Universidade de Aveiro Departamento de Ambiente e Ordenamento
2017

Diego Alexander Parra Sánchez

Air quality assessment in Patio Bonito, Colombia
Avaliação da qualidade do ar em Patio Bonito, Colômbia

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Dissertation presented to the University of Aveiro to fulfill the requisites required to obtain a master degree in Environmental Studies, carried out under the scientific guidance of professor Ana Isabel Couto Neto da Silva Miranda, full professor of the Department of Environment and Planning of the University of Aveiro.

I want to dedicate this work to God, to my grandparents who from heaven take care of me, to my mom and dad, relatives and friends in Colombia, without their support would not have been possible this adventure called “*Portugal*”.

Examination committe

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acknowledgement

I want to thank to God “the number one”, who gave me life, a beautiful family and his blessings. Thank you for being my best adventures companion. I also thank to my mom and my dad for all her love and support, to my relatives, friends, coworkers in Colombia, to my football buddies, to my thesis supervisor, my Portuguese professors and to all those angels who God put in my way. Thanks for believing in me, thanks for all your support, patience and affection.

“Whoever does not love does not know God, because God is love” (1 John 4:8).

“Whatever you do, work at it with all your heart, as working for the Lord, not for human masters” (Colossians 3:23).

palavras-chave

Emissões de fabrico de tijolos, matéria particulada, qualidade do ar, modelação.

resumo

O fabrico artesanal de tijolos gera um efeito direto sobre a qualidade do ar que afeta a saúde das comunidades vizinhas a este tipo de indústria. No município de Nemocón, no distrito rural Patio Bonito, na Colômbia, a grande maioria das pequenas empresas que fabricam tijolos utilizam técnicas artesanais. As infraestruturas são basicamente representadas por um forno e uma parcela de terra denominada "Chircal". Os trabalhadores geralmente usam fornos de fogo direto abastecidos com carvão, maioritariamente gás natural e diesel.

O presente trabalho tem como objetivo caracterizar a qualidade do ar, tendo em consideração o crescimento maciço da atividade de fabrico de tijolos no distrito rural de Patio Bonito, Nemocón, Colômbia, avaliando especificamente a matéria particulada PM10, que é um dos poluentes mais críticos devido ao seu impacto na saúde dos habitantes e no ambiente local. Para este estudo, foi analisado o ano de 2013, que apresentou as maiores concentrações de PM10 dos últimos cinco anos, de acordo com dados históricos da autoridade ambiental da região Cundinamarca, Colômbia. Para avaliar a qualidade do ar no Patio Bonito, aplicou-se uma metodologia de modelação da qualidade do ar recorrendo ao modelo Gaussiano URBAIR, desenvolvido pela Universidade de Aveiro. Para uma simulação adequada, foi necessário compilar dados de entrada como fontes de emissão e dados meteorológicos. O exercicio correspondeu aos períodos de 8 de agosto, 20 e 24 de novembro de 2013, com altas concentrações médias diárias de PM10, acima de 100 µg /m^3, limite regulado pela legislação Colombiana.

Como possíveis medidas de melhoria, foram propostos dois cenários que se avaliaram recorrendo ao modelo URBAIR. O primeiro cenário implicou a substituição de fornos “*Fuego dormido*” por um forno tipo túnel, devido às suas menores emissões de PM10. O segundo cenário, considerou a operação dos fornos Colmena com um sistema de controlo de emissões (ciclone). Os resultados permitiram concluir que as opções de melhoria representam uma redução significativa de PM10 até 44.3%.

keywords

Emissions from brick manufacturing, particulate matter, air quality, modeling.

abstract

The manufacturing brick generates a direct effect in the air quality affecting the health of the surrounding communities of this type of industry. In the Colombian municipality of Nemocón, in the Patio Bonito rural locality, the majority of small and micro-sized brick fields uses craft techniques for manufacturing different types of bricks. The manufacturing plant is basically represented by a kiln and a plot of land as a farmyard; the area where these elements are concentrated is commonly named “Chircal”. Craft brickers usually use kilns of direct fire and upward firing for cooking. The main fuel used in the manufacture of bricks is coal, followed by natural gas and diesel.

The present work aims to characterize air quality, taking into account the massive growth of the brick manufacturing activity in the rural locality of Patio Bonito, Nemocón, Colombia, specifically assessing the particulate matter PM10, which is one of the most critical air pollutant due to its impact on health of its inhabitants and on the local environment. The year 2013 was selected for the analysis, because the highest PM10 concentrations of the last five years that happened in that year, according to historical data from the environmental authority of Cundinamarca region.

For assessing the air quality in Patio Bonito, a Gaussian air quality model named URBAIR, developed by the University of Aveiro, was applied. For an adequate operation of this model, it was necessary to collect input data as emission sources and meteorological data. The modeling periods were August 8th, November 20th and 24th 2013, when daily averaged with concentrations above 100 µg/m^3, limit regulated by Colombian legislation were registered.

Moreover, two improvement scenarios were proposed. The first implied replacing all the “Fuego dormido” kilns by one Tunnel kiln, because it showed the lowest PM10 emissions. The second considered the operation of “Colmena” kilns with an emission control system. Results allowed to conclude that those improvement measures can reduce the PM10 contribution to air pollution levels.

TABLE OF CONTENTS

List of figures

List of tables

Notations

List of abbreviations

ACP	Atmospheric Contingency Plan
APA	Agência Portuguesa do Ambiente
API	Air Pollution Index
APM	Airborne Particulate Matter
AQI	Air Quality Index
BTK	Bulls Trench Kiln
CA	Cluster Analysis
CAEM	Corporación Ambiental Empresarial
CAR	Corporación Autónoma Regional de Cundinamarca
CCDRC	Comissão de Coordenação e Desenvolvimento Regional do Centro
DANE	Departamento Nacional de Estadística
FCBTK	Fixed Chimney Bull Trench Brick Kilns
GIS	Geographical Information System
HACA	Hierarchical Agglomerative Cluster Analysis
ICAR	Colombian Air Quality Index
IDEAM	Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia
ISC3	Industrial Source Complex
ISCST	Industrial Source Complex-Short Term
MCA	Multicriteria Analysis
NAAQS	National Ambient Air Quality Standards
NOx	Nitrogen Oxides
PM	Particulate Matter
PM2.5	Particulate matter with an aerodynamic equivalent diameter smaller than 2.5 microns.
PM10	Particulate matter with an aerodynamic equivalent diameter smaller than 10 microns.

PMF	Positive Matrix Factorization Model
SDA	Secretaria Distrital de Ambiente de Bogotá
SISAIRE	Subsistema de Información de la Calidad del Aire
SOx	Sulfur Oxides
TSP	Total suspended particles
USEPA	Environmental Protection Agency of the United States
VSBK	Vertical Shaft Brick Kilns
WMO	World Meteorological Organization
WHEP	Wuhan Environmental Protection Agency

List of variables

BpHi	Break-point of the concentration at the upper limit of the ICAR category
BpLo	Break point of the concentration at the lower limit of the ICAR category
Cp	Concentration measurement for pollutant p
IHI	Value of the index at the upper limit of the ICAR category
ILo	Value of the index at the lower limit of the ICAR category
Ip	Index for pollutant p
roar	Ambient air density
Cpar	Ambient air heat capacity
Cpas	Ambient dry air heat capacity
Pa	Atmospheric pressure in Pascal unit
Zi	Mixing layer height
hr1	Relative humidity at 2 m
Clas	Stability class
rad	Solar radiation
ta1	Temperature at 2 m
dv1	Wind direction at 10 m
vv1	Wind speed at 10 m

Chemical compounds

CO	Carbon monoxide
CO_2	Carbon dioxide
HCl	Hydrochloric acid
HF	Hydrofluoric acid
NO_2	Nitrogen dioxide
O_3	Ozone
SO_2	Sulfur dioxide

1. INTRODUCTION

The air pollution is defined as the presence in the atmosphere of substances in such amounts that affect humans, vegetation, animals, or material adversely (Li *et al*., 2012). Large scale burning of fuels to supply energy to industries, households and means of transportation is the main cause of air pollution. Li *et al*., (2012) estimated that almost 90% of the air pollution are related with the combustion of fuel. An important air pollution source is the world brick manufacturing activity, which is responsible for an significant contribution of toxic fumes, containing particulate matter (PM) and high concentration of carbon monoxide (CO) and sulfur oxides (SOx), that are harmful to eyes, lungs and throat (Vijay & Menon, 2011).

The global brick production is estimated in 1500 billion bricks per year (Schmidt, 2013). China is the top producer with 1000 billion of units per year (67%). In China, bricks are mainly used as the material to construct walls but they are also used for the construction of pavements, canals, drains, roofs, etc. In India, the second global producer of bricks with 200 billion of units per year (10% of the global brick production), the majority of current brick production is made in artisanal kilns, which are important fixed emission sources (Bhat, Afeefa, Ashok, & Bashir, 2014).

The brick manufacturing in Colombia includes a large number of small kilns known as "Fuego dormido", which do not have emissions control systems neither suitable designs for an optimal combustion. In addition, this type of kilns does not comply the emission limit values and affect the air quality.78% of companies in the mining sector, including brickworks, do not have environmental licenses or do not comply with environmental management plans (Silva & Valencia, 2013). The municipality of Nemocón, rural locality of Patio Bonito, is one example of an area strongly affected by Fuego dormido emissions to the atmosphere. Likewise, according to data of 2013 by Ministry of mines and energy.

The rural locality of Patio Bonito is an industrial corridor known in the region of Cundinamarca, in which almost 80% of the brick demand for the Bogotá D.C and the region is produced (Rodriguez & Piñeros, 2011). The manufacture of these bricks, in most cases, is done in a rudimentary way, using artisan kilns like Fuego dormido. The environmental impact is continuous and has lasted approximately 40 years with this activity. Medium and big brickworks, which have other types of kilns like Hoffman and Colmena kilns, are also installed in the rural locality. Nowadays, they are involved in a process of technological restructuring in order to comply the national emission limits and to improve the air quality.

The present work aims to assess the air quality in Patio Bonito, Nemocón, Cundinamarca, Colombia, for the base year 2013, taking into account a previous characterization of different emission sources and local meteorological conditions (Sánchez, 2016). Criteria pollutant, such as particulate matter with an aerodynamic equivalent diameter smaller than 10 µm (PM10) is addressed, because it is one of the pollutants that Colombia has categorized as more important within its current environmental legislation. A modeling approach to simulate PM10 levels in Patio Bonito, for 2013 selected episodes and for emissions mitigation scenarios was developed and applied allowing to better understand PM10 levels and the brick manufacturing contribution to particulate pollution.

This document is organized as follows. Chapter 2 describes important aspects related to brick manufacturing emissions around the world. It includes cases related to brick kiln emissions and to their impacts on the air quality of different countries that have a significant brick production activity.

Chapter 3 presents the characterization of the municipality of Nemocón and the rural locality Patio Bonito, taking into account local emission sources, climatology and the air quality state. A description of the main emission sources in Nemocón and Patio Bonito is done as well as a calculation of their contribution to PM10 emitted levels. Road traffic emissions are also compared with emissions from the brick kilns.

Chapter 4 is focused on air quality modeling. It presents a description of the Gaussian air quality model URBAIR, its different input and output variables, including meteorological parameters and PM10 emission sources. PM10 pollution episodes are selected for simulating PM10 levels in Patio Bonito, taking into account the operation of different point sources related to the local brick manufacturing activity. Likewise, application and results of the URBAIR model are presented.

Chapter 5 proposes different improvement measures for Patio Bonito. These proposals include short, medium and long term measures. Two of these improvement measures are simulated with the URBAIR model, and their impact on the air quality assessed by comparison of results with those from the 2013 selected episodes. In this chapter, a contingency plan that includes control and prevention measures is also proposed.

Finally, conclusions of this study are presented in Chapter 6.

2. AIR QUALITY ASSESSMENT AND BRICK MANUFACTURING IN THE WORLD

This chapter describes aspects of the brick manufacturing activity around the world, which are related to air pollution. It presents some case studies related to the air quality assessment in countries that have presented a growth of brick production during the last years such as: China, India, Bangladesh, Vietnam, Mexico, Brazil and Colombia, and taking into account their increase of the atmospheric pollutants concentration in the ambient air of the analyzed territories.

In a brick manufacturing facility, different types of kilns can be used to produce bricks, from craft kilns like “Arabian” or “Fuego dormido” to more technological kilns, like Hoffman and Tunnel kilns. The Colmena kilns are similar to Fuego dormido kilns, but they have a stack. Construction and operation costs of Hoffman and Tunnel kilns are high. Figure 1 shows an example of a production process in a developing country like Colombia.

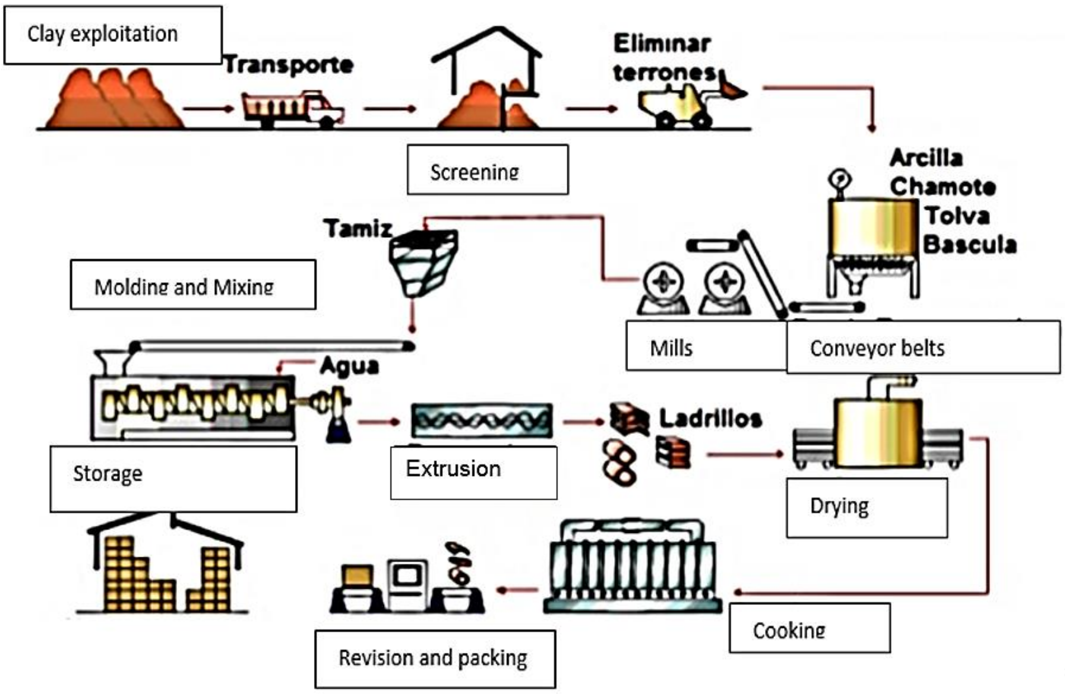


Figure 1 Brick production process (URL 1)

Basically, the productive process of brick manufacturing consists in the following phases:

- ***Exploitation and clay extraction:*** different types of material (silica-calcareous) with appropriated physic-chemical properties are coming from mines for the elaboration of the product.

- ***Maturation and preparation:*** the clay after being extracted from the mine is left in the open air to favor its disintegration. Then it is mixed with sand, being left in rest in an aging process that favors the elaboration of blocks and bricks. The extraction and transport of clay usually takes place with bulldozer or loader, using a vehicle that produces fugitive emissions by its movement. Additionally, the storage of the clay is another source of suspended particulate emissions.

- ***Molding and extrusion:*** in the case of small, medium and large brickworks, this process is carried out in the inner part of the warehouses, and usually has one or two lines of production that operate alternately; the equipment used is basically material hopper, conveyor belts, shredder, laminator, extruder and cutter.

- ***Drying:*** the block is conditioned through a dehydration phase in order to prepare it to a final cooking/firing with the desired properties.

- ***Cooking:*** corresponds to the burning process of the bricks in kilns. The clays mixed with sand are subjected to cooking passing during this process by complex reactions governed by their chemical and mineralogical composition. In cooking, chemical reactions are completed, the bricks undergo a slight contraction and acquire a characteristic structure that gives strength to the finished brick. The temperature varies between 1000°C and 1100°C.

In craft brick kilns, the burning process takes a long time to solidify the bricks from mud and the quality of the burnt fuel is usually low. Therefore, the bricks production activity is a source of atmospheric pollutants, such as PM10, particulate matter with an aerodynamic equivalent diameter smaller than 2.5 µm (PM2.5), SOx, nitrogen oxides NOx, hydrochloric acid (HCl) and hydrofluoric acid (HF).

The primary sources of total suspended particles (TSP), PM10, and PM2.5 emissions are in the raw material grinding, screening operations, and the kilns. Other PM emissions sources include fugitive dust sources, such as paved roads, unpaved roads, and storage piles. Combustion products include sulfur dioxide (SO_2), NOx, CO, and carbon dioxide (CO_2), emitted from fuel combustion in brick kilns and some brick dryers (USEPA, 1997).

Brick manufacturing emissions have been growing during the last decade in the world due to the increase on the demand of brick production. Some countries have developed their own emission factors calculations according to the environmental and operation conditions and have developed national inventories for different fixed sources like craft kilns (Sánchez, 2016).

2.1 China

In the world, China is the first brick producer. It estimated that China produced 340 billion bricks in 2012, contributing with 44% of the global total production (Zhao *et al*., 2013). There are approximately 80,000 brick kilns in China, which 90% are traditional annular type. The annular brick kilns usually have large furnaces with large roof areas but only a single stack.

The most relevant atmospheric pollutants generated by brick manufacturing in China are TSP, SO_2, NOx and PM2.5 (Zhang, Streets, He, & Klimont, 2007). In the last years, non technified kilns like the Bull's Trench Kiln (BTK) have been replaced by Tunnel and Hoffman kilns with emission control systems (Schmidt, 2013).

Some studies have manifested difficulty to estimate emissions from point sources in the brick manufacturing due to the lack of information of emission factors in some districts where exist this activity (Zhang *et al*., 2007). The same difficulty has been presented for the estimation of fugitive emissions for this activity (Chen *et al*., 2017).

Regarding air quality assessment, despite the existence of studies about air pollution levels in different Chinese cities, it is difficult to refer specific researches that directly relate air quality with the brick manufacturing activity (Sánchez, 2016). Nevertheless, some studies identify the air quality status of some Chinese cities. The study of air quality status for the Wuhan city is an example of them (Song, Guang, Li, & Xiang, 2016).

Wuhan is the capital city of Hubei province. It is situated on the east of the Jiang-Han plain, a vast area in the valley of Yangtze River. It is one of the areas with high industrial development in the country, with high coal consumption, steel and brick manufacturing industries and smelting activities, accounting for high emissions of PM (Song *et al.*, 2016). In this study, -concentration of criteria pollutants such as PM10, nitrogen dioxide (NO_2), SO_2, were measured through the operation of nine monitoring stations. The location of the nine monitoring stations is presented in figure 2.

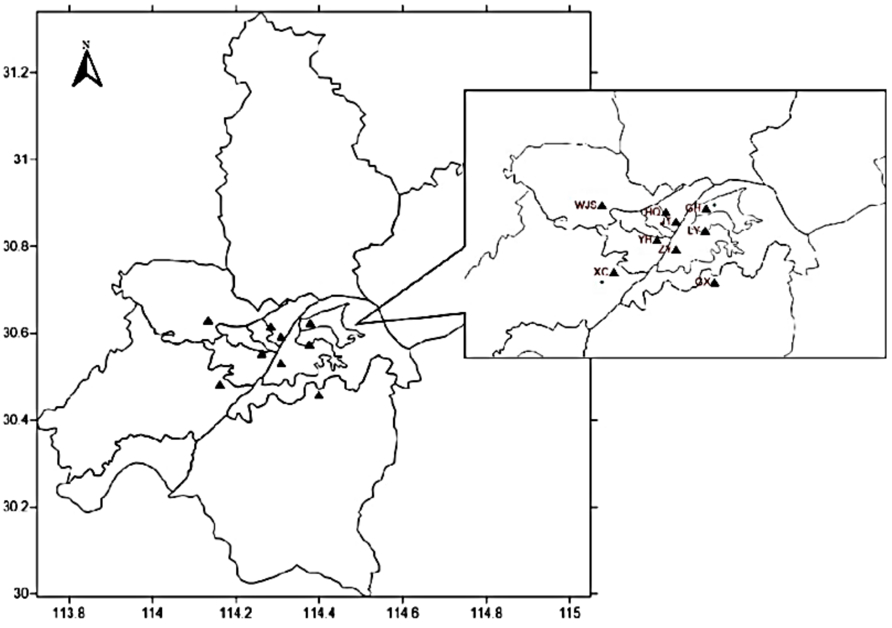


Figure 2 Location of the nine monitoring stations in Wuhan (Song et al., 2016)

The nine urban monitoring sites were classified into three groups (Song *et al.*, 2016). Group I consists of the LY site, which is located in the famous East Lake scenic area with the best air quality. Group II corresponds to three monitoring sites with heavily traffic roads nearby, where relatively severe NO_2 pollution occurs (marked as YH, ZY, and JT sites). Group III comprises the remaining five sites, characterized by PM10 and SO_2 pollution (marked as HQ, GX, XQ, WJS, and GH sites).

Simple descriptive statistics were performed to obtain the annual average. Subsequently, data were compared with the National Ambient Air Quality Standard (NAAQS) to evaluate the overall pollution status in Wuhan. In addition, multivariate statistical methods; among them, the Cluster Analysis (CA), was used for simplifying and classifying the behavior of environmental pollutants in a specific region. In order to examine the spatial pattern of air pollution in Wuhan, the nine monitoring stations were grouped using Hierarchical Agglomerative Cluster Analysis (HACA), a distribution-free ordination technique to group sites with similar characteristics by considering an original group of variables.

Based on the monitoring data, the daily air quality was reported using the Air Pollution Index (API). The API data for those pollutants were collected from the air quality publishing platform supported by the Wuhan Environmental Protection Agency (WHEP).

Figure 3 shows the annual average concentrations of PM10, NO_2, and SO_2 for the period 2001–2014 and the SO_2 concentration for the period 1996–2000. It can be seen that the average concentration of SO_2 remained almost constant during the 1996–1998 period, but dropped clearly in 1999 and 2000. Over the period 2009–2014, a significant decline in the SO_2 concentration occurred steadily, finding in the final period that all the SO_2 concentrations were below the limit value of 60 $\mu g/m^3$ (Song *et al.*, 2016).

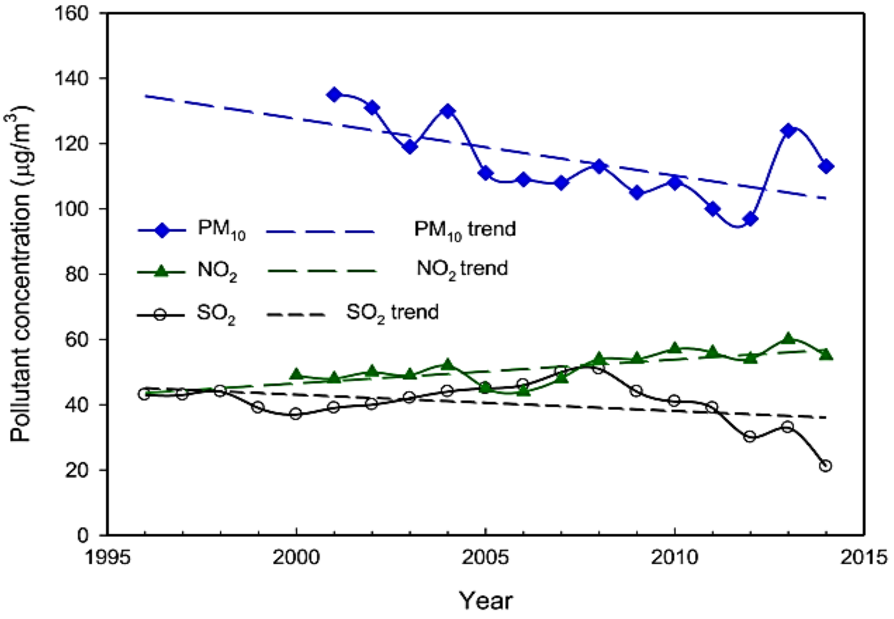


Figure 3 Annual mean concentrations of air pollutants in urban Wuhan (Song et al., 2016)

PM1O concentrations from 2001 to 2014 indicates that PM10 pollution was actually declined. However values are above the annual NAAQS limits of 70 µg/m^3, NO_2 values show a clear trend with slightly increase since 2007; nevertheless, those values are always below the limit standard. In addition, the SO_2 concentration has steadily decreased since 2008, due to the strict implementation of flue gas desulphurization in coal-fired power plants. Finally, results identified that air quality has slightly improved over the recent years.

2.2 India

India is the second-largest brick producer in the world, with 260 billion of bricks every year that represents 13% of the global production. The sector consumes around 40 million tons of coal per year (CCACOALITION, 2012). Despite its size, the brick kiln sector in India remains largely unorganized. In addition, the number of smoke-emitting brick kilns is rising without any improvement in the emission process. Approximately 70% of the Indian brick production comes from 3000 bulls trench kilns (Suresh, Kumar, Mahtta, & Sharma, 2016).

The Continuous Fixed Chimney Bull Trench Brick Kiln (FCBTK) is the main used technology. FCBTK is a horizontal, moving fire kiln in which firing is done continuously during the brick making season

In the 2010 multi-pollutant emissions inventory for the national capital region Delhi, emissions for the brick sector were estimated as: 12,400 tons/year for PM10, 4000 tons/year for SO_2, and 6750 tons/year for NOX, representing 9%, 11% and 1% respectively, of the total emissions from the industrial sector in this region (Guttikunda & Calori, 2012).

An example of air pollution assessment related to brick manufacturing industries, near a populated area, is the one developed in the city of Nagpur, India (Bhanarkar, Gajghate, & Hasan, 2002). The objective of this study was to monitor along 24 hours the ambient air around brick kilns in a populated area, in order to assess the air quality, to know the impact of the brick kilns and to establish the ground level concentrations of main pollutants as TSP NOx and SO_2 using dispersion models.

The study included emissions monitoring during 24 hours in 125 small bricks kilns and 90 mobile chimney units. These brick kilns were divided into three main types: county type kilns, Bull’s trench kilns and high draught kilns.

The micrometeorology data, namely wind speed and direction was collected during 24 hours in areas nearby the brick kilns area by an automatic weather station. The parameters of mixing height and stability class were used for predicting daily average ground level concentrations of PM10, SO_2 and NOx influenced by emissions released from brick kilns, using the dispersion model Industrial Source Complex-Short Term (ISCST2) (Bhanarkar *et al.*, 2002).

Results allowed to identify that ambient air quality was marked by TSP in a range between 312–651 μgm^3. In addition, there was a contribution of fugitive emission due to wind-blown dust, traffic and agricultural activities. The averaged concentration of SO_2 and NOx ranged from 7–9 and 14–29 μgm^3 respectively. The impacted area around brick kilns was about 3 km in radius (Bhanarkar *et al.*, 2002).

Another case study related to air pollution from brick kilns is related to the Panzan village, Budgam district. There are approximately more than 15 brick kilns just within a diameter of 2 km (Skinder, Pandit, Sheikh, & Ganai, 2014). All the brick kilns are Bull's trench kiln type. The estimated amount of coal consumed by each brick kiln (functional only for six months) varies between 2.5 and 3 tons per season.

Criteria pollutants such as SOx, NOx, TSP were monitored during 8 hours periods for the non-operational and operational phases of brick kilns in the months from April to September 2012 (Skinder *et al*., 2014). Three sampling sites were selected for assessing the atmospheric pollutant contribution from brick kilns. Figure 4 shows the location of these sampling sites. A high volume environ-tech air sampler was used.

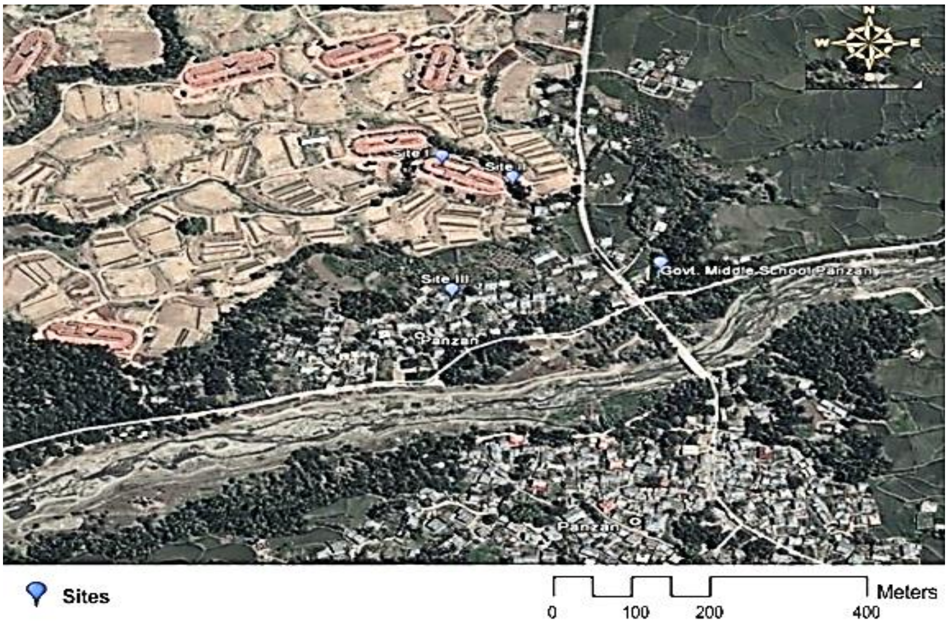
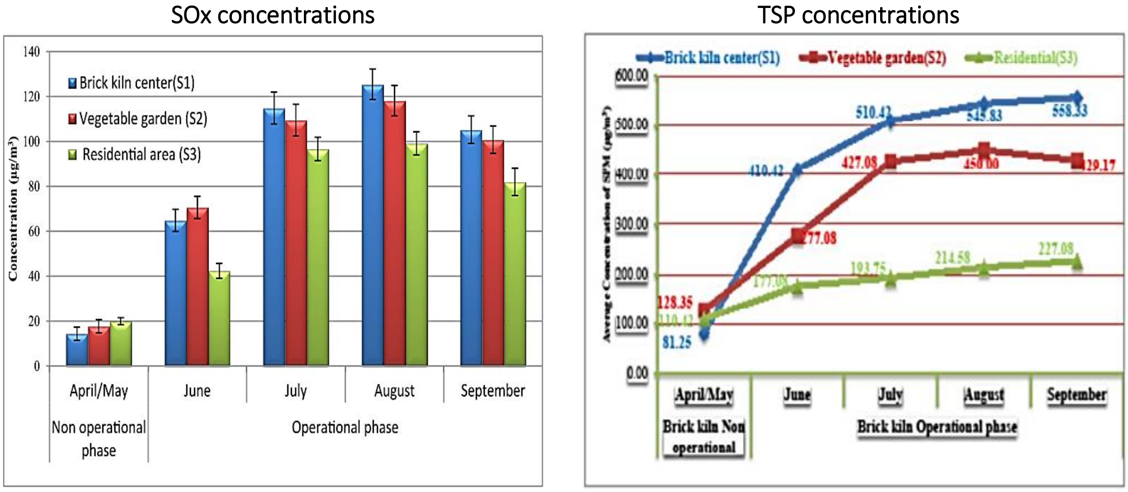


Figure 4 Locations of the sampling sites in Panzan village (Skinder et al., 2014)

The three sampling sites were classified as: brick kiln center (S1), vegetable garden (S2) and residential area nearby brickfields (S3). Figure 5 shows the monthly average of SOx and TSP concentrations for the operational and non-operational phases of brick kilns.


SOx concentrations

TSP concentrations

Figure 5 Monthly average of SOx and TSP during non-operational and operational phases of brick kilns (Skinder et al., 2014)

According to figure 5, SOx concentrations registered during the operational phase of brick kilns were high, especially in July, August and September in the sampling sites (S1, S2 and S3) with values above 120 µg/m³; contrary to this, during the non-operational phase, SOx concentrations values were below 20 µg/m³ (Skinder *et al*., 2014). Likewise, TSP averaged concentrations presented the same trend to increase in the sampling sites during the operational phase of brick kilns and for the same months. Concentrations of these two pollutants are strongly marked in S1 (brick kiln center).

The contribution of brick kilns to air pollution was found to be larger than the contribution from other sources. Coal combustion is the main source of airborne particles. Moreover, all monitored pollutants (SOx, NOx and TSP) were exceeding the limits prescribed by NAAQS during the operational phase of brick kilns. The Air quality Index (AQI) was categorized from severe to high; for the site S2 (residential areas), it ranged from 26 to 37 µg/m³ during non-operational phase from 84 to 148 µg/m³ during the operational phase of brick kilns.

Mitigation measures as the use of pulverized coal of 10 mm size for an optimum combustion, mechanical feeders for effective burning of the coal and introduction of cleaner technologies such as Vertical Shaft Brick Kilns (VSBK) instead of Bull trench kilns, were proposed (Skinder *et al*., 2014).

2.3 Bangladesh

In Bangladesh, 5000 brick kilns are estimated to be actively producing kilns (Guttikunda, Begum, & Wadud, 2013). In particular, there are about 1000 brick kilns in the districts of Dhaka, Gazipur, Manikganj, and Narayanganj. Brick manufacturing produces 3.5 billion bricks per year, using energy-inefficient fixed-chimney as the BTK technology.

According to Guttikunda *et al*., (2013), total annual emissions in Dhaka region are estimated as 23,300 tons of PM2.5 and 15,500 tons of SO_2. Local sources, such as brickfields, contribute to PM concentrations higher than the Bangladesh NAAQS (Begum, Hopke, & Markwitz, 2013). About 30 to 50% of the PM10 in the capital Dhaka is in fine particles with aerodynamic diameter less 2.5 µm. The associated health impacts largely fall on the densely populated districts of Dhaka, Gazipur, and Narayanganj with 20% of the total number of Dhaka residents dying annually as a result of poor air quality, particularly in the dry season when bricks are produced (Guttikunda *et al*., 2013).

In 2008, an air quality model was applied to quantify the contribution of brickfields to air pollution. Measured concentrations of SO_2 and CO, among other pollutants, were compared with the Industrial Source Complex (ISC3) model results. Sampling was done during three days in a zone with 41 brick kilns near Amin Bazar and Savar, during the dry season (Ahmed & Hossain, 2008). The ISC3 model needs emissions and meteorological input data. Meteorological input data used were obtained from the World Meteorological Organization (WMO).

SO_2 concentrations were delivered considering averages of 1 hour and 6 hours, during three days. Figure 6 shows the comparison between measured and modeled values and the Bangladesh SO_2 daily standard.

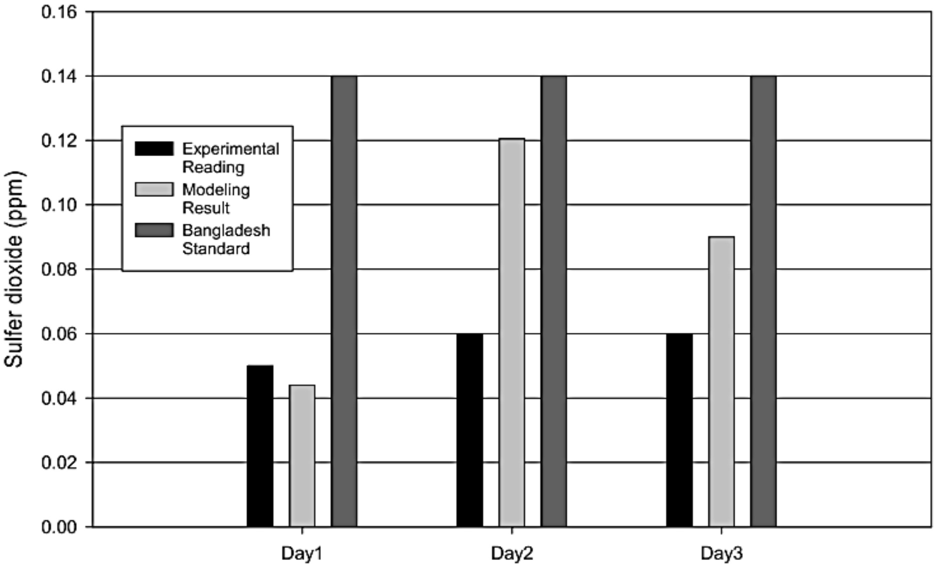


Figure 6 Comparison of different SO_2 data (Ahmed & Hossain, 2008)

According to results, ambient concentration values of SO_2 accomplish the Bangladesh daily standard, with values below 0.14 ppm (370 µg/m³). Day 2 had the highest SO_2 modelled concentrations, with a value of 0.12 ppm (310 µg/m³). Finally, the study concluded that the ambient air quality data generated by the ISC3 model were in agreement with the experimental results, with an average error between 5 and 10%.

More recently, aiming to estimate the impact of industries located in a suburban area, Begum *et al*. (2013) investigated the potential effect on air quality of Airborne Particulate Matter (APM), based on collected long-term data. For this objective, 100 samples were taken from January 2001 to February 2009 and a Positive Matrix Factorization (PMF) model was applied. It is a source-receptor model that calculates the variables distribution in a matrix. The profiles and mass contribution from identified sources were also calculated (Begum *et al*., 2013).

From collected data, the PMF modeling identified seven sources for the PM fine fraction samples. The source four had characteristics of black carbon, sulfur, lead and trace amount of crustal elements and represented the brick kiln source, where burnt coal in kilns contains

4 to 6% sulfur. The average source contributions to fine PM derived from the PMF modeling are shown in table 1.

Table 1 Emission sources and contribution of fine PM mass and black carbon (BC) during the period 2001 – 2009 in Dhaka, Bangladesh (Begum et al., 2013)

Source	Fine PM samples (µg/m^3)					
	2001-2002		2005-2006		2007-2009	
	Mass	BC	Mass	BC	Mass	BC
Motor vehicle	7.16	2.50	5.62	0.3	12.1	0.02
Brick kiln	2.23	1.37	11.1	4.1	7.59	7.41

According to table 1, emissions from brick kilns became higher than any other source in the period 2005-2006 with a contribution of 22%. This is due to the increase in the number of brick kilns in Dhaka. Moreover, Begum *et al*.,(2013) estimated the potential source areas for PM in Pakistan, Bangladesh, India, and Sri Lanka. Figure 7 shows PM probable source locations across the Indian Subcontinent. The deep red color shows the most potential source areas than the yellow ones. It is found that the air masses travel through Iran, Afghanistan and then to Pakistan.

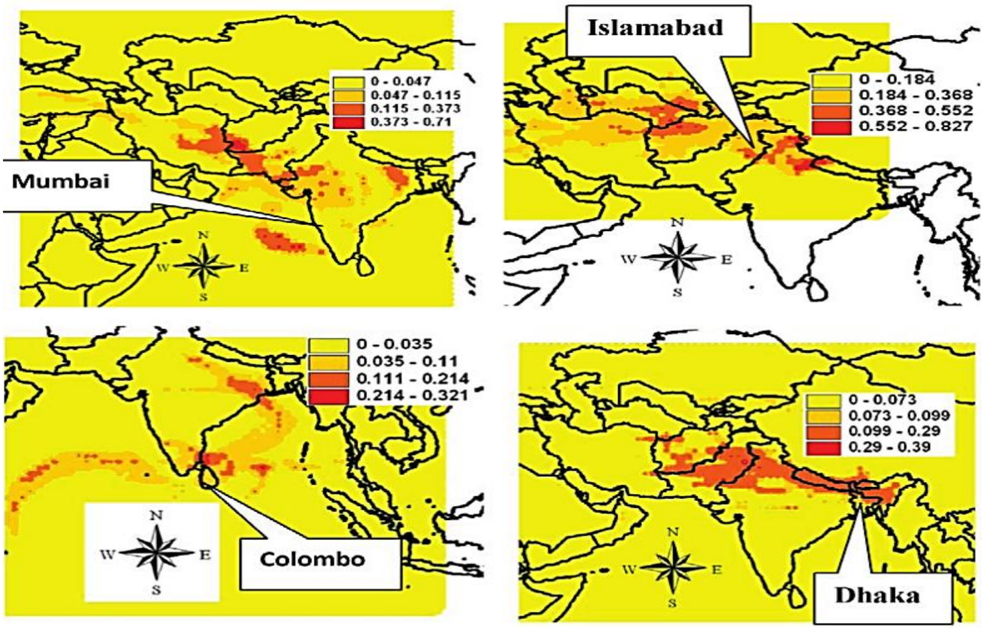


Figure 7 Fine PM probable source locations across the Indian Subcontinent. The red color represents higher probability locations. (Begum et al., 2013).

It was found that in case of Bangladesh and India, the air masses mainly pass through Iran, Afghanistan and reach Pakistan (Islamabad), then curve down to Sri Lanka (Colombo), due to the meteorological conditions in this region (Begum *et al.*, 2013).

2.4 Vietnam

Vietnam is presenting a rapid development of the brick manufacturing activity. This sector includes medium, small and family based enterprises, which increased from 62% in 2001 to over 80% in 2005. Almost 17,000 million brick pieces were produced in 2005 (Le & Oanh, 2010). Le and Oanh (2010), developed a study in the Bac Ninh province in the north of Vietnam, in order to monitor daily brick kiln stack emissions and to derive emission factors. It was based on monitoring and dispersion modelling for the assessment of the environmental effects caused by the brick manufacturing in the village of Song Ho.

In Song Ho village there were 45 brick kilns in 2007. The production varies from 200,000 to 1,000,000 bricks per batch. The average coal consumption is 8.53 tons per 1000 bricks (Le & Oanh, 2010). The averaged emission rate of SO_2, CO and PM from brick kilns during the firing period for seven days was assessed, figure 8 shows the obtained values.

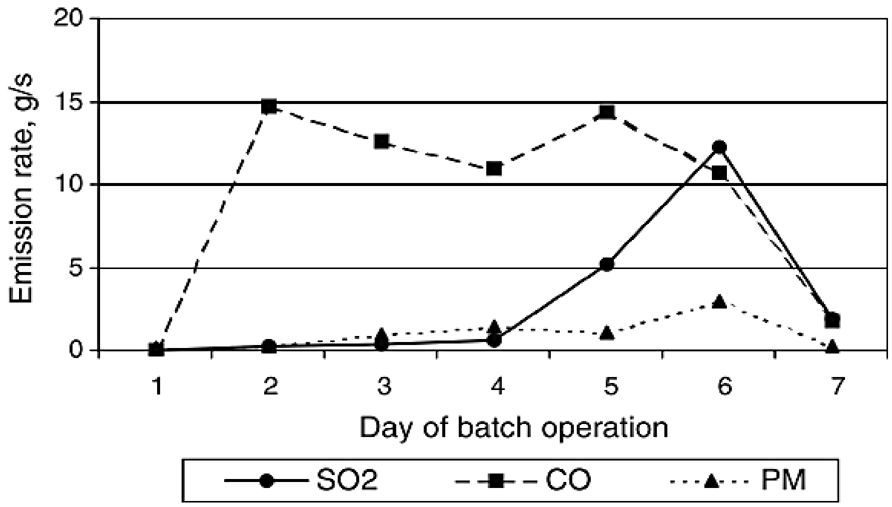


Figure 8 Average emission rate from a brick kiln during the firing period used in modeling for the base case (Le & Oanh, 2010)

The emission rate for SO_2 was the most interesting for modeling due to the increase during the monitoring period in seven days with normal operation of selected kilns. The emission varies from one kiln to another especially for SO_2, which is most probably due to the variation in the sulfur content of coal. In addition, large fluctuations in obtained emission factors among the kilns suggested that more emission measurements are still required to produce representative ranges of values. The average emission factors per 1000 bricks were 0.52-5.9 kg of SO_2 and 0.64-1.4 kg of PM (Le & Oanh, 2010).

Emission factors and PM size distribution were obtained and used as input data to the Industrial Source Complex Short-Term (ISCST3) dispersion model. Figure 9 shows the defined simulation domain, which includes 21 selected brick kilns operating in the village, as well as meteorological and ambient air monitoring sites that operated during 2006 and 2007.

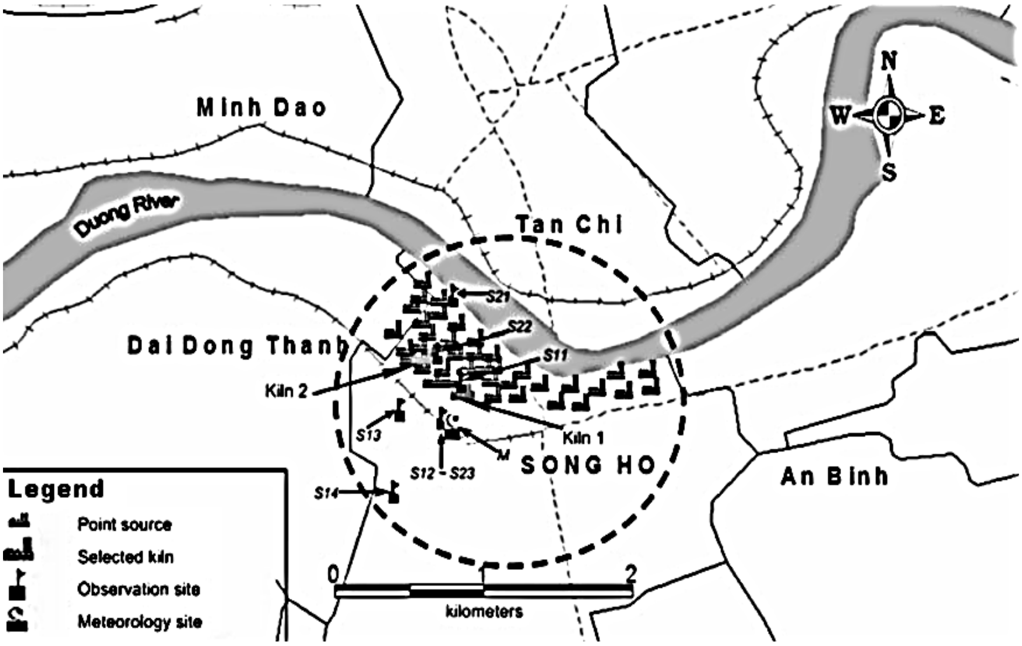


Figure 9 The ISCST3 model domain with the Song Ho brick-making village (Le & Oanh, 2010)

The SO_2 concentrations in the surrounding area of the brick-making village, for different emission scenarios, were estimated. The domain covered 100 km^2 (Cartesian 40 × 40 grids of 250 m) of flat terrain including the Song Ho village. Figure 10 shows the first highest SO_2 concentrations in the 10 x 10 km^2 model domain.

The outermost contour is 1-h NAAQS of 350 µgm^3. The Song Ho village is in the center of the domain. Locations of brick kilns (⊗) and ambient monitoring sites (∗) are marked.

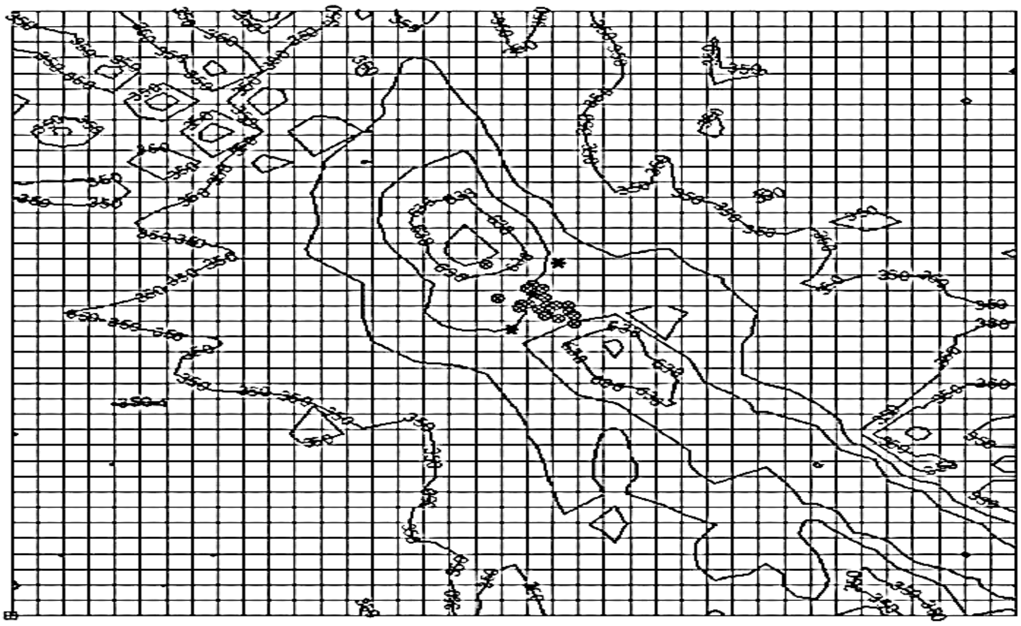


Figure 10 SO$_2$ concentrations distribution in the 10 x 10 km^2 model domain in the base case (2007). (Le & Oanh, 2010)

Results for 21 operated kilns in the village showed that in 2007 the most critical pollutant was SO$_2$, exceeding the hourly national ambient air quality standards (NAAQS) of 350 µgm^3, over 63 km^2 out of the 100 km^2 domain in the base case.

2.5 Mexico

In Latin America, Mexico is an important brick producer. Brick production in Mexico, contrary to other Latin American countries, still is a handmade craft activity, 90% of the producer does not have the appropriate technology to fabricate the bricks (Corral & Covarrubias, 2012). The *Secretaría de Medio Ambiente y Recursos Naturales of Mexico* registered 16,300 kilns in 2011, from which 70% are traditional brick kilns, and identified a growing trend. The Chihuahua State is an example of this increase.

In 2012, Corral and Covarrubias (2012) investigated the impact of brick kilns in this state. The main objectives were to identify the location of the brick kilns in all the municipalities of the Chihuahua State and to determine the best alternatives to relocate the brick kiln industry in order to minimize environmental risk. Multicriteria Analysis (MCA) based on digital cartography and a Geographical Information System (GIS) were used (Corral & Covarrubias, 2012).

Chihuahua city has 296 brick kilns nearby to urban areas. These have a capacity of 20 to 30,000 bricks per kiln. A risk map was developed for five municipalities of the Chihuahua State and an evaluation matrix with weight values by category and factor was delivered (Corral & Covarrubias, 2012). The resulting risk map allowed to propose new locations for the brick industry, as shown in figure 11.

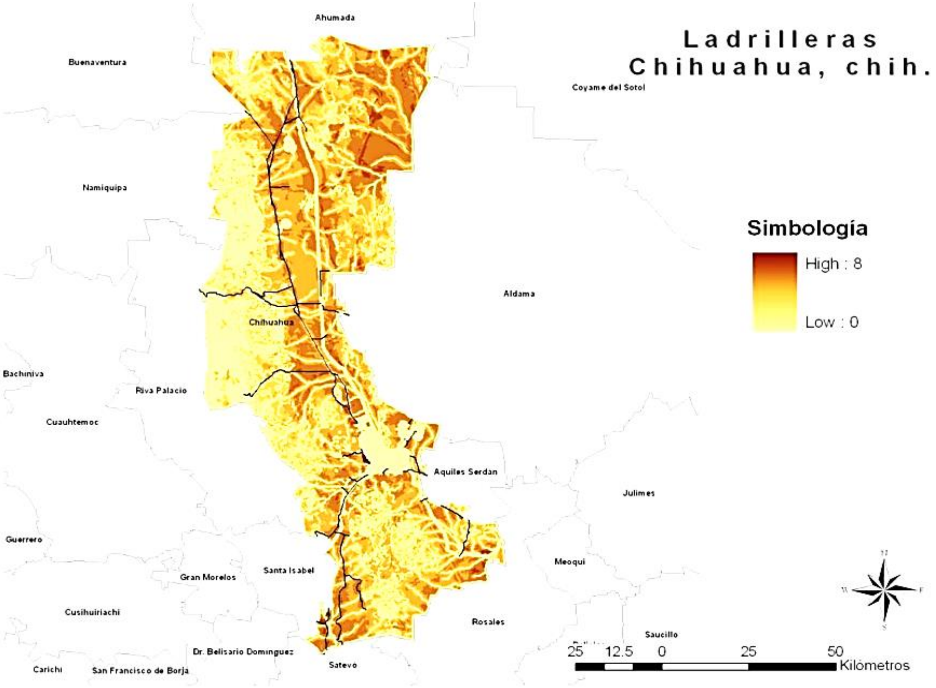


Figure 11 Suitability map for the establishment of the brick industry in Chihuahua, México

(Corral & Covarrubias, 2012)

Figure 11 shows that the best polygons for relocation of brick kilns are in the Northeast side. The study concluded that the environmental risk maps resulting from the combination of the GIS and the MCA are important tools for solving the problem of the brick industry location in Chihuahua State.

2.6 Brazil

Santa Catarina is a Brazilian state with an important industrial sector, that includes the production of red clay ceramics (brick and tile kilns). It is responsible for 14.7% of the Brazilian ceramic production (Camara, Lisboa, Hoinaski, & David, 2015). Camara *et al*., (2015) developed the first diagnosis of brickfields activity, identifying a group of 318 brick manufacturing companies. The aim was to verify how the atmospheric emissions are considered by brickworks companies.

The methodology consisted of a survey, applying two methods: a questionnaire and an evaluation of environmental assessment documents, as emissions reports presented to the environmental authority. The questionnaire was applied to 151 brickwork companies between January and December of 2012.

The first questions were to inquire about the treatment of gases: if brickworks had some form of gas treatment, what type, cost, reason for installation, whether the equipment presented problems, how often, if the manufacturer provides technical assistance. The second phase of questions raised information on the operational part of the brickfields, namely the fuel used, its quantity, the number of kilns, the weekly occupation of the kilns, whether the control equipment operated during the burning period.

Finally, questions were asked about aspects related to environmental licensing: if the company conducts self-monitoring of emissions, if the environmental licenses are in a regular situation and if have ever been notified due to atmospheric emissions. This questionnaire was applied exclusively to the municipalities with the highest number of pottery: Morro da Fumaça (51%), Sangão (31%) and Içara (18%), as shown by figure 12.

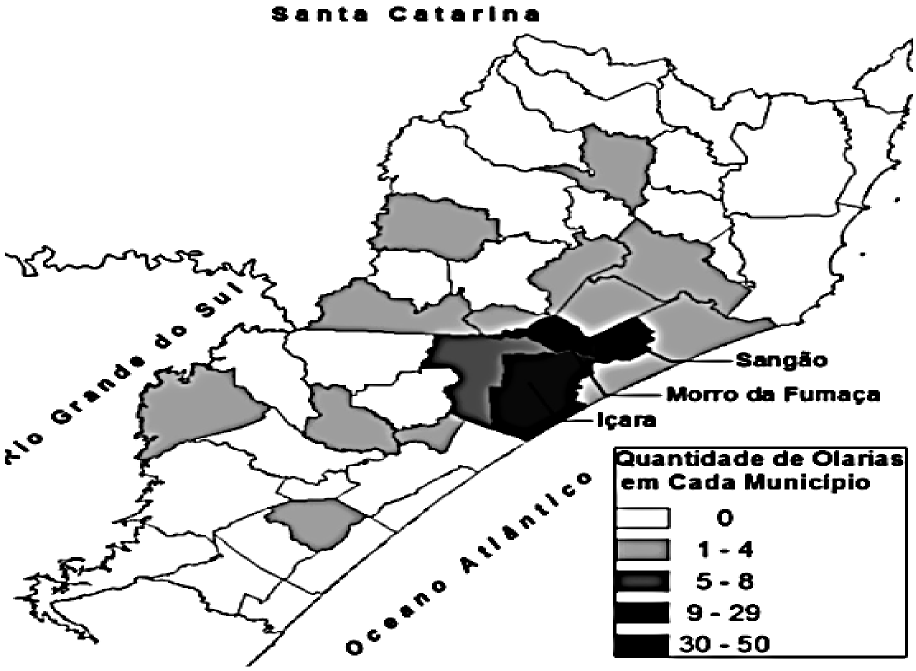


Figure 12 Distribution of kilns at southern Santa Catarina, Brazil (Camara et al., 2015)

The potteries were classified into four groups according to production capacities, having the most relevant brickworks a production between 200,000 and 400,000 bricks (66.7% of total distribution). 66% of pottery produce bricks, 21% tiles and the rest both products.

From 71 companies questioned, 60 (85%) affirmed to have some type of emissions control equipment. Of these companies, 22 reported the occurrence of problems with the operation of this equipment. The most typical pollutants control system is the scrubber. In addition, 44% of total questioned brickworks have some report of their emissions; in these reports, it was pointed that emissions control equipment have an averaged removal efficiency of 62% for PM and of 33% for SOx (Camara *et al*., 2015)

The use of the control system varies during the burning stage of the 61 pottery selected. 53% of producer claimed to leave their system running between 5 and 50% of the total operation time and 9% leave the system in activity during the entire operation time that involves the burning stage.

Finally, from 67 potteries with emission reports it was possible to estimate an annual total PM emission of 324 ton/year. In addition, Santa Catarina region has almost the double of emissions per area (0.703 ton/year in 1 km^2) than an urban region as the metropolitan area of São Paulo (0.385 ton/year in1 km^2) (Camara *et al*., 2015).

2.6 Colombia

In Colombia, brick manufacturing is an important productive sector that has been increasing during the last decade. The brick manufacturing issue is not properly addressed by environmental authorities. A few academic references and municipal authority studies have been produced. The *Corporación Ambiental Empresarial* (CAEM) presented the first national emissions inventory of bricks industries. This identified 1508 brickworks legally registered in 2015, with 2435 kiln units, which, produce 12,703,872 bricks per year (CAEM, 2015).

The national consumption of fuel in brickworks corresponds to the use of mineral coal, especially type CG1 and CG2 coals that are coal with the highest percentage of calorific power in the market, but that contain high degrees of sulfur, impurities and volatile ashes. However, currently some brickworks are using alternative fuels like firewood, biomass and natural gas. Figure 13 shows the fuel consumption in Colombia, for 2015, identifying the type of fuel, and per dimension of brick companies.

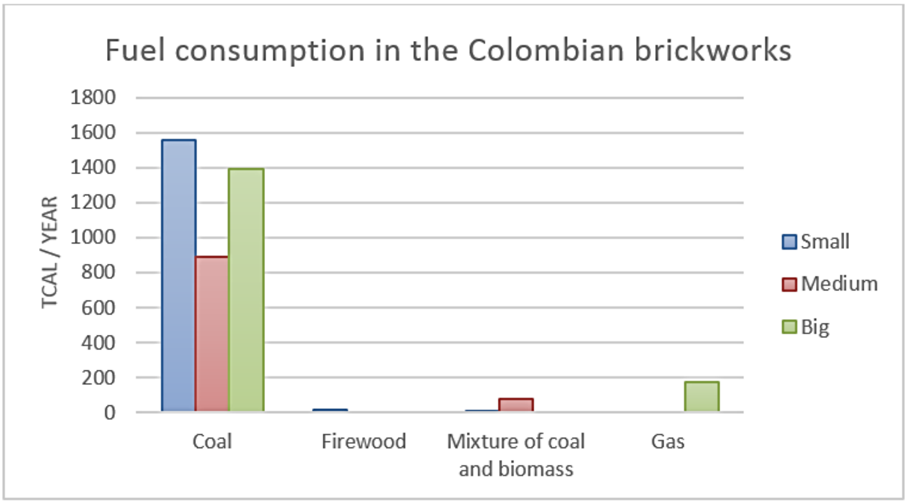


Figure 13 Fuels consumptions (Tera calories/year) in Colombia per size brickworks (CAEM, 2015).

According to figure 13, mineral coal is the most used fuel in this sector. The small brickworks consume an average of 1555 Tcal/year, the medium brickworks consume 888 Tcal/year and the big brickworks consume 1390 Tcal coal/year, representing 41, 23 and 36%, respectively, of the national consumption.

The inventory also mentions that Fuego dormido and the Colmena kilns are the most common, with a major national distribution. Based on the production capacity, technological level of transformation, manufactured product and type of furnace, the brick sector in Colombia can be classified as presented in table 2.

Table 2 Production capacity of kilns in Colombia (CAEM, 2015)

Kiln	Type	Technology	Production capacity (ton/year)
Fuego dormido	Handcrafts	Handcrafts	<600
Colmena	Handcrafts	Mechanized crafts	600-2500
Hoffman	Mechanical	Semi mechanized to mechanized	5000-10000
Tunnel	Mechanical	Mechanized	20000-120000

The Fuego dormido kilns have a smaller production capacity (< 600 tons/year) and a lower energy consumption. A longer burning time per production period is however associated to this kiln and therefore higher particulate matter emissions can be expected.

In the national panorama, craft brickworks represent 51% of the number of kilns and 33% of the total monthly production. Contrary, the big brickworks are 3% of the total number of kilns and represent 25% of the total monthly production (CAEM, 2016).

In Antioquia region, Silva and Valencia, (2013) put into context the current situation of brickworks and tile factories at “Los Gómez” rural locality in the municipality of Itagüí, concerning the environmental impact of this activity for several decades. In this locality there are five brickworks with technified processes.

In Itagüí, PM 2.5 concentrations monitored during the period 2006-2011 were high. Figure 14 shows the annual average of PM2.5 concentrations from 2008 to 2011 in Itagüí; exceedances of the guidance annual value (15 µg/m^3) adopted in Colombia and of the annual limit established by the Resolution 610 of 2010 (25 µg/m^3) are observed.

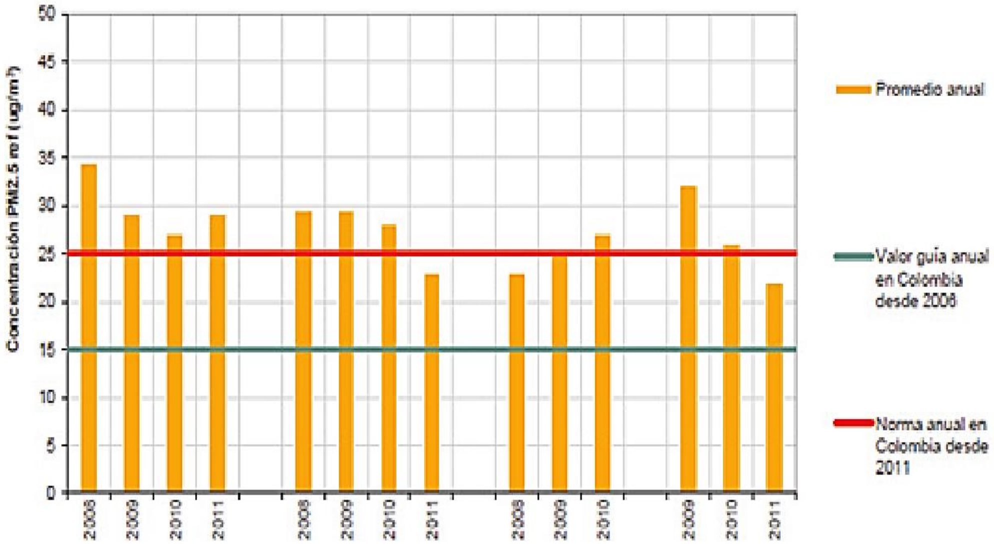


Figure 14 PM2.5 annual concentrations and exceedances for the period 2008 – 2011 (Silva & Valencia, 2013).

For this period, a relation between exposure to PM 2.5 and respiratory disease in the population was identified; 72,585 medical consultations were registered (28% of total population in the municipality) (Silva & Valencia, 2013).

The study concluded that is important to improve the technology in the tiles factories and brickworks, implementing emission control system in order to comply with emission limit established in the current legislation. In addition, it mentions that some of those factories should be relocated due to the environmental risk they represent, not only by their emissions, but also due to the high risk of landslides.

A first approach to air quality assessment in Patio Bonito and other rural localities of Nemocón, Cundinamarca, was developed in 2008 and reported by Rodriguez and Piñeros (2011). The objectives were assessing the local air quality in those rural localities and estimating the emissions from point and mobile sources. The AERMOD dispersion model was used, taking into account an emission sources inventory including 515 brick kilns and an annual average of 135,000 vehicles on nearby highway (Rodriguez & Piñeros, 2011).

Daily concentration values of PM10 were simulated and validated by comparison with data from three monitoring stations. Figure 15 shows the location of these three PM10 sampling points identified as: “La Venta”, “Colegio” and “El Plan”.

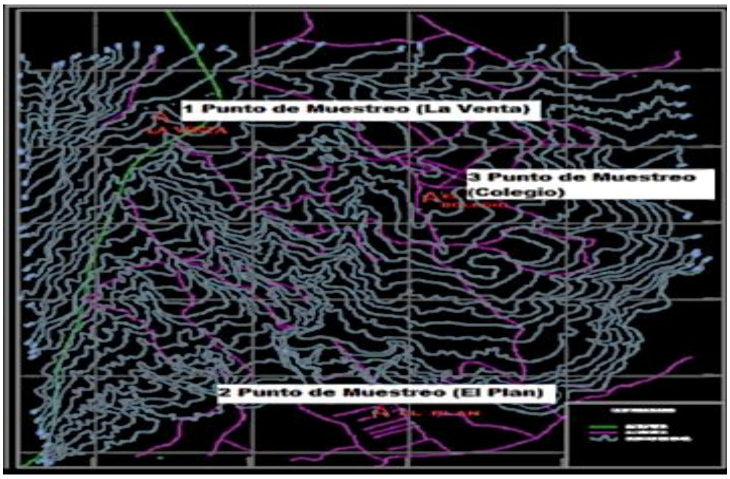


Figure 15 Three PM10 sampling points selected in the study: La venta, Colegio and El Plan

(Rodriguez & Piñeros, 2011)

The monitoring period was from 14 October 2005 to 14 October 2006. In addition, for the air quality assessment, hourly meteorological information (e.g. cloudiness, temperature, relative humidity, atmospheric pressure, wind direction, wind speed, cloud height, precipitation, solar radiation and mixing layer height) was needed in order to run the AERMOD model. This information was taken from the hydro meteorological network of the *Corporación Autónoma Regional de Cundinamarca* (CAR) and from the hydro meteorological network of the *Instituto de Hidrología, Meteorología and Estudios Ambientales* (IDEAM).

Results allowed identifying PM10 concentrations above the annual limit of 70 µg/m^3 established by Resolution 601 of 2006 (modified by Resolution 610 of 2010). In 56 days of the selected period. At the first sampling point (La Venta) the average of the PM10 sampled concentrations was 128 µg/m^3 and the modeled value was 100 µg/m^3. At the second point (El plan), the average of PM10 sampled and modeled concentrations were 86 µg/m^3 and 58 µg/m^3 respectively. Finally, at the third point (Colegio), the average of PM10 sampled and modeled concentrations were 84 µg/m^3 and 58 µg/m^3, respectively.

The AQI calculated was 65.81, and thus the air quality was classified as moderate, which means a risk for the health of the local inhabitants. Moreover, according to the national Decree 979 of 2006, the studied area was classified as an area of high pollution (Class I) which means that concentrations values exceed the annual standard with a frequency equal or larger 75%. These areas require taking contingency measures, suspension of new emission sources and pollution reduction programs to be extended for up to ten years (Ministerio de Ambiente, 2006).

3. CHARACTERIZATION OF PATIO BONITO

The present study is focused on the rural locality Patio Bonito, municipality of Nemocón, region of Cundinamarca. In order to characterize the municipality and the rural locality, general aspects in terms of geography, economy, meteorology and climatology are presented. This chapter also describes the brick manufacturing activity, atmospheric emission sources and local air quality in Patio Bonito.

3.1 General information

According to the *Departamento Nacional de Estadística* (DANE), the municipality of Nemocón has a population of 13,488 inhabitants. The municipality of Nemocón has the main characteristics presented in table 3.

Table 3 Characteristics of the municipality of Nemocón (DANE)

Item	Description
Sea level height	2,585 m
Average Temperature	12.8°C
Precipitation	629.7 mm (153 days per year) from September to December
Driest period	From December to March
Distance from Bogotá D.C	60 km
Area	98.1 km^2
Administrative division	11 rural localities: Agua Blanca, Astorga, Casablanca, Cerro Verde, Checua, La Puerta, Mogua, Oratorio, ***Patio Bonito***, Perico and Susatá
Main land uses	Agricultural and agro industrial

In Nemocón, the brick manufacturing activity is basically developed by hand made in Fuego dormido kilns. These kilns mostly operate in a Chircal, which is a term that designates the operating area of workers taking care of the artisanal elaboration of bricks. The approximate area of a Chircal is 260 m^2.

Patio Bonito is a rural locality strongly affected by brick manufacturing activity. It is located in the 5°13´11.49” North latitude and 73°89´64.32” West longitude. It limits with El Plan rural locality and with a national highway (route 45A). It has an area of 6.5 km^2 and 2500 inhabitants, 1175 belong to the age group between 15 and 44 years old, and 561 between 5-14 years old.

Its height above sea level goes from 2600 m to 2850 m. The terrain is mostly mountainous, having only a semi-flat area to the southwest side; the slope is variable with the lowest (7%) in the half-plane part of the area (Rodriguez & Piñeros, 2011). Figure 16 shows the location of Cundinamarca, Nemocón municipality and Patio Bonito.

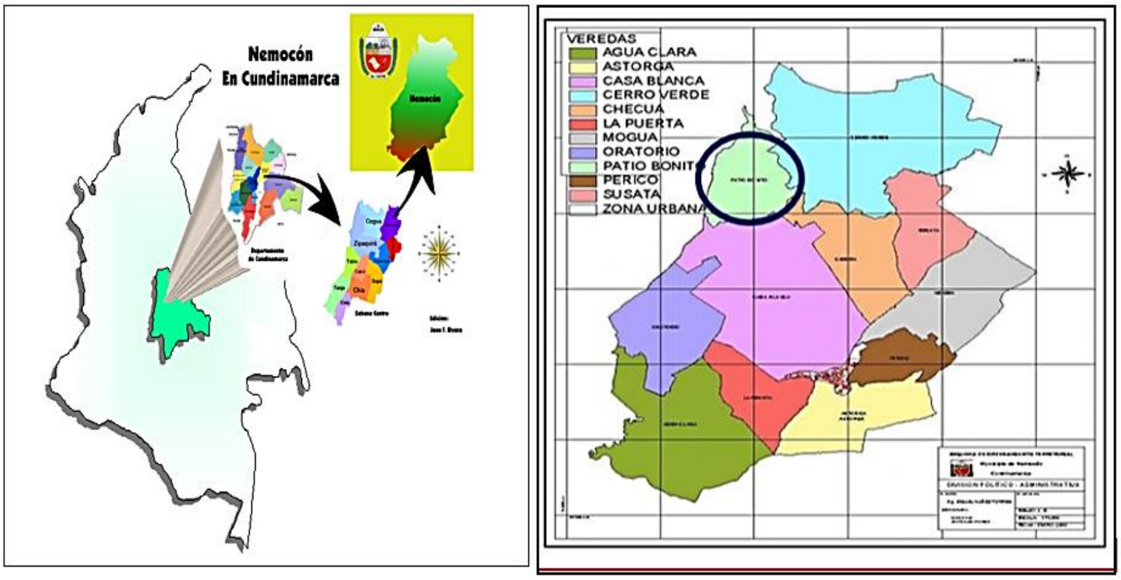


Figure 16 Nemocón and Patio Bonito location (URL 2)

Soils are of medium agrological capacity, characterized by a moderately undulating relief, with high sensitivity to erosion and accelerated by the intense exploitation of clay. These soils have extractive mining functions due to their geological characteristics and are currently the object of mining their minerals, mainly clay and coal, in the open and underground. They are part of the territorial units with mining licenses; their uses are conditioned and are subject to the requirements of the environmental authority (Rodriguez & Piñeros, 2011).

Patio Bonito has an urbanized center, an agricultural area, and an exclusion mining area. The main land use is agricultural. However, there are areas with a land use agro industrial, that allows in a legal way the operation of the brickworks activity.

The emission sources inventory of Patio Bonito, for 2008, developed by Rodriguez and Piñeros (2011) identified 515 Fuego dormido, 50 Colmena, 1 Tunnel and 1 Hoffman kilns. In 2013, CAR estimated 470 brick kilns.During the last five years, a reduction of the number of Fuego dormido kilns has been noted, which could be a result of the competition in the bricks market between medium and big producers, and of their closures due to the lack of land use licenses and sanctions imposed by the municipal and environmental authorities. Currently, the total number of brick kilns is unknown. Figure 17 presents the brick kilns percentage distribution in rural localities of Nemocón in 2013:

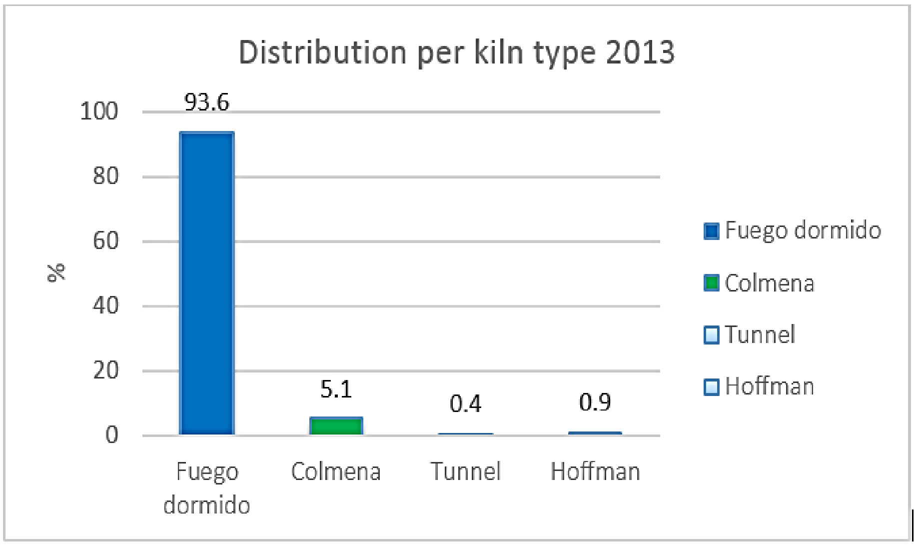


Figure 17 Brick kiln distribution in rural localities of Nemocón in 2013 (Sánchez, 2016)

According to figure 17, Fuego dormido kilns are the most used in Patio Bonito, representing almost 94% of the total kilns, followed by the Colmena kilns. The technological kilns like Hoffman and Tunnel have a low participation in this rural locality.

The majority of brickworks use granulated or pulverized coal known as CG1 and CG2 type. Table 4 shows the main physical-chemical properties of coals used in Nemocón and other municipalities of Cundinamarca region. All values, except humidity of course, are provided as dry basis.

Table 4 Chemical physic properties of used coal in kilns (Sánchez, 2016)

Coal type	Humidity (%)	Ashes (%)	Volatile material (%)	*Sulfur (%)	Calorific power (cal/g)
CG-1	4	13	33	1	7200
CG-2	3	11	33	1	7500

*Maximum limit value in Colombia / Resolution 898 of 1995

These coals contain a significant content of volatile material and ashes; their calorific power is the highest of Cundinamarca region. Regarding control emission systems, brickworks in Nemocón do not have technology as scrubbers, filters, electrostatic precipitator etc., generating emissions that can overpass the national limit values (Sánchez, 2016).

In some rural localities of Nemocón like Patio Bonito, there are populated zones nearby Chircales, where kilns known as Fuego dormido, without stacks for gases dispersion are common. Their emissions affect the health of the local inhabitants and their life quality. Figure 18 shows an example of the distance between population centers and brickfields, which can be less than 200 m (Sánchez, 2016).

Figure 18 Brick kilns coexisting with populated areas (Sánchez, 2016)

According to the municipal health plan of Nemocón 2012-2015, 230 medical consultation were registered; 167 by acute respiratory tract infection for youngest population (between 1 and 14 years old), and 63 cases by respiratory infection for people over 60 years old (Alcaldía de Nemocón, 2016). Morbidity due to unspecified upper respiratory infections registered 305 cases. In this plan, the local authority recognizes as a certain cause the continuous exposure to atmospheric pollutants generated by brickfields and traditional ways of bricks production as occurs in Patio Bonito.

3.2 Characterization and contribution of emission sources

Patio Bonito has different emission sources types. Brick production activity represents an important number of fixed sources, but also exist road traffic activity and fugitive emissions, which are ruled by the Colombian legislation.

The contribution of emission sources can be estimated based on previously compiled information, namely on emission factors for fixed and mobile sources for Colombia. It was necessary a review of emission factors that could apply for brick manufacturing in Colombia, taking into account the guide AP42 from USEPA and other studies. In addition, data of the traffic flow were consulted in the Ministry of transport.

3.2.1 Brick kilns emissions

Into the brick manufacturing activity, the following point sources operate commonly in Patio Bonito rural locality.

1. ***Fuego dormido kilns:*** these kilns can be considered as low production and high pollution sources, due to non-homogeneous burning and incomplete combustion. Once the supply of coal has been completed the kiln is turned on (Herrera, Rodriguez, & López, 2011).The material produced is of low quality, with some scorched bricks.

2. ***Colmena kilns:*** are also known as kilns of inverted flame. The dry material is fed by a side door. The fuel can be supplied manually by means of grills placed on the wall of the kiln or automatically by stokers or carbojets. An advantage of these kilns is that fuel are not in contact with the product due to the partition wall.

3. ***Hoffman kilns:*** consist of two parallel galleries, formed by adjacent compartments connected by a pipe with flare. They operate continuously with a high production. In these kilns, the fire moves through the kiln in a counter-clockwise direction, this system provides high thermal efficiency and production. The fuel supply is performed at the top of the kiln, manually or with carbojets, (Herrera *et al.*, 2011).

4. Tunnel kilns: are characterized by the fact that the product is cooked continuously moved in rollers through long gallery approximately 100 m divided into three sectors, preheating, cooking and cooling. These have a high productivity with capacity ranges from 15 to 90 m^3/day (CAEM, 2011). These recover the heat from the combustion gases to heat the incoming load. Figure 19 shows pictures of some types of kilns as: Fuego dormido, Colmena and Hoffman kilns that operate in Patio Bonito.

(a) Fuego dormido (b) Colmena

(c) Hoffman (d) Tunnel

Figure 19 Different brick kilns in Patio Bonito (Sánchez, 2016)

In 2013, 440 Fuego dormido, 24 Colmena, 4 Hoffman and 2 Tunnel kilns were identified in Patio Bonito by CAR (Sánchez, 2016). According to Rodriguez and Piñeros (2011), the distribution of different classes of Fuego dormido kilns is based on the nominal production capacity during the burning/firing stage. Figure 20 shows the percentage distribution of different Fuego dormido types per nominal production capacity

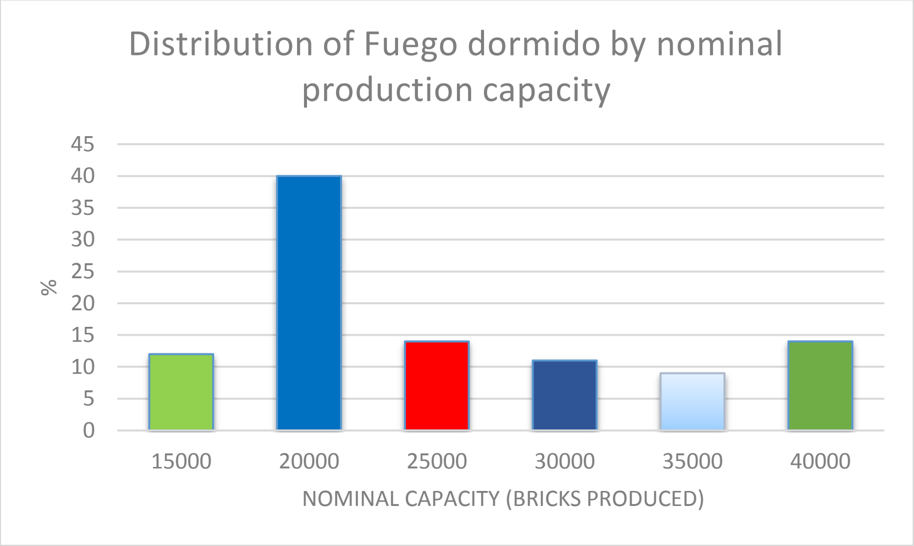


Figure 20 Distribution of Fuego dormido kilns by nominal production capacity (Rodriguez & Piñeros, 2011)

In Patio Bonito, 40% of the total Fuego dormido kilns have a nominal production capacity of 20,000 bricks, followed by kilns with nominal capacity of 40,000 bricks (14%) and with the same distribution kilns of 25,000 bricks (Rodriguez & Piñeros, 2011). Table 5 presents the annual coal consumption of each Fuego dormido kiln that operate in Patio Bonito based on their nominal coal consumption capacity during burning stage.

Table 5 Annual coal consumption per Fuego dormido kiln class (Sánchez, 2016)

Fuego dormido nominal production capacity	Coal consumption (ton coal/year) per kiln	Number of kilns	Total annual coal consumption (ton coal/year)
15000	108	53	5724
20000	144	176	25,344
25000	180	62	11,160
30000	216	48	10,368
35000	252	39	9828
40000	288	62	17,856
Total			**80,280**

Fuego dormido Kilns with a major amount of mineral coal consumed have a major nominal consumption capacity of this fuel. Table 6 identifies the annual coal consumption for other brick kilns based on their nominal capacity.

Table 6 Annual coal consumption of other brick kilns (Sánchez, 2016)

Kiln type	Coal consumption (ton coal/year) per kiln	Number of kilns	Total annual coal consumption (ton coal/year)
Colmena	864	24	20,736
Hoffman	1020	4	4080
Tunnel	1200	2	2400
Total			**27,216**

According to table 6, these brick kilns have greater nominal coal consumption capacity than non technified kilns like Fuego dormido. However, their annual consumption is lower than this artisanal kiln. The calculation of brick kilns emissions was based on the use of emission factors and activity data, applying the guide AP42 from USEPA (USEPA, 1995) and it is presented in equation 1.

$$E = EF \times A \times N \qquad \text{Eq (1)}$$

Where:

E – Emission

EF – Emission factor

A – Activity indicator

N – Number of fixed sources

The emission factors are based on isokinetic monitoring data of kilns in different brickworks companies in Colombia. Fuego dormido, Hoffman and Tunnel kilns emission factors from the Colombian ministry of the environment were considered. For Colmena kilns, an emission factor compiled in the Bogotá decontamination plan 2010, elaborated by the *Secretaría Distrital de Ambiente* (SDA) (Secretaría Distrital de Ambiente, 2010). For all types of brick kilns, the worst scenario was considered, which means brick kilns without emission control systems.

Because of the current amount of brick kilns in Patio Bonito is not known, PM10 emissions were calculated according to the number of brick kilns identified by CAR in 2013. In addition, it was considered the nominal coal consumption by brick kilns presented in tables 5 and 6. Emission factors for PM10 of the USEPA AP 42 guide and other of the ministry of environment were applied (Sánchez, 2016). The estimated annual PM10 emissions from brick kilns is presented in Table 7.

Table 7 Estimated PM10 emissions from brick kilns based on coal consumption (Sánchez, 2016)

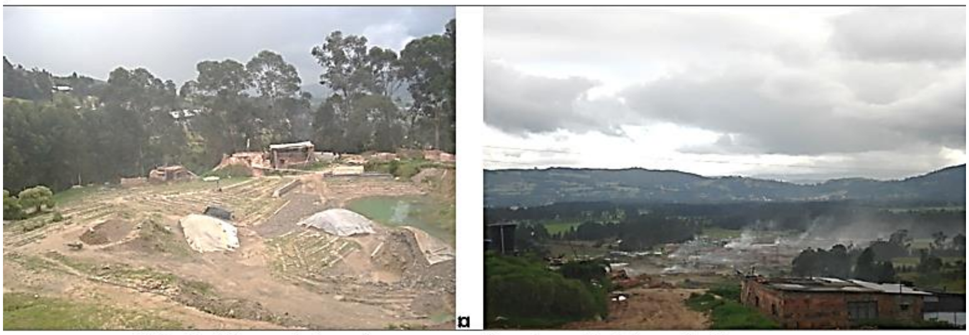
Type kiln	Total annual coal consumption (ton/year)	Emission factor (kg/ton coal) PM10	Total annual PM10 emission (ton/year)
Fuego dormido	80,280	24	1926
Colmena	20,736	10	207
Hoffman	4080	3	12
Tunnel	2400	0.8	1.9
Total			**2147**

According to table 7, the estimated emissions of the Fuego dormido kilns represented 89.7% of the total PM10 emissions in Patio Bonito. Tunnel kilns have the lowest emissions followed by Hoffman kilns (0.5% and 0.08% respectively). It should be noted, that with emission factors used for the different kiln types, in principle more advanced technological kilns, such as Tunnel kilns, are supposed to emit less pollutants to the atmosphere.

3.2.2 Fugitive emissions

Fugitive emissions are the sum of emissions from accidental discharges, equipment leaks, storage losses, venting, etc.. These are an important source of PM in Patio Bonito. Those emissions come from several activities of brick production, such as loading of raw material, fine material storage, extrusion, transport of fine material, among others. Figure 21 presents pictures of different fugitive emissions from brick manufacturing activity in Patio Bonito.

Daily·Fugitive·emissions·from·unpaved·roads·and·brick·production·process·¶



Daily·Fugitive·emissions·from·unpaved·roads·and·brick·production·process·¤

Figure 21 Fugitive emissions from brick production activity (Sánchez, 2016)

The contribution of PM from fugitive emission sources in Patio Bonito is generated mainly by the following activities.

1. ***Dust-carrying clay:*** the dust kicked up by vehicles carrying clay, coal and products to consumer centers, which is done through internal roads 100% uncapped. Likewise, the contribution by the transit of heavy machinery (extrusion machines, bulldozers, carriers etc.) as they exert a great force on surface, spraying the material in their path.

2. ***Aggregates piles (sand, gravel, and clay):*** in the material storage piles as aggregates, held outdoors because of the frequent need of material, the particulate matter emission is generated by wind.

3. ***Carrying and discharging material:*** when there is fall or friction of materials, the particles rise into the atmosphere also by wind action.

Taking into account the referred fugitive emission sources, is important to mention that currently In Colombia there are no inventories or technical information related to this kind of emissions of the brick manufacturing sector and for this reason it was not possible to quantify them.

3.2.3 Road traffic emissions

Road traffic emissions in Patio Bonito, are characterized by daily traffic of heavy vehicles carrying and discharging bricks, sand, gravel and clay. An important highway named carretera central del Norte or route 45A crosses the rural locality. This is a national level highway that connects Bogotá with the Colombian central region and crosses the municipalities of Cogua and Nemocón. The route 45A has a toll named “Casablanca”, which is administered by the Convicol S.A.S company. Figure 22, shows the location and a picture of the toll and a view of this point with traffic road.

Figure 22 Location of the Casablanca Toll and brickworks area (URL 3)

The Casablanca toll is located 1 km from Patio Bonito. According to the transport ministry, the average monthly value of traffic flow during 2013-2015 in this point was 254,832 vehicles and the annual average was 3,057,988 vehicles (URL 4). Road traffic PM10 emissions for

Patio Bonito were calculated based on annual traffic road in 2013, that was 2,814,568 vehicles, with a monthly average of 234,547 vehicles and these are presented in equation 2.

$$E=EF*A*S \qquad \text{Eq (2)}$$

Where:

E - Total emission (g)

EF - Emission factor ($g.km^{-1}.vehicle^{-1}$)

A - Activity factor (km)

S - Number of vehicles

The emission factors were taken from Manzi *et al*., (2014), who applied a model named STREET, which is an empirical model that relates meteorological variables, traffic variables, street geometry and dispersion. This model was applied in an inverse method way for a sample of almost 400,000 vehicles in Bogotá, and results compared with other similar studies in South American cities like Santiago de Chile (Manzi, Belalcazar, Giraldo, ZARATE, & CLAPPIER, 2003).

Engine dynamic and opacity tests were performed by the CAR during the period 2006–2007 in Casablanca toll, covering a sample of 191 vehicles. For this sample, 143 vehicles used gasoline (75%) and 48 vehicles used Diesel (25%). Based on this distribution and on the annual traffic road identified at Casablanca toll in 2013, it was assumed that 2,110,926 vehicles use gasoline and 703,642 use diesel.

Thus, for the PM10 emissions calculation two type of vehicles were assumed: the light category vehicles (vehicle passenger, campers and vans), and the heavy category vehicles (buses and trucks). Another needed variable for the PM10 emissions calculation was the length of the section of the road that crosses Patio Bonito, which is 3.186 km. Table 8 shows the used emission factors, selected variables and the estimated annual PM10 emissions.

Table 8 Estimated emissions from road traffic based on vehicle category (Sánchez, 2016)

Vehicle Category	Fuel	Traffic annual flow (vehicle/year)	Length section of road (km)	Emission factor g/km*vehicle PM10	Total annual PM10 emission (ton/year)
Light	Gasoline	2,110,926	3.186	0.27	1.8
Heavy	Diesel	703,642		2.38	5.3
Total					**7.1**

Despite the larger number of gasoline vehicles, according to data presented, diesel vehicles are the main contributors to PM10 emissions. Aiming to better understand the contribution of kilns and road traffic emissions to atmospheric emissions in Patio Bonito, a comparison using data previously estimated is presented in table 9.

Table 9 Comparison between estimated emissions (Sánchez, 2016)

Emission source	Total annual PM10 emissions (ton/year)
Brick Kilns	2147
Traffic road (Casablanca toll)	7.1
Total	**2154.1**

Even knowing that a high level of uncertainty is associated to presented values, it is clear the strong contribution of brick kilns to PM10 emissions (99.6%), when compared with the traffic road emission sources.

3.3 Air quality

The Regional Autonomous Corporation of Cundinamarca (CAR), which has jurisdiction over the region of Cundinamarca, monitors the air quality in Patio Bonito rural locality. The CAR has a regional air quality network, which operates 19 automatic monitoring stations distributed in all the regional territory, two of them, located in the urban area of the municipality of Nemocón and another one at the public school of Patio Bonito.

The Colombian air quality management has been adopting legal frameworks in the last twenty years. It has been common the use of international references as those related to the Environmental Protection Agency of the United States (USEPA). Currently, legislation on air quality aspects in Colombia are established in the following normative:

- Decree 948 of 1995
- Decree 979 of 2006
- Resolution 909 of 2008
- Resolution 910 of 2008
- Resolution 610 of 2010
- Resolution 651 of 2010
- Resolution 2154 of 2010

Basically, those normative aim defining the maximum permissible levels of criteria and non-conventional atmospheric pollutants (Ministerio de Ambiente, 2010). The limit values are calculated according to how much pollutant can a person be exposed in a short or longer period.

The Resolution 909 of 2008 and the Resolution 910 of 2008 establish the permissible values of air pollutant emissions from stationary and mobile sources respectively. The Resolution 2154 of 2010 identifies types of emission control systems and gives some technical recommendation for monitoring emission sources.

The national legislation is also aimed at sorting source or non-compliance areas. According to the Decree 979 of 2006, different types of source areas can be classified as:

- Class I-areas of high pollution: if the pollutants concentration, in background and dispersion conditions, exceed the annual limit value with a frequency equal or larger than 75%.

- Class II-areas of medium pollution: if the pollutants concentration, in background and dispersion conditions, exceed the annual limit value with a frequency equal or larger than 50% and smaller than 75%.

- Class III-areas of moderate pollution: if the pollutants concentration, in background and dispersion conditions, exceed the annual limit value with a frequency equal or larger than 25% and smallest than 50%.

- Class IV-areas of marginal pollution: if the pollutants concentration, in background and dispersion conditions, exceed the annual limit value with a frequency equal or larger than 10% and smaller than 25%.

Moreover, the Colombian legislation also provides information for the declaration of levels of prevention, early warning and emergency. The definition of those levels is given based on short-term rules for a particular pollutant (Ministerio de Ambiente, 2006).

The Resolution 651 of 2010 created the *Subsistema de Información de la Calidad del Aire* (SISAIRE), as the main national information source. It also establishes the obligation to report air quality information to the SISAIRE by all the regional authorities. The *Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia* (IDEAM) does the administration of the information.

On the other hand, the Colombian Air Quality Index (ICAR) is the index that reports the daily air quality. This is associated to health effects of a exposed population to major air pollutants and recommends preventive actions to be taken (URL 5). For every air pollutant, the ICAR is calculated following the methodology used by the USEPA for the reporting of the daily Air Quality Index (AQI). The reported ICAR is the highest value obtained from the different individual equations (IDEAM, 2012) as shown in equation 3.

$$\mathbf{Ip} = \frac{\mathbf{IHi} - \mathbf{ILo}}{\mathbf{BpHi} - \mathbf{BpLo}} (\mathbf{Cp} - \mathbf{BpLo}) + \mathbf{ILo} \qquad \text{Eq (3)}$$

Where:

Ip = Index for pollutant p

Cp = concentration measurement for pollutant p

BpHi = Break-point of the concentration at the upper limit of the ICAR category

BpLo = Break point of the concentration at the lower limit of the ICAR category

IHI = Value of the index at the upper limit of the ICAR category, corresponding to BpHi

ILo = Value of the index at the lower limit of the ICAR category, corresponding to BPLo

The index Ip corresponds to a dimensionless value calculated from concentration values recorded by monitoring stations, taking into account the limits established by the legislation and the harmful health effects, for SO_2, NO_2, Ozone (O_3), CO, PM10 and TSP. The ICAR values vary between 0 and 500, with the higher index representing the worst air quality. The zero value corresponds to a zero pollutant concentration, and for an index higher than 100 population should be informed for health protection. Table 10 presents the ICAR values and the levels of health concern.

Table 10 Air quality index values

Air quality Index values (ICAR category)	Levels of health concern	Break-point of the concentration		
		PM10 24 h µg/m^3	SO_2 24 h µg/m^3	NO_2 1h µg/m^3
0 to 50	Good	0	0	0
		54	90	100
51-100	Moderate	55	91	101
		154	200	190
101 -150	Unhealthy for sensitive groups	155	201	191
		254	480	680
151-200	Unhealthy	255	490	681
		354	800	1220
201-300	Very unhealthy	355	801	1221
		424	1580	1880
301 to 500	Hazardous	425	1581	2350
		504	2100	3100

In 2009 air quality monitoring started in Patio Bonito with the operation of one monitoring station administrated by the CAR. It is located at the local public rural school of Patio Bonito and is identified as Checua station. Using the values from table 10 is possible to calculate the ICAR, based on historical daily values from the air quality monitoring station in Patio Bonito (Checua station). Table 11 presents the highest daily averages of PM10 and SO_2 during the period 2013-2015 and the calculation of the ICAR.

Table 11 Air quality Index ICAR (2013-2015)

Date	Pollutant	Daily average concentration (µg/m^3)	Daily limit Res. 610/2010 (µg/m^3)	Ip Value	ICAR
08/08/2013	PM10	285.65	100	166.1	UNHEALTHY
20/11/2013	PM10	281.47	100	164.1	
24/11/2013	PM10	251.78	100	149	UNHEALTHY FOR SENSITIVE GROUPS
10/10/2014	PM10	79.19	100	63	MODERATE
14/10/2014	SO_2	60.18	250	33.4	GOOD
10/05/2015	PM10	80.81	100	63.7	MODERATE
21/10/2015	SO_2	49.71	50	27.6	GOOD

Results from table 11 show that the air quality monitoring data in Patio Bonito presented an air quality between good and unhealthy for the period 2013-2015. The unhealthy air quality index is due to daily PM10 concentrations, which, in some days exceed the daily limit value (100 µg/m^3) defined in the Resolution 610 of 2010 and the WHO daily limit (50 µg/m^3).

The moderate air quality implies that for some pollutants there may be a moderate health concern for individuals who are unusually sensitive to air pollution (USEPA, 2014). An unhealthy air quality implies that people may begin to experience health effects, members of sensitive groups may experience more serious health effects. Thus, prevention measures should be implemented, especially for sensitive people with asthma, with cardio-cerebrovascular disease as arterial hypertension, lung disease, emphysema and chronic bronchitis; strong or prolonged physical activity should be reduced (IDEAM, 2012).

4. AIR QUALITY MODELING

Air quality numerical modeling comprises the mathematical simulation of air pollutants dispersion in the atmosphere. Dispersion models are used to estimate concentration of air pollutants emitted from sources such as industrial plants and vehicular traffic.

The Gaussian model is perhaps the oldest and the most commonly used model type. It assumes dispersion based on the Gaussian distribution, meaning that the pollutants have a normal probability distribution. Gaussian models are most often used for predicting the dispersion of continuous, buoyant air pollution plumes originating from ground-level or elevated sources.

4.1 The Gaussian air quality model URBAIR

The URBAIR model was selected for the simulation of PM10 levels in Patio Bonito because of its simple and accurate handling of the input variables. It is a second generation Gaussian atmospheric dispersion model developed at Universidade de Aveiro (Borrego *et al*., 2011). This model is different from traditional Gaussian dispersion models, because its dispersion parameters have a continuous variation with the atmospheric stability. The model is suitable to be used for distances up to about 10 km from the source (Borrego & Martins, 1997).

The URBAIR model has been used in different European study cases, for instance cases in Helsinki, Athens and Gliwice (Borrego *et al*., 2011) where traffic emissions were estimated and concentration of different air pollutants in an hourly basis for the entire year of 2008 were simulated (Borrego *et al*., 2011). One of the advantages of this model is that it provides almost real time results to support planning decision at urban level in a GIS definition platform using maps (Oliveira, 2012). It also integrates the pre-processing of urban morphology, meteorological data and traffic emissions in a single tool.

This model can consider different types of sources as well the temporal and spatial variability of pollutant emissions, simulating short or long term periods and different pollutants (including heavy gases).

The model needs input data that are categorized as control, meteorological, topography, land use sources and pollutant emissions. Table 12 lists the main input data of URBAIR model.

Table 12 Main inputs data for URBAIR model

Cartography	Meteorology	Buildings	Sources	Receptors
-Digital area -GIS integrated	-Hourly values of wind speed, wind direction, temperature and atmospheric pressure. -Daily values of mixing layer height	-Location -Heights and overall dimensions (3D)	-Location -Stacks height -Stacks diameter -Exit gases temperature -Exit gases speed -Traffic flow -Average speed and vehicles fleet	-Definition by grids -Surface height

The application of the URBAIR model within this study is specifically focused on the assessment of the contribution of brick manufacturing industry to the PM10 levels in the Patio Bonito rural locality. Other emission sources like fugitive sources are not included in the present case study because of the lack of information. Road traffic emissions were not considered because of their small contribution in relation to the brick kiln sources.

4.2 Selection of episodes

For the application of the model it was necessary to define a simulation period. August 8, November 20 and 24 of 2013, were selected, coinciding with the days with the highest daily exceedances of PM10 concentrations. Figure 23 shows the daily time series of PM10 concentrations in 2013 measured by the CAR in Patio Bonito (Checua station). The WHO guidance value for human health protection and the Colombian PM10 daily limit value are also shown.

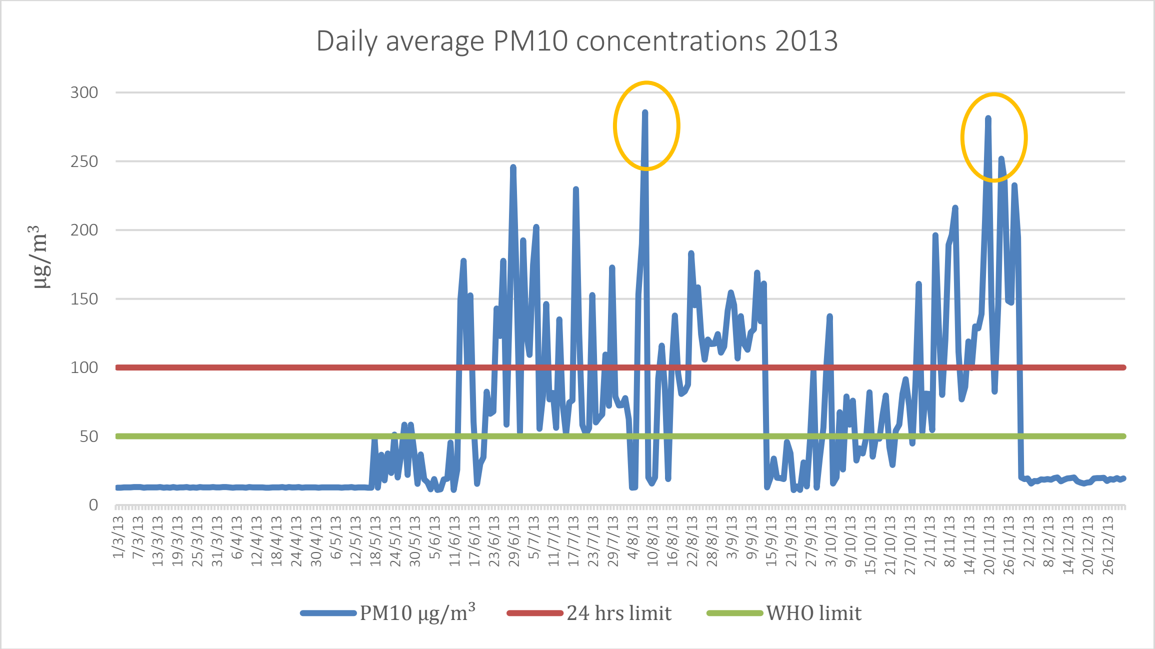


Figure 23 Daily average PM10 concentrations (µg/m^3) in 2013

Between January and May, daily PM10 concentration values were below 100 µg/m^3, which is the daily limit regulated by the Resolution 610 of 2010. However, the observation of the data for this period indicates a potential problem with PM10 measured data. Between June, July, August, September and in November the highest PM10 concentration values were measured, which were frequently above 100 µg/m^3.

Aiming to better understand a seasonal trend, monthly averages of PM10 concentrations in Patio Bonito were calculated and presented in figure 24.

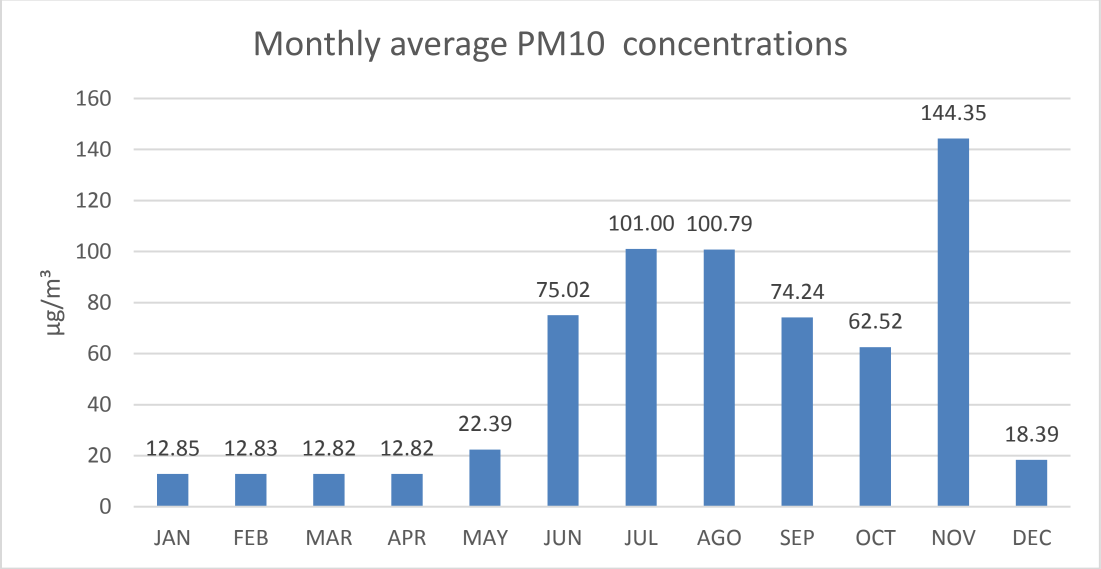


Figure 24 Monthly average PM10 concentrations in 2013

In general winter months present the highest values of PM10 concentrations. In 2013, there is a particular peak in November, which declines rapidly in December. Figure 25 presents the daily PM10 exceedances values along August and November.

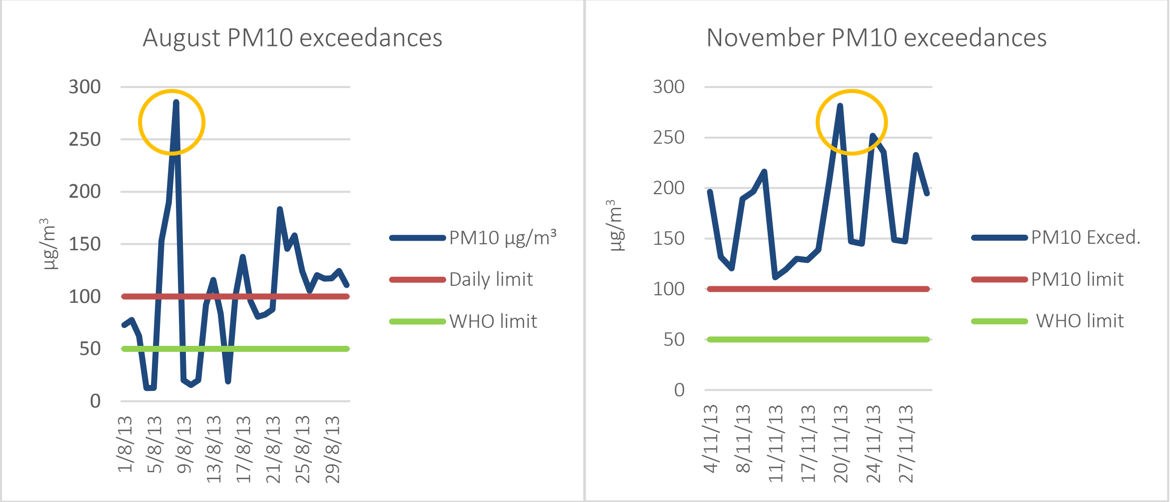


Figure 25 PM10 exceedances in August and November in 2013

Although daily PM10 concentrations are high, daily exceedances values do not exceed the limits for declaring an exceptional state such as prevention, alert and emergency established in the article 10 of the Resolution 610 of 2010 (300 µg/m³, 400 µg/m³ and 500 µg/m³ respectively). The peaks of PM10 concentrations were registered in August 8, November 20 and 24 and these periods were identified as:

- Episode 1: August 8, registered exceedances of PM10 concentrations of 285.65 µg/m^3.
- Episode 2: November 20, registered exceedances of PM10 concentrations of 281.47 µg/m^3.
- Episode 3: November 24, registered exceedances of PM10 concentrations of 251.78 µg/m^3.

4.3 Application of the air quality model URBAIR

The URBAIR model was applied to the Patio Bonito study case, simulating PM10 hourly ground level concentrations for the three air pollutants episodes. In order to run the model properly, it is necessary to provide the different types of input data for a selected simulation domain.

4.3.1 Simulation domain

The definition of the study domain is a very important step to start a simulation exercise. A regular Cartesian grid was defined for the calculation of PM10 concentrations values, with spatial resolution of 20 m x 20 m. Figure 26 shows the selected domain that has a dimension of 2 km x 3 km including the rural locality of Patio Bonito and covers strategic areas as a brickworks cluster and its populated center.

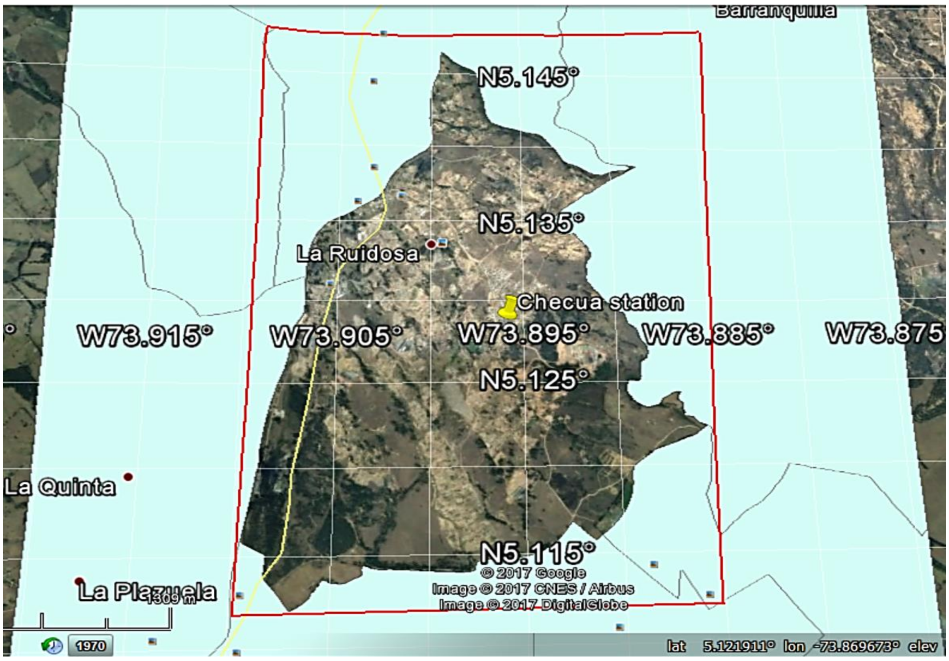


Figure 26 Satellite image of the study domain Google Earth, (2017)

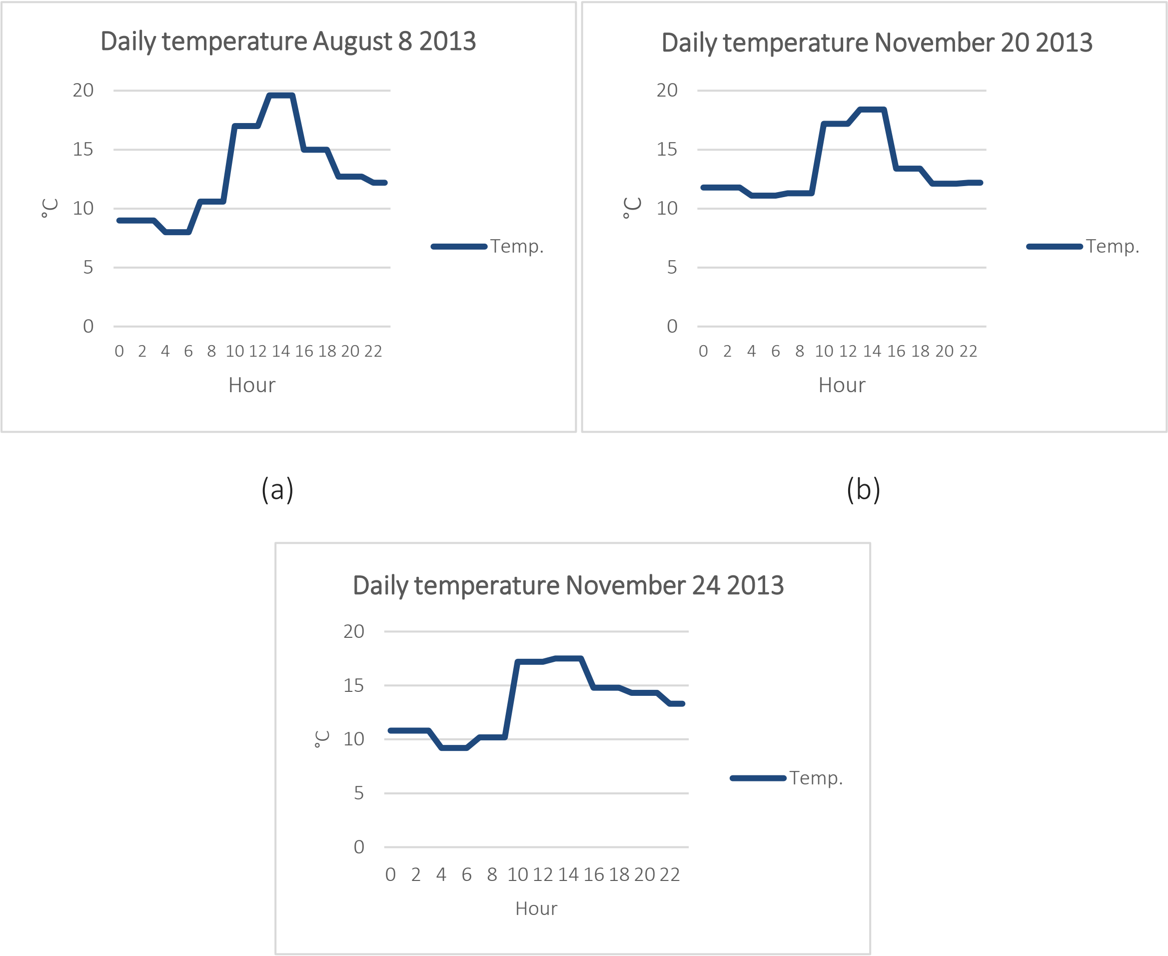
The selected domain corresponds to Patio Bonito and includes boundaries with other rural localities such as “Cerro Verde”, “Pajarito”, “Chorrillo” and “Casa Blanca”, with brickfields that also surround the populated area of Patio Bonito. Buildings volumetry was not considered, because only 150 small houses are in the domain. The topography was assumed as flat terrain. The local air quality monitoring station (Checua) is a particular receptor point. It is located in the rural school of Patio Bonito, that has 650 students, who are vulnerable population to air pollution.

4.3.2 Meteorological data

The meteorological input parameters correspond to data registered in the meteorological station of the international airport El Dorado in Bogotá D.C (WMO ID 80222), operated since 2009 and located approximately 70 km from Patio Bonito rural locality. It was not possible collecting data from the local station due to a lack of information for the year 2013. These parameters correspond to tri-hourly data.

Meteorological hourly data were used for the selected periods, considering the following variables: temperature at 2 m (ta1) (°C), wind speed at 10 m (vv1) (m/s), wind direction at 10 m (dv1) (°), atmospheric pressure (Pa) (Pascal), relative humidity at 2 m (hr1) (%), solar radiation (rad) (W/m^2), ambient air density (roar) (kg/m^3), ambient air heat capacity (Cpar) (J·kg^{-1}K^{-1}), ambient dry air heat capacity (Cpas) (J·kg^{-1}K^{-1}), stability class (clas) and mixing layer height (zi) (m). The surface roughness height was 0.5 m for rural terrain (I.Taviv *et al.*, 1987).

Figure 27 presents the daily temperature variation at 1 m height for the three selected days, considering three hours period constant values, due to the lack of hourly data.



(a) (b)

(c)

Figure 27 Daily temperature (°C) for August 8, November 20 and 24 of 2013

Historically the annual average temperature in Patio Bonito is 12.8°C. Based on Figure 27 it is possible to observe temperature values above 10°C for August 8 (a), with a daily average of 12.8°C. November 20 and 24 also show temperatures above 10°C (b and c), with daily averages of 13.4°C and 13.3°C, respectively; the hourly period with values above 10°C occurs between 10:00 and 15:00 hrs. Figure 28 presents the monthly wind speed and direction for August and November 2013. Data were collected from the database of the meteorological station El Dorado airport.

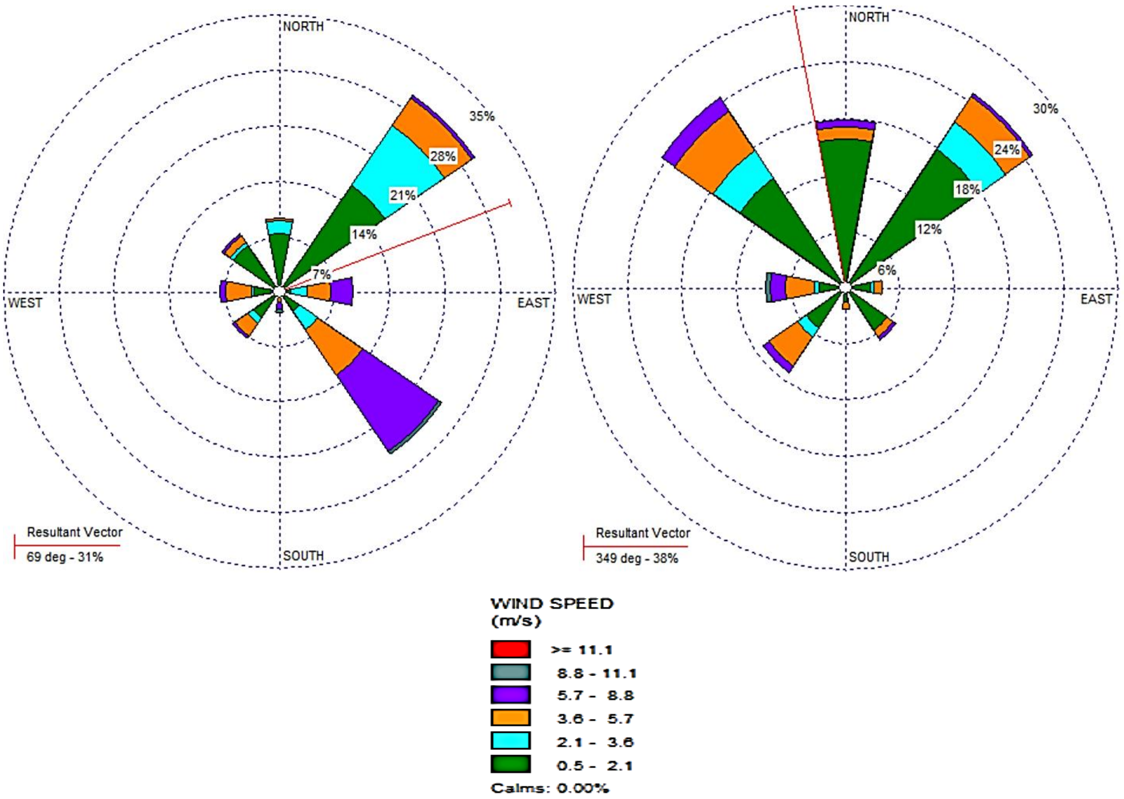
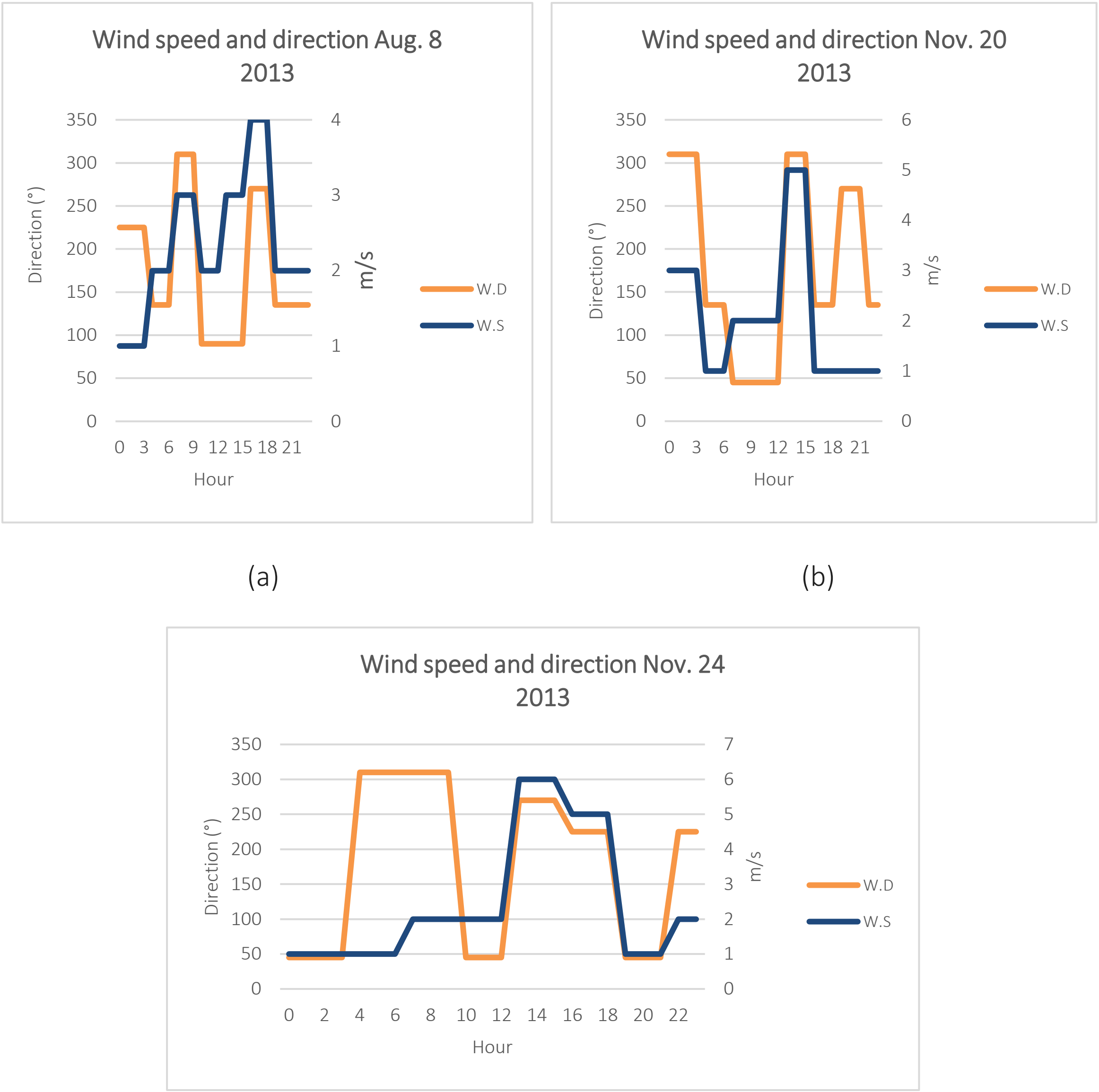


Figure 28 Monthly wind rose for August and November 2013

During August, wind is mainly blowing from Northeast and Southeast. In November, Northeast still is an important sector, but wind is also blowing from North and Northwest. According to figure 28, the predominant wind directions is Northeast, followed by Northwest and Southeast. The averaged wind speed was 3.4 and 2.5 m/s, respectively. The major frequency of the wind speed class was between 0.5 and 2.1 m/s with 42 and 65%, respectively. Figure 29 shows the wind speed and direction at 1 m height for the selected episodes.



(a) (b)

(c)

Figure 29 Wind speed and direction for August 8 (a) November 20 (b) and November 24 (c) 2013

Figure 29 shows the relation between wind speed and direction for the three selected days. These are mainly blowing from Northwest, Southwest and Southeast (a and b). The highest wind speed value was 7 m/s (c), presented in November 24. Calm wind conditions are not observed. The daily average of wind speed was 2.3 m/s.

4.3.3 Brick kiln emissions

Within the selected domain and taking into account information from the municipal authorities, 74 kilns were identified and simulated as point sources. Table 13 lists the number and type of kilns considered by URBAIR and figure 30 shows the location of these emitting sources.

Table 13 Emission point sources

Kiln type	Number
Fuego dormido	61
Colmena	9
Hoffman	3
Tunnel	1
Total kilns	**74**

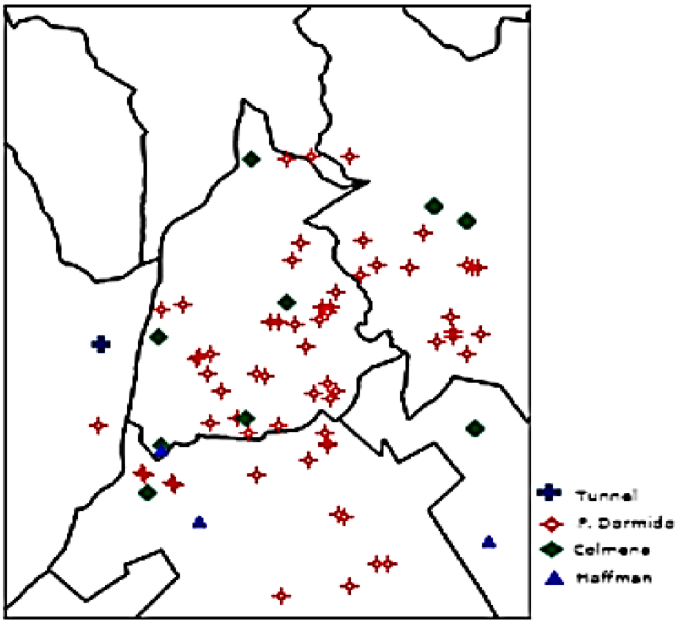


Figure 30 Emission point sources in Patio Bonito influence area

The first type of brick kilns is categorized as artisanal, second as semi-technified and the other two as technified kilns. 61 Fuego dormido kilns were considered due to their nearby location of the rural school and populated center of Patio Bonito. The other kilns are part of the area of Patio Bonito and some of them are located in boundaries of other rural localities. Based on emissions information of Patio Bonito. Emissions from brick kilns were estimated and are presented in table 14.

Table 14 Emission source data from 74 brick kilns for URBAIR

Type kiln	Total annual Coal consumption (ton/year) Per kiln	Emission factor (kg/ton coal) PM10	Total annual emission (ton/year) PM10
Fuego dormido	11,129	24	267
Colmena	7776	10	78
Hoffman	3060	3	9.2
Tunnel	1200	0.8	0.96
Total			**355.2**

Table 14 shows the estimated emissions for the selected number of brick kilns in the study area. 61 Fuego dormido kilns have the highest PM10 emissions and a high annual coal consumption. The three Hoffman and one Tunnel kilns are lesser contributors to PM10 emissions and annual coal consumption.

However, for a better simulation exercise, PM10 emissions and source characteristics for the Colmena, Hoffman and Tunnel kilns are based on emissions reports from some brick manufacturing companies of the study area (in normal operational conditions). Table 15 shows these emission values as provided to URBAIR.

Table 15 Emission sources input data URBAIR

Type kiln	Source	Stack height (m)	Stack diameter (m)	Gas flow rate (g/s)	Gas exit speed (m/s)	Temp (°K)
Hoffman	1	15	0.78	0.8	13.9	360
	2	15	0.9	1.1	11.7	343
	3	16.7	0.83	1.6	13.6	355
Colmena	4	17.7	0.95	0.34	5	500
	5	17	1.56	0.61	4.8	598
	6	18.5	1	0.75	5.4	561
	7	18	1	1.1	5.9	575
	8	16	0.85	0.58	4.8	550
	9	15.5	0.9	0.55	4.9	550
	10	16	0.8	0.44	4.9	500
	11	15.5	0.95	0.45	5.5	490
	12	17	1.1	0.35	5	480
Tunnel	13	15	0.9	0.05	10	320

Because of the lack of emission source data for the Fuego dormido kilns, PM10 emissions and source characteristics are based on the study developed by Rodriguez and Piñeros (2011), Table 16 shows these emission values as provided to URBAIR.

Table 16 Emission sources input data URBAIR

Type kiln	Source	Stack height (m)	Stack diameter (m)	Gas flow rate (g/s)	Gas exit speed (m/s)	Temp (°K)
F.dormido 15000	14-20	6	5	0.08	0.3	399
F.dormido 20000	21-44	6.3	5.5	0.11	0.35	401
F.dormido 25000	45-53	6.6	6	0.14	0.4	398
F.dormido 30000	54-60	7	6.5	0.17	0.45	403
F.dormido 35000	61-65	7.3	7	0.2	0.5	403
F.dormido 40000	66-74	7.7	7.5	0.23	0.55	412

Rodriguez and Piñeros (2011) also considered the nominal coal consumption capacity per Fuego dormido kiln and calculated the individual characteristics of these emission sources.

4.3.4 Background concentration

The background concentration value is important because it represents the concentration of a given air pollutant in which anthropogenic emissions are negligible (in a natural condition). The PM10 background concentrations were estimated for 2013, selecting values below the guidance value established by the WHO (50 µg/m^3). Figure 31 shows the PM10 background concentrations of 2013 in Patio Bonito.

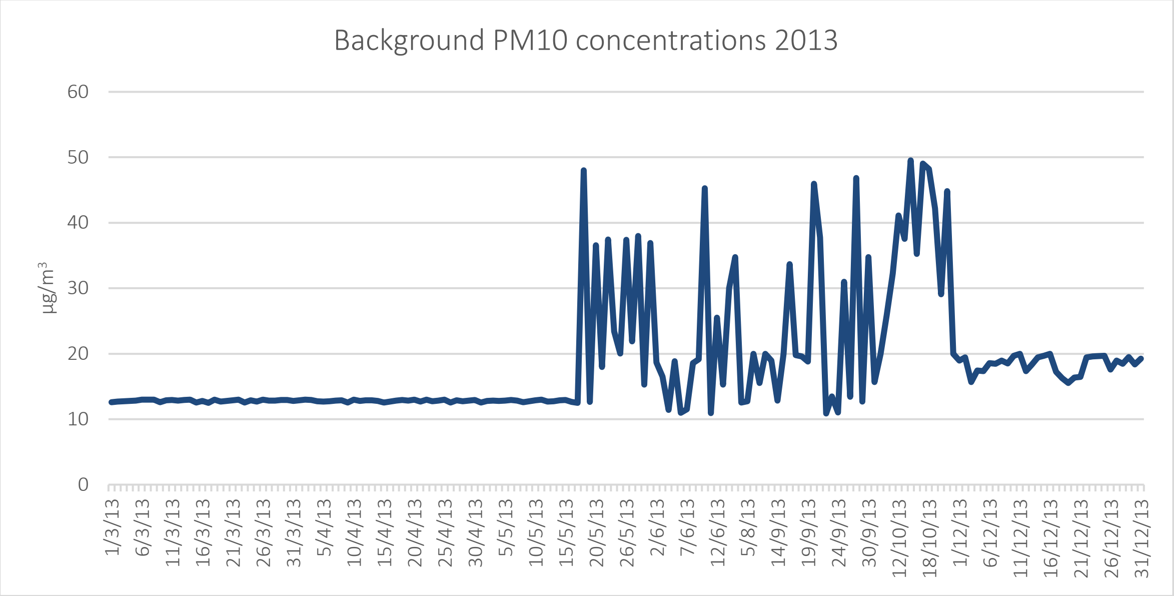


Figure 31 PM10 background concentrations in 2013

The PM10 background concentrations in 2013 had an average of 18.5 µg/m^3, value estimated according to the data from the air quality station Checua operated by the CAR. It is important to mention that this environmental authority does not count with a background air quality station, which could assess this kind of concentration.

4.4 Results

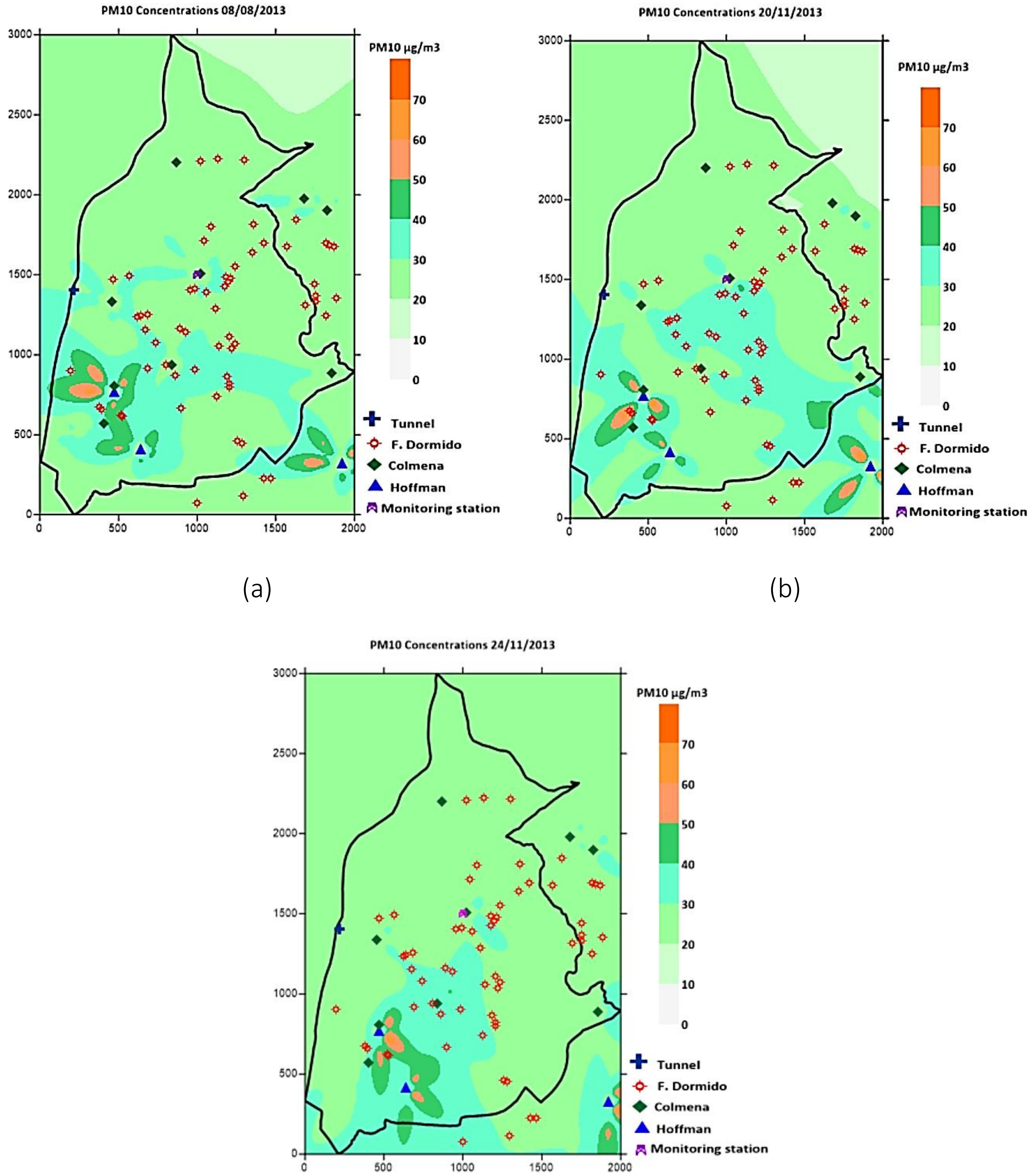
Once the pollutant dispersion simulations are carried out, it is necessary to perform a post processing of the obtained data, for a subsequent representation of the results generated by the model. The output data of the URBAIR model provided hourly concentration for each receptor of the grid, for the three simulation period (August 8, November 20 and 24 of 2013).

After the processing of the output information of the URBAIR model, namely the calculation of daily averages, results were represented using the SURFER 9 software. This software spatially interpolates concentration values.

Figure 32 presents the spatial distribution of daily averaged values of PM10 concentrations for August 8, November 20 and 24 of 2013 generated by the 74 brick kilns in operation and includes the PM10 background value averaged. It is important to note that the modeling exercise did not take into account the PM10 contribution resulting from fugitive sources due to lack of information; those could also impact air quality and the community of Patio Bonito.

The simulated PM10 concentrations had maximum values of 62.8, 69.8 and 66.7 µg/m^3 for the three selected days respectively. It is noted concentrations between 40 and 60 µg/m^3, mainly around the location of the Hoffman kilns (a, b and c).

The Southwest zone, where Hoffman, Colmena and Fuego dormido kilns are concentrated and characterized by having the highest PM10 concentrations; PM10 concentrations below 40 µg/m^3 were calculated in the zone where the Tunnel kiln is located (a, b and c). The area where is located the rural school (the monitoring station Checua) presented PM10 concentrations ≤ 30 µg/m^3. The North zones present concentrations of 10 µg/m^3 (a and b).



(a)

(b)

(c)

Figure 32 Spatial distribution of the PM10 concentrations in 2013, resulting from the simulation of August 8 (a), November20 (b) and November 24 (c), considering 74 brick kilns emissions

The simulated PM10 concentrations exceed the daily value recommended by the WHO (50 µg/m^3). These values are considered as responsible for a moderate air and represent a certain risk for the health of Patio Bonito inhabitants. However, these PM10 values are below the daily allowed limit regulated by the Resolution 610 of 2010 (100 µg/m^3).

Finally, it is important to mention that the resulting simulated values were not compared with the measured values due to the lack of daily information of PM10 concentration measured in 2013 by the CAR.

5. IMPROVEMENT MEASURES

In order to control emissions generated from kilns sources and therefore improve the air quality in Patio Bonito some measures are proposed. These measures can be implemented in a short, medium or long term.

5.1 Short terms measures

These measures include a set of actions that can be done and that promote the use of better processes and brickwork technologies in Patio Bonito.

- ***Technological reconversion program:*** it is important to maintain the kilns technological reconversion program in medium and big brick industries, which is promoted by the *Corporación Ambiental Empresarial* (CAEM) with the support of different governmental entities and joining more industries. This program helps micro-enterprises to facilitate the acquisition and implementation of clean technologies as dosage systems, stockers, carbojets and coal gasifiers (CAEM, 2011).

  The program also contemplates the substitution of Fuego dormido kilns by Colmena kilns with emission control systems and offers technical assistance for its adequate operation.

- ***Coal storage and feed:*** the coal should be stacked on a raised platform with flooring and proper drainage arrangements. Coal should preferably be stored under shed with proper ventilation. Systems should be established to measure and control the dosage of fuels by means of flow meters for either liquid or gaseous fuels. In addition, it is necessary to establish a better control in the cooking to eliminate the cooked or undercooked brick, this would save fuel and has a greater efficiency in the production.

- ***Size of coal:*** small sized coal improves air-fuel mixing thus accelerating the rate of combustion. Appropriate size of coal can be obtained by screening/crushing of large sized coal. The coal crushing should be done in an enclosed area with high walls to avoid fugitive emissions.

- ***Mitigation of fugitive emissions:*** in brick plants, the reused water should be sprinkled frequently over roads. The frequency of irrigation should be defined according to the climatic conditions that predominate in the area. In addition, vacuum cleaners systems can be applied in kilns and in main work areas of brickworks to reduce fugitive emissions. The vehicle circulation areas of brick plants must be of sufficient humidity to minimize the lifting of particulate matter. Likewise, rows of trees could be planted along the outer periphery of brickworks.

- ***Operational conditions of kilns:*** kilns must be checked and periodic maintenance performed to ensure proper operation. It can be done by the mutual collaboration between owners, consulters specialized in brick kilns and the environmental authorities at national and regional levels. It is important that government entities support the formation and training of workers to reach the better operational conditions in brick kilns.

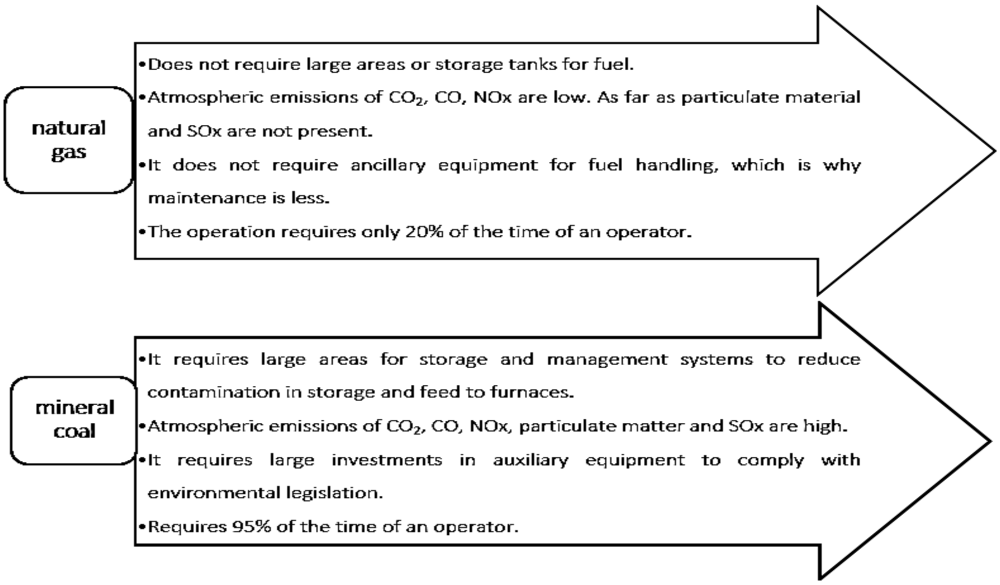
5.2 Medium term measures

The following measures can be implemented in a medium term (between 1 and 3 years) in Patio Bonito.

- ***Mitigation and control policies:*** in order to avoid an increasing number of Fuego dormido kilns, and to face illegality problems of brickworks, is necessary to control the licenses granted (environmental, mining and land-use) and to organize community cooperatives to acquire efficient kilns. Brickworks legally registered in environmental programs, as those offered by CAEM and Ministry of environment, will have technical support and economic benefits, because there is an investment in environmental improvement of their productive processes.

- ***Improvement of unpaved roads:*** in Patio Bonito the dust emissions from unpaved roads can be mitigated with an improvement plan of local roads executed by the municipal authority.

- ***Change of fuel:*** the majority of kilns in Patio Bonito use coal and it is important to carry out a replacement of fuels. In Colombia one of the most viable alternatives to replace coal is the use of natural gas due to its important reserves. In the case of kilns like Colmena and Hoffman, coal can be replaced by gas. It is necessary the enlargement and construction of connections to provide this change. The use of natural gas as fuel could decrease the emission of NOx, SOx and PM that are emitted with the use of coal. The substitution of coal by natural gas has several advantages. Figure 33 compares the use of natural gas and coal as fuel for semi and technified brick kilns.



- Does not require large areas or storage tanks for fuel.
- Atmospheric emissions of CO_2, CO, NOx are low. As far as particulate material and SOx are not present.
- It does not require ancillary equipment for fuel handling, which is why maintenance is less.
- The operation requires only 20% of the time of an operator.

- It requires large areas for storage and management systems to reduce contamination in storage and feed to furnaces.
- Atmospheric emissions of CO_2, CO, NOx, particulate matter and SOx are high.
- It requires large investments in auxiliary equipment to comply with environmental legislation.
- Requires 95% of the time of an operator.

Figure 33 Comparison between Natural gas and mineral coal (Rodriguez & Piñeros, 2011)

- *Energy save in drying phase:* kilns like Colmena, Hoffman and Tunnel can adapt heat recovery systems in order to improve the drying of the bricks and reuse the energy of the production process.

- *Emission control systems:* implementation of different type of filters, scrubbers or another kind of control system allows to control the pollutant emissions and to ensure compliance with the current legislation. Taking into account that this is a medium term applicable option, a particular scenario of improvement is proposed, which takes into account the installation of cyclone control systems in Colmena kilns in Patio Bonito. The impact of this measure in the PM10 levels was assessed through the application of the URBAIR model.

Scenario 1: Colmena kilns operating with emission control systems

Taking into account the emission control system recommended for Colombia and established in the Resolution 2153 of 2010 (monitoring and control protocol for fixed emission sources), a control measure for reducing emissions from Colmena kilns was simulated considering 9 Colmena kilns operating with conventional cyclones instead of the current 9 Colmena kilns without any type of control system.

The cyclone is essentially a sedimentation chamber in which the gravitational acceleration is replaced with the centrifugal acceleration. They are suitable for separating particles with diameters greater than 5 µm, although many smaller particles, in certain cases, can be separated. They can be made from a wide range of materials and can be designed for high temperatures (up to 1000°C) and operating pressures. In Colombia, conventional cyclones for brick manufacturing activities usually have an removal efficiency between 30-90% for pollutants as PM10. (Londoño Echeverri, 2006).

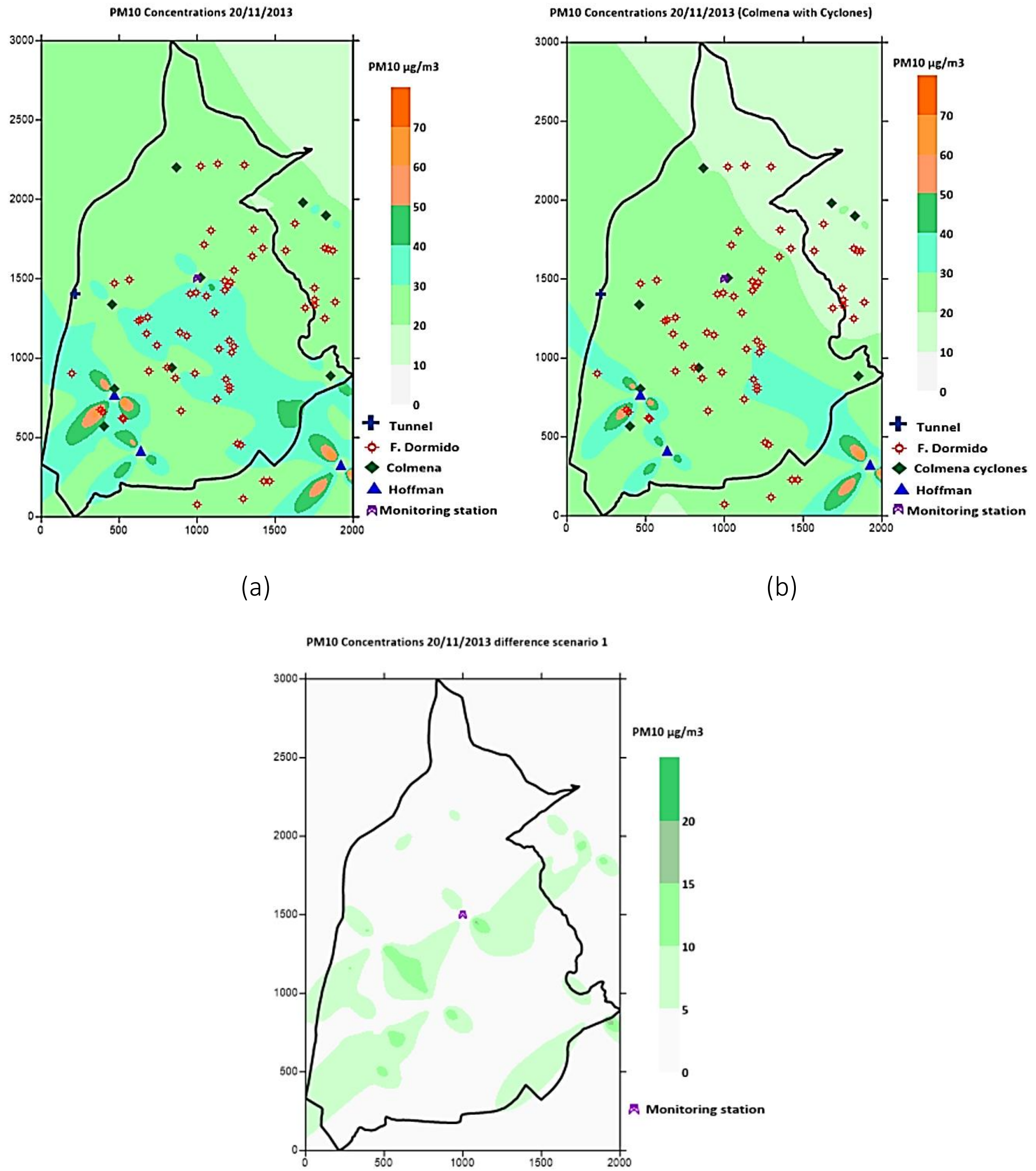
The proposed improvement scenario was based on a cyclone control system with a removal efficiency of 90% for the 9 Colmena kilns in the study area of Patio Bonito. URBAIR was applied with the same input data and considering the meteorology of the November 20 of 2013, which was the worst PM10 pollution episode.

This scenario considered 9 Colmena kilns from the list of 74 brick kilns for selected episode of November 20 2013. The emission sources input data are presented in table 17.

Table 17 Emission sources input data (improvement scenario 1)

Type kiln	Source	Coo X	Coo Y	Stack height (m)	Stack diameter (m)	Gas flow rate (g/s)	Gas exit speed (m/s)	Temp. (°K)
Colmena	1	470	808	17.7	0.95	0.034	5	500
	2	404	571	17	1.56	0.061	4.8	598
	3	839	939	18.5	1	0.075	5.4	561
	4	1853	887	18	1	0.11	5.9	575
	5	457	1334	16	0.85	0.058	4.8	550
	6	1023	1505	15.5	0.9	0.055	4.9	550
	7	1826	1900	16	0.8	0.044	4.9	500
	8	1682	1979	15.5	0.95	0.045	5.5	490
	9	865	2202	17	1.1	0.035	5	480

Figure 34 shows the spatial distribution of PM10 levels according to the previous simulated episode of November 20 of 2013 without emission control systems; in addition, it includes the improvement scenario 1 and a difference scenario.



(a) (b)

(c)

Figure 34 Spatial distribution of the PM10 concentrations for November 20/11/2013 (a), simulation including Colmena kilns with control system cyclones (b) and the difference scenario (c)

The maximum simulated PM10 value for this scenario was 69.1 µg/m^3 (reduction of 0.7 µg/m^3 compared to the simulated episode of November 20). The central area of Patio Bonito presents a reduction of PM10 concentrations levels of 10 µg/m^3 (b) compared to the simulated normal episode (a). In the zone where the rural school is located, the PM10 levels were 20 µg/m^3 (b). Thus, it is evident a reduction of PM10 contribution from brick kilns with the implementation of this type of improvement measures. The difference scenario of simulated PM10 concentrations reached a maximum value of 17.2 µg/m^3 (c) (below WHO recommended daily value), having a positive impact on air quality and on human health.

5.3 Long-term measures

Long term measures include measures that can be adopted in the brickworks for a period longer than five years.

- ***Feed fuel technology:*** the implementation of a system as coal gasifier for mechanized kilns, could reduce the PM emissions and save fuel in the normal operation. In Colombia there is a brick industry that use this type of technology, which was imported from China and Italy.

A coal gasifier and a gas station compose this system. It adopts a mixture of steam and air as gasifying medium and bituminous coal bulk or anthracite as fuel (diameter between 20 and 60 mm). The coal gasifier has an output suitable for all type of kilns. This technology is defined according to requirements of different kilns. The whole system includes coal yard, slag yard, coal lifting system, coalbunker, coal feeding system, air combustion system, single-stage gasifier, gasifying system, dust removing, auto-control system and safety control, etc. Figure 35 shows a picture of a coal gasifier of single stage.

Figure 35 Coal gasifier of single stage (URL 6)

The characteristics of this system are: simple structure, easy operation and high safety, closed system, direct fire operation, no gas leakage and high utilization of sensible heat.

- ***Replacement of Fuego dormido kilns:*** replacing Fuego dormido kilns by cleaner technologies (e.g. Hoffman and Tunnel kilns with emission control system), would reduce PM and would allow a better dispersion and control of pollutants. It would also increase productivity, generating higher incomes for owners with a better quality of bricks.

Taking into account that those are a long term applicable options, a particular scenario of improvement is proposed to Hoffman and Tunnel kilns operating with emission control system (cyclones) instead of the current kilns without any type of control system.

Scenario 2. Hoffman and Tunnel kilns operating with emission control system

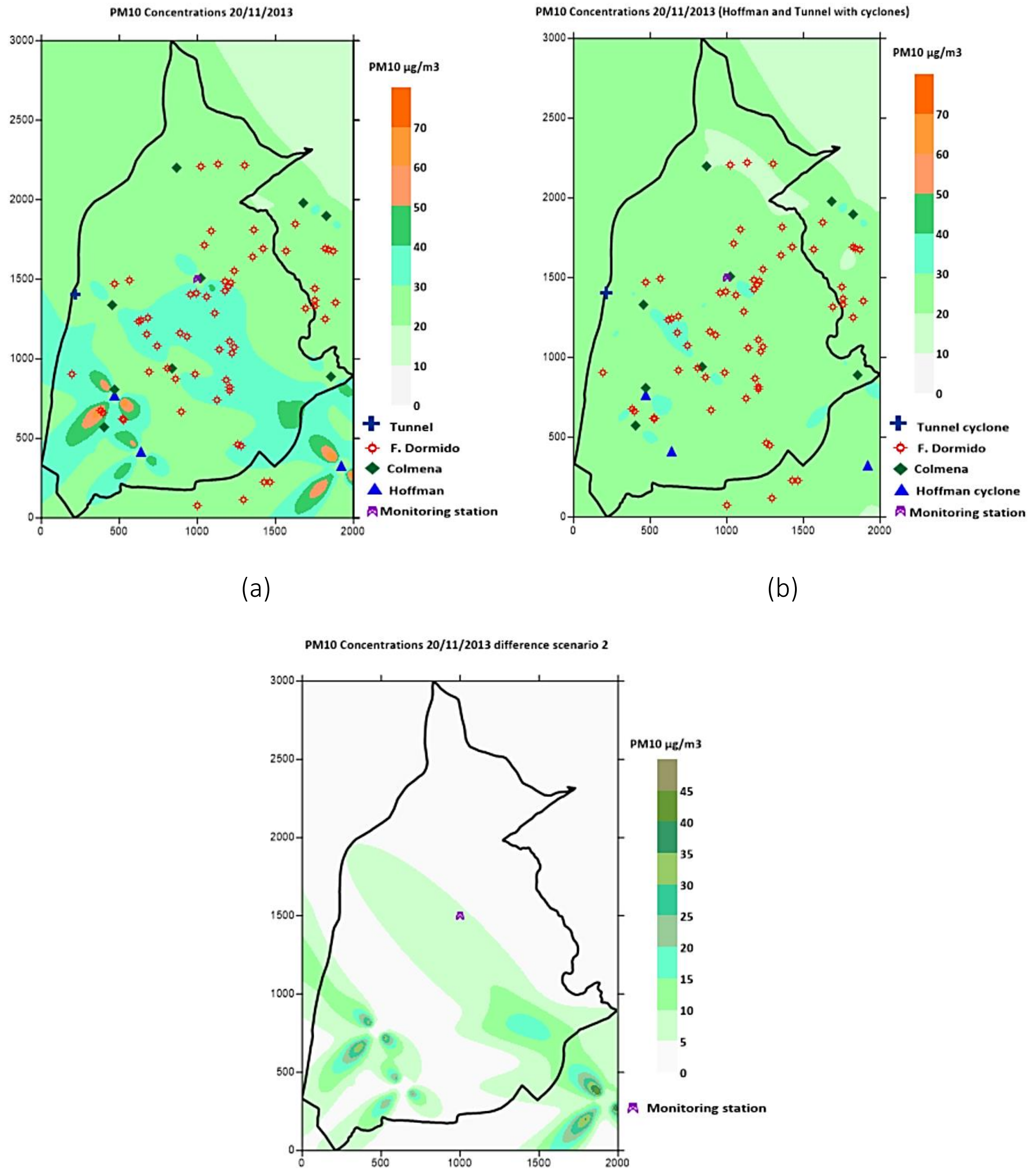
This scenario was based on a cyclone control system with a removal efficiency of 90% for 3 Hoffman and 1 Tunnel kilns in the study area of Patio Bonito. URABIR was applied with the same input data and for the meteorology conditions of the November 20 of 2013, which was the worst PM10 pollution episode.

This scenario considered 3 Hoffman and 1 Tunnel kilns from the list of 74 brick kilns for selected episode of November 20 2013. The emission sources input data are presented in table 18.

Table 18 Emission sources input data (improvement scenario 2)

Type kiln	Source	Coo X	Coo Y	Stack height (m)	Stack diameter (m)	Gas flow rate (g/s)	Gas exit speed (m/s)	Temp (°K)
Hoffman	1	641	413	15	0.78	0.08	13.9	360
	2	470	768	15	0.9	0.11	11.7	343
	3	1922	324	16.7	0.83	0.16	13.6	355
Tunnel	4	276	469	15	0.9	0.05	10	320

Figure 36 shows the spatial distribution of PM10 levels according to the previous simulated episode of November 20 of 2013 without emission control systems; in addition, it includes the improvement scenario 2 and a difference scenario.



(a)

(b)

(c)

Figure 36 Spatial distribution of the PM10 concentrations for November 20/11/2013 (a), simulation including Hoffman and Tunnel kilns with control system cyclones (b) and the difference scenario (c)

The maximum simulated PM10 value for this scenario was 38.9 µg/m^3 (reduction of 30.9 µg/m^3 compared to the simulated episode of November 20).The improvement scenario shows a reduction of the PM10 concentrations levels of 30 µg/m^3 (b).The central area of Patio Bonito presents a reduction of PM10 levels of 10 µg/m^3 (b) compared with the simulated normal episode (a). In the zone where the rural school is located, the PM10 levels were 20 µg/m^3 (b). Thus, it evidence an important reduction of PM10 contribution from brick kilns with the implementation of this type of improvement measures. The difference scenario of simulated PM10 concentrations reached a maximum value of 44 µg/m^3 (c) (below WHO recommended daily value), having a positive impact on air quality and on human health.

5.4 Contingency plan

In the Colombian legislation, the article 94 of the Decree 948 of 1995 (Ministerio de Ambiente, 1995) established the obligation to implement atmospheric contingency plan in order to face air pollution episodes; it was the first in regulating and declaring of pollution source areas In addition, the Resolution 610 of 2010 established the levels of prevention, alert and emergency for air pollution episodes in the national territory. At the urban level is common in Bogotá D.C and Medellín to implement atmospheric contingency plans when an air pollution episode occurs, applying different prevention and control measures like the restriction of heavy vehicles and the stop of some industries.

In Colombia the legislation establishes a daily limit of 100 µg/m^3 for PM10 and an annual limit of 50 µg/m^3 that must be referred in the plan. In addition, has to be considered the ICAR based on the air quality values recommended by the WHO (Bautista, García Bátiz, & González R., 1995). However, this legislation is not clear defining how to implement an contingency plan in a municipality or rural locality like Patio Bonito, where there is a continuous brick manufacturing activity. In this sense, it is important to propose the implementation of a contingency plan that can be applied under this specific condition.

The atmospheric contingency plan (ACP) is the document which establishes procedures and actions to apply by competent authorities, enterprises, and institutions of society in case of an atmospheric contingency. This kind of plan must consider some main aspects that are described below.

Involved sectors: contingency plan should involve at least the following sectors:

- Health sector: with the implementation of an environmental health protocol that makes possible to evaluate the impacts of air quality on local people's health.

- Transport sector: it is recommended to implement restrictive measures focused on local vehicular traffic, especially those heavy vehicles (trucks) that load fine material and bulk fuel (coal).

- Industrial sector: implementing emission reduction measures including restriction in operation of some industries, particularly local brickworks. In addition, the environmental authorities should give technical support in order to control the emissions from these industries and closing those that does not accomplish the emission limits values. Likewise, carry out permanent operations to monitor vehicle emissions, with emphasis on trucks, buses, and motorcycles that transit in the national route 45A and cross the Casablanca toll, is an adequate measure to control the contribution of road traffic emissions. However, in an episode of air pollution, in any case would be possible to limit the operation of ambulances or vehicles intended for the transport of patients, fire-fighting vehicles and law enforcement vehicles.

Participants: various actors that can be responsible to implement the contingency plan, such as municipal environmental secretary, regional environmental authority, municipal and regional mobility secretaries, municipal health secretary, regional environmental health authority, municipal education secretary, municipal public media secretary and the ministry of the environment.

Application zone: the application zone is extended to all territory of Nemocón, with special careless of those rural localities where exist a concentration of brick manufacturing activity.

Infraestructure of the monitoring and surveillance system: in this case it is necessary to count with an authomatic monitoring network in Patio Bonito, which generates continuous information of air quality. This network should be operated by the regional environmental authority CAR and the information daily validated by the ministry of the environment and communicated to the municipal competent authorities.

Besides this, the awareness and publication of the adopted measures must be widely disseminated to the public. The environmental authority as CAR should daily deliver the AQI through its website and should also publish it in the website of the national air quality modeling network SISAIRE. The municipal authority should have a channel of information to local inhabitants, especially those who live in rural localities. This kind of media would allow to take decisions like, for example, to order the suspension of activities of the local educational institutions and order, if needed, the evacuation of the exposed population.

On the other hand, according to the current municipal health plan for Nemocón 2012-2015 (Alcaldia Municipal Nemocón, 2016), a database of the historical medical consults of the Patio Bonito inhabitants is needed, as well a local health protocol that links health with the atmospheric contingency episodes. The technical support and the surveillance by the regional environmental authority and the regional environmental health secretary is fundamental.

The ACP is activated by the environmental authority CAR, that has to inform all participants located in the influence area. Main phases of the contingency plan are shown in figure 37.

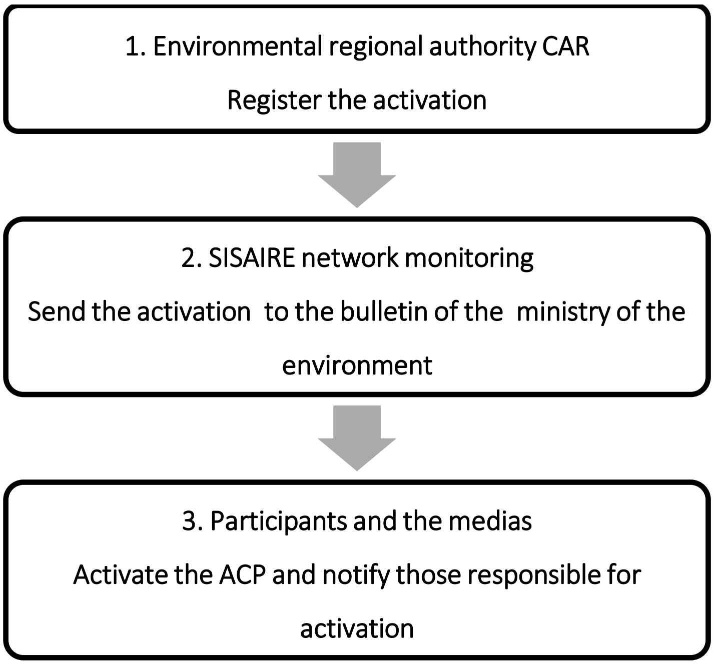


Figure 37 Atmospheric contingency plan-activation phases

The deactivation of the contingency plan follows the same phases. A final report should be sent to the ministry of the environment and be feed in the SISAIRE network in order to implement action plans to prevent, control and monitor all activities developed before, during and after each event and to correct possible fails of procedure (Bautista *et al*., 1995).

The activation criteria of a pre-contingency phase for PM10, could be based on concentrations equal or larger than 80 µg/m^3 during two hours (SIMAJ, 2014). In a contingency phase, the activation criteria could consider concentrations equal or larger than 100 µg/m^3 according to the Resolution 610 of 2010. A deactivate criteria could be based on concentrations equal or lesser than 70 µg/m^3 during two hours. The measures in both cases should be supervised by the environmental authorities (SIMAJ, 2014).

6. CONCLUSIONS

- The main aim of this study was to explore the relationship between the brick manufacturing activity and the air quality in the rural locality of Patio Bonito, Nemocón. Several research studies have referred that in brick kilns cluster areas like Patio Bonito, it presents high concentrations of atmospheric pollutants, especially of PM10, that represent a risk to air quality and to human health.

- The air quality monitored in Patio Bonito, in 2013, presented several noncompliance of the PM10 daily value recommended by the WHO and the established by the Colombian legislation, with peaks values that overpassed 100 µg/m^3, especially in August and November. For this reason, it was characterized as a year which represented risk for the health of the local inhabitants.

- The air pollution from brick manufacturing activity depends basically on the local air quality conditions, the fuel used, the manufacturing technologies, the types of kilns, the meteorological conditions, the efficiency of the emission control systems and the budget applied to the environmental issues by industrial and governmental sectors.

- The exercise of calculating emissions from different type of brick kilns in Patio Bonito, allowed to conclude that the Fuego dormido kilns are the major contributors to PM10 emissions, affecting the air quality in the locality.

- Colmena kilns also constitute an important emission source in Patio Bonito. However, as an improvement measure, these sources can be adjusted to technological reconversion to improve the dispersion of pollutants and mitigate the impact over the local air quality. The adaptation to coal dosage systems that helps to obtain better combustion parameters and emission control systems are also options to reduce atmospheric emissions.

- Hoffman and Tunnel kilns are the most technified kilns in Patio Bonito. However, they are also an important source of emissions and should operate with emission control systems.

- Road traffic represents another emissions source that affects the local air quality in Patio Bonito. The estimated emissions showed that vehicles crossing the Casablanca toll in the route 45A also are emission sources of PM10; however, in comparison to brick kilns, those represent less than 1% of contribution to PM10 emissions for the rural locality.

- In the estimation of PM10 emissions in Patio Bonito, fugitive sources were not included due to the lack of information related to the local emission sources of the brickworks. It is important to note that those are sources of TSP, PM10, and PM2.5 emissions and they are in the raw material grinding, screening operations, and in the brick kilns area. Other sources of PM fugitive emissions include dust sources such as unpaved roads, and storage piles. For this reason, it is important that in Colombia this type of emissions be regulated and included in a future national inventory for the brick production sector.

- The two proposed improvement scenarios evaluated the impact of the operation of Colmena, Hoffman and Tunnel kilns with emission control systems (cyclones) instead of the actual no controlled ones. Results evidenced a reduction of the PM10 concentration levels for the simulated episode of November 20 of 2013. It would be a good alternative to reduce the PM10 contribution because represents a better air quality in Patio Bonito. The difference scenarios of the two proposed improvement scenarios showed PM10 concentrations levels below of the daily value recommended by the WHO, considering as a positive impact on health for the Patio Bonito community.

- One of the most adaptable improvement measure in short and medium term is the creation of associative labor companies, which allows focusing on technological reconversion and improvement of the operational conditions of brick industries.

- Nowadays, there is a lack of hourly data of air quality monitoring and of meteorological parameters from different stations as Checua, which makes difficult the development of research studies about air quality in several municipalities with air pollution episodes, like Patio Bonito. Thus, an improvement of the national air quality-monitoring network is necessary, acquiring new and automatic equipment, and with more technical staff for better monitoring and processing data.

- The dispersion models are an interesting and useful tool for analyzing the air quality status in any territory. Its use allows taking better political decisions to reduce air pollution and to improve the quality of life of populations. In Colombia, It should be mandatory into the a legal framework and the air quality management.

- Taking into account future air pollution episodes, it is necessary that the competent authorities design and implement the atmospheric contingency plan in Patio Bonito, which guarantees the accomplishment of the Colombian legislation and avoids significant impacts over local air quality and health of its inhabitants.

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APPENDIX A

Meteorological input data of the selected episodes used in the URBAIR model

For the simulated episode August 8 2013, the main meteorological input data are presented in table A.1.

Table A.1 Meteorological input data August 8 2013

ta1	vv1	dv1	Pa	hr1	rad	roar	Cpar	Cpas	clas	zi
9	1	225	75247	95	140	1	1012	1004	3	200
9	1	225	75247	78	140	1	1012	1004	3	200
9	1	225	75247	78	140	1	1012	1004	3	200
9	1	225	75247	78	140	1	1012	1004	3	200
8	2	0	75207	99	140	1	1012	1004	4	200
8	2	0	75207	99	140	1	1012	1004	4	560
8	2	0	75207	99	201	1	1012	1004	4	560
10.6	3	310	75273	90	201	1	1012	1004	5	1200
10.6	3	310	75273	90	201	1	1012	1004	5	1200
10.6	3	310	75273	90	201	1	1012	1004	5	1200
17	2	90	75300	57	201	1	1012	1004	5	1200
17	2	90	75300	57	201	1	1012	1004	1	1200
17	2	90	75300	57	201	1	1012	1004	1	1200
19.6	3	90	75153	42	201	1	1012	1004	1	560
19.6	3	90	75153	42	201	1	1012	1004	4	560
19.6	3	90	75153	42	201	1	1012	1004	4	560
15	4	270	74993	90	201	1	1012	1004	4	560
15	4	270	74993	90	201	1	1012	1004	4	560
15	4	270	74993	90	140	1	1012	1004	4	560
12.7	2	135	75140	93	140	1	1012	1004	4	200
12.7	2	135	75140	93	140	1	1012	1004	4	200
12.7	2	135	75140	93	140	1	1012	1004	4	200
12.2	2	135	75300	95	140	1	1012	1004	4	200
12.2	2	135	75300	95	140	1	1012	1004	4	200

APPENDIX B

Meteorological input data of the selected episodes used in the URBAIR model

For the simulated episode November 20 2013, the main meteorological input data are presented in table B.1.

Table B.1 Meteorological input data November 20 2013

ta1	vv1	dv1	Pa	hr1	rad	roar	Cpar	Cpas	clas	zi
11.8	3	310	75193	91	140	1	1012	1004	5	200
11.8	3	310	75193	91	140	1	1012	1004	5	200
11.8	3	310	75193	91	140	1	1012	1004	5	200
11.8	3	310	75193	91	140	1	1012	1004	5	200
11.1	1	135	75113	92	140	1	1012	1004	5	200
11.1	1	135	75113	92	140	1	1012	1004	5	560
11.1	1	135	75113	92	201	1	1012	1004	4	560
11.3	2	45	75313	92	201	1	1012	1004	4	1200
11.3	2	45	75313	92	201	1	1012	1004	4	1200
11.3	2	45	75313	92	201	1	1012	1004	4	1200
17.2	2	45	75380	62	201	1	1012	1004	4	1200
17.2	2	45	75380	62	211	1	1012	1004	1	1200
17.2	2	45	75380	62	211	1	1012	1004	1	1200
18.4	5	310	75153	56	211	1	1012	1004	1	560
18.4	5	310	75153	56	201	1	1012	1004	4	560
18.4	5	310	75153	56	201	1	1012	1004	4	560
13.4	1	135	75140	91	201	1	1012	1004	4	560
13.4	1	135	75140	91	201	1	1012	1004	5	560
13.4	1	135	75140	91	140	1	1012	1004	5	560
12.1	1	270	75233	90	140	1	1012	1004	5	200
12.1	1	270	75233	90	140	1	1012	1004	4	200
12.1	1	270	75233	90	140	1	1012	1004	4	200
12.2	1	135	75233	93	140	1	1012	1004	4	200
12.2	1	135	75233	93	140	1	1012	1004	4	200

APPENDIX C

Meteorological input data of the selected episodes used in the URBAIR model

For the simulated episode November 24 2013, the main meteorological input data are presented in table C.1.

Table C.1 Meteorological input data November 24 2013

ta1	vv1	dv1	Pa	hr1	rad	roar	Cpar	Cpas	clas	zi
11.8	3	310	75193	91	140	1	1012	1004	5	200
11.8	3	310	75193	91	140	1	1012	1004	5	200
11.8	3	310	75193	91	140	1	1012	1004	5	200
11.8	3	310	75193	91	140	1	1012	1004	5	200
11.1	1	135	75113	92	140	1	1012	1004	5	200
11.1	1	135	75113	92	140	1	1012	1004	5	560
11.1	1	135	75113	92	201	1	1012	1004	4	560
11.3	2	45	75313	92	201	1	1012	1004	4	1200
11.3	2	45	75313	92	201	1	1012	1004	4	1200
11.3	2	45	75313	92	201	1	1012	1004	4	1200
17.2	2	45	75380	62	201	1	1012	1004	4	1200
17.2	2	45	75380	62	211	1	1012	1004	1	1200
17.2	2	45	75380	62	211	1	1012	1004	1	1200
18.4	5	310	75153	56	211	1	1012	1004	1	560
18.4	5	310	75153	56	201	1	1012	1004	4	560
18.4	5	310	75153	56	201	1	1012	1004	4	560
13.4	1	135	75140	91	201	1	1012	1004	4	560
13.4	1	135	75140	91	140	1	1012	1004	5	560
13.4	1	135	75140	91	140	1	1012	1004	5	560
12.1	1	270	75233	90	140	1	1012	1004	5	200
12.1	1	270	75233	90	140	1	1012	1004	5	200
12.1	1	270	75233	90	140	1	1012	1004	5	200
12.2	1	135	75233	93	140	1	1012	1004	5	200
12.2	1	135	75233	93	140	1	1012	1004	5	200