2.5} levels showed a 240.8% (810.06 µg/m³) increase.



The second intervention where an additional 90cm*80cm window was added and only the second window was kept open throughout the day showed the lowest CO levels from all three interventions.

In the third intervention all windows were kept open while the cooking stove was moved. The northeastern side of the house is comparatively less affected by the smoke coming from outside cooking hence, moving the second opening and the stove there should have decreased indoor pollution levels. Although both windows were kept open and the interior layout was adjusted the pollution levels showed even less improvement compared to the first two interventions. CO increased by 1370.9% (16.04 ppm) while PM_{2.5} showed a 210.2% (707.12µg/m³) increase. Although the recorded levels increased the CO measurements showed better result than the first intervention.

The intervention that was believed to succeed prior to the experiment was intervention three but all three interventions failed to decrease the pollution levels. Intervention one had the least increase in pollution levels compared to the remaining interventions. The heavy vegetation in the immediate surroundings of the house contributed to the limited fresh air gain and increase in pollution levels in HHID724.

Although two additional windows in standard sizes and orientation were provided just like the other study houses, the occupants failed to keep some variables uniform. The cooking pattern was unpredictable including the type of fuel they used. During the existing pollution measurement stage, the female head of the house used crop residue to prepare food which showed a smaller concentration but she switched to animal dung in the remaining days which is the most significant influence for the increased concentration. The second prominent reason for the concentration increase is the thick surrounding vegetation blocking air flow in the wind ward side, the added windows mostly increased the amount of smoke entering the house from their outdoor cooking area. The house has a lower roof which limited the size and constructability of windows in a desirable location. The full-length partitions that obstruct air flow and the cluttered condition of the house which only increased during the study as more neighbors visited to observe the study is another possible reason for the unique results. All these factors contributed to the increased pollution concentration levels which showed a 1370.9% or 16.04 ppm increase in CO and a 210.2% or 707.12 µg/m³ increase in PM_{2.5}.



4.6.CO AND PM_{2.5} CONCENTRATION LEVEL SUMMARY

Table 5: PATS+ Result Summary

S. N	Study HH ID	PATS+ ID	Concentration	Variables	Before Intervention	After First window Open	After second window open	All window open & change Stove location	difference
1	HHID770.1	P7717	CO (PPM)	Mean	6.66 PPM	1.99 PPM	0.82 PPM	5.95 PPM	0.71 PPM
				SD	8.62 PPM	3.60 PPM	2.74 PPM	24.12 PPM	-15.5 PPM
			PM _{2.5} (µg/m ³)	Mean	448.85 µg/m ³	285.34 µg/m ³	226.07 µg/m ³	248.02 µg/m ³	200.83 µg/m ³
				SD	914.70 µg/m ³	588.78 µg/m ³	596.80 µg/m ³	512.57 µg/m ³	402.13 µg/m ³
2	HHID818.2	P7714	CO (PPM)	Mean	3.43 PPM	7.70 PPM	3.22 PPM	1.82 PPM	1.61 PPM
				SD	6.59 PPM	7.22 PPM	5.22 PPM	3.86 PPM	2.73 PPM
			PM _{2.5} (µg/m ³)	Mean	336.39 µg/m ³	427.14 µg/m ³	335.81 µg/m ³	300.01 µg/m ³	36.38 µg/m ³
				SD	632.65 µg/m ³	735.10 µg/m ³	618.94 µg/m ³	593.75 µg/m ³	38.9 µg/m ³
3	HHID 724	P7713	CO (PPM)	Mean	1.17 PPM	21.71 PPM	12.08 PPM	17.21 PPM	-16.04 PPM
				SD	3.09 PPM	67.11 PPM	17.33 PPM	29.81 PPM	-26.72 PPM
			PM _{2.5} (µg/m ³)	Mean	336.27 µg/m ³	768.87 µg/m ³	1146.33µg/m ³	1043.39 µg/m ³	-707.12 µg/m ³
				SD	681.76 µg/m ³	1413.8 µg/m ³	1630.1 µg/m ³	1706.00 µg/m ³	-1024.2µg/m ³

Among the three Study Households, two houses HHID 770.1 and HHID 818.2 showed a reduced PM_{2.5} concentration after the interventions (448.2 µg/m³ to 226.07 µg/m³ and 336.39 µg/m³ to 300.01 (µg/m³) respectively. But in household 724 both PM_{2.5} and CO levels increase significantly. This is believed to be a result of cooking patterns, family size which affects the cooking pattern, change in fuel types used for cooking, changing of the stove area, wind direction of the study house window opening in relation to outdoor cooking, layout of the interior including the partition height and ambient air pollution exposure.

It must be noted the findings in each house vary depending on the existing preconditions of the house including but not limited to the size of the house, the number of openings, the cooking pattern which is also affected by the number of temporary residents, the type of fuel used, the type and location of the stove, the type of food the occupants prepare, the age, room height and overall condition of the house.



Indoor air pollution: Pragmatic smoke mitigating interventions for reducing CO and PM_{2.5} in traditional tukul houses. The case of Butajira area

Predetermined variables listed in previous chapters were kept constant throughout the intervention these factors include the location of the measurement device, the starting time and length of the recording (to avoid variations in temperature and humidity), the number of permanent occupants, cooking pattern and type of fuel.



4.7. SUMMARY OF FINDINGS

4.8.COMPARATIVE REPRESENTATION OF FINDINGS ACROSS ALL HOUSES

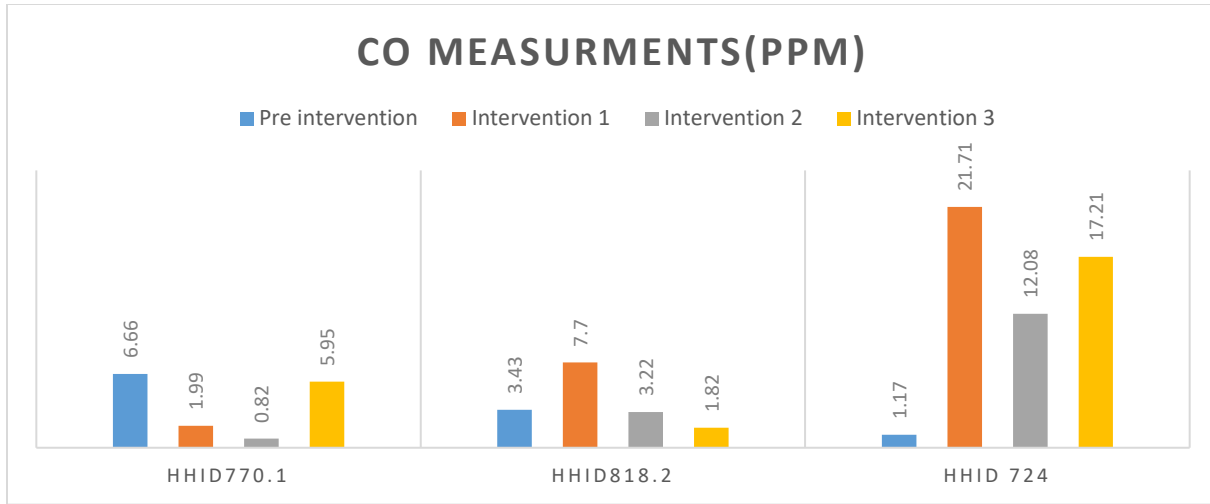


Figure 28:CO measurements for all study houses in ppm

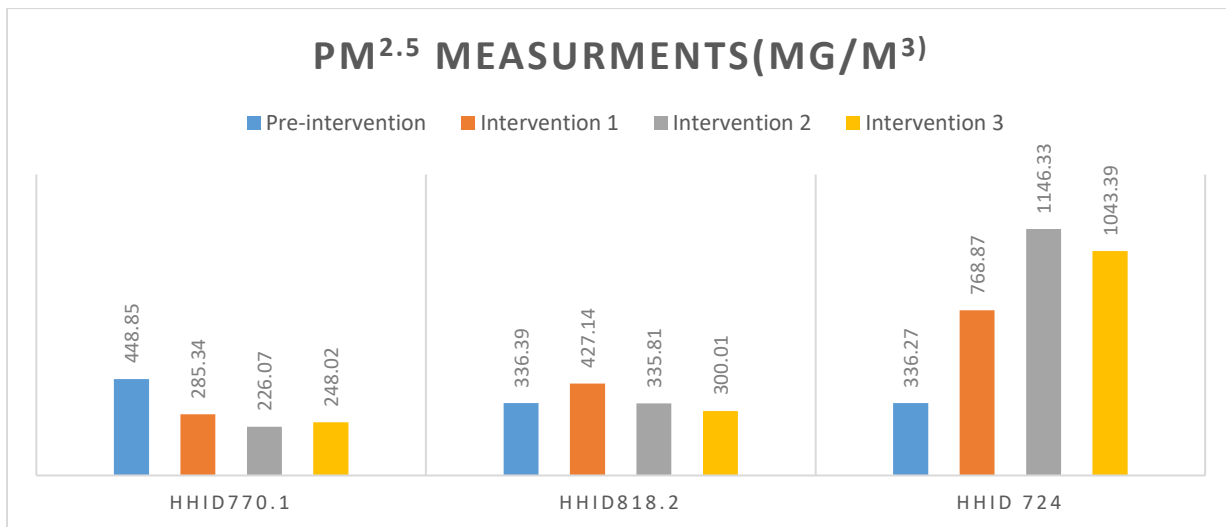


Figure 29:PM_{2.5} measurements for all study houses in µg/m³

The final results show varying success rates even though similar interventions were conducted in all households. HHID770.1 showed lower pollution levels after every intervention, the second intervention was the most successful with the lowest CO and PM concentrations. This house hold benefited the most from the second window which has a bigger size as there were limited influences from the surrounding. The interior layout changes only lowered the PM_{2.5} concentrations while CO showed the lowest decrease from the remaining interventions. Overall this household was the most successful in each intervention with lower CO and PM_{2.5} concentrations.



HHID818.2 Showed positive results in intervention two and three while a slight increase was recorded after the first intervention. Unlike HHID770.1 the most successful intervention was intervention three where the stove was moved from the door way which allowed the smoke to exit the house instead of getting pushed back. The back flow of pollutants in to the house as a result of poor opening location was observed in (Parajuli et al., 2016) where the study concludes “The effect of back flow is a major problem found in a chimney of a short height nearby a window that allows pollutants back into the house. Therefore, the future research should focus more on technical chimney orientation and height to prevent backflow problems” (Parajuli et al., 2016) hence, opening arrangement, sill height and opening size were important factors in the research interventions. Aside from backflow the density of surrounding vegetation heavily influenced the amount of fresh air gain which contributed to the limited concentration level improvements. Both CO and PM_{2.5} showed the lowest measurements in intervention three. Generally, this household showed success in the second and third interventions while a slight increase was recorded after intervention one. The increase after intervention one is a result of the outdoor cooking location.

HHID724 showed an increase in pollutant concentration in all three interventions. The highest CO increase was recorded after intervention one while the highest increase in PM_{2.5} was recorded after intervention two. Intervention two showed the lowest increase in CO and intervention one showed the lowest increase in PM_{2.5} after intervention one. Intervention three showed consistent increase in both CO and PM_{2.5}. Intervention two and three were comparatively more successful in all households. HHID770.1 and HHID818.2 showed lower pollution levels where HHID724 failed to show similar success.

Similar to results obtained in (Tamire et al., 2021), the initial concentration levels and the improved concentration levels showed immense measurements compared to the WHO guidelines which recommend “25 µg/m³ 24-h mean for maintaining safe indoor air quality in low- and middle-income countries” (Tamire et al., 2021). The positive effect of providing strategic openings was confirmed to align with studies such as (Weaver et al., 2017) that conclude having more openings resulted in lower pollutant concentration levels.



The size of the windows, the length of time the windows/doors were left open and the cooking time had significant effect in the results of this study as previously acknowledged by reviewed literatures. “Previous studies from different countries reported similar findings of lower pollution concentrations in houses with adequate ventilation practices and availability of more doors and windows. Optimizing ventilation has been considered as an important practice for reducing the health risks. The practice of not opening a window or if there are no windows is due to the cultural perception related to security or a fear of theft in the area as reported in our previous study and might also be related with the weather conditions” (Tamire et al., 2021)

This research set out to identify architectural methods that can bridge the gap between the ideal indoor air quality suggestions and the heavily excessive pollution patterns that are observed in vernacularly designed Ethiopian rural houses. Over the course of this research the initial research questions were addressed through literature review, onsite measurements and architectural design interventions. The initial concentration measurements in each household (from the controlled experiment) coupled with the concentration levels reviewed in the literature address the first objective where finding the 24hr concentration levels of selected traditional households was questioned. The second objective of the research where the current state and architectural characteristics of the houses was inquired was answered through detailed architectural plans, site analysis with pictures and field questioners. Similarly, the third objective was addressed through a series of literature reviews that propose computational, ventilation, material and other mitigating solutions. The final objective was achieved through a rigorous site work that included measuring the current conditions in selected houses and implementing the controlled experiment with equivalent design interventions. The changes that came as a result of the intervention were recorded and discussed thoroughly in the findings.

The research was focused in testing ventilation options to lower the indoor air pollution concentrations of PM_{2.5} and CO. The intervention was designed after the site was studied and the existing conditions of the houses were taken into consideration. Three houses were purposively selected for the controlled experimental study before implementing the interventions. The architectural measurement, occupant background and existing pollution data of each house was well documented. The intervention is designed to target the facilitation of maximum air movement which will increase fresh air gain.



The results further cemented the crucial role architecture has in attaining ideal indoor air quality. The controlled experiment has shown the importance of well-made openings. High pollution levels were observed in the initial measurements across the three study houses; however, the numbers showed a fivefold increase of CO and double the PM_{2.5} measurements in HHID770.1 compared to the other households. There were no openings in HHID770.1 prior to the intervention.

The highest before intervention measurements correlating to the study house with no windows shows the lower pollutant concentrations observed in HHID818.2 and HHID724 are a result of ventilation measures.



CHAPTER FIVE

5. CONCLUSION

The pre-intervention measurements show very high numbers well above the WHO recommendations, the lowest recorded PM_{2.5} concentration levels were over 13 times higher than the recommended limit. This shows most rural houses are in dire need of ventilation measures. The first intervention where a southwest opening was constructed in all three study houses showed improvements but the opening location alone is not the factor that contributed to the lowest pollution concentrations. The opening location in relation to the wind direction is a standard analysis that is commonly considered in the design stage but this study showed the importance of layout and contextual influences. The first intervention showed a slight increase in HHID818.2 because the location of the stove didn't correlate with the openings. The fresh air coming through all openings has the potential to create backflow. In the case of HHID818.2 the air coming through the door was obstructing the elimination of polluted air. Hence, it's important to have a complete picture of the interior layout to compare possible outcomes of various opening arrangements.

The context of the house including outdoor cooking in neighboring compounds and surrounding vegetation is another factor that should be considered before fenestration design. In HHID724 the concentration levels were affected by outdoor air pollution (as a result of outdoor cooking by neighbors) and in HHID818.2 the heavy vegetation on the windward side affected the wind speed and quality. In such cases openings should be moved to unobstructed side and the consideration of various cooking locations is advisable. Studying the cooking pattern of occupants will help avoid unnecessary design layouts since the occupants often change the type of fuel (wood, crop residue, animal waste) and the cooking location according to the weather. Thus, when designing ventilation measures considering the cooking patterns of various seasons is imperative.

The size and operability of openings is another factor that impacts the ventilation of a properly oriented household. Originally HHID818.2 had a suitably oriented window in a difficult side of the house which limits the operability.



HHID724 had an incorrectly oriented small opening that was obstructed by the roof overhead. The openings constructed during the intervention has a two-winged opening with wall hooks to keep the window open. The windows had a sill height that considered the room height of the tukul and the roof coverage as well. The initial openings constructed by the owners in HHID818.2 and HHID724 faced technical issues which impacted the effectiveness of said openings.

Regarding the intervention; the uniform solution that was implemented in all three study houses was working differently for each household. Among the key intervention elements that resulted in decreased indoor air pollution; the opening size, the ease of operability, the correct orientation of openings, interior layout, and consideration of annual cooking pattern are included.

Other elements such as room height, partition location (height), family size, cooking time and fuel type had a negative implication on reducing the concentration measurements. In HHID724 the location of the internal partition, the room height, outdoor cooking and the change in type of fuel affected the outcomes while the remaining households showed positive results. Although the concentration levels didn't change as a result of the intervention this household is the best demonstration for showing the negative influence these elements can have in correctly ventilated houses.

The research can confirm the positive impact well designed building elements such as fenestration have on lowering indoor air pollution. It's evident from the literature that there is limited interest in constructing traditional tukul houses. Although people are not constructing tukul's alike older generations, majority of the rural population still lives in tukul's constructed decades ago. The occupants in these tukul's may be in an economic disadvantage to build well ventilated modern houses but they shouldn't face health drawbacks when small but well-designed options can make a big difference in indoor air quality. The transitional period of rural housing towards modern houses may take decades so developing a larger study with more study houses will help identify more ways of improving indoor air quality in tukul houses.



CHAPTER SIX

6. RECOMMENDATIONS

According to the premise and findings of the study a wider pilot study is strongly recommended. Understanding the cooking pattern of occupants before intervening with openings will increase the success rate and lower indoor air pollution levels. Providing fixed spaces for kitchens and incorporating modern cook stoves will prevent occupants from altering the opening design with change in cooking location. Kitchens should be designed with non-movable stove areas that will prevent occupants from altering the point of pollution. Having similar sized openings and providing alternative window operations that will keep windows open is important. Awareness creation on keeping windows open should also be provided to occupants.

The orientation of openings should be studied in context with the sun path, wind direction and surrounding vegetation. In addition to sun, wind and context the neighboring activities should be one of the major considerations. Outdoor cooking locations must be well observed before designing ventilation measures. Just like outdoor cooking, the location of neighboring windows can increase pollution instead of providing fresh air, so the ventilation measures should be studied at an urban scale before coming to individual architectural interventions.

When designing tukul house interventions, the interior layout should be the main focus in conjunction with the openings. Positive results were observed when cook stoves were moved to ideal locations along with opening orientation and design. However, the age of the tukuls, the roof height and interior partitions and other unexpected variables will impact a well-designed ventilation measure thus designing a communal kitchen outside the tukuls that can be shared by multiple households is recommended.

Providing the houses with a well partitioned kitchen that can contain the pollutants instead of affecting the air quality of the living and sleeping spaces is strongly recommended. Partitioning the kitchen should be followed by dedicated chimney, window or other well-proportioned air supply and exhaust element. The partition of the houses should consider the 24hr activity pattern of occupants, the family size and storage requirements to avoid post occupation modifications.



Outside architectural interventions the adaptation of modern cook stoves and well-located water supplies can affect the cooking pattern for the better. Discreet kitchens outside the main house should be adopted for heavy cooking instead of open outdoor cooking.

The government should enforce the building regulation requirements for new houses after a slight adaptation is made for urban spaces. The recommended regulation should consider the overall structure of the houses where the minimum size, interior layout, opening arrangement (in relation to adjoining plots) and local cooking fuel and pattern are confined.

A pilot tukul design in an urban scale where limited houses are well designed can show the residents the merits of vernacular design when it is supported by modern scientific knowledge. Hence, constructing such studies in a controlled manner can slow the rapid transformation to modern tin houses.



CHAPTER SEVEN

7. FURTHER RESEARCH RECOMMENDATION

Future researchers can use the data from this study to expand the scope of the controlled experiment and perform a bigger experiment by increasing the number of study houses. This can generate additional findings that allow future researchers to find new and improved ways of achieving ideal indoor air quality. It is recommended to focus on cooking pattern mapping with regard to annual seasonal changes and interior design experiments with focus on stove location and interior partition. This topic can still be further studied with other architectural science considerations; elements such as indoor daylight gain and thermal comfort can be improved through further research.

CHAPTER EIGHT

8. DESIGN RECOMMENDATION

Analysis: Major architectural issues

- Lack of space for separate functions
- Indoor cooking
- Lack of economy for big expansion or reconstruction
- Residents believe the smoke is good for live stock
- Detached outdoor kitchens expose residents to animal attack at night/early mornings

Design concept

- The intervention will include expanding the tukul in order to separate the kitchen while maintaining the continuity so it is easily accessed from inside. The main concept is creating a parasite space between the inside and outside. The space must be easily openable to facilitate ventilation while cooking. Additionally, it must be easily constructible and adoptable so residents can effortlessly duplicate it.

Design attributes

- Well separated service spaces and detached kitchen
- Foldable walls that can easily be opened during cooking
- Locally available materials
- Easy construction technique

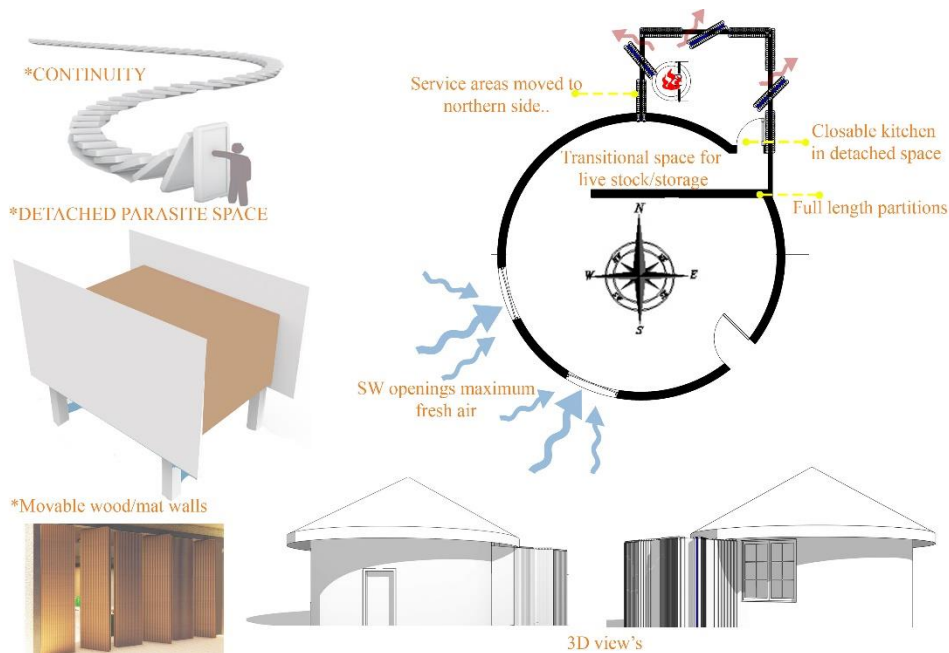
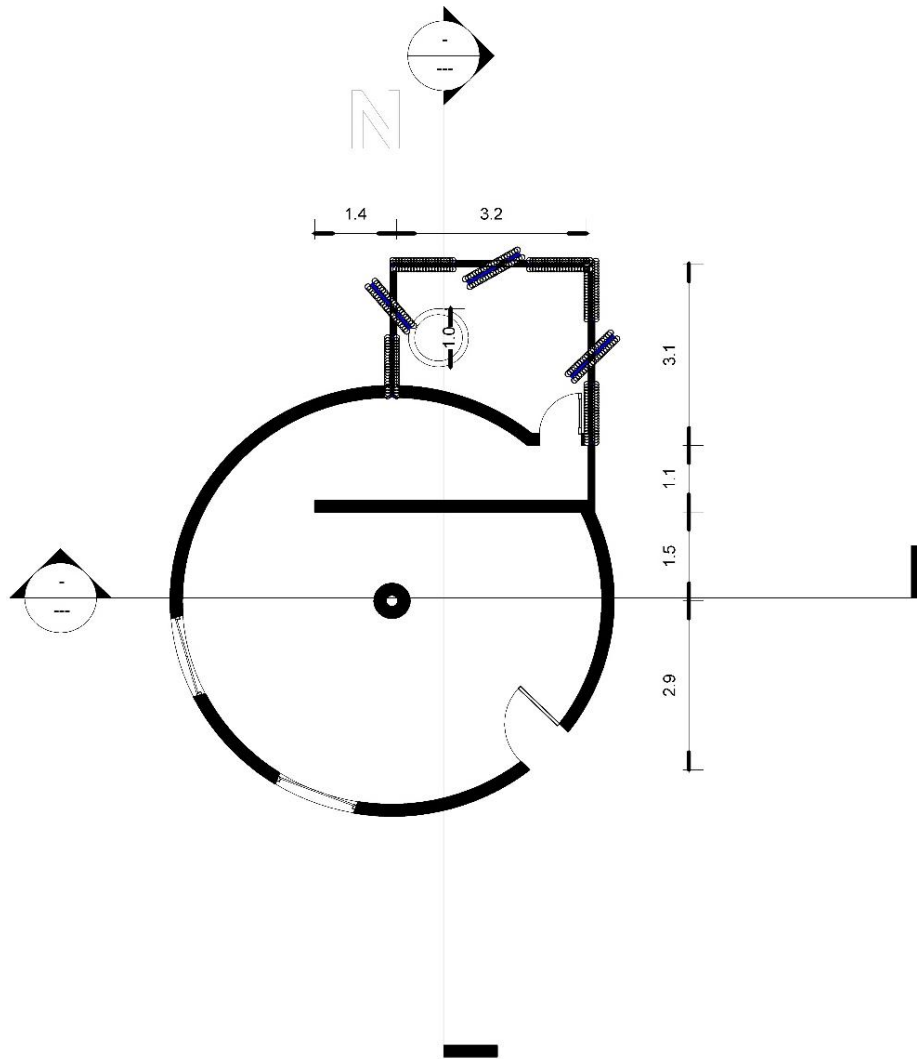


Figure 30: Conceptual diagrams



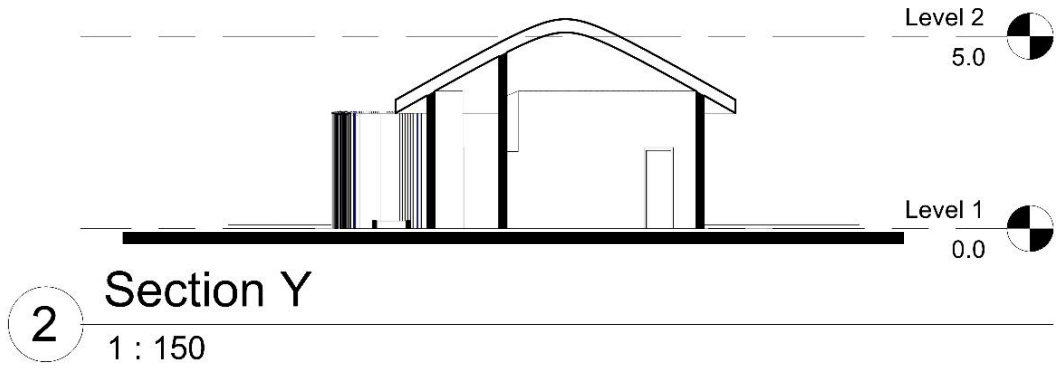
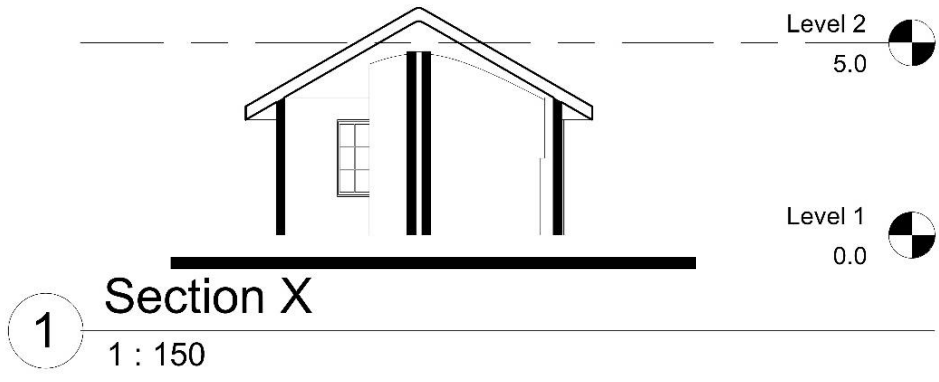
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Level 1

1 : 100

Tekul House	Project number	01	G.Floor
	Date	Issue Date	
	Checked by	Checker	

Figure 31: Floor plan



Tekul House	Project number	01	Section
	Date	Issue Date	
	Checked by	Checker	

Figure 32:Section plan



Figure 33: 3D views of the sample design



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APPENDICES A: Publication

ABSTRACT

A considerable amount of people reside in substandard spaces that fall below the WHO recommended air quality limits. The wide use of solid biomass coupled with indoor cooking are major contributing factors for high concentration of indoor air pollutants. Over 95% of the Ethiopian population relies on solid biomass for household energy consumption, majority of them reside in rural vernacular houses where multiple functional spaces are overlapped in a single space. The lack of ventilation in these spaces and the amount of time spent indoors from cooking to sleeping etc. makes the occupants vulnerable to multiple diseases. The common diseases in the study area are recognized as side effects of prolonged exposure to indoor air pollutants. This research investigates the relationship between indoor air pollution in rural tukul houses and architectural modifications that can decrease selected indoor air pollutant concentrations. The aim was to measure the 24hr PM_{2.5} and CO concentrations, study the architectural features of the tukuls and experiment with ventilation by providing multiple openings and altering the interior layout. A controlled experimental was conducted in three selected households. The experiment had four phases where the first one measured the initial concentration levels, the second one introduced a window in the correct orientation, the third one provided a second opening to control the air path and the final phase altered the location of the cookstove to achieve maximum efficiency. The results of the experiment confirmed the current pollutant concentrations profoundly exceed ideal WHO limits. The lowest before intervention CO concentrations were over two times higher than homes without indoor cooking and WHO recommended limits. Similarly, the lowest initial PM_{2.5} limits were 13 times higher than the maximum WHO limits. In two of the study houses the intervention successfully decreased both CO and PM_{2.5} concentrations. The best results were recorded in the fourth phase where PM_{2.5} dropped by 49.6% and CO showed an 87.6% decrease. The combined intervention where both openings and interior layout were altered showed the most positive results. In one study house the impact of context, activity pattern and existing architectural elements resulted in increased measurements. It was concluded that the contextual influence at an urban scale, interior layout/partition, cooking pattern and complete detachment of cooking spaces have the best potential for improving indoor air quality in existing tukul houses.

Keywords: Indoor air pollution, Ventilation, Opening design, Controlled experiment, Tukul houses



INTRODUCTION

Indoor air quality is considered as an important aspect of the general public's quality of life. It is concerned with the quality of air in buildings in relation to the health and comfort of occupants. Studying indoor air quality is imperative since people spend majority of their time indoors, Previous studies infer more than 80% of the sub-Saharan African (SSA) population relies on solid biomass for daily cooking and lighting consumption; such as fire wood, charcoal, agricultural by-products, and animal waste (Natei Ermias Benti, 2021). Above 90% of the population in Ethiopia relies on traditional energy sources (biofuel) for domestic energy consumptions (Natei Ermias Benti, 2021). Hence, it can be concluded that majority of the rural areas in Ethiopia use fire wood for cooking and other house hold energy and heat source requirements.

Although biomass has several benefits, inefficient use of it has gravely cost the African continent. Aside from a major loss of the forest ecosystem, serious setbacks were recorded in the climate, the wellbeing of all inhabitants and overall economic development. The availability of biomass in rural area makes is an easy energy choice, hence finding an alternative energy source or introducing systematic improvements to minimize the negative health effects is important.

Ethiopia is the second most populous country in the African continent, as a result the country has shown prompt urbanization rates. Conversely this urban growth largely fails to benefit majority of the population as it is unpredicted and overwhelming. The resulting side effects from this rapid urbanization include scattered settlements that require large scale urban planning to access basic facilities including road networks, electricity and telecommunication and similar urban components. The rapid urbanization rate will fail to keep up with the limited economical capacity of the country, forcing majority of the rural community to continue living with currently existing living conditions. As a result, modifying existing living conditions is the best option to combat the immediate threats faced by the population. The severity of health conditions resulting from indoor air pollution require immediate modifications in the form of architectural (improved building designs), mechanical (improved ventilation systems) or electrical (improved cook stoves) interventions. Considering the current accessibility of electrical and mechanical options by the rural community, architectural modifications are the best intervening measures. The main objective of this research is to investigate into suitability/effectiveness of selected architectural interventions to reduce indoor air pollution in rural houses by improving air ventilation.



The following are specific objectives of the research devised from the main objective: *Measure the concentration of selected pollutants for a minimum of 24hrs in traditional houses in southern Ethiopia around Butajira area. *Asses the current state of the houses and study the architectural layouts. Propose mitigating solutions that expand the impact of ventilation on vernacular architecture and improve indoor air quality. *Perform a controlled experiment in the traditional tukul houses to test the architectural interventions and record any improvement in indoor air quality. Air pollution is a multidimensional scourge of our time and a major contributor for climate change. A significant effect of air pollution on an individual level is its impact on health. Air pollutants affect human health when they are concentrated above a certain acceptable level. Miniature pollutants like Particulate Matter (PM) can penetrate the respiratory system and cause cardiovascular and respiratory problems. Similarly, high concentration of ground level ozone can negatively affect the respiratory system and cause chronic health problems. Direct and prolonged exposure to pollutants such as carbon monoxide and lead can go as far as provoking direct poisoning and prolonged inebriation.

Basic factors that signify the air quality and indoor comfort level of a certain location can be induced from natural climatic elements such as the wind, sun and water (rainfall). These three natural phenomena's are deduced to different numerical values by different measurement tools unique to all three. Each element has more than one measurable component that will define and determine the boundaries of envelop design in response to the environment. By referring to the three main elements, other climatic elements such as air temperature, solar radiation, humidity, precipitation, clouds, wind speed and direction could be documented. The enclosure of a building protects and modifies the intended space to achieve the ideal indoor atmosphere.

The building envelop has various functions that can roughly be categorized in to these three categories:

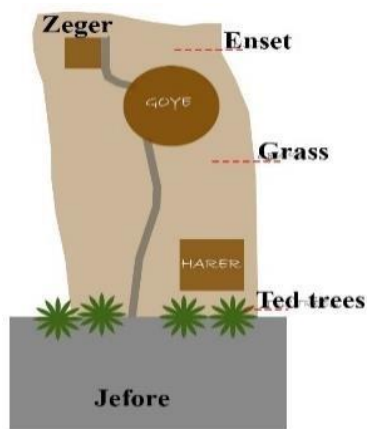
- **Support:** to resist different external loads and forces and assure strength and rigidity.
- **Control:** to control the exchange and flow of wind, temperature, humidity, and radiation between the interior and exterior of the building.
- **Finish:** the look of the building, this is the aesthetics and overall appearance of the building. The fenestration pattern, its size and orientation especially in relation to wind direction are design elements that can be manipulated to attain ideal indoor air quality. The inclusion of openings in the building envelope is necessary to achieve optimal indoor comfort through ventilation, heat exchange, natural light radiation and access to the inside and outside. Openings such as windows can promote passive solar heating and cooling; as well as providing natural points of ventilation, air circulation and fire exits



The relationship between fenestration and improved indoor air pollution and health of occupants is closely related increased number of well-designed openings is known to decrease the pollutant concentration levels.

Architectural practice employed to solve a specific regions housing problem based on local knowledge and native resources is identified as vernacular architecture. Vernacular architecture is known for its sustainability and adoptability. It is unique to the original location; the climate and available materials in the area have a big impact on the design. Vernacular architecture is a reflection of the culture, tradition and social practices of a region, distinctive architectural programs are designed to accommodate the unique social practices.

Traditional houses in southern share three similar spatial features; the main residence, the traditional kitchen and the cattle and crop storage space. These spaces can be found under the same roof or in various houses depending on the region and culture.



The traditional houses around Butajira share similar spatial features. The most common settlement in south region specifically gurage zone is called 'Qaya' which is based on a main avenue. The main avenue is called 'Jefore' which has multiple households along the road. Single settlement on each sides of the road may hold up to 80 people within 13 households on each side of the road. (Teku, 2017)

The road is wide enough to accommodate communal gatherings and children activities. There are multiple houses in a single compound. Two dominant types of housing styles can be observed around the study region (Nilsson, 2016); the traditional circular house made of wood plastered with mud covered in thatched grass roofs and modern houses with iron sheet roofs and concrete block Walls. The traditional tukul houses have vertical supports made of wood pieces mount in the ground. The woods are stalked on top of each other to achieve the desired height. Relatively thinner wood pieces are integrated horizontally, both elements are joined by mud-straw mix and cow dung plastering. The traditional houses lack internal partitions that separate the various functions in the house including the kitchen. There is only one opening in most of the traditional houses around the study area, aside from the door all other surfaces lack openings.



One of the best architectural interventions for ensuring indoor air quality is providing effective openings that provide adequate ventilation throughout the space. Ventilation is the exchange of air inside and outside the building commonly defined as the process of intentionally introducing clean air into a space. It can be introduced by natural or mechanical options depending on the climate of the site and with the use of windows, doors, atriums and other form of building fenestrations. These openings on the building envelop need to consider various aspects of the building and the climate.

Under favorable climatic conditions natural ventilation methods are the ideal choice, natural ventilation can save 10% to 30% of total energy consumption. (Walker, 2016) There are two common types of natural ventilation methods: Wind-driven ventilation (cross ventilation) is the exchange of air through the use of wind movement from one opening to another. When openings are placed on opposite sides it becomes cross ventilation; for maximum results wind direction and wind speed should be considered. To produce the maximum total airflow through a space, both inlet and outlet openings should be as large as possible. The inlet opening will define the direction of the air stream entering. To get the maximum localized air velocity, the inlet opening should be much smaller than the outlet” (Szokolay, 2004).

Before taking any ventilation measures its best to determine what kind of ventilation method the design will benefit from. For hot and dry climates, a closed building ventilation approach is preferable while an open building approach works best for warm and humid areas. The movement of wind in and around a building is heavily influenced by the architectural design of the house. Indoor air quality is specifically connected to the type and layout of the kitchen in relation to wind pressure which is expedited through openings. The design of architectural characteristics especially the common sources of pollution such as the kitchen has a big influence in the personal and environmental pollutant exposure measurements.

The importance of effective natural ventilation is evidenced by findings of prior studies in this area

Related studies suggest various indoor air pollution control options including eradicating the source of pollution, ventilating the room to lower the concentration of pollutants and filtering the air to eliminate the pollutants. The ideal option would be to improve or eliminate the source of pollution but in existing structures where switching to sustainable energy is not an option, working on the spatial properties and ventilation is the preminent option.

Currently very limited local research data targeting the architectural interventions for indoor air pollution is available. Architectural aspects of indoor air pollution have not been studied as much as the health, technological and other related indoor air pollution aspects. Conducting a specific study on architectural interventions targeting ventilation measures in a detailed controlled experiment will contribute new and up to date air quality data, explore possible solutions and other similar advantageous outcomes.



Similar studies reviewed during the literature study show lack of consideration to the vernacularism and social values in the community; this can be evidenced by the communities' restraint to widely integrate most housing related pilot projects in their traditional construction techniques.

Hence a research that targets existing structures with small but essential changes that can improve indoor air quality without disrupting the vernacular aspects of traditional tukul houses will benefit the public in numerous ways. A study that is conducted on existing structures with minimal cost and lifestyle change could fill the gap created in the integration of previous research outcomes with pure scientific and socioeconomic changes.

Although various health professionals have published papers (reviewed in the previous chapter) indicating air pollution as a cause of multiple respiratory, visual and other chronic diseases especially in women and children. Previous concentration measurements in Ethiopia show increased PM_{2.5} concentrations compared to similar study results from Ghana, Nepal and India (Mulugeta Tamire, 2021). They also indicate a prominent need to provide alternative housing designs that target effective ventilation and quality air flow, fire resistance, indoor light gain and thermal comfort especially (Addissie, 2019), (Teku, 2017) and (Nilsson, 2016) (Mulugeta Tamire, 2021). To provide a typology that can be widely adopted by the rural society the major environmental elements that influence the occupant's health and comfort need to be tested to achieve the ideal indoor atmosphere.

The lack of abundant resource, knowledge and recent technique in the rural housing development is the main obstacle that result in substandard indoor spaces. The effect of wind in relation to opening size and location with consideration to the vernacular values of the society have yet to be perfected. This study will explore the effects of natural elements such as orientation and wind in relation to ventilation and indoor air quality whilst maintaining the positive aspects of the traditional tukuls.



RESEARCH METHODOLOGY

The research methodology was done by using an experimental approach. The study was conducted from September 2022 to December 2023 in SNNP region, gurage zone wurib worda. Butajira is located around 150Km south of Addis Ababa. The district represents all the three agro-ecology sites of Ethiopia: kola/warm, woyina dega/temperate, and dega/cold. A controlled experimental study was used to measure the link between ventilation and indoor air pollution in three houses in rural Butajira zone. Experimental houses in lower lands of wurib worda were chosen to be part of the study. The houses were selected based on size, proximity and weather data. The selection parameters were used to specify three experimental tukul houses with varying size and pollution level in order to make the research inclusive. The number of experimental houses will be limited to three to thoroughly experiment with the design interventions and measure the pollution level of each house. The precise number allowed the researcher to implement various interventions repeatedly and select the best outcome. The size of the houses varies including the number of partitions, clear usable space and the overall size in design and materials.

The experimental houses had varying sizes to ensure the pollutant concentration isn't affected by congestion due to size. The second parameter is proximity to public facilities. The consideration given to proximity accounts for the level of development of that specific area. The awareness about pollution and indoor air quality decreases in places with limited access. The final selection parameter is the weather data which can affect the houses with varying weather data during the experiment taking this into consideration will produce a holistic research that won't be influenced by the seasonal weather-related energy usage.

The houses were chosen using purposive sampling method. Population and housing data were collected from the local AAU campus which is a local institute that records the housing, social, population, and other socioeconomic changes of the area. The data gathered from the AAU campus was be used to choose ideal locations/houses from the 10 worda's in Butajira region. The research data was collected twice, the first data collection session was used to identify the experimental houses, gather the owners' information and take a 24hr measurement of selected indoor air pollutants. Additionally, the existing context of the site including weather, orientation, number/size of openings, cooking patterns and related information were gathered. Professional data collectors were employed to mount PATS+ devices in each house and record the indoor air data. PATS+ devices were used to measure personal exposure to PM_{2.5} concentrations. The methods of opening and re-construction of windows and measuring the 24hr PM_{2.5} (in µg/m³) and CO (in PPM) concentrations using PATS+ sensor was conducted four times in all households. The first reading before intervention, the second reading after introducing the first window, the third reading after introducing a second window and Fourth reading was taken after changing the previous stove location and opening all available windows in the house.



The Standard operating procedure that recommends measuring 1.5 meter above the ground level of the households taken from WHO guidelines along with the construction of multiple standard windows in each household. The results showed a mixed outcome that differed from the initial expected outcomes. Majority of the intervention showed success in decreasing the PM_{2.5} and CO concentrations while various success levels were achieved in different intervention types across all sample houses.

The first experimental house HHID770.1 is found in rural wurib woreda where the house doesn't have direct access from the vehicular road. The house has been in use for over Ten years, it is showing significant signs of structural failure especially on the roof and walls. There are five permanent residents in the house. The findings in HHID770.1 show the most positive overall improvement. The house had only one opening (a door) prior to the intervention. The occupant size and cooking pattern is comparatively smaller than the rest of the sample houses. During the day, the occupants don't perform activities other than cooking inside the house. There is no heavy vegetation in the immediate surroundings of the house.

Compared to the other study houses this house is small in size. Intervention two where two openings were provided in the existing layout showed the best result with 88.48% (5.84 ppm) decrease in CO and a 49.6% (222.78 $\mu\text{g}/\text{m}^3$) decrease in PM_{2.5}, the change in the stove location showed an increase in the concentrations although both windows were open. The female resident consistently used crop residue to cook food during the study period. Compared to the remaining study houses she also kept a very clutter free and clean house.

The second experimental house HHID818.2 is also in rural wurib woreda around 200m from the main road. This house is along the secondary main road with direct vehicular access. The house is considerably larger than other tukul houses in the neighborhood, it was built around 30 years ago. The owners have built a modern tin house in their compound but they still cook, eat and sleep in the tukul house. There are seven residents in the house. The findings in HHID818.2 show positive improvement especially in intervention three where the interior layout was altered. This is the biggest and most well-kept house (structurally), the best result showed a 49.9% (1.61 ppm) decrease in CO and a 10.8% (36.38 $\mu\text{g}/\text{m}^3$) decrease in PM_{2.5}. The house had two openings prior to the study, it had one well oriented 60cm*80cm window on the southwest side. The high pollution concentration is a result of larger family size that resulted in repetitive cooking, the use of animal waste as fuel (which exerts more smoke) and the location of the stove which is directly next to the door allowing the wind coming through the door to push the smoke back into the house. Adding two more windows for a better air movement coupled with proper placement of the stove to the northern side of the house showed great improvement. The existence of large vegetation on the southwestern side of the house may limit the fresh air gain of the house as it lacks the proper distance between the window and the plants this was countered by adding additional window on the windward side of the house.



The third experimental house HHID724 is a traditional tukul house with similar characteristics to the first house. This is a considerably older house built around thirty years ago. There are five residents in the house. The findings in HHID724 show differing results, this is the oldest house with the largest number of occupants additionally the occupants performed multiple activities in the house throughout the day. The structural state of the house doesn't allow for the release of smoke through the roof which shows visible amount of smoke, dust and similar substance buildup.

Similarly surrounding dust particles and smoke (they typically cook outside to avoid the heavy smoke) can enter through the cracks on the lower parts of the wall which show small openings. The pollution concentration in the house is so bad the occupants only cook specific foods inside and keep all openings open day and night. There were two openings in the house prior to the study, the existing window was too small (50cm*70cm) and in the wrong orientation.

RESULTS

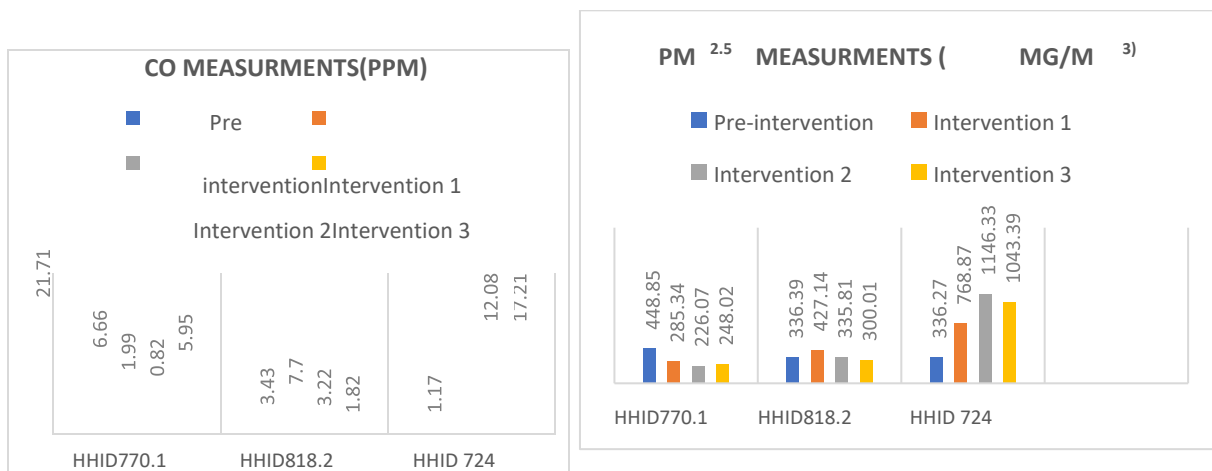
Table 1: PATS+ Result Summary

S. N	Study ID	HH ID	PATS+ ID	Concentration	Variables	Before Intervention	After First window Open	After second window open	All window open & change Stove location	difference
1	HHID770.1	P7717	CO (PPM)	Mean	6.66 PPM	1.99 PPM	0.82 PPM	5.95 PPM	0.71 PPM	
				SD	8.62 PPM	3.60 PPM	2.74 PPM	24.12 PPM	-15.5 PPM	
				Mean	448.85 µg/m ³	285.34 µg/m ³	226.07 µg/m ³	248.02 µg/m ³	200.83 µg/m ³	
				SD	914.70 µg/m ³	588.78 µg/m ³	596.80 µg/m ³	512.57 µg/m ³	402.13 µg/m ³	
2	HHID818.2	P7714	CO (PPM)	Mean	3.43 PPM	7.70 PPM	3.22 PPM	1.82 PPM	1.61 PPM	
				SD	6.59 PPM	7.22 PPM	5.22 PPM	3.86 PPM	2.73 PPM	
				Mean	336.39 µg/m ³	427.14 µg/m ³	335.81 µg/m ³	300.01 µg/m ³	36.38 µg/m ³	
				SD	632.65 µg/m ³	735.10 µg/m ³	618.94 µg/m ³	593.75 µg/m ³	38.9 µg/m ³	
3	HHID 724	P7713	CO (PPM)	Mean	1.17 PPM	21.71 PPM	12.08 PPM	17.21 PPM	-16.04 PPM	
				SD	3.09 PPM	67.11 PPM	17.33 PPM	29.81 PPM	-26.72 PPM	
				Mean	336.27 µg/m ³	768.87 µg/m ³	1146.33µg/m ³	1043.39 µg/m ³	-707.12 µg/m ³	
				SD	681.76 µg/m ³	1413.8 µg/m ³	1630.1 µg/m ³	1706.00 µg/m ³	-1024.2µg/m ³	



Among the three Study Households, two houses HHID 770.1 and HHID 818.2 showed a reduced PM_{2.5} concentration after the interventions (448.2 µg/m³ to 226.07 µg/m³ and 336.39 µg/m³ to 300.01 (µg/m³) respectively. But in household 724 both PM_{2.5} and CO levels increase significantly. This is believed to be a result of cooking patterns, family size which affects the cooking pattern, change in fuel types used for cooking, changing of the stove area, wind direction of the study house window opening in relation to outdoor cooking, layout of the interior including the partition height and ambient air pollution exposure. It must be noted the findings in each house vary depending on the existing preconditions of the house including but not limited to the size of the house, the number of openings, the cooking pattern which is also affected by the number of temporary residents, the type of fuel used, the type and location of the stove, the type of food the occupants prepare, the age, room height and overall condition of the house. All predetermined variables were kept constant throughout the intervention these factors include the location of the measurement device, the starting time and length of the recording (to avoid variations in temperature and humidity), the number of permanent occupants, cooking pattern and type of fuel.

A comparative representation of findings across all houses is summarized below.



The final results show varying success rates even though similar interventions were conducted in all households. HHID770.1 showed lower pollution levels after every intervention, the second intervention was the most successful with the lowest CO and PM concentrations. This house hold benefited the most from the second window which has a bigger size as there were limited influences from the surrounding. The interior layout changes only lowered the PM_{2.5} concentrations while CO showed the lowest decrease from the remaining interventions. Overall this household was the most successful in each intervention with lower CO and PM_{2.5} concentrations.



HHID818.2 Showed positive results in intervention two and three while a slight increase was recorded after the first intervention. Unlike HHID770.1 the most successful intervention was intervention three where the stove was moved from the door way which allowed the smoke to exit the house instead of getting pushed back. The back flow of pollutants in to the house as a result of poor opening location was observed. Aside from backflow the density of surrounding vegetation heavily influenced the amount of fresh air gain which contributed to the limited concentration level improvements. Both CO and PM_{2.5} showed the lowest measurements in intervention three. Generally, this household showed success in the second and third interventions while a slight increase was recorded after intervention one. The increase after intervention one is a result of the outdoor cooking location.

HHID724 showed an increase in pollutant concentration in all three interventions. The highest CO increase was recorded after intervention one while the highest increase in PM_{2.5} was recorded after intervention two. Intervention two showed the lowest increase in CO and intervention one showed the lowest increase in PM_{2.5} after intervention one. Intervention three showed consistent increase in both CO and PM_{2.5}. Intervention two and three were comparatively more successful in all households. HHID770.1 and HHID818.2 showed lower pollution levels where HHID724 failed to show similar success.

Similar to results obtained in (Mulugeta Tamire, 2021), the initial concentration levels and the improved concentration levels showed immense measurements compared to the WHO guidelines which recommend “25 $\mu\text{g}/\text{m}^3$ 24-h mean for maintaining safe indoor air quality in low- and middle-income countries” (Mulugeta Tamire, 2021). The positive effect of providing strategic openings was confirmed to align with studies such as (Anne M. Weaver, 2017) that conclude having more openings resulted in lower pollutant concentration levels. The size of the windows, the length of time the windows/doors were left open and the cooking time had significant effect in the results of this study as previously acknowledged by reviewed literatures.

CONCLUSION

This research set out to identify architectural methods that can bridge the gap between the ideal indoor air quality suggestions and the heavily excessive pollution patterns that are observed in vernacularly designed Ethiopian households. Over the course of this research the initial research questions were addressed through literature review, onsite measurements and architectural design interventions. The initial concentration measurements in each household (from the controlled experiment) coupled with the concentration levels reviewed in the literature address the first objective where finding the 24hr concentration levels of selected traditional households was questioned.



The second objective of the research where the current state and architectural characteristics of the houses was inquired was answered through detailed architectural plans, site analysis with pictures and field questioners. Similarly, the third objective was addressed through a serious of literature reviews that propose computational, ventilation, material and other mitigating solutions. The final objective was achieved through a rigorous site work that included measuring the current conditions in selected houses and implementing the controlled experiment with equivalent design interventions. The changes that came as a result of the intervention were recorded and discussed thoroughly in the findings.

The research was focused in testing ventilation options to lower the indoor air pollution concentrations of PM_{2.5} and CO. The intervention was designed after the site was studied and the existing conditions of the houses were taken in to consideration. Three houses were purposively selected for the controlled experimental study before implementing the interventions. The architectural measurement, occupant background and existing pollution data of each house was well documented. The intervention is designed to target the facilitation of maximum air movement which will increase fresh air gain.

The results further cemented the crucial role architecture has in attaining ideal indoor air quality. The controlled experiment has shown the importance of well-made openings. High pollution levels were observed in the initial measurements across the three study houses; however, the numbers showed a fivefold increase of CO and double the PM_{2.5} measurements in HHID770.1 compared to the other households. There were no openings in HHID770.1 prior to the intervention. The highest before intervention measurements correlating to the study house with no windows shows the lower pollutant concentrations observed in HHID818.2 and HHID724 are a result of ventilation measures.

The pre-intervention measurements show very high numbers well above the WHO recommendations, the lowest recorded PM_{2.5} concentration levels were over 13 times higher than the recommended limit. This shows most rural houses are in dire need of ventilation measures. The first intervention where a southwest opening was constructed in all three study houses showed improvements but the opening location alone is not the factor that contributed to the lowest pollution concentrations. The opening location in relation to the wind direction is a standard analysis that is commonly considered in the design stage but this study showed the importance of layout and contextual influences. The first intervention showed a slight increase in HHID818.2 because the location of the stove didn't correlate with the openings. The fresh air coming through all openings has the potential to create backflow. In the case of HHID818.2 the air coming through the door was obstructing the elimination of polluted air. Hence, it's important to have a complete picture of the interior layout to compare possible outcomes of various opening arrangements.



The context of the house including outdoor cooking in neighboring compounds and surrounding vegetation is another factor that should be considered before fenestration design. In HHID724 the concentration levels were affected by outdoor air pollution (as a result of outdoor cooking by neighbors) and in HHID818.2 the heavy vegetation on the windward side affected the wind speed and quality. In such cases openings should be moved to unobstructed side and the consideration of various cooking locations is advisable. Studying the cooking pattern of occupants will help avoid unnecessary design layouts since the occupants often change the type of fuel (wood, crop residue, animal waste) and the cooking location according to the weather. Thus, when designing ventilation measures considering the cooking patterns of various seasons is imperative.

The size and operability of openings is another factor that impacts the ventilation of a properly oriented household. Originally HHID818.2 had a suitably oriented window in a difficult side of the house which limits the operability. HHID724 had an incorrectly oriented small opening that was obstructed by the roof overhead. The openings constructed during the intervention has a two-winged opening with wall hooks to keep the window open. The windows had a sill height that considered the room height of the tukul and the roof coverage as well. The initial openings constructed by the owners in HHID818.2 and HHID724 faced technical issues which impacted the effectiveness of said openings.

Other elements such as room height, partition location (height), family size, cooking time and fuel type had a negative implication on reducing the concentration measurements. In HHID724 the location of the internal partition, the room height, outdoor cooking and the change in type of fuel affected the outcomes while the remaining households showed positive results. Although the concentration levels didn't change as a result of the intervention this household is the best demonstration for showing the negative influence these elements can have in correctly ventilated houses.

The research can confirm the positive impact well designed building elements such as fenestration have on lowering indoor air pollution. It's evident from the literature that there is limited interest in constructing traditional tukul houses. Although people are not constructing tukul's alike older generations, majority of the rural population still lives in tukul's constructed decades ago. The occupants in these tukul's may be in an economic disadvantage to build well ventilated modern houses but they shouldn't face health drawbacks when small but well-designed options can make a big difference in indoor air quality.

According to the premise and findings of the study a wider pilot study is strongly recommended. Understanding the cooking pattern of occupants before intervening with openings will increase the success rate and lower indoor air pollution levels. Providing fixed spaces for kitchens and incorporating modern cook stoves will prevent occupants from altering the opening design with change in cooking location.



Kitchens should be designed with non-movable stove areas that will prevent occupants from altering the point of pollution. Having similar sized openings and providing alternative window operations that will keep windows open is important. Awareness creation on keeping windows open should also be provided to occupants.

The orientation of openings should be studied in context with the sun path, wind direction and surrounding vegetation. In addition to sun, wind and context the neighboring activities should be one of the major considerations. Outdoor cooking locations must be well observed before designing ventilation measures. Just like outdoor cooking, the location of neighboring windows can increase pollution instead of providing fresh air, so the ventilation measures should be studied at an urban scale before coming to individual architectural interventions.

When designing tukul house interventions, the interior layout should be the main focus in conjunction with the openings. Positive results were observed when cook stoves were moved to ideal locations along with opening orientation and design. However, the age of the tukuls, the roof height and interior partitions and other unexpected variables will impact a well-designed ventilation measure thus designing a communal kitchen outside the tukuls that can be shared by multiple households is recommended.

Providing the houses with a well partitioned kitchen that can contain the pollutants instead of affecting the air quality of the living and sleeping spaces is strongly recommended. Partitioning the kitchen should be followed by dedicated chimney, window or other well-proportioned air supply and exhaust element. The partition of the houses should consider the 24hr activity pattern of occupants, the family size and storage requirements to avoid post occupation modifications.

Outside architectural interventions the adaptation of modern cook stoves and well-located water supplies can affect the cooking pattern for the better. Discreet kitchens outside the main house should be adopted for heavy cooking instead of open outdoor cooking. The government should enforce the building regulation requirements for new houses after a slight adaptation is made for urban spaces. The recommended regulation should consider the overall structure of the houses where the minimum size, interior layout, opening arrangement (in relation to adjoining plots) and local cooking fuel and pattern are confined.

A pilot tukul design in an urban scale where limited houses are well designed can show the residents the merits of vernacular design when it is supported by modern scientific knowledge. Hence, constructing such studies in a controlled manner can slow the rapid transformation to modern tin houses.



Indoor air pollution: Pragmatic smoke mitigating interventions for reducing CO and PM_{2.5} in traditional tukul houses. The case of Butajira area

APPENDICES B: Indoor Air Pollution: Pragmatic smoke mitigating interventions for reducing CO and PM_{2.5} in traditional tukul houses the case of Butajira area interview

Student: Dagmawit Kidane

Dear Ms/Mr, under the guidance of the EiABC MSC program in Master of Advanced Architectural Design, I am conducting a study entitled “Indoor Air Pollution: Pragmatic Smoke Mitigating Interventions for Ventilating Traditional Tukul Houses; The Case of Butajira Area.” your residence and life style is an ideal candidate for the success of my research. Although you are busy with work/house chores, your active and honest participation is a vital part of the research, I would gravely appreciate it if you could take the time to respond honestly to the questions in this questionnaire. For your comfort this questionnaire will be anonymous and generalized.

I would like to thank you in advance for your time and active participation in this research study.

DAGMAWIT KIDANE

MSC candidate



APPENDICES C: Household questionnaire to access the socioeconomic background of the study participants

1. Do you prefer to live in a traditional tukul house or a relatively modern tin house? **Y/N**
2. What is the biggest challenge you are facing while living in a traditional tukul house?
3. Can you suggest any improvements that would make you more comfortable in traditional tukul house?
4. What attracts you most about the modern tin houses?
5. What attracts you most about the traditional tukul houses?
6. Do you think living in a tin house would impact your socioeconomic standing?
7. Would you be willing to alter the structure, opening and layout of your house to improve the indoor comfort (note that multiple aspects of the house may be altered more than once)?
8. What parts of the traditional tukul house have cultural values?
9. What parts of the traditional tukul house are off limits (can't be altered)?
10. Have you observed any breathing related difficulties on your family members?
 - a. If so, how old is he/she/, where does he/she spend majority of his/her time, what is his/her role in the family (including household chore)?
11. Why do you cook in open kitchens located in the main house?
12. Are there any cultural insinuations behind your spatial layout? **If yes please explain?**
13. Why do you keep your windows closed majority of the time?



APPENDICES D: Household questionnaire to crosscheck the post measurement data and the personal experience of the study participants (second questionnaire/observational check list)

1. Did you keep the device in the same place? Y/N
2. Did you alter the device in any way? Y/N
3. Did you cover the device with cloth, furniture or any other object? Y/N
4. Did you open additional windows during the time the device was mounted? Y/N
5. What type of energy source did you use?
6. Would you say the activity you performed during the recording is your typical routine?
7. What kind of activities took place on_____ (the interviewer specifies the time that shows the highest concentration on the device)?
8. What type of food did you cook on_____ (the interviewer specifies the time that shows the highest concentration on the device)?
9. Did you notice any difference in your usual living pattern during the measurement period?



APPENDICES E: Check list for the researcher (data collectors)

The researcher should fill the following questionnaire during the data collection session of each house.

1. Was the data collection device properly reset before placement?

YES NO

2. Was the data collection device mounted in the correct place?

YES NO

3. Did the device record data continuously with no interruptions?

YES NO

4. Did the recorded cooking pattern match with the occupant's interview answers?

YES NO

5. Did the interview cover the type of food and fuel used during peak recording times?

YES NO

6. Did the occupants stray from their usual pattern during the recording?

YES NO

7. Did the occupants understand the pre and post measurement interviews properly?

YES NO



APPENDICES F: The before the intervention and after the first window open data

DSS HHID	PATS+ 7717		Control experimental intervention			Remark
HHID 06B770.1	CONC		Before	After 1 st window open	difference	
770.1	CO_(PPM)	Mean	6.66	1.99	4.67	
		SD	8.62	3.60	5.02	No window in Tukul
	PM2.5 (µg/m3)	Mean	448.85	285.34	163.51	
		SD	914.70	588.78	325.92	

DSS HHID	PATS+ 7714		Control experiment intervention			Remark
HH 06B 818.2	CONC	Variables	Before	After 1 st window open	difference	
818.2	CO_(PPM)	Mean	3.43	7.70	-4.28	1 window previously opened
		SD	6.59	7.22	-0.62	
	PM2.5 (µg/m3)	Mean	336.39	427.14	-90.76	
		SD	632.65	735.10	-102.45	

DSS HHID	PATS+ 7713		Control experimental intervention			Remark
HHID 06B724	CONC		Before	After 1 st window open	Difference	
724	CO	Mean	1.17	21.71	-20.53	
		SD	3.09	67.11	-64.02	1 window previously opened
	PM2.5	Mean	336.27	768.87	-432.60	
		SD	681.76	1413.81	-732.05	



The second window opening and the first window closed data

DSS HHID	PATS+ 7717		Control experimental intervention			Remark
HHID 06B770.1	CONC		Before	After 2 nd window open and 1 st closed	difference	
770.1	CO_(PPM)	Mean	6.66	0.82	5.84	Pollution level declining
		SD	8.62	2.74	5.88	
	PM2.5 (µg/m3)	Mean	448.85	226.07	222.78	
		SD	914.70	596.80	317.9	

DSS HHID	PATS+ 7714		Control experimental intervention			Remark
HH 06B 818.2	CONC		Before	After 2 nd window open and 1 st closed	difference	
818.2	CO_(PPM)	Mean	3.43	3.22	0.21	Pollution level declining
		SD	6.59	5.22	1.37	
	PM2.5 (µg/m3)	Mean	336.39	335.81	0.58	
		SD	632.65	618.94	13.71	

DSS HHID	PATS+ 7713		Control experimental intervention			Remark
HHID 06B724	CONC		Before	After 2 nd window open and 1 st closed	difference	
724	CO_(PPM)	Mean	1.17	12.08	-10.91	Pollution level escalating after intervention
		SD	3.09	17.33	-14.24	
	PM2.5 (µg/m3)	Mean	336.27	1146.33	-810.06	
		SD	681.76	1630.11	-948.35	



The three windows open at day time and changing the previous stove location data

DSS HHID	PATs+ 7717 measured data		Control experimental intervention			Windows opening intervention in the HH	stove area changing
HHID 06B770.1			Before	All window open	difference		
770.1	CO_(PPM)	Mean	6.66	5.95	0.71	No window before intervention	traditional 3 stone & movable metal stove Not changed
		SD	8.62	24.12	-15.5		
	PM2.5 (µg/m3)	Mean	448.85	248.02	200.83	Two windows added after intervention	
		SD	914.70	512.57	402.13		

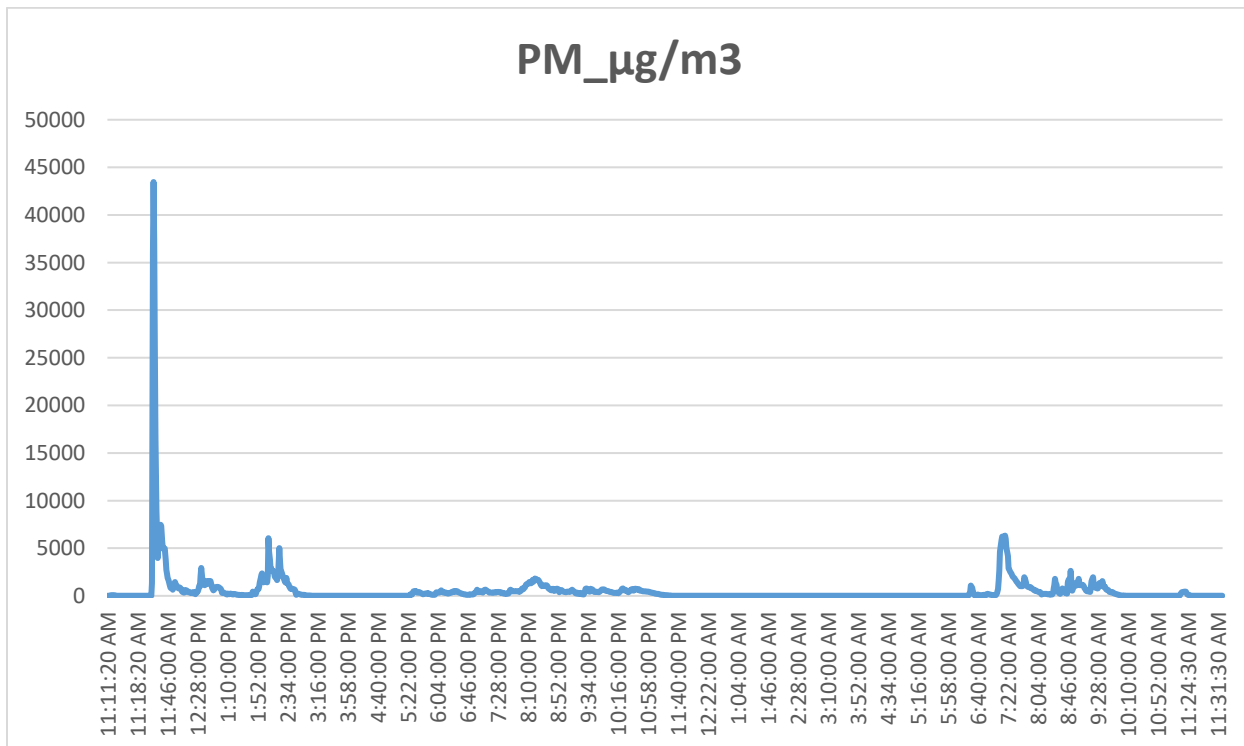
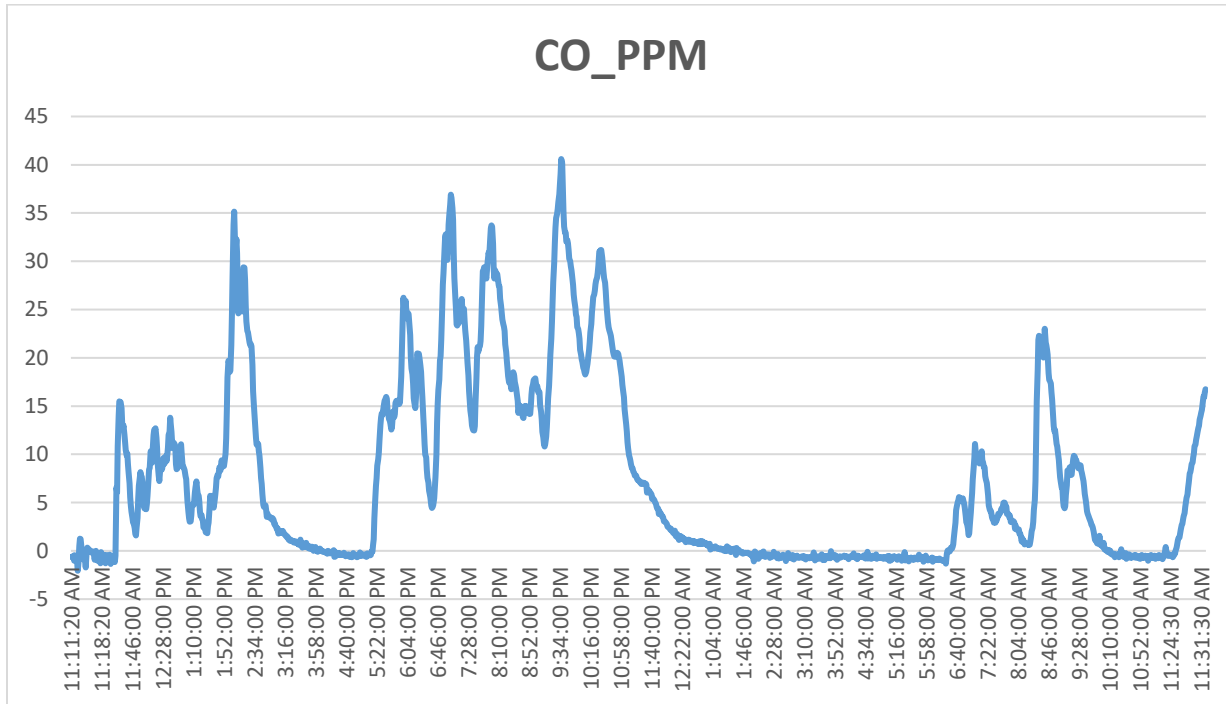
DSS HHID	PATs+ 7714 measured data		Control experimental intervention			Windows intervention	stove area changing
HH 06B 818.2			Before	All window open	difference		
818.2	CO_(PPM)	Mean	3.43	1.82	1.61	1 window before intervention	traditional 3 stone & movable metal stove yes changed
		SD	6.59	3.86	2.73		
	PM2.5 (µg/m3)	Mean	336.39	300.01	36.38	Two windows added after intervention	
		SD	632.65	593.75	38.9		

DSS HHID	PATs+ 7713 measured data		Control experimental intervention			Windows intervention	stove area changing
HHID 06B724			Before	All windows open	difference		
724	CO_(PPM)	Mean	1.17	17.21	-16.04	1 window before intervention	traditional 3 stone & movable metal stove yes changed
		SD	3.09	29.81	-26.72		
	PM2.5 (µg/m3)	Mean	336.27	1043.39	-707.12	Two windows added after intervention	
		SD	681.76	1706.00	-1024.24		



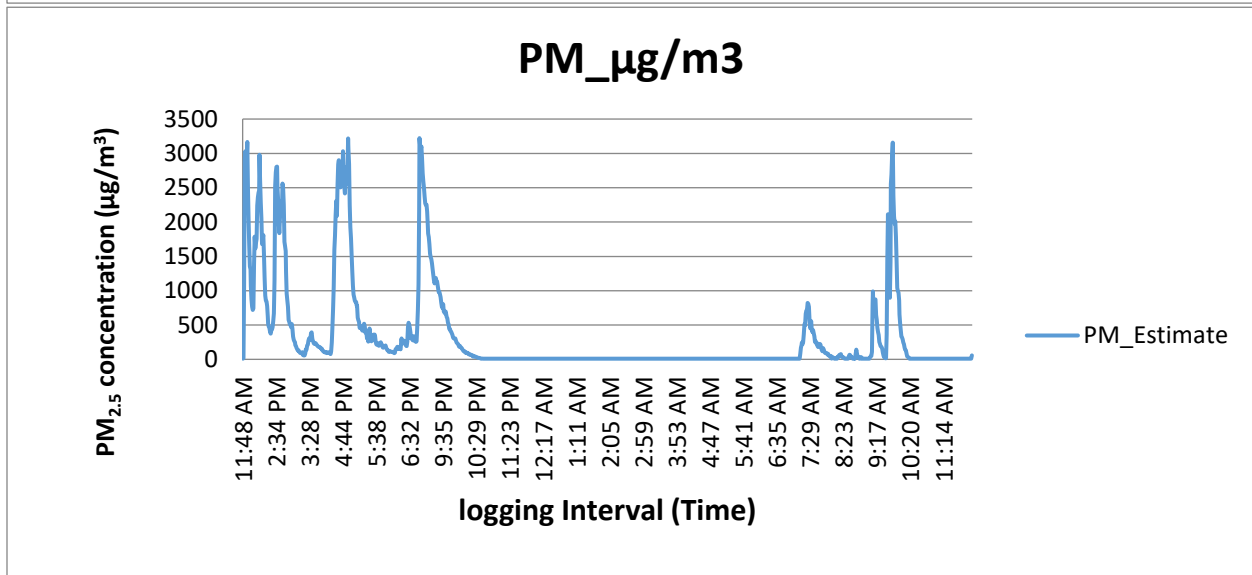
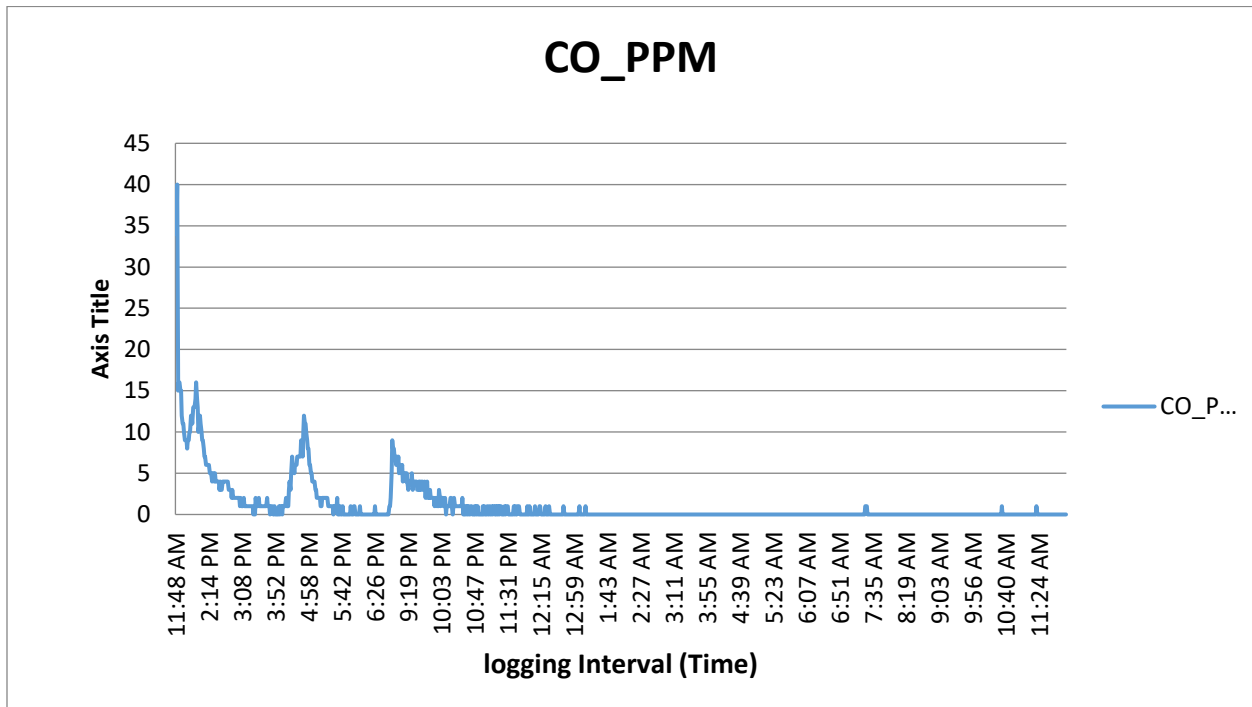
APPENDICES G: CO and PM_{2.5} measurement before intervention

- **HHID770.1**





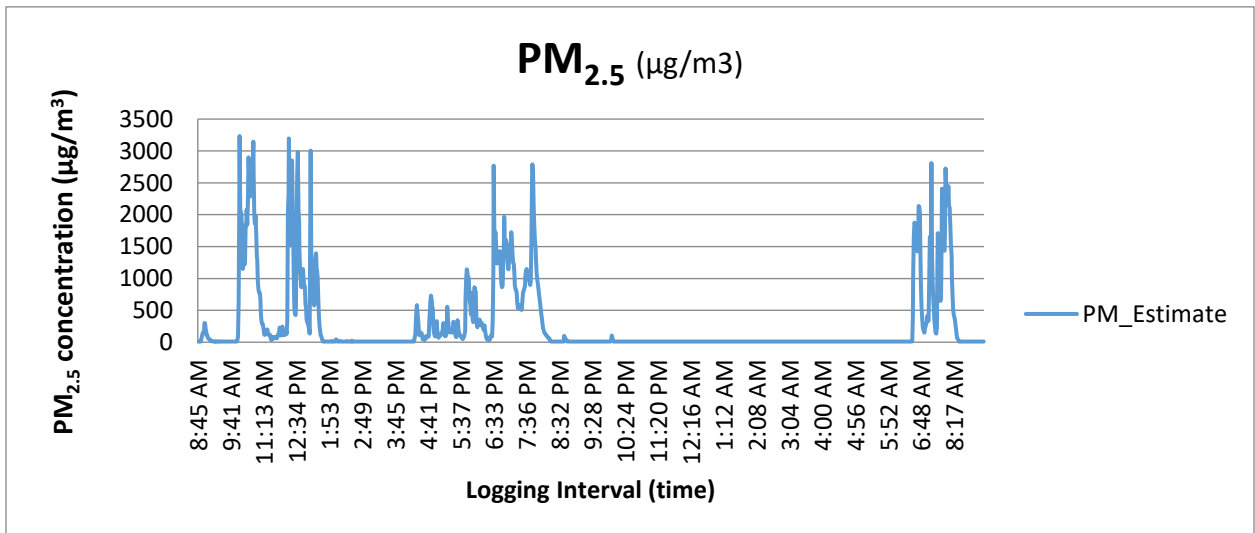
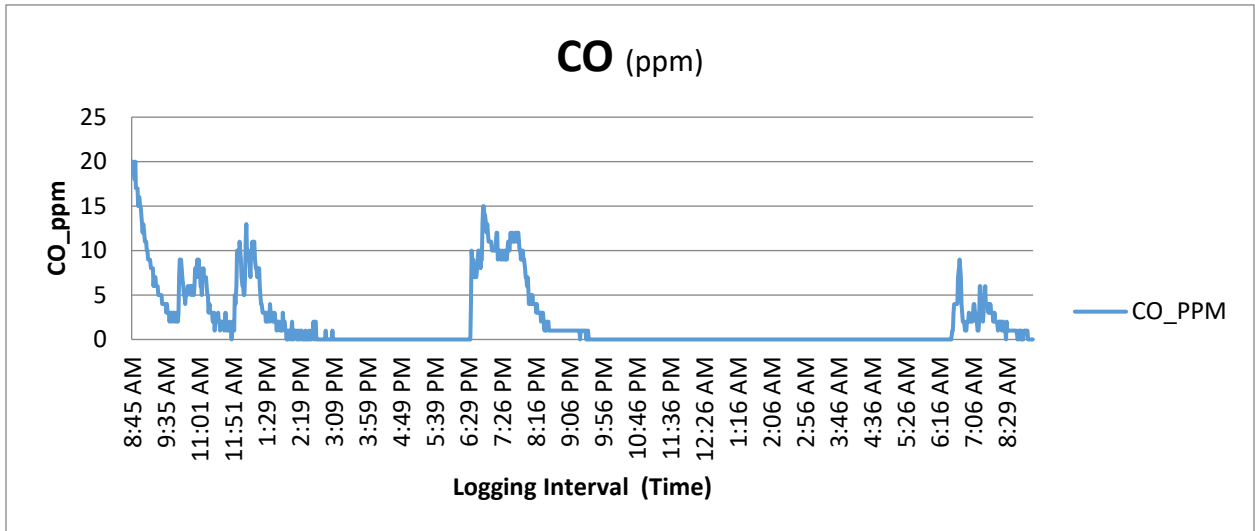
- HHID 724





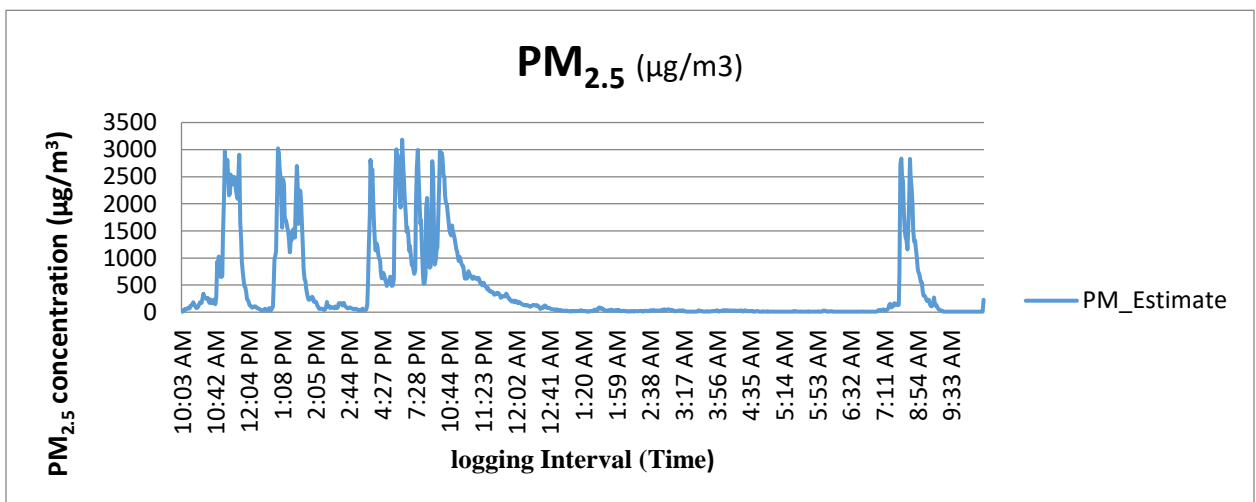
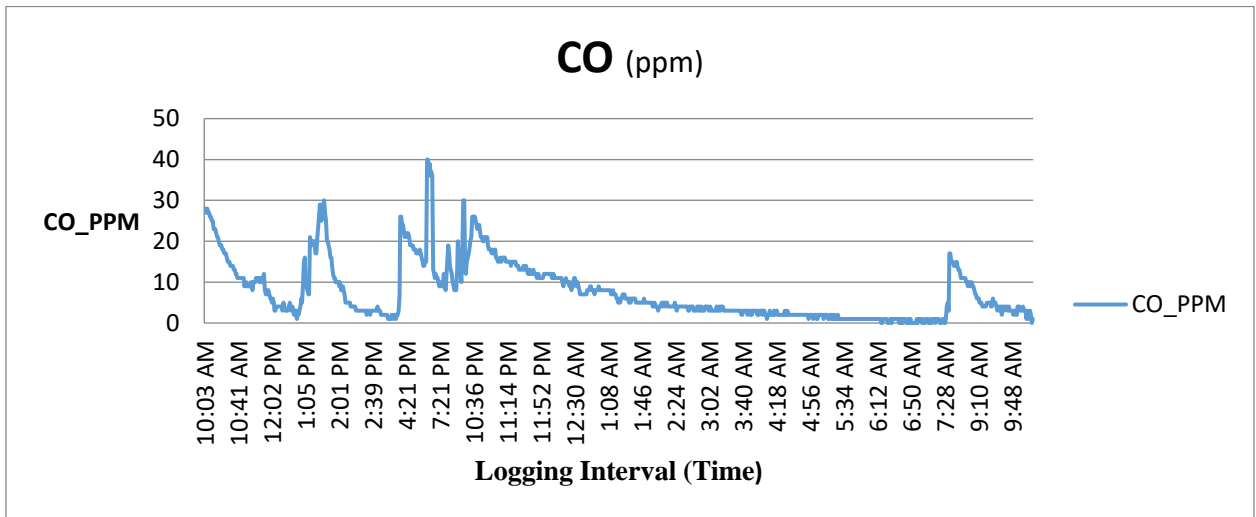
CO AND PM_{2.5} MEASUREMENT AFTER INTERVENTION ONE

- HHID770.1



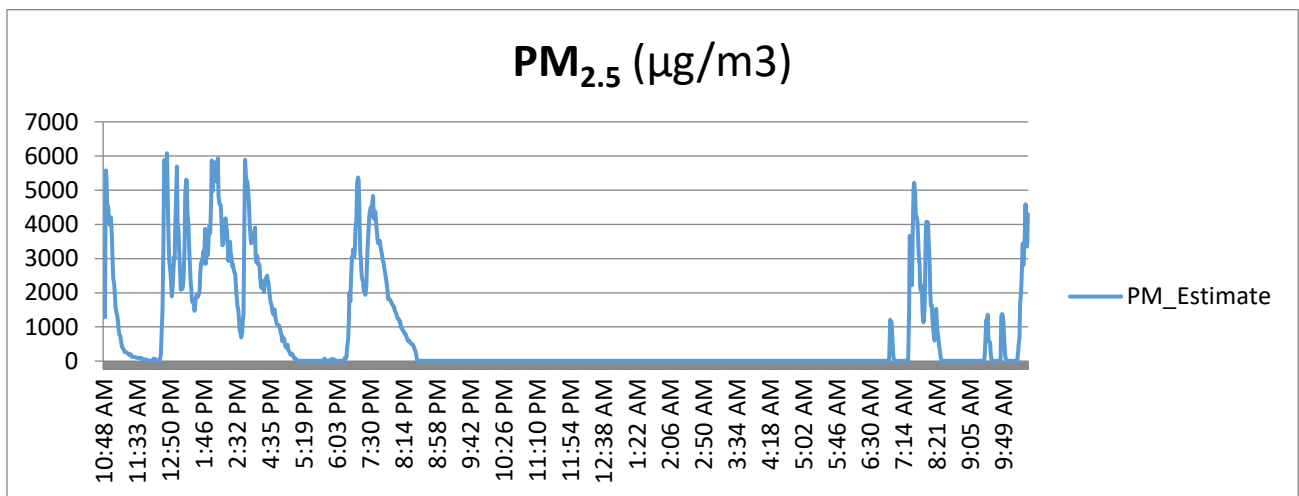
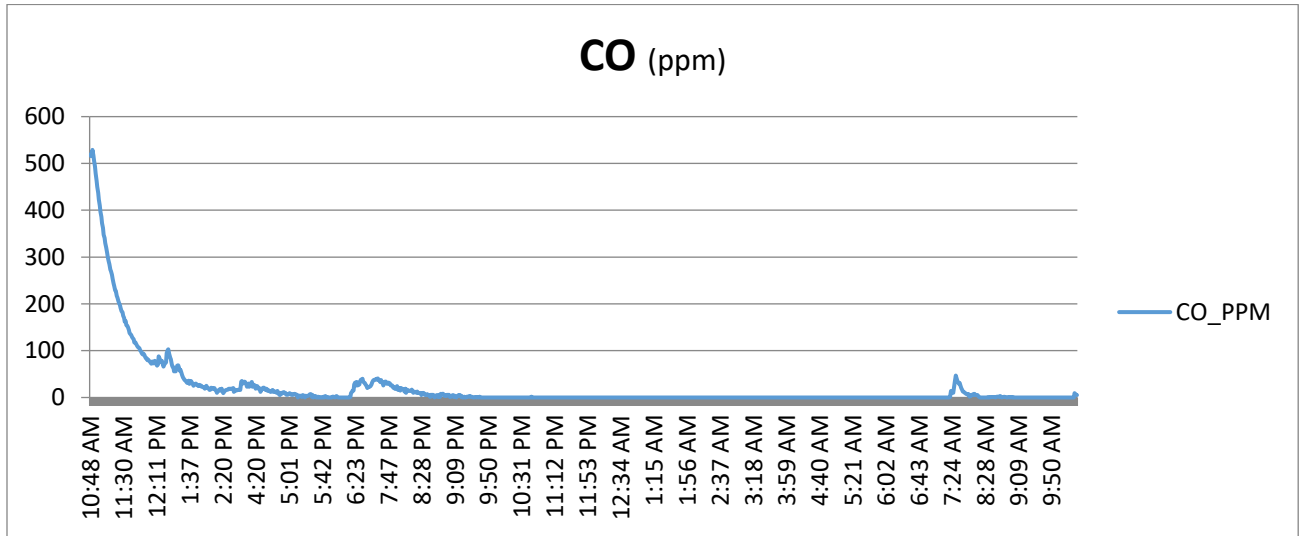


- HHID818.2





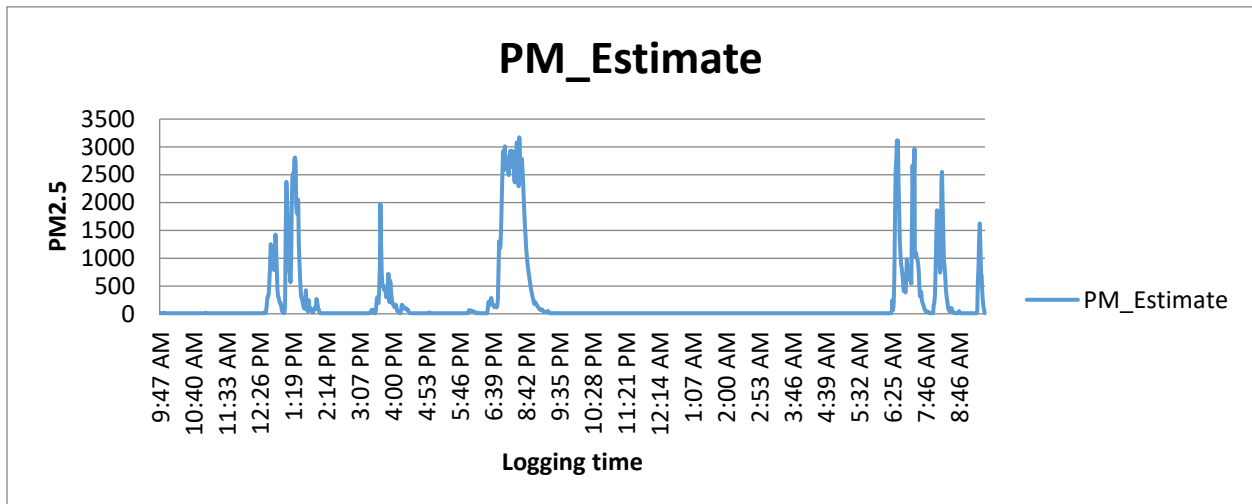
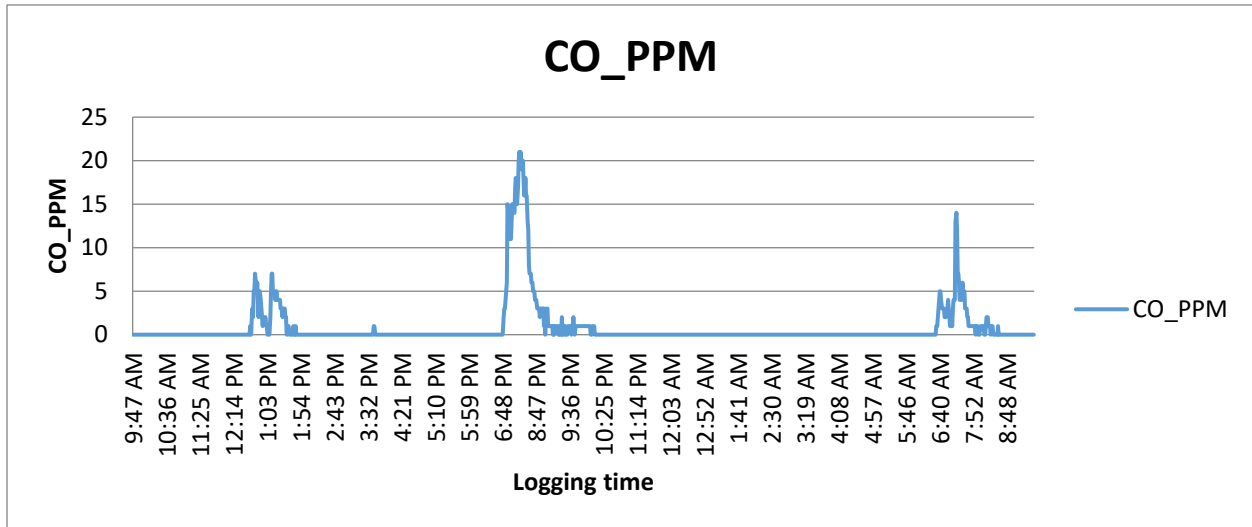
- **HHID 724**





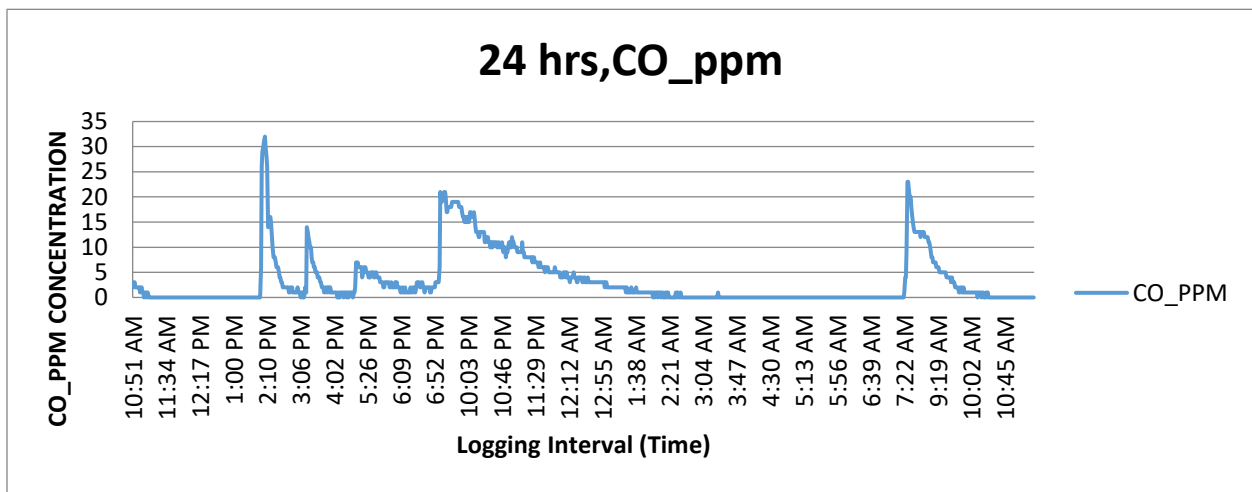
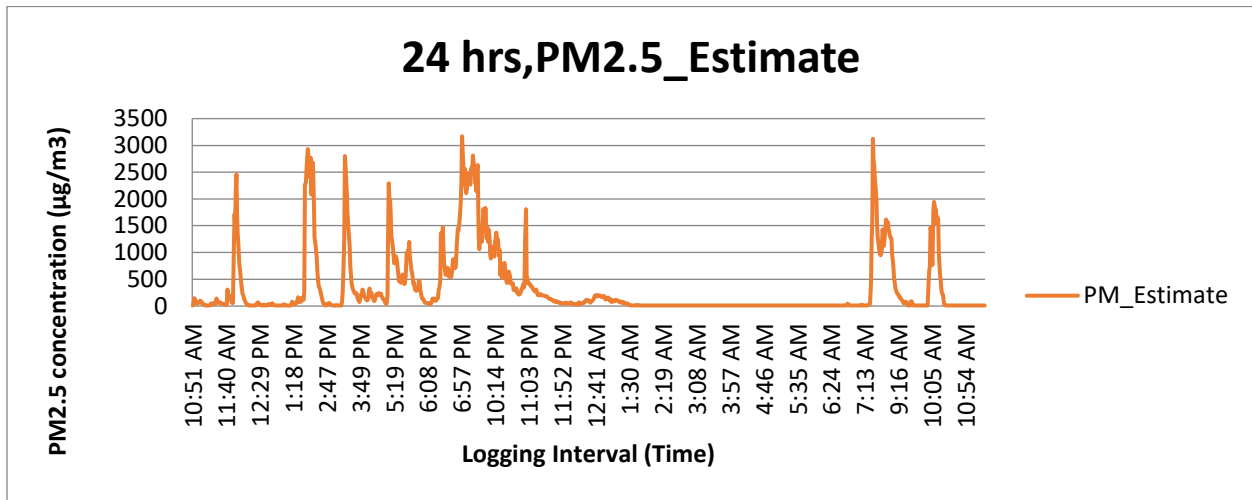
CO AND PM_{2.5} MEASUREMENT AFTER INTERVENTION TWO

- HHID770.1



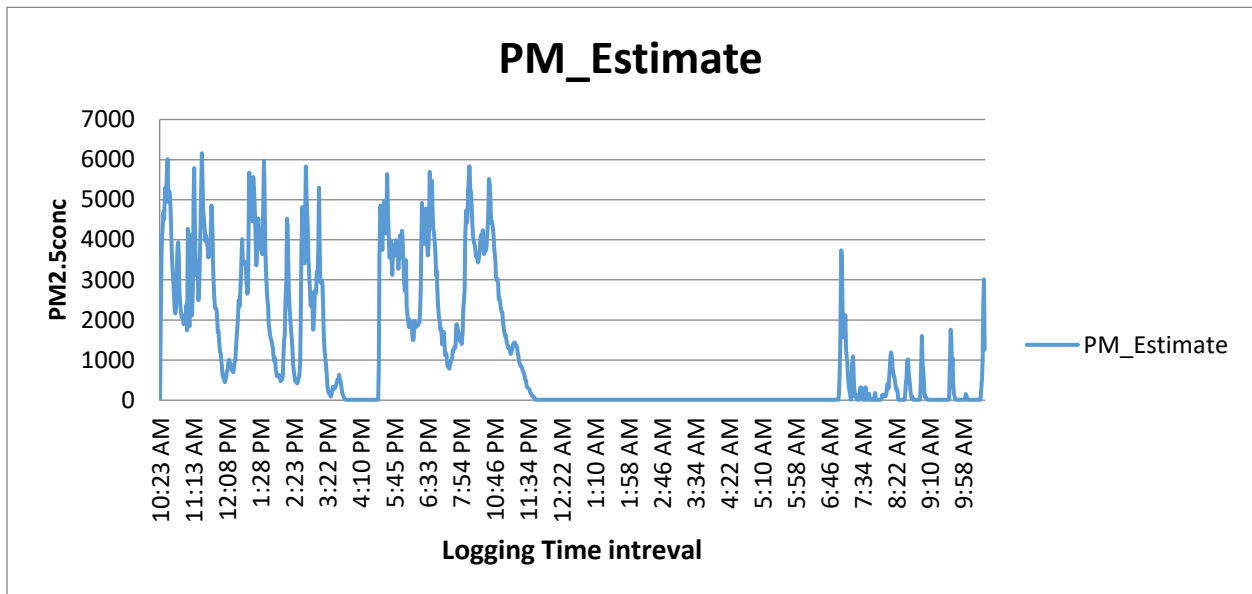
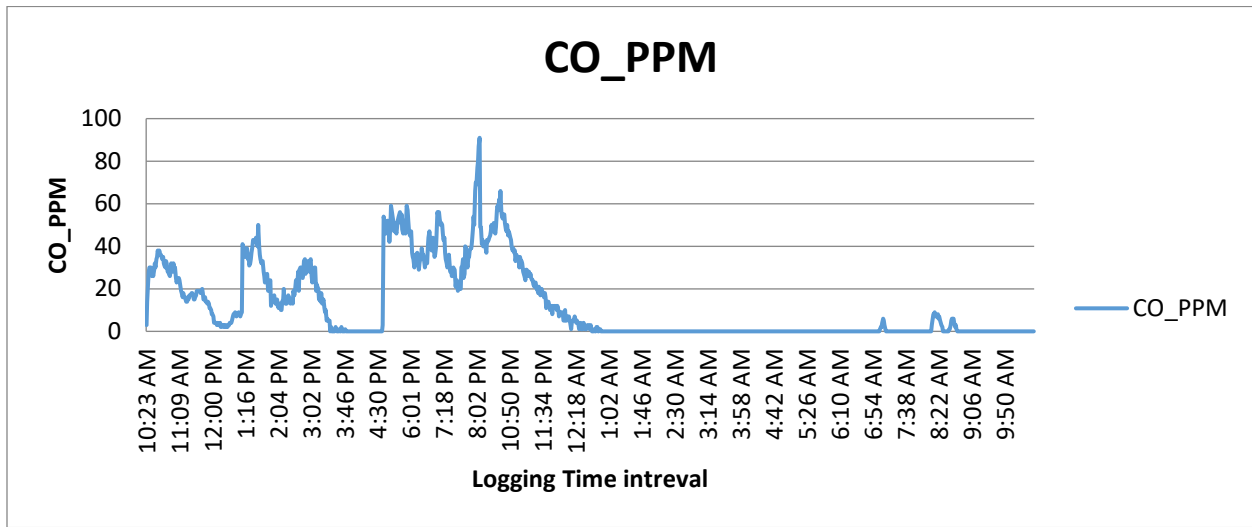


- **HHID818.2**





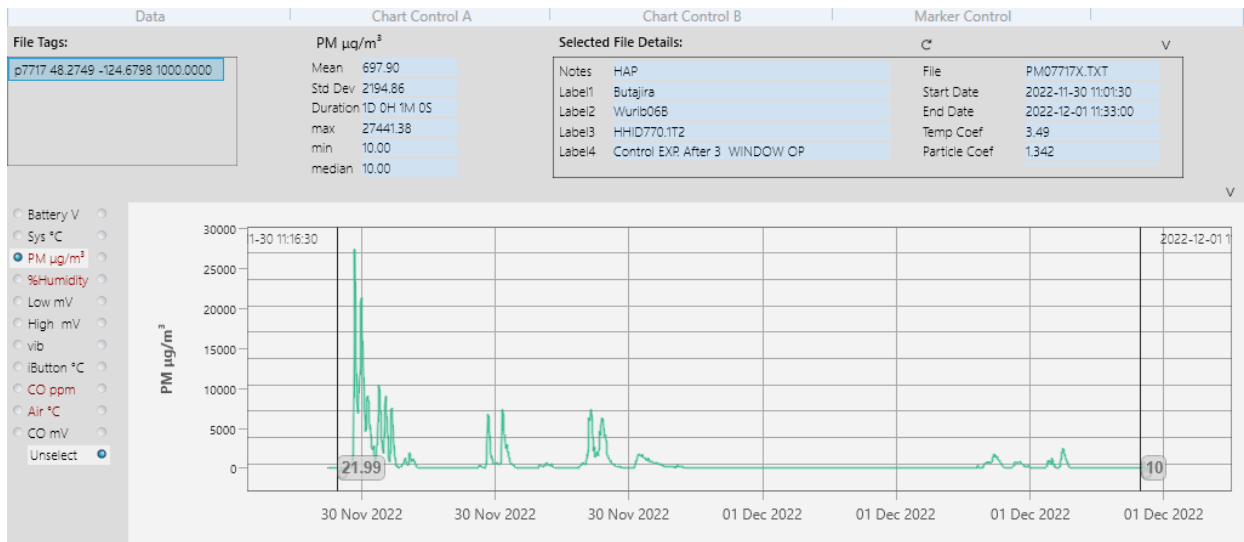
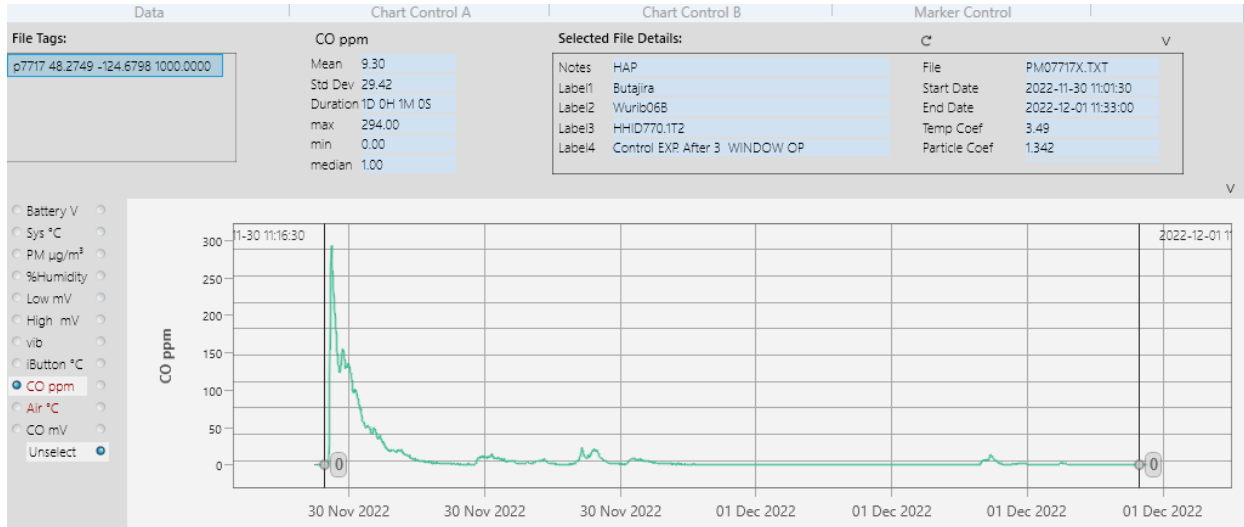
- **HHID 724**





CO AND PM_{2.5} MEASUREMENT AFTER INTERVENTION THREE

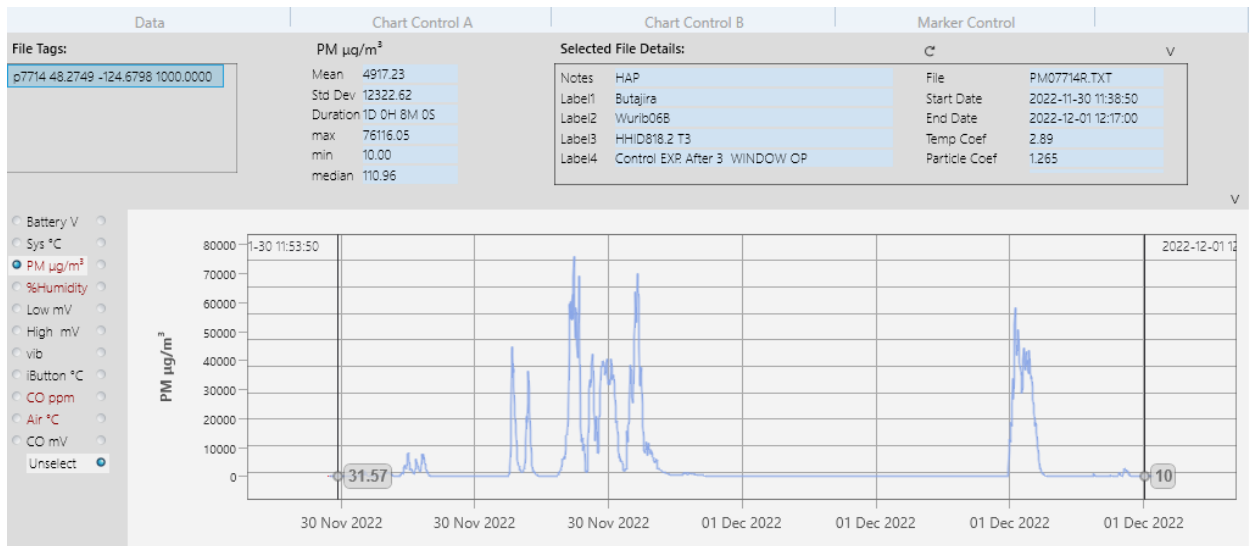
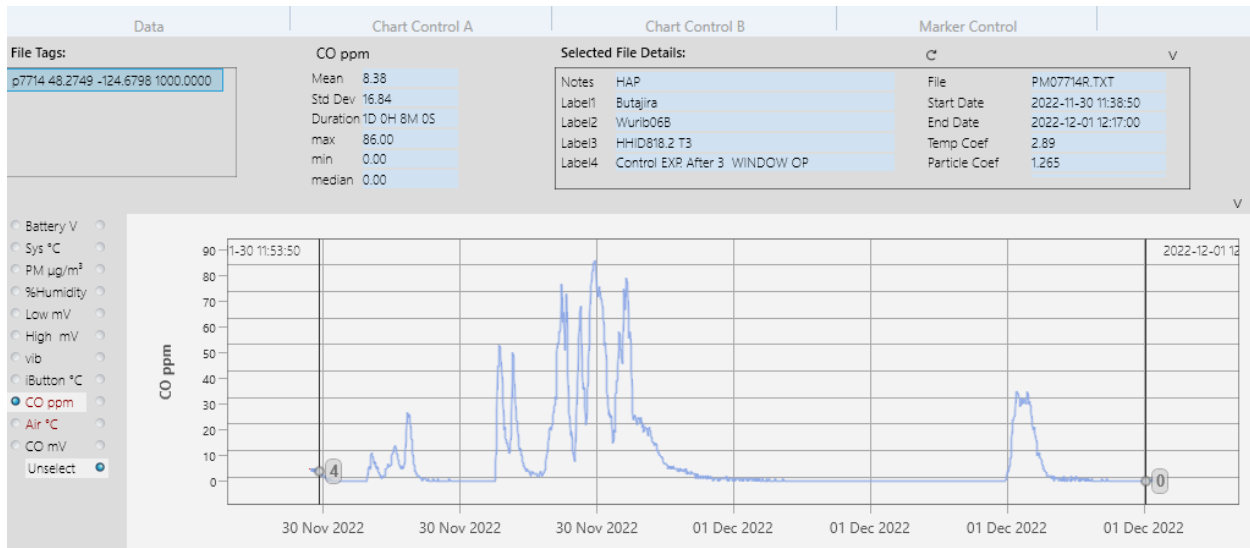
- **HHID 770.1**





Indoor air pollution: Pragmatic smoke mitigating interventions for reducing CO and PM_{2.5} in traditional tukul houses. The case of Butajira area

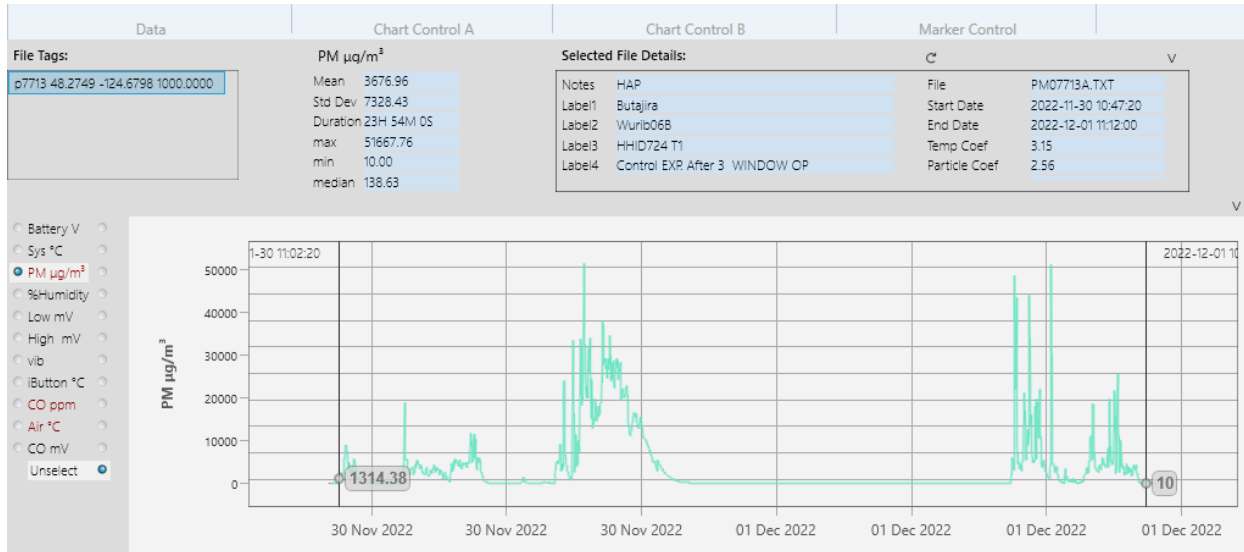
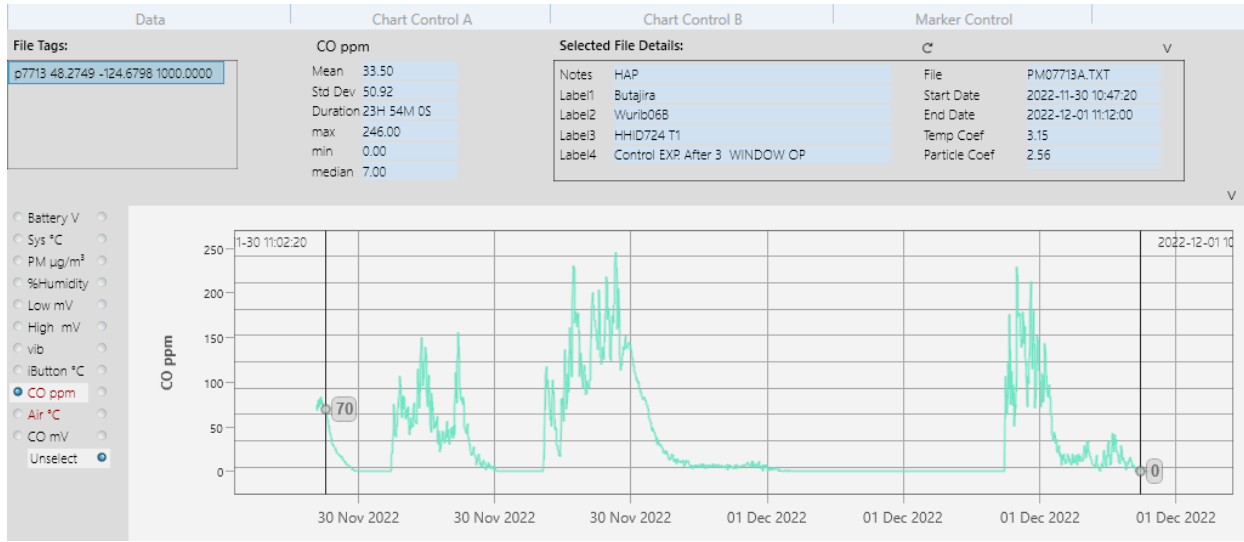
- **HHID 818.2**





Indoor air pollution: Pragmatic smoke mitigating interventions for reducing CO and PM_{2.5} in traditional tukul houses. The case of Butajira area

- HHID 724**



APPENDIX H: Pictures taken during the intervention





Demolition



Window installation



Window installation



Mud plastering



Air drying after plastering



Indoor air pollution: Pragmatic smoke mitigating interventions for reducing CO and PM_{2.5} in traditional tukul houses. The case of Butajira area



Mud plastering



Mud plastering



Mud plastering



PATs+ device mounting location



Outdoor cooking (affecting the neighbors)