Exposure to household air pollution among mothers and children in Ethiopia

Socio-cultural factors and association with airway health

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Gothenburg, Sweden, 2020

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ISBN 978-91-8009-138-1 (PRINT)
ISBN 978-91-8009-139-8 (PDF)
http://hdl.handle.net/2077/66813

Printed in Gothenburg, Sweden 2020
Printed by Stema Specialtryck AB, Borås

“Stop the killer in the kitchen”

Dedicated to my wife Rihanna and our sons Hebron and Nathan

Abstract

Using solid fuel generates emissions of many health-damaging pollutants including inhalable fine particulate matter ($PM_{2.5}$). Such exposure is known to cause morbidity and mortality in low- and middle-income countries, including Ethiopia, where solid fuel, mainly wood, is a primary source of energy. This thesis aimed to explore the reasons of using solid fuel and traditional stoves and to determine the levels of pollution and associated effects on the respiratory health of mothers and their children.

Qualitative exploration in the **first paper** showed that economic status, lack of commitment, cultural views and concern along with safety and security issues were barriers to change from traditional to cleaner means of cooking in rural areas of Butajira, Ethiopia. The community perceived wood smoke to have negative health effects on their eyes and respiratory health but as beneficial for postpartum mothers and newborns, ridding the house of bad smells and insects. The **second paper** involved 545 mothers from urban and rural settings to assess the association between solid fuel use and self-reported respiratory symptoms and lung function, as determined by spirometry with reversibility testing. Significantly higher prevalence of cough, phlegm, wheeze and irritation of nose and lower forced expiratory volume in the first second (FEV1) were found among mothers using solid fuels than among those using cleaner fuels. The odds of developing at least one respiratory symptom were twice as high for women who cooked inside the house when compared with those using cleaner fuels. In the **third paper**, nasopharyngeal swabs were taken from 168 mothers and 175 children and analyzed for bacteria and virus by multiplex PCR. Detection of *Streptococcus pneumoniae* and *Haemophilus influenzae* was significantly more frequent among solid fuel users, when compared with those using cleaner energy. In the **fourth paper**, measurements of $PM_{2.5}$ were conducted in 147 rural households for 24 hours during both rainy and dry seasons. The 24-hour mean level of $PM_{2.5}$ was 410 $\mu g/m^3$, 16 times higher than the WHO 24-hour mean air quality guideline of 25 $\mu g/m^3$.

Based on the high level of $PM_{2.5}$ emission and sole reliance on solid fuel use, there is an unaddressed threat for the health of Ethiopian women and children. Sustainable measures to shift to the use of cleaner energy along with education for awareness of their health and cultural myths, need to be addressed to solve this problem.

Keywords: Household air pollution, solid fuel use, *Streptococcus pneumoniae,* particulate matter, socio-cultural barriers, Ethiopia.

Sammanfattning på svenska

Användningen av fast bränsle för matlagning och för att värma upp bostaden genererar många skadliga föroreningar, bland annat små partiklar mindre än 2,5 mikrometer. Sådan exponering är känd för att orsaka sjukdom och död i låg- och medelinkomstländer, inklusive i Etiopien, där fast bränsle i form av i första hand ved är den primära energikällan. Syftet med denna avhandling var att undersöka skälen till att använda fast bränsle och traditionella spisar, och att bestämma luftföroreningsnivåer samt associerade effekter på luftvägshälsan bland kvinnor och deras barn.

I det första arbetet genomfördes kvalitativ forskning med gruppdiskussioner, där det framkom att ekonomisk status, brist på engagemang, kulturella åsikter och farhågor, tillsammans med säkerhetsaspekter, upplevdes vara hinder för att byta från traditionell till renare typ av matlagning på landsbygden i Butajira, Etiopien. Deltagarna uppfattade att vedrök hade negativa effekter på deras ögon och luftvägshälsa, men att den var gynnsam för nyblivna mödrar och nyfödda, genom att ta bort dålig lukt och insekter.

Det andra arbetet involverade 545 mödrar från stad och landsbygd i Etiopien och där undersöktes sambandet mellan användningen av fast bränsle och självrapporterade luftvägssymtom och lungfunktion, vilken bestämdes med lungfunktionstest (spirometri). Signifikant högre förekomst av hosta, slembildning, pip, näsirritation och lägre forcerad utandad volym på 1 sekund (FEV1), dvs trånga luftrör, noterades bland mödrar som använde fast bränsle jämfört med de som använde renare typ av bränsle. Risken att utveckla åtminstone ett luftvägssymtom jämfört med de som använde renare bränsle var dubbelt så hög för kvinnor som lagade mat med fast bränsle inomhus.

I det tredje arbetet togs prover från övre luftvägarna hos 168 mödrar and 175 barn och analyserades avseende förekomst av bakterier och virus som kan orsaka luftvägsinfektioner. Fynd av bakterierna *Streptococcus pneumoniae* (pneumokocker) och *Haemophilus influenzae* var vanligare bland de som använde fast bränsle jämfört med de som använde renare bränsle.

I det fjärde arbetet utfördes mätningar av rökpartiklar i hushåll på landsbygden under 24 timmar, både under regnperioden och under torrperioden. Medelvärdet under 24 timmar var 410 $\mu g/m^3$, vilket är 16 gånger högre än medelvärdet som rekommenderas av världshälsoorgani-sationen WHO.

Mot bakgrund av de höga nivåerna av skadliga rökpartiklar och utbredd användning av fast bränsle, finns det ett hot gentemot kvinnors och barns hälsa i Etiopien. Hållbara strategier för att byta till användning av renare energi, tillsammans med utbildning för ökad medvetenhet om hälsa och kulturella myter, behövs för att komma till rätta med problemet.

List of papers

This thesis is based on the following studies, referred to in the text by their Roman numerals.

I . Tamire M, Addissie A, Skovbjerg S, Andersson R, Lärstad M. *Socio-cultural reasons and community perceptions regarding indoor cooking using biomass fuel and traditional stoves in rural Ethiopia: A qualitative study*. Int J Environ Res Public Health 2018; 15: 2035.

II Tamire M, Addissie A, Kumie A, Husmark E, Skovbjerg S, Andersson R, Lärstad M. *Respiratory symptoms and lung function among Ethiopian women in relation to household fuel use*. Int J Environ Res Public Health 2019; 17: 41.

III Tamire M, Addissie A, Gizaw S, Abebe T, Geravandi S, Nilsson S, Gonzales Siles L, Lärstad M, Nordén R, Andersson R, Skovbjerg S. *Household fuel use and its association with potential respiratory pathogens among healthy mothers and children in Ethiopia.* Manuscript.

IV . Tamire M, Kumie A, Addissie A, Ayalew M, Boman J, Skovbjerg S, Andersson R, Lärstad M. *High levels of particulate matter ($PM_{2.5}$) from burning solid fuels in rural households of Butajira, Ethiopia.* Manuscript.

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Abbreviations

ALRI Acute Lower Respiratory Infections
AOR Adjusted Odds Ratio
ATS American Thoracic Society
BCG Bacillus Calmette–Guerin
CDC Centres for Disease Control and Prevention
CI Confidence Interval
COPD Chronic Obstructive Pulmonary Disease
Ct Cycle threshold
DSS Demographic Surveillance System
ERS European Respiratory Society
FEV1 Forced Expiratory Flow in 1 s
FGD Focus Group Discussion
FVC Forced Vital Capacity
GOLD Global Initiative for Chronic Obstructive Lung Disease
HAP Household Air pollution
KI Key Informant
MRC Medical Research Council
NRERC National Research Ethics Review Committee
OR Odds Ratio
PATS+ Particle and Temperature Sensor
PCR Polymerase Chain Reaction
PCV Pneumococcal Conjugate Vaccine
PEF Peak Expiratory Flow
PICA Platform for Integrated Cook stove Assessment
PM Particulate matter
SD Standard Deviation
WHO World Health Organization
VOC Volatile Organic Compound

1. Introduction

1.1 Household air pollution and health

Globally, the burden of morbidity and mortality due to Household Air Pollution (HAP) remains as an issue of concern yet unsolved. According to the World Health Organization (WHO), nearly four million annual deaths and half the deaths due to pneumonia among under-five children are attributed to HAP, mostly in low- and middle-income countries (1). Being a Sub-Saharan country with its sole dependence on solid fuel use, the situation of HAP in Ethiopia is one of the main health threats.

1.1.1. Solid fuel use and household air pollution

Shelter and food are basic for human survival, thus, housing and cooking are the most important parts of daily life. The inventions of modern technologies lead to advancement in both aspects of life and some parts of the world or part of global population get them without harm. The decline in the burden of the problem due to this advance in technology and shift to the cleaner energy sources showed high progress in the developed world. However, the burning of solid fuels by three billion people, i.e. nearly half of global population, for cooking food, heating and lighting their homes leads to the occurrence of HAP (1). Those solid fuels used in the low- and middle income countries mainly in Asia and Africa, include wood, charcoal, animal dung, crop residues and/or coal, which have poor combustion efficiency. Not only the fuels used, but also the types of stoves used in the regions, especially in Sub-Saharan Africa, are traditional, mainly three leg stones or clay (2).

Though the problem of solid fuel use and housing could be mainly linked with the socio-economic or development status of the regions (3, 4), studies from different parts of the world reported the existence of other social and cultural reasons found to contribute to the existence of the problems up to now (5, 6). A previous meta-analysis study concluded that the decision of a household depends on more than only income and identified other factors including cultural and custom background, household characteristics such as age, labor activity and household external factors like access to fuels and price level of the fuels (7).

In spite of different interventions including both the millennium development goals and sustainable development goals, aimed to halt the effects of HAP, the current burdens from the problem indicate there is a long way to go (8). For promoting reduced use of solid fuels and traditional cooking stoves in the affected parts of the world, more studies are still needed, especially interventional and interdisciplinary studies, as the introduction of innovative actions might be challenging for policy makers at different levels (9).

1.1.2. Composition and types of pollutants

There are different types of pollutants or other substances emitted from the burning process or other materials in the indoor environment, the major pollutants being indoor particulate matter, carbon monoxide, nitrogen dioxide, radon and asbestos. Nevertheless, those with highest public health impacts receive attention for research and other interventions. The composition and types of household air pollutants may also vary based on the types of fuels used and other behavioral and policy issues of the specific countries (10).

1.1.2.1 Particulate matter

Particles of different sizes are found suspended in the air in a mixture of complex form either in solid, liquid or gaseous states. Based on their sizes, specifically, the aerodynamic diameter, particles are classified into groups, namely inhalable coarse particles and fine particulates. The former includes particle diameter size ranging from 2.5 to 10 micrometers (μm) while the latter, which is the principal component of wood smoke, refers to diameter size up to 2.5 μm (11). There are also ultrafine particles with a diameter of <0.1 μm (12).

The sources of indoor particulate matter (PM) may vary and so do the physical and chemical characteristics (13). Combustion, mainly wood burning for cooking or heating in the developing world, is the major and important source of PM (14). Other sources include cigarette smoking (15), other burning incenses and human activities (16), building materials and the use of cleaning supplies, paints and insecticides (17). There have also been studies indicating the existence of the infiltration of outdoor origin of $PM_{2.5}$ that has potential human health effects (16, 18).

The size of the particles is associated with health effects on the human body, those less than 10 micrometers are considered as harmful. However, the fine particles ($PM_{2.5}$) are known to cause the greatest health risk as they may get deep into the lungs and impair its function as the particles irritate and corrode the alveolar wall, some may reach the blood stream (16). That means, as the size of the particles get smaller, the health risk posed will be greater (19).

1.1.2.2 Other types of pollutants

There are other forms of pollutants that have been measured in the indoor environment by different researchers and are known to be other health damaging pollutants from burning solid fuels. Carbon monoxide can result from incomplete combustion during wood burning and other heating processes. It can be inhaled when too much appears in the household air and is known to be harmful for human health by replacing the oxygen in the red blood cells leading to damage in the brain and heart and even cause instant death (20). VOCs, which may constitute benzene, ethylene glycol, formaldehyde, methylene chloride, tetrachloroethylene, toluene, xylene, and 1,3-butadiene, are other forms of pollutants that can be produced in the burning process, or exist inside a house being emitted from household products contain organic solvents (21-23). Exposure to them are also linked with respiratory and cardiovascular health problems (24). In addition, oxides of nitrogen and sulfur, mainly nitrogen dioxide and sulfur dioxide, are also related to the burning process of solid fuels (25, 26).

1.1.3. Exposure to household air pollution

Exposure to HAP is common among the population living in the developing world due to the economic and other socio-cultural and behavioral factors (27). In most societies of those area, women take the responsibility of cooking and spend most of their time at the domestic hearth making them more exposed to the pollutants compared with other members of the community (28). The poor educational status of the women might be affected bi-directionally. Girls might not attend school because of the burden of cooking and firewood collection at a young age, this may also force them to engage in homemaking, thus, the cycle continues (29, 30). Children of those mothers, especially the younger ones, could be victims as they spend time with the mothers in the cooking area, carried on their back or sitting beside them during the cooking process (31).

In addition to the mothers and children, older adults have an increased risk and higher exposure to the pollutants. They may have limited mobility and stay longer inside the house or possibly because they may have an underlying undiagnosed risk condition. People with previous heart and lung problems including the undiagnosed groups are also at higher risk of the health problems from exposure to PM (32).

Figure 1: A mother holding her baby while cooking using a traditional stove indoor (A photo taken by a field facilitator in Butajira (2020))

The WHO and other institutions made guidelines for the upper 24-hour and annual exposure to such PM, 20 μg/m³ and 50 μg/m³ for PM10 and 25 μg/m³ and 10 μg/m³ for $PM_{2.5}$, respectively (33). Nevertheless, studies from different parts of the world, especially from Asia and Africa, measured much higher levels of $PM_{2.5}$ exceeding the WHO limit from double to over 20 times, both in the living rooms and kitchens (34-37).

While other sources might contribute to the exposure to PM in the developed world, the main source for the high exposure for the majority of the population in the developing world is attributed to the reliance on solid fuels and use of traditional stoves (27, 38). Unlike other part of the developing world, the total population exposed and the duration and level of exposure did not decline in the Sub-Saharan Africa because of the increase in population in the region (39).

The extent of the effect of pollutants and the exposure to them are also dependent on other factors, which affect the quality of the household environment. This may also include the type of living house, mainly the design, construction and operating parameters which in turn affect air exchange rate and ventilation, outdoor climate and weather conditions and the behavior of the members of the households. The behavior component and role of outdoor climate/weather comprises the practice of opening the windows and doors during and after cooking practice, using dry wood or other efficient fuel types and keeping children away from the cooking area (40).

1.1.4. Solid fuel use and exposure level in Ethiopia

Solid fuel is the only fuel option for over 90% of population in Ethiopia and used universally in the rural area (41). Limited research evidence from Ethiopia showed existence of high level exposure to different types of household air pollutants both in the urban and rural settings. The 24-hour measures of $PM_{2.5}$ were recorded to be at a high level by Okello et al. (42) in the rural settings and Graham (43) and Admasie et al. (44) in the urban context. Kumie et al. also reported a high indoor magnitude of oxides of nitrogen in the southern Ethiopia (45).

Different factors aggravate the condition of HAP in Ethiopia. The majority, over 80%, of the population live in the rural parts of the country in traditional tukul houses with poor ventilation mechanisms. In addition, having a large family size and sharing the living room with animals could aggravate the situation. Other factors may extend to the culture of cooking traditional foods inside the living room, which includes main food (injera or bread) along with curry and the Ethiopian coffee preparation ceremony so extending the duration of burning and exposure. The behaviour of inhabitants regarding not opening windows and doors during cooking inside could also play a role of increasing the risk (46).

Figure 2: A photo showing the inside of a rural house with central cooking place, animals and children's sleeping place. (A photo taken in the morning by a field facilitator in Butajira (2020))

1.2 Biological mechanisms

The pollutants in the air we breathe get into the body through our respiratory systems and the destination is based on primarily the size of the particles. While the cilia and mucus in the respiratory tract could trap the coarse PM, the fine PM could reach the terminal bronchioles and alveoli whereas ultrafine PM can enter the alveoli and may even enter the blood stream (47, 48).

Inhaled particles deposit in the airways and trigger a cascade of inflammatory processes, involving reactive oxygen species and subsequent oxidative stress. The particles affect the epithelial cells lining the airways and alveoli leading to the generation of inflammatory mediators, for example cytokines. This leads to activation and also of the recruitment of inflammatory cells such as neutrophils and macrophages. A study among preschool children indicated the production of pro-inflammatory cytokines was stimulated by exposure to PM (49). Another study also found an increase in C-reactive protein, a protein secreted into the bloodstream in response to inflammation, associated with $PM_{2.5}$ exposure in different population subgroups (50). Exposure to HAP can modulate the immune system and impair pulmonary defense. This can be performed by increasing epithelial permeability and disrupt barrier defenses, upregulation of receptors important for pathogen invasion and depressing the phagocytosis and intracellular killing by macrophages (51).

1.3 Health effects of household air pollution

The generation of substantial emissions from the use of solid fuels and associated HAP result in damaging the health of the exposed population at global level. This section describes the wide range of health outcomes, some are short-term effects while others are chronic problems as on the respiratory systems and the heart. The exposure to some pollutants e.g. carbon monoxide in a higher dose can lead to immediate death. The health effects related to HAP can happen in children and adults while the exposure in childhood can obviously lead to a deterioration of the health at later age.

1.3.1 Effects on respiratory diseases and lung function

The association between exposure to HAP due to solid fuel use and respiratory system diseases recently received the attention of the researchers and is evidenced in many countries (52, 53). The PM in the smoke during the burning process affects the respiratory system in many ways. Occurrence of acute lower respiratory infections (ALRI) such as pneumonia amongst children less than five years of age is a major health problem causing morbidity and mortality all over the world but more common in the low-and middle-income countries (54).There were 515,000 deaths among children globally, especially in low-income countries, in 2015 attributed to *S. pneumoniae* (the pneumococcus) a major bacterial pathogen causing respiratory tract infections (55). There have been many other studies, which identified the use of solid fuel as one of the factors associated with ALRI especially in low-and middle-income countries (56-61). On the other hand, reducing HAP was associated with a decline in mortality from lower respiratory infection among under five children in those affected countries at global level by 8.4% from 1990 to 2017 (62).

There are different respiratory health problems in adults attributed to the exposure to HAP. There have been studies reporting higher occurrence of different respiratory symptoms among mothers from households using solid fuels compared with those using cleaner energy sources (63, 64). In addition, long term exposure to HAP accounts for impaired lung function, which might indicate the existence of other chronic respiratory health problems (64, 65). Many studies have shown the link between chronic obstructive pulmonary disease (COPD) and exposure to HAP including among non-smokers (66-68). To this end, the use of a pulmonary function test is an indicator of an existence of respiratory health problem thus Global Initiative for Chronic Obstructive Lung Disease (GOLD) recommends using spirometry to confirm clinical diagnosis of COPD (69). Exposure to solid fuel was also reported to be associated with an occurrence of asthma or modifying severity of asthma and nasopharyngeal and lung cancers (66, 70-72). Generally, pulmonary function increases from birth and matures at the mid-20s, thereafter it begins declining with ageing (73). Exposure starting from childhood and increase in lifetime in Sub-Saharan Africa including Ethiopia (74), puts the people in the region at a higher risk of COPD in the future.

1.3.2 Effects on microbes in the respiratory tract

Detection of potential pathogens, bacteria and viruses, in the respiratory tract were found to be associated with HAP and the use of solid fuels. Carriage of *S. pneumoniae* and *Haemophilus influenzae* type b (Hib) is known to cause large number of deaths and pneumonia cases in low- and middle-income countries (75-77). Exposure to PM from wood was also found to increase the vulnerability to pneumococcal lung infections by increasing platelet-activating factor receptor, which facilitates adhesion (78, 79). This may indicate that the use of solid fuel in developing countries contributes to the continuing of the diseases caused by the bacteria in the era of general childhood vaccination with conjugated pneumococcal vaccines, in addition to the observed change of circulating pneumococcal serotypes to non-vaccine serotypes (80).

Regarding the types of childhood vaccination against respiratory infections in Ethiopia, the service is given following the schedules recommended by the WHO. Accordingly, bacillus Calmette–Guerin (BCG) is given at birth or as soon as possible; followed by three doses of each of Penta-valent (diphtheria, tetanus, pertussis, hepatitis B and *Haemophilus influenzae* type b) and pneumococcal vaccines which are given at the 6th, 10th and 14th weeks of age and finally the first dose for measles at the 9th month (81). Universal immunization of children against the vaccine-preventable diseases; tuberculosis, diphtheria, whooping cough (pertussis), tetanus, polio, and measles, is crucial for reducing infant and child mortality (82). The 13-valent pneumococcal conjugate vaccine (PCV 13), which protects against severe infections caused by *S. pneumoniae*, including pneumonia and meningitis, was introduced into the national's infant immunization program in 2011 (83).

1.3.3 Other health effects of household air pollution

The effect of HAP on human health is not limited to the respiratory system and respiratory diseases. There is evidence indicating HAP causes non-communicable diseases and is associated with other grave human health risks. The effects may be different during pregnancy as it could be a double effects on the mother and the fetus.

Cardiovascular diseases and related disabilities and mortalities, which could have been averted by changing the energy use, across the globe could be the most reported and studied health effect of HAP and solid fuel use (84-88). There is also evidence and biologically plausible hypothesis that exposure to HAP is associated with blindness due to cataract (89, 90) and with irritation of the eyes (31). Pregnancy and birth related threats from exposure to HAP and the use of solid fuels have been evidenced by complications during pregnancy like preeclampsia/ eclampsia symptoms (91, 92), low birth weight and still birth (90, 93, 94). In addition, associations have been suggested between exposure to HAP from solid fuel use and tuberculosis (95, 96), gastrointestinal (97) and female reproductive organ cancers (98-100). Moreover, risk of fire burning is also there for the young children spending time in the cooking area with their mothers either because of falling and scalding or touching the fire and other hot objects (101).

1.3.4 Assessment of respiratory health effects

Multiple methods can be used to assess the health outcomes associated with the exposure to HAP due to the use of solid fuel. The methods can vary from asking the exposed persons about the occurrences of symptoms to use of different clinical and laboratory based tests and analysis.

There have been different studies, all over the world, implementing the use of questionnaires to identify and measure respiratory symptoms. While a cough, wheeze phlegm, breathlessness and irritation of the nose are studied in adults (31, 64, 102-105), coughs and symptoms of acute respiratory infections are mainly analyzed in children (106-109) on association with solid fuel use. The use of spirometry tests with reversibility to evaluate the lung function among adults have been used to assess risks on airway obstructions (64, 65, 110). Associations between the occurrence of potential respiratory pathogens and air pollution has also been studied (111). Moreover, statistical modelling and follow up studies used to analyze the effects of solid fuel uses on the health outcomes including mainly COPD and lung cancer (67, 112). The results of the assessments showed the use of solid fuel was a risk factor for impaired health in the exposed group.

1.4 Other effects of solid fuel use and household air pollution

Besides the health issues, the short and long term effects of using solid fuels including the burning of wood could be a global concern. These effects may affect the life of individuals, the socio-economic status of the given society or the environment for the flora and fauna, which in turn have devastating consequences for human health. In fact, the level of the effects and mitigation of the problems might be different for different nations and specific populations based of the local socio-economic conditions and policy directions.

In many low income countries, the women and young girls take the responsibility of cooking and the collecting of fuel wood (113, 114). This activity obviously affects them physically due to long travel, heavy loads and risks for injuries (115, 116), reduces their economic engagements, school attendance and other productive activities (117). Moreover, there could be risks for sexual abuses including rape (118), which in turn can affect their social and psychological well-being and lead to unwanted pregnancy and acquiring sexually transmitted infections.

The reliance on wood as a main energy source, especially by the rural community also leads to degradation of the forest resources as demonstrated in Ethiopia (119) and other Sub-Saharan countries (120). This deforestation can lead to erosion and nearby land degradation and extends the effects to food insecurity (121), access to clean energy (122) and contributes to climate change (123, 124).

2. Aims

The overall objective of this thesis was to study the effects of HAP on the respiratory health and presence of microbes in the respiratory tract of children and women in Ethiopia. Subsequently, we aimed to explore the reasons of using solid fuel and traditional stoves and to determine the level of air pollution.

Specific aims were to:

- Explore perceptions of the community towards indoor cooking and the socio-cultural barriers to bring change in Butajira, rural Ethiopia (Paper I).
- Assess respiratory symptoms and lung function among Ethiopian women in relation to exposure to HAP (Paper II).
- Assess the association between HAP due to solid fuel use and the nasopharyngeal occurrence of potential pathogens among mothers and their children in Ethiopia (Paper III).
- Measure HAP using fine particulate matter ($PM_{2.5}$) in rural Butajira, Ethiopia (Paper IV).

3. Materials and methods

3.1 Overview

In this section, the summary of methods used for the four studies are presented. The first paper was conducted using qualitative approach while the second and third ones were quantitative studies involving questionnaire, spirometry and nasopharyngeal sample analysis. The final paper used the measurement of the level of fine particulate matters ($PM_{2.5}$) during a 24-hours period.

Table 1. Summary of study design, population, data collection methods and dependent variables in each paper.

Paper	**Paper I**	**Paper II**	**Paper III**	**Paper IV**
Design	Qualitative content analysis	Comparative cross-sectional		24-hour exposure measurement
Study population	Community members and Health extension workers	Mothers of reproductive age groups	Mothers and children	Households and mothers
Data collection methods	Focus group discussion and Key informant interviews	Interviewer based questionnaire and spirometry	Interviewer based questionnaire and nasopharyngeal samples	Interviewer based questionnaire and $PM_{2.5}$ measurement
Outcome variable	Categories and codes	Respiratory symptoms and lung function test result	Detection of potential pathogens	Level of pollution
Analysis used	Content analysis	Descriptive statistics and Logistic regression	Descriptive statistics and Logistic regression	Descriptive statistics

3.2 Study area

Two of the studies (Paper I and IV) were conducted in rural Butajira, in the Gurage Zone of Southern Nations, Nationalities and People Region (SNNPR), about 135 km southwest from Addis Ababa (the capital city of Ethiopia). One urban and nine rural kebeles (the lowest administrative level) of the area have been sites of the Demographic Surveillance System (DSS) of Addis Ababa University Rural Health Program, since 1987 (125).We included five different kebeles, namely Dirama, Dobena, Misrak Meskan, Shersherabido of rural Butajira. The selection of villages was based on their proximity to the district city, Butajira, from all geographic directions. The other two studies (Paper II and III) were conducted both in Butajira and Addis Ababa. The reason for including the two settings was for comparing the role of HAP from the solid fuel use with cleaner energy use, which was only practiced in the city of Addis Ababa.

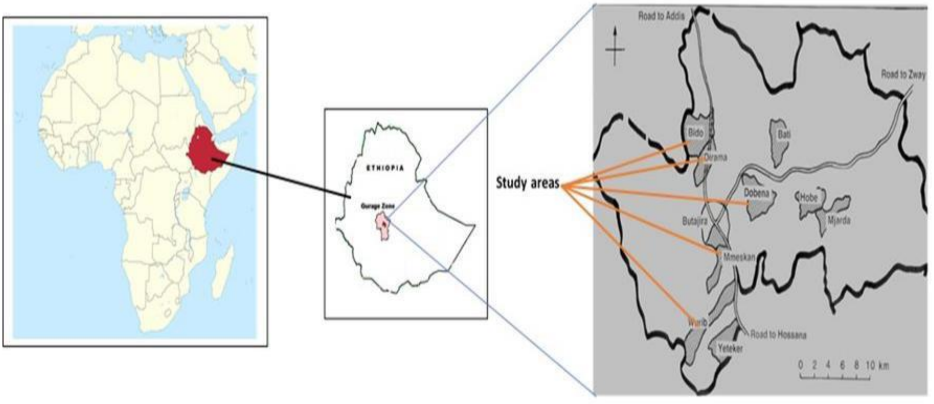


Figure 3: Map of the study area (Butajira demographic and surveillance site of Addis Ababa University)

3.3 Study design and population

3.3.1 Paper I

A descriptive qualitative study was conducted using the content analysis approach to describe the reasons for indoor cooking using solid fuels and traditional stoves together with the perception of the community. The study was conducted in two rounds in August 2016 and February 2018. Community representatives from both genders, permanent residents of the locality and knowledgeable about their community and the phenomenon under consideration, were recruited to take part in focus group discussions (FGD). The participants were purposively recruited using snow-ball sampling technique, where the potential participants were asked at the initial contact if they know of others who could enhance a better understanding of the phenomenon under consideration.

3.3.2 Paper II and III

The second and third papers were from a comparative cross-sectional study carried out from March to August 2016. In paper II, 545 mothers with children below the age of 2 years were included in Addis Ababa (n = 266) and in four rural kebeles of Butajira (n = 279) using systematic sampling technique. For paper III, nasopharyngeal samples were collected from a fraction of the mothers and their children. The number of participants was determined by the availability of the materials to obtain nasopharyngeal secretions. Accordingly, the samples were collected from 85 mothers and 87 children from Addis Ababa and 83 mothers and 88 children from rural Butajira. Mothers who came with their children for the vaccination service at the health centres were included in Addis Ababa. In the rural settings, mothers were recruited from the villages at Butajira because health extension workers gave most children vaccinations in their villages and not at health centres. None of the participants were current or previous smokers and the frequency of tobacco smoking is low among females at national level (126).

3.3.3 Paper IV

Measurement of $PM_{2.5}$ levels was conducted during two periods: from August to October in 2018 and from January to March in 2019. While the former period includes rainy season, the latter is a typical dry season in the area. Measurements during 24-hours were performed at 150 randomly selected households from each village using their unique codes from the DSS office.

3.4 Data collection

3.4.1 Paper I

Qualitative data was collected from male and female community representatives and health extension workers in the selected kebeles. Focus Group Discussions (FGDs) were used to collect data from the community representatives while key informant interviews were conducted for the health extension workers. A total of 10 FGDs, five with males and five with females, and two key informant interviews were held using semi-structured guides with open-ended and probing questions in the Amharic language. On average seven participants were involved in each FGD. All the FGDs and interviews were carried out at noise free places within the community and audio-recorded while appropriate notes were taken throughout the data collection. The main discussion points were summarized at the end of each FGD with the participants. To check for the saturation of the data, a point where no new theme was emerging, we reviewed the field notes and listened to the audio and conducted one more FGD from both and determined real saturation had been reached.

3.4.2 Paper II and III

Face-to-face interviews were conducted using a structured questionnaire including questions about socio-demographic factors, housing characteristics and cooking procedures at the household. Data on respiratory symptoms from the mothers was adopted from the Medical Research Council questionnaire on respiratory symptoms, United Kingdom (127) with contextual modification. The questionnaire was prepared in English and translated to Amharic (national language) with back translation to check for consistency. For paper two, additional standard anthropometric measurement, height and weight, were taken wearing light clothes and bare feet while spirometry tests were carried out following American Thoracic Society/European Respiratory Society (ATS/ERS) guidelines (128) using a portable spirometer. In paper III nasopharyngeal secretions were obtained from mothers and children by inserting a flocked swab into the nostril and rotating it over the nasopharyngeal surface, before being kept in 1 mL of Liquid Amies medium. The samples were cultured for pneumococci at the Bacteriological laboratory at Tikur Anbessa Specialized Hospital, Addis Ababa University then stored frozen at -80°C and later transported to Gothenburg, Sweden for further analyses with PCR (see below).

3.4.3 Paper IV

Data were collected from 150 households by measuring the 24-hour mean concentration of $PM_{2.5}$ using a Particle and Temperature Sensor (PATS+) instrument from Berkeley Air Monitoring Group (25), which is a portable, data-logging, battery-operated instrument measuring real-time PM ($PM_{2.5}$) concentrations along with the Platform for Integrated Cook stove Assessment (PICA) software. To obtain data about the housing and cooking process as well as the cooking practice during the measuring time, face-to-face interviews were conducted with the mothers in the households both before and after installation of the particle sensor instruments. The questionnaire included questions about family size, housing conditions, stove types, fuel use and cooking processes, including cooking time and frequency.

3.5 Data management and analysis

3.5.1 Paper I

After completing the FGDs and in-depth interviews, all audio-records were transcribed verbatim and translated into English by an experienced translator for analysis by trained persons. Translated texts were read and re-read by the principal investigator with qualitative research experience to define categories and sub-categories guided by the objective of the study. A codebook was then prepared and content analysis carried out using ATLAS.ti version 8.0 software (Scientific Software Development GmbH, Berlin, Germany) to code the transcripts based on the codebook. Then main and sub-categories were formed to describe the findings.

3.5.2 Paper II and III

Data entry and cleaning using statistical software for epidemiology EPI-Info version 3.5.4 (CDC) were made and exported to IBM SPSS statistics version 24 for analysis. After visualizing the general features of the data, descriptive statistics such as mean and standard deviation for continuous variables and frequency and percentage for categorical variables were determined separately for urban and rural participants. We used Chi-square test of independence to test whether or not a statistically significant relationship existed between pathogen occurrence in relation to the place of residence and fuel type used. We also used Fisher exact test for cells with an expected count of less than five to not violate assumptions of the Pearson Chi-square test. Finally, we applied logistic regression to determine the distribution of the study subjects by independent variable of interest and to see crude associations. Multivariable logistic regression analysis with adjusted odds ratio was used to evaluate the relative effects of solid fuel use by including those variables with p-value below 0.25 in the bivariate analysis. For all tests, a 95% confidence interval was used and the p-value was set to <0.05 to determine significance. Fuel use was re-categorized as rural solid fuel users, urban solid fuel users and cleaner energy users to exclude residence from the regression model for its multicollinearity with fuel type because all rural households used solid fuel.

3.5.3 Paper IV

We applied descriptive statistics using frequency and percentage for categorical variables and Independent t-tests to check for statistically significant mean differences between different groups. Before starting the t-test analysis, we checked for skewness and equality of variance. Thus, the data had a tolerable level of skewness (1.1) and the Levene’s test did not show any evidence of inequality in the variances or any test statistic resulting in a p-value above our chosen alpha (0.05). We also applied correlation analysis to assess a possible linear association or statistical relationships between the 24-hour mean $PM_{2.5}$ concentration and total duration of cooking at the same period.

3.6 Outcome measurements

3.6.1 Paper I

After transcribing the audio records to text, we open coded the data following Schreier qualitative content analysis approach (129) and the main and sub-categories were presented with continuous text and quotes to describe the findings.

3.6.2 Paper II and III

3.6.2.1 Respiratory symptoms

We assessed self-reported respiratory symptoms such as cough, phlegm, breathlessness, wheezing and irritation of the nose in the past 12 months. The following operational definitions were used:

Cough: We considered someone to have cough if their answer was “yes” to at least one of the following four questions. (i) cough first thing in the morning; (ii) cough during the day or night; (iii) cough as much as four to six times a day in a week (iv) cough for most of the day for as much as three consecutive months during a year.

Phlegm: We considered someone to have phlegm if they usually bring up phlegm from their chest (deep down in her lungs) first thing in the morning or during the day in the last 12 months.

Breathlessness: We considered some to have breathlessness if troubled by a shortness of breath when hurrying on level ground, walking up a slight hill, when walking at their own pace on the level ground and stop for breath after a few min/100 m or breathless when dressing/undressing or cooking.

Wheezing: We considered someone to have wheezing if her chest (lungs) ever sound wheezy (whistling sound).

At least one respiratory symptom: At least one of either cough, phlegm, wheezing, breathlessness or nose irritation.

3.6.2.2 Lung function test

In the lung function test we measured forced vital capacity (FVC), forced expiratory volume in the first second (FEV1) and we calculated the ratio FEV1/FVC. We also carried reversibility of FEV1 and measured Peak expiratory flow (PEF) was also measured.

3.6.2.3 Bacterial and viral nucleic acid detection

A multiplex PCR was performed at the Department of Infectious Disease, University of Gothenburg, on the nasopharyngeal sections for detection of viruses and bacteria. In the PCR, a sample was considered to be positive if the cycle threshold (Ct)-value was lower than 35, whereas Ct<30 denoted high amounts of nucleic acids. *S. pneumoniae* was identified by detection of the pneumococcal autolysin *lytA* gene or the pneumococcal capsule *cpsA* gene (130).

3.6.2.4 Serotyping of S. pneumoniae

Another multiplex real-time PCR capable of detecting 40 different serotypes or serogroups in addition to the *cpsA* gene was performed according to a previously published protocol by the Center for Disease Control and Prevention (CDC), Atlanta, Georgia, US with slight modifications (130).

3.6.3 Paper IV

In this paper, we measured real-time particulate matter ($PM_{2.5}$) using optical devices (PATS+) and calculated 24-hour mean concentration.

3.7 Ethical issues

Ethical approvals were obtained from the Institutional Review Board of the College of Health Sciences of Addis Ababa University (for all papers), the National Research Ethics Review Committee (NRERC, 3.10/168/2016), Ministry of Science and Technology, Ethiopia (for papers I-III) and the Regional Ethics Committee in Gothenburg, Sweden (D-nr 115-17) (for paper III). Permissions to conduct the research were secured from respective organizations at both settings. All mothers were asked to give informed consent whereas confidentiality and anonymity were kept throughout the study. All the photos used in this thesis, including the cover page, were used with permission from respective persons.

4. Results

4.1. Overview

The residences of the participants in paper I and IV were in rural settings except for the two key informants, whereas in the other papers it was nearly an equal distribution between urban and rural settings. Overall, the educational status of the mothers was found to be low in all study parts with more than two-thirds of the mothers, either only attended elementary school or did not have schooling at all. Accordingly, the occupation of the mothers was mainly home making while there were some employees in the urban settings and rural mothers involved in farming and selling commodities in local markets. Family size ranged from three to eleven in some rural households with an overall average of five persons. The use of solid fuel was the only option for the rural inhabitants while nearly 30% of the urban dwellers used a cleaner energy source, mainly electricity. Data were available regarding the type of ventilation in the cooking area for papers II and III and the options were either having a permanent hole in the cooking area or only a door or one additional window for ventilation. In the qualitative discussion (paper I) it was described that opening the available window was not common during cooking and doors were also kept closed at night time.

Table 2: Background characteristics

Parameters	Paper I N (%)	Paper II N (%)	Paper III N (%)	Paper IV N (%)
Participants	FGD=69+KI=2	545	168M +175C	147
Mean age (Range)	43 (30-65)	30 (19-49)	M: 31 (19-49) C: 10 (9-11)[a]	33 (21-52)
Residence				
Rural	69 (100)	279 (51)	M:83 (49) C: 88 (50)	147 (100)
Urban	2 (KI)	266 (49)	M: 85 (50) C:87 (50)	0
Education level attended (Mother)				
No education	24 (35)	171 (31)	45 (27)	56 (38)
Primary	43 (62)	215 (39)	62 (37)	77 (52)
High school	2 (3)	102 (19)	35 (22)	14 (10)
College and above	2 (KI)	57 (11)	26 (16)	0
Employment (Mothers)				
Employed	2 (KI)	49 (9)	18 (11)	0
Homemaker	37 (54)	350 (64)	107 (64)	100(68)
Merchant	0	36 (7)	13 (8)	17 (12)
Farmer	32 (46)		30 (18)	30 (20)
Household size				
Five or less	3 to 11	382 (70)	126 (75)	54 (37)
Six and above	(mean=7)	163 (30)	42 (25)	93 (63)
Fuel types used				
Solid fuel	69(100)	392 (71.9)	121 (69)	147 (100)
Cleaner energy	2 (KI)	153 (28.1)	54 (31)	0

M= Mothers C= Children[a] = Age in monthsFGD= Focus group discussion KI=Key informant

4.2. Socio-cultural conditions related to cooking (Paper I)

The qualitative exploration of the perception and related socio-cultural conditions regarding cooking food revealed the following main findings.

The households in the rural area used wood as a main and sustainable type of fuel while crop residues, straws and dung were used in dry seasons. Though there were some households using local available improved cooking stoves (Figure 4) provided by a Non-Governmental Organization, traditional stoves were commonly used. Cooking inside the living houses i.e in the center of the house, where the pet animals cohabit is an old tradition for the community.

Figure 4: Types of stoves used by households in rural Butajira (Taken by a data collector (2019))

The practices continue because of different reasons perceived by the community as explained by the participants in the focus group discussions. These included reasons linked with economical incapability, lack of awareness on the related consequences, types of food not suitable to cook outside and lack of alternatives fuel options. Other aspects mentioned were safety issues because of fire hazard if cooked outside and local believed myths that cooking and eating outside could lead to acquiring diseases. Lack of adequate ventilation options like windows and openings were also associated with reduced risks for potential thief entrance during night time and when no one was around the home.

Culturally, there were also beliefs that the smoke from burning wood has beneficial effects for the inhabitants and the house itself. All participants agreed the smoke is useful to refresh the smell of the house in the morning from animal smells and other suffocations. They perceived that insects cannot stay inside the house with smoke, thus, they used it for controlling vectors of humans and animals. In addition to heating the living room, burning wood inside the room was also believed to strengthen the house and to give good health for a postpartum mother and the newborn.

The participants' perceptions on the health risks of cooking inside the living house were also explored during the discussions. Accordingly, different types of respiratory diseases, problems on eyes, burning accidents and effects on aesthetic values due to sweating and smell from the smoke were mentioned. Meanwhile, deforestation or using own land for growing trees for future use were indicated as problems. While cutting the forest caused land degradation and lack of soil productivity, the use of crop land for planting trees also affected their own and neighboring farmers land fertility and lead to conflicts.

The community's attitude towards adoption of the locally available improved cooking stoves was identified to be different among the groups based on the responses from the participants. The advantages of improved cooking stoves on fuel efficiency, shorter duration of cooking and lessening the effects of nose and eye irritation emphasized by those with the intention of favoring adoption. On the other hands, existence of computing needs and lack of health awareness and commitment were raised as obstacles by the laggards. As interventions, using public education, offering loans and delivering the improved cooking stoves to sell during the harvesting seasons were suggested as solutions to bring changes in the future.

4.3 Respiratory symptoms and potential pathogens (Papers II and III)

4.3.1 Respiratory symptoms and potential pathogens by fuel and ventilation types

Cross tabulation of the respiratory symptoms by the fuel types used and available ventilation showed significantly higher prevalence of cough, irritation at nose and eyes of the mothers using solid fuel with only a door when compared with those using cleaner energy and with a permanent opening for ventilation in the cooking place. The presence of one of the respiratory symptoms (i.e. cough, phlegm, wheeze, breathlessness, and/or nose irritation) was higher in the same type of fuel and ventilation options. Significantly higher prevalence of the potentially pathogenic bacteria, *S. pneumoniae and H. influenzae*, was seen among groups using solid fuels compared with those using cleaner energy. Around three-quarters of the children had a positive PCR result for both of these bacteria whereas the prevalence was around one-third among the mothers.

Table 3: Prevalence of respiratory symptoms and potential respiratory pathogens by fuel use and ventilation types

Parameters	**Fuel types N (%)**		**Ventilation types N (%)**		
	Solid fuel	Cleaner energy	Only door	Window	Permanent opening
Respiratory symptoms among mothers (N=545)					
	N=392	N=153	N=348	N=104	N=93
Cough	94 (24)*	22 (14)*	79 (23)*	27 (26)*	10 (11)*
Phlegm	46 (18)	10 (7)	36 (10)	14 (14)	6 (7)
Wheeze	21 (5)	6 (4)	20 (6)	5 (5)	2 (2)
Breathlessness	38 (10)	17 (31)	33 (10)	12 (12)	10 (11)
Nose irritation	131 (33)**	14 (9)**	100 (29)*	32 (31)*	13(14)*
At least one symptom	185 (47)**	43 (28)**	132 (38)*	37 (37)*	17 (18)*
Eye Irritation	161 (41)**	25 (16)**	152 (44)*	49 (47)*	27 (29)*
Detection of respiratory pathogens among mothers (N=168)					
S. pneumoniae	48 (41)**	12 (23)**	45 (38)	5 (30)	10 (32)
H. influenzae	37 (32)**	6 (12)**	32 (27)	4 (24)	7 (23)
At least one bacterial species	58 (50)*	16 (31)*	54 (45)	8 (47)	12 (39)
Rhinovirus	22 (19)	9 (17)	21 (18)	2 (12)	8 (26)
Enterovirus	12 (10)	5 (10)	10 (8)	2 (12)	5 (16)
At least one virus	32 (28)	14 (27)	32 (28)	4 (24)	10 (32)
Detection of potential respiratory pathogens among children (N=175)					
S. pneumoniae	98 (81)**	26 (48)**	95 (76)	12 (67)	17 (53)
H. influenzae	86 (71)**	13 (24)**	77 (62)	9 (50)	13 (41)
At least one bacterial species	104 (86)**	29 (54)**	99 (79)	14 (79)	20 (63)
Rhinovirus	57 (47)	18 (33)	53 (42)	6 (33)	16 (50)
Enterovirus	29 (24)	6 (11)	26 (21)	1 (6)	8 (25)
At least one virus	69 (57)	24 (44)	68 (54)	9 (50)	16 (50)

** Significant at significance level of 0.05 ** Significant at significance level of 0.01*

4.3.2 Respiratory symptoms by place of residence

Overall, there were higher numbers of mothers with respiratory symptoms in the rural settlements compared with those living in the urban setting. A higher prevalence of all the respiratory symptoms, except breathlessness, which was nearly the same, was observed among the women living in the rural area compared with the urban groups (Figure 5)

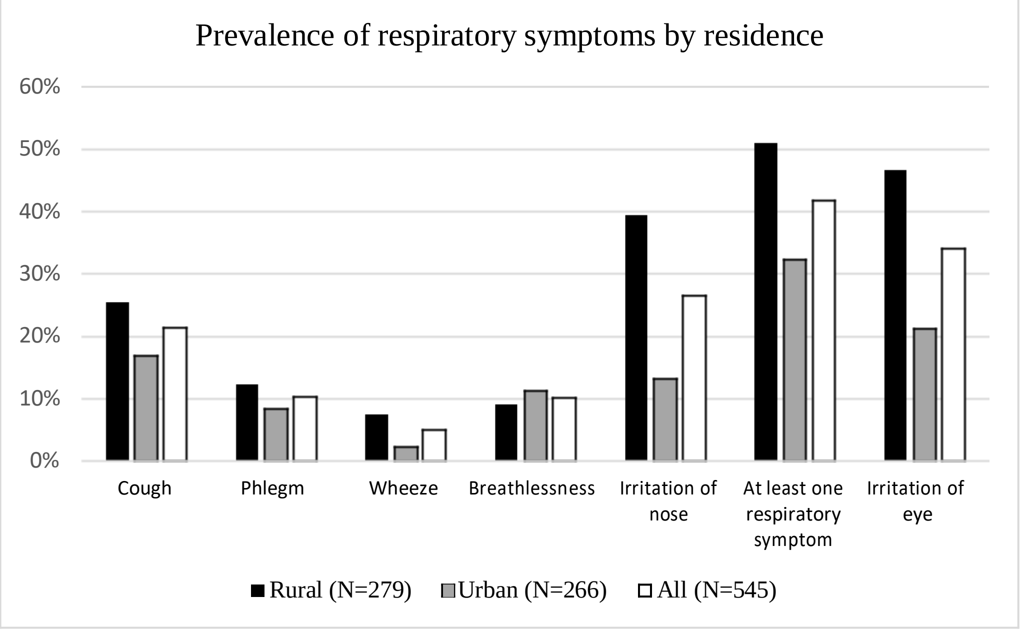


Figure 5: Respiratory symptoms by place of residence

4.3.3 Factors associated with the airways health of children and mothers

The factors associated with the detection of *S. pneumoniae* among the children and at least one respiratory symptom among the mothers are presented in Table 4. There was a significantly higher occurrence of any of the respiratory symptoms (either cough, phlegm, wheeze, breathlessness or nose irritation) for the mothers from the households cooking inside the living house using solid fuel compared with cleaner energy users. The odds being nearly double (OR 1.89; 95% CI 1.11–3.24) after adjusting for age, residence, ventilation and second hand smoke. Similarly, the prevalence of *S. pneumoniae* was higher in the children of rural households using solid fuel with over four times higher odds compared with children form households using cleaner energy. Maternal education below high school level also showed significantly higher odds of detection of *S. pneumoniae* from their children compared with children whose mothers completed high school and above.

Table 4: Association of variables with occurrence of pneumonia detection and respiratory symptoms among children and mothers, respectively.

Parameter	***S.pneumoniae*** **N (%)**	**AOR (95% CI)**	***p*-value**	**Parameter**	**Any respiratory symptom N (%)**	**AOR**	***p*-value**
Fuel type by residence				**Fuel type and cooking place**			
Solid fuel rural	80/88 (91)	4.39 (1.38-13.92)	0.012	Solid fuel inside the living house	161/474 (51)	1.89 (1.11-3.24)	0.019
Solid fuel urban	18/33 (55)	0.86 (0.33-2.26)	0.76	Solid fuel in separated kitchen	24/103 (30)	0.83 (0.42-1.67)	0.612
Cleaner energy rural	26/54 (48)	1		Cleaner energy (both places)	43/196 (28)	1	
Mothers educational status				**Area (Place of residence)**			
Below high school	98/115 (85)	4.17 (1.72-10.11)	0.002	Urban	86/352 (32.3)	0.65 (0.40–1.07)	0.091
High school and above	26/60 (43)	1		Rural	142/421(50.9)	1	

4.3.4 Pneumococcal serotype distribution

Serotype identification was carried out among samples from 136 children and 105 mothers, who were positive for *S. pneumoniae* by PCR. Accordingly, 60 pneumococcal serotypes/serogroups could be detected directly in the nasopharyngeal secretion from 48 children and 36 serotypes/serogroups could be identified in 34 mothers. Out of all identified serotypes/groups, 26 (43%) in the children and 16 (44%) in the mothers were serotypes or groups included in PCV13.

4.3.5 Lung function

Acceptable spirometry test results with at least three good manoeuvres were obtained from 231 (42%) women. The test results in Table 5 show that 28 (12%) and 57 (24%) women had FVC and FEV1 percent predicted below 80%, respectively. There was statistically significant lower FVC, FEV1 and FEV1 percent predicted among women from rural areas when compared with urban groups.

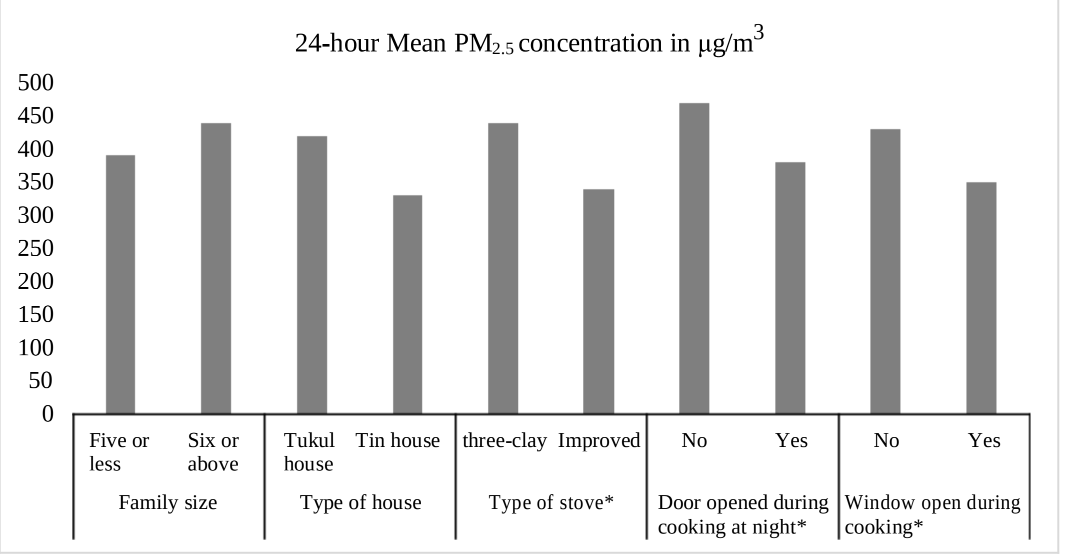
Table 5: Lung function test results by residence and fuel type used

Pre bronchodilator Mean (SD)	**Urban (n=126)**	**Rural (n=105)**	**Clean energy (n=73)**	**Solid fuel (n=158)**
FVC, L	3.17 (0.4)	3.05 (0.43)	3.20 (0.44)	3.08 (0.41)
FVC % predicted	94.03 (10.7)	91.84 (10.5)	94.21 (11.1)	92.49 (10.5)
FEV1, L	2.62 (0.4)	2.49 (0.39)	2.64 (0.42)	2.53 (0.37)
FEV1 % predicted	89.47 (11.0)	86.42 (11.1)	89.63 (11.2)	87.37 (11.2)
FEV1/FVC	0.83 (0.05)	0.81 (0.06)	0.83 (0.06)	0.82 (0.05)
PEF (L/min)	6.45 (1.40)	6.34 (1.49)	6.39 (1.43)	6.41 (1.45)
Post bronchodilator	**n=110**	**n=87**	**n=62**	**n=135**
FVC, L	3.14 (0.48)	3.09 (0.44)	3.20 (0.57)	3.08 (0.41)
FEV1, L	2.68 (0.41)	2.63 (0.37)	2.73 (0.45)	2.63 (0.35)
FEV1 reversibility (%)	2.85 (5.24)	4.46 (7.31)	2.52 (5.86)	4.04 (6.42)
FEV1/FVC	0.86 (0.05)	0.85 (0.05)	0.85 (0.04)	0.85 (0.04)
PEF (L/min)	6.56 (1.72)	6.93 (1.25)	6.62 (1.63)	6.76 (1.50)

FVC: forced vital capacity, FEV1: forced expiratory flow in 1 second, PEF: peak expiratory flow SD: Standard deviation

4.4 Level of fine particular matter in rural house-holds (Paper IV)

Measurement of 24-hour mean concentration of fine particulate matter ($PM_{2.5}$) showed very high levels of pollution, 410 μg/m^3, in the rural households. The concentration was attributed to the sole use of wood as the primary fuel with crop residues, dung and straws as secondary fuel options during the dry seasons. The mean concentration measurement was significantly higher in the households where traditional stoves were used and windows and doors not opened during cooking compared with their counterparts. The result also showed correlation with the duration of cooking; concentration increasing with increased duration of cooking.



** Significant at significance level of 0.05*

Figure 6: Mean $PM_{2.5}$ concentration in relation to housing and cooking conditions

$PM_{2.5}$ measurement in relation to duration of cooking

The graphs (Figure 7) of 24-hour $PM_{2.5}$ monitoring showed the smoke stayed longer than the duration of cooking, which extends the time of exposure. For example, in the Figure below the cooking started at 10:40 pm and ended around 11:20 PM, however, the smoke was available until 1:03 am after mid-night.

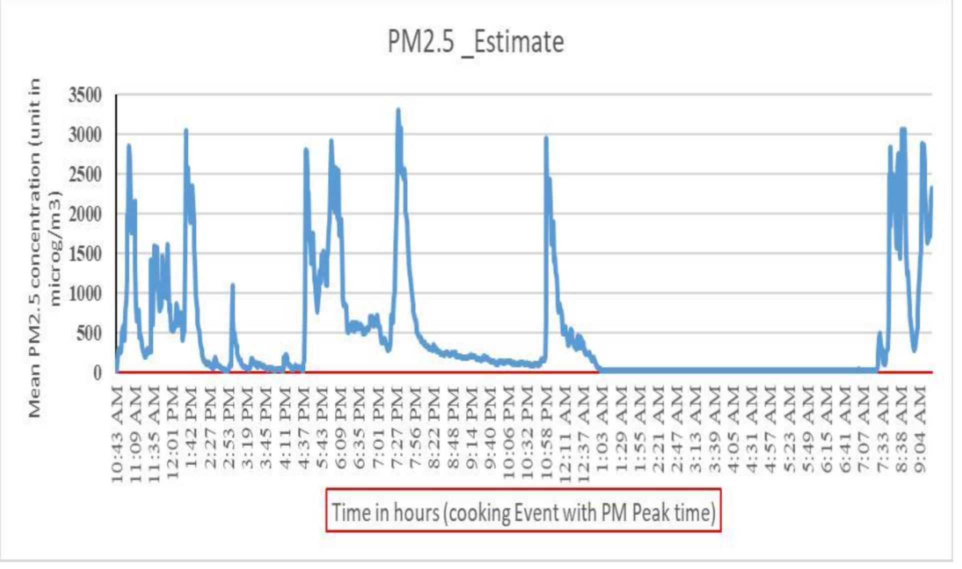


Figure 7: Sample 24-hour $PM_{2.5}$ measurement with cooking events

5. Discussion

5.1. Discussion of the main findings

5.1.1. Paper I

In the qualitative exploration, cultural and economic reasons for the use of solid fuel and traditional stoves were analyzed. The use of solid fuel as the only fuel alternative is not unique for the area as all other rural communities in Ethiopia as well as other low-income countries rely on it (131-133). However, the issue of cooking inside the living and sleeping house, where the cattle and other pet animals cohabit are unique for the community in our study and in major parts of Ethiopia when compared with other countries.

Participants of our study mentioned the low economic status of the community, and lack of awareness of the health effects for the lack of adoption of locally available cooking stoves. Similarly, other studies from northern Ethiopia found user knowledge and financial factors as reasons for lower adoption of improved stoves (134, 135). It is true that income plays a role in investing for such commodities, however, lack of commitment and tendencies to maintain social status were reflected as barriers on top of the economic reasons. The justification given for lack of commitment was that at least one mobile phone was available in the majority of households in the community. This might indicate a tradeoff between investing for health and other needs. Inconsistent to this is a study from Kenya showing a high interest and willingness to invest in and purchasing improved cooking stoves (136).

Not only low awareness and the economic incapability to afford but also the perception of the community about the benefits of smoke and cultural values favored the continuation of the problem. In this community, it was believed that burning inside the house can increase the life span of the house, and is of importance for the good health of a postpartum mother and the newborn and prevents odor and the entrance of insects. Even though previous studies have identified culture as a determinant in the household energy choice (137), the belief surrounding the importance of wood smoke for the health of the postpartum mother and the newborn are unique for this community. It is also against the scientific evidence indicating the health risks of solid fuel use for the health of mothers and their children (138-140). To this end, a shortage of fire wood and the use of farm land to plant trees for future use could be used as an opportunity to shift to cleaner energy use.

In addition to the health impacts, there were other socio-economic and environmental effects associated with the use of wood burning for cooking food. Similar to previous findings (113, 114), the responsibility of cooking and firewood collection was given for the mothers and their daughters in the community. The time spent for cooking and fuel collection obviously affected their engagement in other socio-economic activities including school attendance. This was supported by the low educational status of participants in our quantitative studies (Paper II-IV). Cutting forest trees and bush for burning also lead to surface erosion, which in turn, as they perceived, decreased soil fertility and crop yield in the area. There is evidence indicating the contribution of deforestation to problems in the environment and soil degradation by which highland ecosystems of Ethiopia have already been affected (141).

5.1.2. Paper II and III

There was a significantly higher occurrence of respiratory symptoms among women cooking inside the living house using solid fuels compared with those using cleaner energy. The odds of developing one of the respiratory symptoms were twice as high for them compared with their counterparts. Other studies from Africa (102, 142) and other low- and middle-income countries of the world (104, 143-145) also reported higher prevalence of respiratory symptoms among women using solid fuel. It is important to note that the proportion of the women with respiratory symptoms in this study was even higher than in the others studies.

Given the housing conditions in the area and lack of adequate ventilation, the irritation of the nose and eyes were daily sufferings for the inhabitants. Both the qualitative and quantitative findings in our study indicated the problems were common for all mothers. In fact, this problem could also affect the rest of the family members as cooking at night time when all stayed at home and doors and windows were closed.

Although occurrence of COPD is more common among smokers (146, 147) and after the age of 40 (147-149), which is above the mean age of participants of this study, spirometry test results with lower FEV1 among solid fuel users indicate future risks. None of the participants in this study was ever a smoker and their mean age also was lower (30 years). This may indicate the non-smoking women in low-income countries like Ethiopia might face the problem because of solid fuel use. Previous systematic reviews (150-152) and follow up studies (153, 154) also consistently reported the association between using solid fuel and occurrence of COPD.

The prevalence of *S. pneumoniae and H. influenzae* in the nasopharynx were significantly higher among mothers and children in households using solid fuel compared with those from households using cleaner energy. Children from households using solid fuel and those who had mothers with education below high school had four times higher odds to have *S. pneumoniae* compared with cleaner fuel users and those with mothers who had attended high school or higher education. Other studies also reported association between fuel use and carriage of *S. pneumoniae* among children (155, 156). Similarly, lower maternal education showed higher carriage of *S. pneumoniae* or other respiratory pathogens in previous studies (157).

5.1.3. Paper IV

Our measurement of 24-hour mean concentration of $PM_{2.5}$ showed very high levels in the rural households in Butajira. All the enrolled 147 households in the study had mean levels above the recommended 24-hour mean concentration of 25 $\mu g/m^3$ for $PM_{2.5}$ by the WHO (33). The lowest measure, 100 $\mu g/m^3$, was four times higher than the recommendation whereas the highest measure of 1200 $\mu g/m^3$ was almost 50 times higher. Other researchers have also reported high levels of HAP in low- and middle-income countries. Our findings were higher than 24-hour mean values from previous study in Ethiopia and Uganda (158). However, there were also others reporting even higher levels of 24-hour mean concentration of $PM_{2.5}$ from solid fuel use in some African countries (159, 160). It is important to note that the type of instruments used for the measurement can cause variations in the level of $PM_{2.5}$. Evidence indicates the optical devices can exaggerate the mean concentration compared to gravimetric ones (158).

The predominant use of traditional stoves, which are three leg clay, in the rural area contributed to the higher level of emission of $PM_{2.5}$ in line with previous studies (161). Based on the qualitative finding, it was evident that even those who had locally made improved stoves were using the traditional stoves for cooking some types of foods and for coffee preparation. The perception of the community regarding the use of wood smoke to prevent insects from entering the house, avoid unpleasant odor from animals’ scat and strengthen the house also lead them to burn the fire when there was no cooking. Such perception could be viewed as unique for this community, though there were studies showing lack of sustained or exclusive use of improved stoves in previous studies like in Malawi (162), Rwanda (163) and China (164) for other barriers.

The high level of $PM_{2.5}$ could be attributed to the types of ventilation and other environmental factors in the study areas (165, 166). It is obvious the living context of the rural community in this study and lack of adequate means of ventilation might also contribute. Having the animals in the living room aggravates the already crowded condition because of the tradition of constructing tukul houses in a circle with one door and window. Obviously, availability of adequate ventilation and opening the doors and windows during cooking were reported to have effects on the wind flow and room ventilation (167, 168). In fact, having good ventilation in the living houses could have double advantages of reducing the risk of acquiring respiratory diseases as identified by previous studies (169).

Having such a high level of mean concentration of the $PM_{2.5}$, might increase the health risk of the population in Ethiopia and may need attention given the housing condition and the socio-economic factors of the country. There is evidence indicating that the level of income, education, nutrition and food security affect the general human health status and occurrence of chronic health problems (170). Addressing the health risks from HAP might contribute to reducing high morbidities and mortalities.

This study involved the measurement of $PM_{2.5}$ both in dry and rainy seasons. Lack of statistically significant differences between the seasons could lead to two possible implications. The first one might be the use of dung and crop residues during the dry seasons as indicated in the qualitative findings. Such fuels are inefficient and found at the bottom level in the energy ladder as they are the biggest polluters even higher than burning wood (171) thus may result in high pollution in the dry season. Secondly, the rural community in the area, especially the mothers and children, are at higher impaired health risks throughout the year though this need to be confirmed by follow up studies.

5.2 General remarks

The respiratory health and other effects from solid fuel use are of high importance in Ethiopia. Over 80% of the total population of Ethiopia live in rural settings with solid fuel as the only energy source. In addition, more than half the total population are females facing the same problem especially in rural settings. As far as HAP is linked with many health problems, there should be collaborative interventions between the health and energy sectors to protect of the health of public and reduce the overall disease burden.

The construction of hydroelectric dams including the Grand Ethiopian Renaissance Dam (GERD) (172, 173) may alleviate the problem. However, the time until the electricity becomes the main source of energy for cooking purposes at national level may be long as biomass accounts for 98% of the residential power supply in the country (174). In addition, there are other developmental sectors and the industrial boom, which needs much electric power. The high proportion of the population using solid fuel for cooking while they are connected to the national electric grid in small towns is a good example for the insufficient electric power for other services (44). In addition to inadequacy for the manufacturing companies the cost of electricity is also another concern (175). A prediction of the fuel options in the country for the year 2030 also indicates that only 15% of the urban and 6% of the rural population were estimated to have access of electricity for cooking purposes (174).

Therefore, exploring sustainable use of other existing resources could be one of the alternatives to mitigate health related and other effects of solid fuel use in the low income countries. There are existing strategic suggestions and previous attempts of other bioenergy generation from wood than direct burning (176, 177). Being in the tropical region near the equator, not using solar energy as a primary energy source is another missed opportunity to provide cleaner energy to the nation (178). In addition to health advantages, if managed properly and applied on a large scale, the use of renewable energy source for example solar energy could have other socio-economic benefits (179) including agricultural production (180).

5.3. Strengths and limitations of the study

To my knowledge, this is the first study, to assess the association of solid fuel use with respiratory symptoms, lung function, and the occurrence of bacteria and viruses in the nasopharynx of women and children in Ethiopia. We also measured the 24-hour mean concentration of $PM_{2.5}$ in both rainy and dry seasons. Our findings from the qualitative study also added value for future interventions to consider the socio-cultural reasons and community perceptions regarding cooking inside the living house and use of traditional stoves. Measurement of lung function using spirometry and reversibility testing at community level for the first time will avail baseline data as for future use.

As limitations, the research project involved cross-sectional studies, thus, cannot show the cause and effect relationship. Above half of the women could not properly perform three acceptable manoeuvres because of lack of previous exposure, some were afraid of the procedure even after getting adequate information and clarification. Our measurement used an optical measurement device without using gravimetric validation. However, a previous comparison study using optical and gravimetric devices found the measurements were in agreement except an overestimation of the exposure by the optical devices (158). In addition, we followed a standard procedure of measurement for all households and PATS+ laboratory normalization and calibration by the company was done with wood smoke (181).

6. Conclusions

This thesis used both qualitative and quantitative studies to explore the socio-cultural reasons for the use of solid fuel and traditional stoves to cook food mainly inside the living house and to assess its association to the airway health. Accordingly, the following main findings were identified:

- Solid fuel use was the only fuel source for the rural community of Butajira.
- Culturally, the community viewed wood smoke beneficial to strengthen the house, control vectors and keep good health of the postpartum mother and the newborn.
- In spite of the perception about the negative health effects of wood smoke and sufferings of cooking mothers by irritation of the nose and eyes, the use of locally available improved cooking stoves was traded off against other competing interests and cultural and economic problems.
- Shortage of forest wood, which forces the community to use farmland for planting firewood trees for future use was a missed opportunity to shift to bioenergy and solar energy at the community level.
- Compared with the WHO 24-hour guideline limit of 25 $\mu g/m^3$, the 24-hour mean concentration of $PM_{2.5}$, 410 µg/m3, in this study was unacceptably high.
- Use of solid fuel was found to be associated with a higher prevalence of potential respiratory pathogens among mothers and children.
- Higher prevalence of respiratory symptoms and reduced lung function was found among solid fuel users compared with those using cleaner energy.

Based on these results, we can conclude that multiple health risks were there for the mothers and children in Ethiopia. Community based interventions are demanded to prevent or at least to mitigate the effects by creating awareness on the risks and shifting the energy use sources.

7. Future Perspectives

The effects of solid fuel use on human health and other socio-economic and environmental aspects are important to be studied in Ethiopia and other low-income countries. Use of solid fuels, mainly wood, for cooking food and heating the living house is the only available energy source for the whole rural population in Ethiopia. This exposes the population, especially the women and children, to a higher risk of impaired health. The fire wood collection and cooking responsibility for the females also affects their engagement in other educational and developmental activities. Conducting short and long-term follow up interventional studies with application of appropriate modeling analysis is demanded.

While a lot of economic investment is needed for the development of a country, it is also crucial to invest in the health of the people. Understanding the determinants of human health is also critical to design and implement interventions. From this study and other research to date, enough evidence are available and shows the multiple health risks of HAP from using solid fuel use. Therefore, interventions to reduce the level of pollutants needs to be in place with short and long-term plans. Evaluating and using locally available improved cooking stoves, improving ventilation and giving health education to bring behavioral change from exposing postpartum mother and newborn need immediate actions. Meanwhile, it is mandatory to plan shifting the fuel options by investing in renewable energy sources from the already available resources like bioenergy and solar energies.

This thesis covered socio-cultural aspects, respiratory symptoms and lung function and microbiology all showing the existence of association with solid fuel use. There was also high levels of HAP measuring. Therefore, it is important to think from multidisciplinary point of view for future interventions targeting addressing the problem of HAP. In this regard, there has been a collaborative research team from Addis Ababa University in Ethiopia, and the University of Gothenburg, Chalmers University of Technology and Örebro University in Sweden. Our team also initiated collaboration with local and international organizations including FARM AFRICA, the Ministries of Energy, Health, Construction, and Urban Development and Housing. Departments and professionals from Architecture, Housing, Appropriate Construction Technology, Environmental Studies, Public Health, Atmosphere Science, Microbiology, Social Anthropology and Sociology, Economics; and Education and Behavioral Studies are included in the team to deal with the spatial, social, cultural, environmental, technical, medical and cost effectiveness aspects. We secured a small travel and workshop grant to write for additional grants and pilot small interventions focusing on the use of locally available improved cooking stoves, and design and construction of the living houses. Equally important in the planning of the interventions is understanding of the cultural and local contexts by involving the community.

The government could also play key roles in developing policies that will enable a shift to cleaner fuel use through economic interventions. Good examples may include freeing or lowering tax on stoves and fuels for the cleaner energy, provision of loans for the rural households and availing electricity supply. Meanwhile, maternal education should receive attention considering its positive association in this study and overall impact on women's' life.

Acknowledgements

I would like to thank the following people and those I forget to mention, for their help and support throughout this thesis work.

To my main supervisor Dr. Mona Lärstad and all co-supervisors Prof. Rune Andersson, Dr. Susann Skovbjerg, Dr. Adamu Addissie and Dr. Abera Kumie for the continuous guidance and feedback since the beginning to the end of this research project. I really appreciated your commitments and supports. I have learnt a lot from all of you and I look forward to work with you in the future!

To my lovely wife, Rihanna Amedala and our sons Hebron and Nathan for your patience and understanding during all the four busy years. You were all a source of energy and happiness on those tiresome days.

To all, those supported me with the laboratory works. Dr. Tamrat Abebe, Solomon Gizaw, Zelalem Desalegn and others from College of Health Sciences, Addis Ababa University and Dr. Rickard Nordén, Shadi Geravandi and Lucia Gonzales-Siles from Sahlgrenska Academy, University of Gothenburg.

To Dr. Mirgissa Kaba, Dr. Mitike Molla, Dr. Abera Kumie, Prof. Wakgari Deressa and Prof. Damen Hailemariam from the School of Public Health, to Dr. Eva Kantelhardt from the Martin-Luther-University Halle-Wittenberg and to Prof. Jan Hedner from the University of Gothenburg for supporting my travels to Sweden or other countries at different times and other supports related to my PhD studies.

To all my colleagues at the School of Public Health, Addis Ababa University for your encouragements and supports during my PhD studies. The co-operation of the team at Butajira Demographic Surveillance Site and the leaderships at the school made the field data collection possible.

To Prof. Johan Boman and Dr. Staffan Nilsson for their professional advice regarding measuring apparatuses and statistical analysis, respectively and Emma Husmark, Annika Claesson and Elin Berglund for involving in spirometry training for data collectors and assisting part of the field work.

To my friend Tayue Tateke, his wife Yemisrach Berhanu and adorable kids Hiyaw, Kidus and a new baby girl Betsina. Your presence and unlimited support has made my stay in Gothenburg easy and enjoyable. Tayue, you have an amazing personality.

To Judy Price for your support in proof reading all the manuscripts and this thesis work. Your commitment to help and your critical review has been amazing. Much respect!

To my parents, Tamire Awono and Amarech Wolde for nurturing me with positive words, trust and big dreams. You helped me to be assertive, hopeful in life and dare facing challenges.

To my parents-in-law, Haji Imam Amedala Ergudo and Amarech Beyene for all the supports for me. I am so lucky and happy to be part of this peaceful family. My heart was also broken because of the sudden death of my brother-in-law during finalizing this thesis write-up. Rest in Peace Eyoba!

Last but not least, I am thankful to all the field data collectors, drivers and study participants for their co-operation in different aspects.

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