CONSULTORIA INTERNACIONAL & ESTATAL DE PROYECTOS S.A.S.

HACE CONSTAR:

Que el señor **WILSON RAFAEL SALAS CHÁVEZ** con cédula de ciudadanía No. **1.130.675.674** de Cali, Valle del Cauca, mayor de edad, domiciliado en la ciudad de Santiago de Cali, prestó sus servicios profesionales a **CONSULTORIA INTERNACIONAL & ESTATAL DE PROYECTOS S.A.S.,** identificada con Nit. 901.644.860-1, para dar cumplimiento al contrato número **4145.010.26.1.1597- 2023** realizado para la Secretaría Distrital de Salud de Cali de la siguiente manera:

OBJETO: "Realizar estudio de carga de la enfermedad por afectaciones en la salud por la Exposición de las personas a Enfermedades Trasmitidas por Vectores "MEJORAMIENTO DE LA GESTIÓN EN LA PREVENCIÓN Y VIGILANCIA DE INSECTOS VECTORES DE ENFERMEDADES EN SANTIAGO CALI; BP: 2600306.

VALOR DEL CONTRATO: fijado en NUEVE MILLONES DE PESOS MCTE ($9.000.000) moneda corriente.

PLAZO DE EJECUCIÓN: Desde el primero (01) de septiembre del 2023 hasta el treinta y uno (31) de diciembre del 2023.

Se expide la presente constancia en Santiago de Cali, Valle del Cauca a los diecinueve (19) días del mes de enero de 2024 a solicitud del interesado.

FUNCIONES DESEMPEÑADAS:

1. Presentar el Cronograma de actividades tendientes a realizar el estudio de carga de la enfermedad en la salud por la Exposición de las personas a Enfermedades trasmitidas por Vectores.

2. Solicitar a la secretaria de salud de Cali las bases de datos con las características necesarias de calidad y cobertura de los datos de la institución, para la estimación de la carga de enfermedad por la Exposición de las personas a Enfermedades trasmitidas por Vectores, para realizar el estudio al inicio del contrato.

3. Revisar la calidad y cobertura de los datos de información disponibles en el Sistema de Vigilancia epidemiológica de la institución SIVIGILA las de mortalidad y morbilidad de los RIPS, y demás fuentes de información relacionados con los eventos en salud a analizar y evaluar, que suministra la Secretaría Distrital para la estimación de la carga de la enfermedad por Exposición de las personas a Enfermedades trasmitidas por Vectores.

4. Analizar y evaluar las bases de datos suministradas para la obtención de la información necesaria para la realización del estudio de carga de la enfermedad en la salud por la Exposición de las personas a enfermedades trasmitidas por vectores

5. Debe presentar un informe de la calidad de la información suministrada en la base de datos entregados para el estudio de carga de la enfermedad en la salud por Enfermedades trasmitidas por Vectores. En caso de existir deficiente calidad de la información o rangos de datos faltantes deberá solicitarlo inmediatamente.

6. Presentar el informe de análisis y evaluación de los resultados obtenidos por los eventos Dengue, Sika y Chikungunya.

7. Estimar la valoración económica de los costos de atención de los eventos estudiados al sistema de salud en una métrica común, en este caso un valor monetario, con lo cual se pueden comparar los beneficios en salud con los costos de implementación de un programa o de medidas de control.

8. Realizar la socialización y capacitación de este estudio, análisis y resultado al grupo de funcionarios de la Secretaria de Salud de Cali, para que se apropie de la metodología aplicada, análisis e interpretación de resultados para su posterior replicación en el tiempo.

9. Generar un informe final que consolide, el resultado técnico epidemiológico y la información económica obtenida del análisis y evaluación de los ejercicios anteriores.

10. Las demás obligaciones que se deriven de la ejecución del contrato 4145.010.26.1.1597-2023 cuyo objeto es Realizar estudio de carga de la enfermedad por afectaciones en la salud por la Exposición de las personas a Enfermedades Trasmitidas por Vectores **"MEJORAMIENTO DE LA GESTIÓN EN LA PREVENCIÓN Y VIGILANCIA DE INSECTOS VECTORES DE ENFERMEDADES EN SANTIAGO CALI**; BP: 26003060, para la Secretaría de Salud de la Alcaldía de Cali Valle del Cauca.

Atentamente,

VIRGINIA PORTELA VEGA
Representante Legal
C.C. No. 28.732.592

El suscrito JEFE DE LA UNIDAD DE APOYO A LA GESTIÓN del DEPARTAMENTO ADMINISTRATIVO DE GESTIÓN DEL MEDIO AMBIENTE – DAGMA, con base en la información que reposa en el archivo de la entidad y la publicada en el Sistema Electrónico de Contratación Pública – SECOP, hace constar que WILSON RAFAEL SALAS CHAVEZ, identificado con la Cedula de ciudadanía número 1.130.675.674 suscribió los siguientes contratos:

AÑO	2022
TIPO	PRESTACION DE SERVICIOS
No.	4133.010.26.1.1009 de 2022.
FECHA DE SUSCRIPCIÓN	04/08/2022
PORCENTAJE DE PARTICIPACIÓN DEL CONSORCIO O UNIÓN TEMPORAL	N/A
OBJETO	Prestar los servicios profesionales al Departamento Administrativo de Gestión del Medio Ambiente – DAGMA.
PLAZO (DESDE –HASTA)	04/08/2022 Hasta 31/10/2022 Otrosi, por la suma de ocho millones quinientos setenta y seis mil pesos m/cte ($8.576.000) hasta el 31 de diciembre 2022.
VALOR	DIECISIETE MILLONES CIENTO CINCUENTA Y DOS MIL PESOS M/CTE ($ 17.152.000)
VALOR EJECUTADO HASTA LA FECHA (APLICA PARA CONTRATOS EN EJECUCIÓN)	N/A
VALOR FINAL DEL CONTRATO (APLICA PARA CONTRATOS EJECUTADOS)	VEINTICINCO MILLONES SETECIENTOS VEINTIOCHO MIL PESOS M/CTE ($ 25.728.000)
ESTADO DEL CONTRATO	TERMINADO

NIVEL DE CUMPLIMIENTO (APLICA PARA CONTRATOS EJECUTADOS)	Se evidencio la ejecución del contrato el cumplimiento de las actividades y obligaciones pactadas a satisfacción entregando a satisfacción los productos y//o resultados exigidos, dentro del tiempo estipulado en el contrato. No. 4133.010.26.1.1009-2022.

OBLIGACIONES GENERALES
NO REQUERIDAS POR EL SOLICITANTE
OBLIGACIONES ESPECIFICAS
1) Participar en la implementación de políticas y procedimientos del sistema de gestión de la calidad del SVCASC. 2) Realizar las actividades desde la dirección técnica que garanticen técnicamente la planificación, la implementación, mantenimiento, verificación y mejoramiento del Sistema de Gestión de la calidad del SVCASC. 3) Liderar las actividades del Sistema de Vigilancia de Calidad del Aire de Santiago de Cali - SVCASC, orientando y supervisando al equipo humano que las desarrolla. 4) Atender la auditoría interna y/o externa del Sistema de Gestión de Calidad del SVCASC y la implementación de su Plan de Acción. 5) Revisar y aprobar los informes periódicos de resultados del SVCASC antes de su publicación. 6) Supervisar al personal encargado del mantenimiento y operación del SVCASC de acuerdo a los métodos y procedimientos, el objetivo de cada ensayo y la evaluación de los resultados de los ensayos. 7) Analizar los parámetros de calidad del aire y meteorología registrados por el SVCASC para el grupo de calidad del aire, siguiendo los procedimientos para garantizar la trazabilidad y calidad de los datos generados por el SVCASC, para lo cual se deberá implementar continuamente los métodos normalizados de calidad del aire bajo el estándar de la ISO 17025 y del Hand Book de la EPA. 8) Supervisar los procedimientos de depuración y validación de los datos registrados por las estaciones de monitoreo del Sistema de Vigilancia de Calidad del Aire de Santiago de Cali – SVCASC. 9) Atender las solicitudes relacionadas con la gestión de la calidad del aire 10) Realizar la toma de muestra, el acondicionamiento y pesaje de filtros de acuerdo a los procedimientos establecidos. 11) Participar en la mesa técnica de formulación de proyectos 12) Participar en la planeación, gestión y seguimiento a la implementación de acciones del Plan Integral de Gestión del Cambio Climático para Santiago de Cali. 13) Participar en la planeación, gestión y seguimiento a la implementación de acciones del Programa de Aire Limpio para Santiago de Cali. 14) Participar en la mesa técnica de calidad del aire del COTSA 15) Participar

Departamento Administrativo de Gestión del Medio Ambiente - DAGMA
Avenida 5 AN # 20 N – 08 – Edificio Fuente Versalles – Piso 11 – Teléfono 6680583
www.cali.gov.co

en el proceso de transición urbana de barrios a ecobarrios en Santiago de Cali. 16) Las demás actividades que sean asignadas por la dirección del DAGMA y/o la supervisión que tengan relación directa con el objeto del contrato.

AÑO	2022
TIPO	PRESTACION DE SERVICIOS
No.	4133.010.26.1.482-2022
FECHA DE SUSCRIPCIÓN	25/01/2022
PORCENTAJE DE PARTICIPACIÓN DEL CONSORCIO O UNIÓN TEMPORAL	N/A
OBJETO	Prestar los servicios profesionales al Departamento Administrativo de Gestión del Medio Ambiente – DAGMA.
PLAZO (DESDE –HASTA)	25/01/2022 Hasta 30/06/2022
VALOR	VEINTICINCO MILLONES SETECIENTOS VEINTIOCHO MIL PESOS M/CTE ($25.728.000)
VALOR EJECUTADO HASTA LA FECHA (APLICA PARA CONTRATOS EN EJECUCIÓN)	N/A
VALOR FINAL DEL CONTRATO (APLICA PARA CONTRATOS EJECUTADOS)	VEINTICINCO MILLONES SETECIENTOS VEINTIOCHO MIL PESOS M/CTE ($25.728.000)
ESTADO DEL CONTRATO	TERMINADO
NIVEL DE CUMPLIMIENTO (APLICA PARA CONTRATOS EJECUTADOS)	Se evidencio la ejecución del contrato el cumplimiento de las actividades y obligaciones pactadas a satisfacción entregando a satisfacción los productos y//o resultados exigidos, dentro del tiempo estipulado en el contrato. No. 4133.010.26.1.482-2022.

OBLIGACIONES GENERALES

NO REQUERIDAS POR EL SOLICITANTE
OBLIGACIONES ESPECIFICAS
1) Participar en la implementación de políticas y procedimientos del sistema de gestión de la calidad del SVCASC. 2) Realizar las actividades que garanticen la planificación, la implementación, mantenimiento, verificación y mejoramiento del Sistema de Gestión de la calidad del SVCASC. 3) Atender la auditoría interna y/o externa del Sistema de Gestión de Calidad del SVCASC y la implementación de su Plan de Acción. 4) Supervisar al personal encargado del mantenimiento y operación del SVCASC de acuerdo a los métodos y procedimientos, el objetivo de cada ensayo y la evaluación de los resultados de los ensayos. 5) Analizar los parámetros de calidad del aire y meteorología registrados por el SVCASC, siguiendo los procedimientos para garantizar la trazabilidad y calidad de los datos generados por el SVCASC, para lo cual se deberá implementar continuamente los métodos normalizados de calidad del aire bajo el estándar de la ISO 17025 y del Hand Book de la EPA. 6) Supervisar el desarrollo y la implementación de la 2da fase de la modelación de calidad del aire en Santiago de Cali. 7) Compilar la información SIG del Sistema de Vigilancia de Calidad de Aire de Santiago de Cali 8) Supervisar los procedimientos de depuración y validación de los datos registrados por las estaciones de monitoreo del Sistema de Vigilancia de Calidad del Aire de Santiago de Cali – SVCASC. 9) Atender las quejas y solicitudes que le sean asignadas relacionados con Calidad del Aire. 10) Realizar la toma de muestra, el acondicionamiento y pesaje de filtros de acuerdo a los procedimientos establecidos. 11) Participar en las jornadas, eventos y campañas relacionadas con la calidad del aire y sustentabilidad ambiental. 12) Participar en la planeación, gestión e implementación de acciones del Programa de Aire Limpio para Santiago de Cali. 13) Participar en la mesa interinstitucional de Calidad Cali – Región. 14) Las demás actividades que sean asignadas por la dirección del DAGMA y/o la supervisión que tengan relación directa con el objeto del contrato.

INFORMACIÓN ADICIONAL: N/A

Esta certificación no tiene validez sin las estampillas de ley (Teniendo en cuenta el Concepto jurídico del cobro de estampillas Pro-Desarrollo Urbano Radicado No. 201741210100043214 del 01/11/2017 de la Dirección del Departamento Administrativo de Gestión Jurídica Pública, recibido en esta Oficina el 07/11/2017 y la Resolución 000063 del 14 de noviembre del 2017, se adjunta y se anulan estampillas Pro-Hospitales

ALCALDÍA DE SANTIAGO DE CALI GESTIÓN JURÍDICO ADMINISTRATIVA ADQUISICIÓN DE BIENES, OBRAS Y SERVICIOS	SISTEMAS DE GESTIÓN Y CONTROL INTEGRADOS (SISTEDA, SGC y MECI)	MAJA01.02.02.18.P12.F01	
		VERSIÓN	1
	CERTIFICACION DE CONTRATO / CONVENIO	FECHA DE ENTRADA EN VIGENCIA	04/mar/2019

Universitarios del Valle de $4000, Pro Salud Departamental de $4000, Pro Desarrollo Urbano $ 1.500 y Pro cultura de $ 1.500.).

Para constancia se firma en Santiago de Cali, a los cinco (05) días del mes de enero del dos mil veintitrés (2023).

DIEGO CARVAJAL TRUJILLO
DEPARTAMENTO ADMINISTRATIVO DE GESTIÓN DEL MEDIO AMBIENTE - DAGMA

Proyectó: Emilse Ceron Tejada – Auxiliar Administrativa
Elaboró: Emilse Ceron Tejada – Auxiliar Administrativa

ESTAMPILLAS

Recibo oficial Número: 333301352899

GOBERNACIÓN VALLE DEL CAUCA

Rcbo No: [illegible] C.C: [illegible]
WILSON RAFAEL SALAS CHAVEZ
DAGMA
LOS CERTIFICADOS O CONSTANCIAS EXPEDIDAS POR FUNCIONARIOS
VALOR TOTAL DEL ACTO O DOCUMENTO: 8000
[illegible] 16/11/2022 03:06:32 p.m. 1 DE 1

El suscrito JEFE DE LA UNIDAD DE APOYO A LA GESTIÓN del DEPARTAMENTO ADMINISTRATIVO DE GESTIÓN DEL MEDIO AMBIENTE – DAGMA, con base en la información que reposa en el archivo de la entidad y la publicada en el Sistema Electrónico de Contratación Pública – SECOP, hace constar que WILSON RAFAEL SALAS CHAVEZ, identificado(a) con la Cédula de Ciudadanía número 1130675674 suscribió los siguientes contratos:

AÑO	2021
TIPO	PRESTACION DE SERVICIOS
No.	4133.010.26.1.734-2021
FECHA DE SUSCRIPCIÓN	29 de julio de 2021
PORCENTAJE DE PARTICIPACIÓN DEL CONSORCIO O UNIÓN TEMPORAL	N/A
OBJETO	PRESTAR LOS SERVICIOS PROFESIONALES AL DEPARTAMENTO ADMINISTRATIVO DE GESTION DEL MEDIO AMBIENTE DAGMA
PLAZO (DESDE –HASTA)	DESDE 2 de agosto de 2021 Hasta 27 de diciembre de 2021
VALOR	(25728000) VEINTICINCO MILLONES SETECIENTOS VEINTIOCHO MIL PESOS M/CTE.
VALOR EJECUTADO HASTA LA FECHA (APLICA PARA CONTRATOS EN EJECUCIÓN)	N/A
VALOR FINAL DEL CONTRATO (APLICA PARA CONTRATOS EJECUTADOS)	(25728000)VEINTICINCO MILLONES SETECIENTOS VEINTIOCHO MIL PESOS M/CTE.
ESTADO DEL CONTRATO	TERMINADO
NIVEL DE CUMPLIMIENTO (APLICA PARA CONTRATOS EJECUTADOS)	Se evidenció la ejecución del contrato el cumplimiento de las actividades y obligaciones pactadas a satisfacción, entregando a satisfacción los productos y/o resultados exigidos, dentro del tiempo estipulado en el contrato. No 4133.010.26.1.734-2021
OBLIGACIONES GENERALES	
NO REQUERIDAS POR EL SOLICITANTE	
OBLIGACIONES ESPECIFICAS	
1) Participar en la implementación de políticas y procedimientos del sistema de gestión de la calidad del SVCASC. 2) Realizar las actividades que garanticen la planificación, la implementación, mantenimiento, verificación y mejoramiento del Sistema de Gestión dela calidad	

del SVCASC. 3) Atender la auditoría interna y/o externa del Sistema de Gestión de Calidad del SVCASC y la implementación de su Plan de Acción. 4) Supervisar al personal encargado del mantenimiento y operación del SVCASC de acuerdo a los métodos y procedimientos, el objetivo de cada ensayo y la evaluación de los resultados de los ensayos. 5) Analizar los parámetros de calidad del aire y meteorología registrados por el SVCASC, siguiendo los procedimientos para garantizar la trazabilidad y calidad delos datos generados por el SVCASC, para lo cual se deberá implementar continuamente los métodos normalizados de calidad del aire bajo el estándar de la ISO 17025 y del Hándbol de la EPA. 6) Supervisar el desarrollo y la implementación de la 2da fase de remodelación de calidad del aire en Santiago de Cali. 7) Compilar la información SIG del Sistema de Vigilancia de Calidad de Aire de Santiago de Cali 8) Supervisar los procedimientos de depuración y validación de los datos registrados por las estaciones de monitoreo del Sistema de Vigilancia de Calidad del Aire de Santiago de Cali – SVCASC.9) Atender las quejas y solicitudes que le sean asignadas relacionados con Calidad del Aire. 10) Realizar la toma de muestra, el acondicionamiento y pesaje de filtros de acuerdo a los procedimientos establecidos. 11) Participar en las jornadas, eventos y campañas relacionadas con la calidad del aire y sustentabilidad ambiental. 12) Participar en la planeación, gestión e implementación de acciones del Programa de Aire Limpio para Santiago de Cali. 13) Participar en la mesa interinstitucional de Calidad Cali – Región.14) Las demás actividades que sean asignadas por la dirección del DAGMA y/o la supervisión que tengan relación directa con el objeto del contrato.

AÑO	2021
TIPO	PRESTACION DE SERVICIOS
No.	4133.010.26.1.177-2021
FECHA DE SUSCRIPCIÓN	29 de enero de 2021
PORCENTAJE DE PARTICIPACIÓN DEL CONSORCIO O UNIÓN TEMPORAL	N/A
OBJETO	PRESTAR LOS SERVICIOS PROFESIONALES AL DEPARTAMENTO ADMINISTRATIVO DE GESTION DEL MEDIO AMBIENTE DAGMA
PLAZO (DESDE –HASTA)	DESDE 29 de enero de 2021 Hasta 30 de junio de 2021
VALOR	(25728000) VEINTICINCO MILLONES SETECIENTOS VEINTIOCHO MIL PESOS M/CTE.
VALOR EJECUTADO HASTA LA FECHA (APLICA PARA CONTRATOS EN EJECUCIÓN)	N/A
VALOR FINAL DEL CONTRATO (APLICA PARA CONTRATOS EJECUTADOS)	(25728000)VEINTICINCO MILLONES SETECIENTOS VEINTIOCHO MIL PESOS M/CTE.

ESTADO DEL CONTRATO	TERMINADO
NIVEL DE CUMPLIMIENTO (APLICA PARA CONTRATOS EJECUTADOS)	Se evidenció la ejecución del contrato el cumplimiento de las actividades y obligaciones pactadas a satisfacción, entregando a satisfacción los productos y/o resultados exigidos, dentro del tiempo estipulado en el contrato. No 4133.010.26.1.177-2021
OBLIGACIONES GENERALES	
NO REQUERIDAS POR EL SOLICITANTE	
OBLIGACIONES ESPECIFICAS	
1) Apoyar la implementación de políticas y procedimientos del sistema de gestión de la calidad del SVCASC.2) Apoyar las actividades que garanticen la planificación, implementación, mantenimiento, verificación y mejoramiento del Sistema de Gestión de la calidad del SVCASC.3) Ayudar en la formulación, implementación y cumplimiento del Plan de Acción de la Auditoría Interna y/o externa.4) Brindar apoyo al personal encargado del mantenimiento y operación del SVCASC de acuerdo a los métodos y procedimientos, el objetivo de cada ensayo y la evaluación de los resultados de los ensayos.5) Analizar los parámetros de calidad del aire y meteorología registrados por el SVCASC, siguiendo los procedimientos para garantizar la trazabilidad y calidad de los datos generados por el SVCASC, para lo cual se deberá implementar continuamente los métodos normalizados de calidad del aire bajo el estándar de la ISO 17025 y del Hand Book de la EPA.6) Apoyar el desarrollo y la implementación de la 2da fase de la modelación de calidad del aire en Santiago de Cali.7) Brindar apoyo en el proceso de obtención, evaluación, sistematización y verificación de la información del SVCASC que alimente la base de datos del Sistema de información geográfica SIG.8) Apoyo a la supervisión de los procedimientos de validación de los datos registrados por las estaciones de monitoreo del Sistema de Vigilancia de Calidad del Aire de Santiago de Cali – SVCASC.9) Atender las quejas y solicitudes que le sean asignadas relacionados con Calidad del Aire.10) Apoyar las actividades que garanticen la planificación, implementación, verificación y mejoramiento de los Sistemas de Gestión de la calidad del SVCASC.11) Realizar la toma de muestra, el acondicionamiento y pesaje de filtros de acuerdo a los procedimientos establecidos y la validación de los métodos de ensayo a su cargo.12) Apoyar y participar en la coordinación de jornadas, eventos y campañas relacionadas con la calidad del aire y sustentabilidad ambiental.13) Brindar apoyo en la planeación, gestión e implementación de acciones del Programa de Aire Limpio para Santiago de Cali.14) Las demás actividades que sean asignadas por la dirección del DAGMA y/o la supervisión que tengan relación directa con el objeto del contrato.	

INFORMACIÓN ADICIONAL:

Esta certificación no tiene validez sin las estampillas de ley, (Teniendo en cuenta el Concepto jurídico del cobro de estampillas Pro-Desarrollo Urbano Radicado No. 201741210100043214 del 01/11/2017, de la Dirección del Departamento Administrativo de Gestión Jurídica Pública, recibido en esta Oficina el 07/11/2017 y la Resolución 000063 del 14 de noviembre del 2017), se adjunta y se anulan estampillas Pro-Hospitales Universitarios del Valle, Pro Salud Departamental, Pro Desarrollo Urbano y Pro cultura, con base al valor vigente, para cada una de las estampillas.

Para constancia se firma en Santiago de Cali, a los treinta días (30) días del mes de diciembre del dos mil veintiuno (2021).

DIEGO CARVAJAL TRUJILLO
DEPARTAMENTO ADMINISTRATIVO DE GESTIÓN DEL MEDIO AMBIENTE – DAGMA

Proyectó: Emilse Cerón Tejada - Auxiliar Administrativo

GOBERNACIÓN VALLE DEL CAUCA

ALCALDÍA MUNICIPAL DE SANTIAGO DE CALI
LOS CERTIFICADOS O CONSTANCIAS EXPEDIDAS POR FUNCIONARIOS
VALOR TOTAL DEL ACTO O DOCUMENTO

La suscrita JEFE DE LA UNIDAD DE APOYO A LA GESTIÓN del DEPARTAMENTO ADMINISTRATIVO DE GESTIÓN DEL MEDIO AMBIENTE – DAGMA, con base en la información que reposa en el archivo de la entidad y la publicada en el Sistema Electrónico de Contratación Pública – SECOP, hace constar que WILSON RAFAEL SALAS CHAVEZ identificado(a) con la Cedula de ciudadanía número 1.130.675.674, suscribió los siguientes contratos:

AÑO	2020
TIPO	PRESTACION DE SERVICIOS
No.	4133.010.26.1.681-2020
FECHA DE SUSCRIPCIÓN	24 de julio de 2020
PORCENTAJE DE PARTICIPACIÓN DEL CONSORCIO O UNIÓN TEMPORAL	N/A
OBJETO	Prestar los servicios profesionales al Departamento Administrativo de Gestión del Medio Ambiente DAGMA
PLAZO (DESDE –HASTA)	28 de julio de 2020 - 30 de octubre de 2020 OTRO SI POR LA SUMA DE OCHO MILLONES CUATROCIENTOS TREINTA Y NUEVE MIL NOVECIENTOS CUARENTA PESOS M/CTE ($ 8.439.940) HASTA EL DIA 28 DICIEMBRE 2020.
VALOR	DIECISEIS MILLONES OCHOCIENTOS SETENTA Y NUEVE MIL OCHOCIENTOS OCHENTA PESOS M/CTE ($16.879.880)
VALOR EJECUTADO HASTA LA FECHA (APLICA PARA CONTRATOS EN EJECUCIÓN)	N/A
VALOR FINAL DEL CONTRATO (APLICA PARA CONTRATOS EJECUTADOS)	VEINTICINCO MILLONES TRESCIENTOS DIECINUEVE MIL OCHOCIENTOS VEINTE PESOS M/CTE ($25.319.820)
ESTADO DEL CONTRATO	TERMINADO
NIVEL DE CUMPLIMIENTO (APLICA PARA CONTRATOS	Se evidencio la ejecución del contrato el

EJECUTADOS)	cumplimiento de las actividades y obligaciones pactadas a satisfacción entregando a satisfacción los productos y/o resultados exigidos, dentro del tiempo estipulado en el contrato. No 4133.010.26.1.681-2020
OBLIGACIONES GENERALES	
NO REQUERIDAS POR EL SOLICITANTE	
OBLIGACIONES ESPECIFICAS	

1) Apoyar la implementación de políticas y procedimientos del sistema de gestión de la calidad del SVCASC.
2) Apoyar las actividades que garanticen la planificación, implementación, mantenimiento, verificación y mejoramiento del Sistema de Gestión de la calidad del SVCASC.
3) Ayudar en la formulación, implementación y cumplimiento del Plan de Acción de la Auditoría Interna y/o externa.
4) Brindar apoyo al personal encargado del mantenimiento y operación del SVCASC de acuerdo a los métodos y procedimientos, el objetivo de cada ensayo y la evaluación de los resultados de los ensayos.
5) Analizar los parámetros de calidad del aire y meteorología registrados por el SVCASC, siguiendo los procedimientos para garantizar la trazabilidad y calidad de los datos generados por el SVCASC, para lo cual se deberá implementar continuamente los metodos normalizados de calidad del aire bajo el estandar de la ISO 17025 y del Hand Book de la EPA.
6) Apoyar el desarrollo y la implementación de la 2da fase de la modelación de calidad del aire en Santiago de Cali.
7) Brindar apoyo en el proceso de obtención, evaluación, sistematización y verificación de la información del SVCASC que alimente la base de datos del Sistema de información geográfica SIG.
8) Apoyo a la supervisión de los procedimientos de validación de los datos registrados por las estaciones de monitoreo del Sistema de Vigilancia de Calidad del Aire de Santiago de Cali – SVCASC.
9) Atender las quejas y solicitudes que le sean asignadas relacionados con Calidad del Aire.
10) Apoyar las actividades que garanticen la planificación, implementación, verificación y mejoramiento de los Sistemas de Gestión de la calidad del SVCASC.
11) Realizar la toma de muestra, el acondicionamiento y pesaje de filtros de acuerdo a los procedimientos establecidos y la validación de los métodos de ensayo a su cargo.
12) Apoyar y participar en la coordinación de jornadas, eventos y campañas

relacionadas con la calidad del aire y sustentabilidad ambiental.
13) Brindar apoyo en la planeación, gestión e implementación de acciones del Programa de Aire Limpio para Santiago de Cali.
14) Las demás actividades que sean asignadas por la dirección del DAGMA y/o la supervisión que tengan relación directa con el objeto del contrato.

AÑO	2020
TIPO	PRESTACION DE SERVICIOS
No.	4133.010.26.1.275-2020
FECHA DE SUSCRIPCIÓN	16 de abril de 2020
PORCENTAJE DE PARTICIPACIÓN DEL CONSORCIO O UNIÓN TEMPORAL	N/A
OBJETO	Prestar sus servicios profesionales en el Departamento Administrativo de Gestión del Medio Ambiente DAGMA
PLAZO (DESDE –HASTA)	17 de abril de 2020 - 30 de junio de 2020
VALOR	DOCE MILLONES SESICIENTOS CINCUENTA Y NUEVE ML NOVECIENTOS DIEZ PESOS M/CTE ($12.659.910)
VALOR EJECUTADO HASTA LA FECHA (APLICA PARA CONTRATOS EN EJECUCIÓN)	N/A
VALOR FINAL DEL CONTRATO (APLICA PARA CONTRATOS EJECUTADOS)	DOCE MILLONES SESICIENTOS CINCUENTA Y NUEVE ML NOVECIENTOS DIEZ PESOS M/CTE ($12.659.910)
ESTADO DEL CONTRATO	TERMINADO
NIVEL DE CUMPLIMIENTO (APLICA PARA CONTRATOS EJECUTADOS)	Se evidencio la ejecución del contrato el cumplimiento de las actividades y obligaciones pactadas a satisfacción entregando a satisfacción los productos y/o resultados exigidos, dentro del tiempo estipulado en el contrato. No 4133.010.26.1.275-2020
OBLIGACIONES GENERALES	

NO REQUERIDAS POR EL SOLICITANTE
OBLIGACIONES ESPECIFICAS
1) Apoyar la implementación de políticas y procedimientos del sistema de gestión de la calidad del SVCASC. 2) Apoyar las actividades que garanticen la planificación, implementación, mantenimiento, verificación y mejoramiento del Sistema de Gestión de la calidad del SVCASC. 3) Ayudar en la formulación, implementación y cumplimiento del Plan de Acción de la Auditoría Interna y/o externa. 4) Brindar apoyo al personal encargado del mantenimiento y operación del SVCASC de acuerdo a los métodos y procedimientos, el objetivo de cada ensayo y la evaluación de los resultados de los ensayos. 5) Analizar los parámetros de calidad del aire y meteorología registrados por el SVCASC, siguiendo los procedimientos para garantizar la trazabilidad y calidad de los datos generados por el SVCASC, para lo cual se deberá implementar continuamente los metodos normalizados de calidad del aire bajo el estandar de la ISO 17025 y del Hand Book de la EPA. 6) Apoyar el desarrollo y la implementación de la 2da fase de la modelación de calidad del aire en Santiago de Cali. 7) Brindar apoyo en el proceso de obtención, evaluación, sistematización y verificación de la información del SVCASC que alimente la base de datos del Sistema de información geográfica SIG. 8) Apoyo a la supervisión de los procedimientos de validación de los datos registrados por las estaciones de monitoreo del Sistema de Vigilancia de Calidad del Aire de Santiago de Cali – SVCASC. 9) Atender las quejas y solicitudes que le sean asignadas relacionados con Calidad del Aire. 10) Apoyar las actividades que garanticen la planificación, implementación, verificación y mejoramiento de los Sistemas de Gestión de la calidad del SVCASC. 11) Realizar la toma de muestra, el acondicionamiento y pesaje de filtros de acuerdo a los procedimientos establecidos y la validación de los métodos de ensayo a su cargo. 12) Apoyar y participar en la coordinación de jornadas, eventos y campañas relacionadas con la calidad del aire y sustentabilidad ambiental. 13) Brindar apoyo en la planeación, gestión e implementación de acciones del Programa de Aire Limpio para Santiago de Cali. 14) Las demás actividades que sean asignadas por la dirección del DAGMA y/o la supervisión que tengan relación directa con el objeto del contrato.

AÑO	2020
TIPO	PRESTACION DE SERVICIOS
No.	4133.010.26.1.027-2020
FECHA DE SUSCRIPCIÓN	30 de enero de 2020
PORCENTAJE DE PARTICIPACIÓN DEL CONSORCIO O UNIÓN TEMPORAL	N/A
OBJETO	Prestar servicios profesionales para el análisis y validación de datos del sistema de vigilancia de calidad del aire de Santiago de Cali svcasc y la implementación del programa de aire limpio, que adelante el DAGMA en la presente vigencia fiscal 2020.
PLAZO (DESDE –HASTA)	3 de febrero de 2020 - 31 de marzo de 2020
VALOR	CATORCE MILLONES NOVECIENTOS DIECINUEVE MIL TRESCIENTOS VEINTISIETE PESOS M/CTE ($14.919.327)
VALOR EJECUTADO HASTA LA FECHA (APLICA PARA CONTRATOS EN EJECUCIÓN)	N/A
VALOR FINAL DEL CONTRATO (APLICA PARA CONTRATOS EJECUTADOS)	CATORCE MILLONES NOVECIENTOS DIECINUEVE MIL TRESCIENTOS VEINTISIETE PESOS M/CTE ($14.919.327)
ESTADO DEL CONTRATO	TERMINADO
NIVEL DE CUMPLIMIENTO (APLICA PARA CONTRATOS EJECUTADOS)	Se evidencio la ejecución del contrato el cumplimiento de las actividades y obligaciones pactadas a satisfacción entregando a satisfacción los productos y/o resultados exigidos, dentro del tiempo estipulado en el contrato. No 4133.010.26.1.027-2020
OBLIGACIONES GENERALES	
NO REQUERIDAS POR EL SOLICITANTE	
OBLIGACIONES ESPECIFICAS	
1) Apoyar la implementación de políticas y procedimientos del sistema de gestión de la	

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calidad del SVCASC. 2) Apoyar las actividades que garanticen la planificación, implementación, mantenimiento, verificación y mejoramiento del Sistema de Gestión de la calidad del SVCASC. 3) Ayudar en la formulación, implementación y cumplimiento del Plan de Acción de la Auditoría Interna y/o externa. 4) Brindar apoyo al personal encargado del mantenimiento y operación del SVCASC de acuerdo a los métodos y procedimientos, el objetivo de cada ensayo y la evaluación de los resultados de los ensayos. 5) Analizar los parámetros de calidad del aire y meteorología registrados por el SVCASC, siguiendo los procedimientos para garantizar la trazabilidad y calidad de los datos generados por el SVCASC, para lo cual se deberá implementar continuamente los metodos normalizados de calidad del aire bajo el estandar de la ISO 17025 y del Hand Book de la EPA. 6) Apoyar el desarrollo y la implementación de la 2da fase de la modelación de calidad del aire en Santiago de Cali. 7) Brindar apoyo en el proceso de obtención, evaluación, sistematización y verificación de la información del SVCASC que alimente la base de datos del Sistema de información geográfica SIG. 8) Apoyo a la supervisión de los procedimientos de validación de los datos registrados por las estaciones de monitoreo del Sistema de Vigilancia de Calidad del Aire de Santiago de Cali – SVCASC. 9) Atender las quejas y solicitudes que le sean asignadas relacionados con Calidad del Aire. 10) Apoyar las actividades que garanticen la planificación, implementación, verificación y mejoramiento de los Sistemas de Gestión de la calidad del SVCASC. 11) Realizar la toma de muestra, el acondicionamiento y pesaje de filtros de acuerdo a los procedimientos establecidos y la validación de los métodos de ensayo a su cargo. 12) Apoyar y participar en la coordinación de jornadas, eventos y campañas relacionadas con la calidad del aire y sustentabilidad ambiental. 13) Brindar apoyo en la planeación, gestión e implementación de acciones del Programa de Aire Limpio para Santiago de Cali. 14) Las demás actividades que sean asignadas por la dirección del DAGMA y/o la supervisión que tengan relación directa con el objeto del contrato.

INFORMACIÓN ADICIONAL: N/A

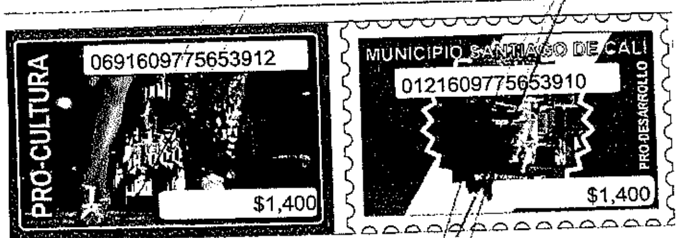
Esta certificación no tiene validez sin las estampillas de ley (Teniendo en cuenta el Concepto jurídico del cobro de estampillas Pro-Desarrollo Urbano Radicado No. 201741210100043214 del 01/11/2017 de la Dirección del Departamento Administrativo de Gestión Jurídica Pública, recibido en esta Oficina el 07/11/2017 y la Resolución 000063 del 14 de noviembre del 2017, se adjunta y se anulan estampillas Pro-Hospitales Universitarios del Valle de $3000, Pro Salud Departamental de $3000, Pro Desarrollo Urbano $ 1.300 y Pro cultura de $ 1.300.).

Para constancia se firma en Santiago de Cali, a los siete (07) días del mes de enero del dos mil veintiuno (2021).

Paola Rodriguez

PAOLA RODRIGUEZ MORENO
DEPARTAMENTO ADMINISTRATIVO DE GESTIÓN DEL MEDIO AMBIENTE - DAGMA

Proyectó: Maricel Grijalba Zapata – Secretaria Administrativa
Elaboró: Maricel Grijalba Zapata – Secretaria Administrativa



GOBERNACIÓN VALLE DEL CAUCA

Rcbo No: 99010000000004378108 C.C: 1130675674
WILSON RAFAEL SALAS CHAVEZ
DAGMA
LOS CERTIFICADOS O CONSTANCIAS EXPEDIDAS POR FUNCIONARIOS
VALOR TOTAL DEL ACTO O DOCUMENTO: 7200
9451242401 05/01 /2021 07:40:59 a.m. 1 DE 1

El suscrito DIRECTOR del DEPARTAMENTO ADMINISTRATIVO DE GESTIÓN DEL MEDIO AMBIENTE - DAGMA, con base en la información que reposa en el archivo de la entidad y la publicada en el Sistema Electrónico de Contratación Pública – SECOP, hace constar que WILSON RAFAEL SALAS CHÁVEZ, identificado con la cédula de ciudadanía número 1.130.675.674, suscribió los siguientes contratos:

AÑO	2019
TIPO	PRESTACIÓN DE SERVICIOS
No.	4133.010.26.1.840-2019
FECHA DE SUSCRIPCIÓN	15/05/2019
PORCENTAJE DE PARTICIPACIÓN DEL CONSORCIO O UNIÓN TEMPORAL	N/A
OBJETO	Prestar servicios profesionales para el análisis y validación de datos del Sistema de Vigilancia de Calidad del Aire de Santiago de Cali (SVCASC) y la implementación del Programa de Aire Limpio, que adelante el DAGMA en la presente vigencia fiscal 2019.
PLAZO (DESDE –HASTA)	20/05/2019 hasta el 31/12/2019.
VALOR	TREINTA Y DOS MILLONES OCHOCIENTOS MIL PESOS M/CTE ($32.800.000.oo).
VALOR EJECUTADO HASTA LA FECHA (APLICA PARA CONTRATOS EN EJECUCIÓN)	N/A
VALOR FINAL DEL CONTRATO (APLICA PARA CONTRATOS EJECUTADOS)	TREINTA Y DOS MILLONES OCHOCIENTOS MIL PESOS M/CTE ($32.800.000.oo).
ESTADO DEL CONTRATO	TERMINADO
NIVEL DE CUMPLIMIENTO (APLICA PARA CONTRATOS EJECUTADOS)	El contratista cumplió a cabalidad con las actividades y obligaciones contempladas en el contrato de prestación de servicios No.4133.010.26.1.840 – 2019.

OBLIGACIONES GENERALES
NO REQUERIDAS POR EL SOLICITANTE
OBLIGACIONES ESPECÍFICAS

1. Apoyar la implementación de políticas y procedimientos del sistema de gestión de la calidad del SVCASC.
2. Apoyar las actividades que garanticen la planificación, implementación, mantenimiento, verificación y mejoramiento del Sistema de Gestión de Calidad del SVCASC.
3. Ayudar en la formulación, implementación y cumplimiento del Plan de Acción de la Auditoria Interna y/o externa.
4. Brindar apoyo al personal encargado del mantenimiento y operación de SVCASC de acuerdo a los métodos y procedimientos, el objetivo de cada ensayo y la evaluación de los resultados de los ensayos.
5. Analizar los parámetros de calidad del aire y meteorología registrados por el SVCASC.
6. Evaluar y diagnosticar la calidad del aire a través de los resultados de monitoreo del SVCASC.
7. Brindar apoyo en el proceso de obtención, evaluación y sistematización de la información del SVCASC que alimente la base de datos del Sistema de Información Geográfica SIG.
8. Apoyo a la supervisión de los procedimientos de validación de los datos registrados por las estaciones de monitoreo del Sistema de Vigilancia de Calidad del Aire de Santiago de Cali – SVCASC.
9. Atender las quejas y solicitudes que le sean asignadas relacionadas con Calidad del Aire.
10. Apoyar las actividades que garanticen la planificación, implementación, verificación y mejoramiento de los Sistemas de Gestión de la calidad del SVCASC.
11. Realizar el acondicionamiento y pesaje de filtros de acuerdo a los procedimientos establecidos y la validación de los métodos de ensayo a su cargo.
12. Apoyar y participar en la coordinación de jornadas, eventos y campañas relacionadas con la calidad del aire y sustentabilidad ambiental.
13. Brindar apoyo en la planeación, gestión e implementación de acciones del Programa de Aire Limpio para Santiago de Cali.
14. Las demás que sean asignadas por la Dirección del DAGMA y/o la supervisión que tengan relación directa con el objeto del contrato.

AÑO	2019
TIPO	PRESTACIÓN DE SERVICIOS
No.	4133.010.26.1.204-2019
FECHA DE SUSCRIPCIÓN	22/01/2019
PORCENTAJE DE PARTICIPACIÓN DEL CONSORCIO O UNIÓN TEMPORAL	N/A
OBJETO	Prestar servicios profesionales para el análisis y validación de datos del Sistema de Vigilancia de Calidad del Aire de Santiago de Cali (SVCASC) y la implementación del Programa de Aire Limpio
PLAZO (DESDE –HASTA)	24/01/2019 hasta el 30/04/2019.
VALOR	DIECISÉIS MILLONES CUATROCIENTOS MIL PESOS M/CTE ($16.400.000.oo).
VALOR EJECUTADO HASTA LA FECHA (APLICA PARA CONTRATOS EN EJECUCIÓN)	N/A
VALOR FINAL DEL CONTRATO (APLICA PARA CONTRATOS EJECUTADOS)	DIECISÉIS MILLONES CUATROCIENTOS MIL PESOS M/CTE ($16.400.000.oo).
ESTADO DEL CONTRATO	TERMINADO
NIVEL DE CUMPLIMIENTO (APLICA PARA CONTRATOS EJECUTADOS)	El contratista cumplió a cabalidad con las actividades y obligaciones contempladas en el contrato de prestación de servicios No.4133.010.26.1. 204 – 2019.
OBLIGACIONES GENERALES	
NO REQUERIDAS POR EL SOLICITANTE	
OBLIGACIONES ESPECÍFICAS	
1. Apoyar la implementación de políticas y procedimientos del sistema de gestión de la calidad del SVCASC.	

2. Apoyar las actividades que garanticen la planificación, implementación, mantenimiento, verificación y mejoramiento del Sistema de Gestión de Calidad del SVCASC.
3. Brindar apoyo en la formulación, implementación y cumplimiento del Plan de Acción de la Auditoría Interna y/o externa.
4. Brindar apoyo al personal encargado del mantenimiento y operación de SVCASC de acuerdo a los métodos y procedimientos, el objetivo de cada ensayo y la evaluación de los resultados de los ensayos.
5. Brindará apoyo en el análisis de los parámetros de calidad del aire y meteorología registrados por el SVCASC.
6. Brindará apoyo en la evaluación y diagnóstico de la calidad del aire a través de los resultados de monitoreo del SVCASC.
7. Brindar apoyo en el proceso de obtención, evaluación y sistematización de la información del SVCASC que alimente la base de datos del Sistema de Información Geográfica SIG.
8. Brindará apoyo a la supervisión de los procedimientos de validación de los datos registrados por las estaciones de monitoreo del Sistema de Vigilancia de Calidad del Aire de Santiago de Cali – SVCASC.
9. Brindará apoyo en la atención de las quejas y solicitudes que le sean asignadas relacionadas con Calidad del Aire.
10. Brindará apoyo en las actividades que garanticen la planificación, implementación, verificación y mejoramiento de los Sistemas de Gestión de la calidad del SVCASC.
11. Brindará apoyo en el acondicionamiento y pesaje de filtros de acuerdo a los procedimientos establecidos y la validación de los métodos de ensayo a su cargo.
12. Apoyar y participar en la coordinación de jornadas, eventos y campañas relacionadas con la calidad del aire y sustentabilidad ambiental.
13. Brindar apoyo en la planeación, gestión e implementación de acciones del Programa de Aire Limpio para Santiago de Cali.
14. Brindará apoyo en la atención de los PQRS asignados relacionados con temas de calidad del aire.
15. Las demás que sean asignadas por la Dirección y/o la Subdirección de Gestión de Calidad Ambiental y/o la supervisión que tengan relación directa con el objeto del contrato.

INFORMACIÓN ADICIONAL: No aplica.

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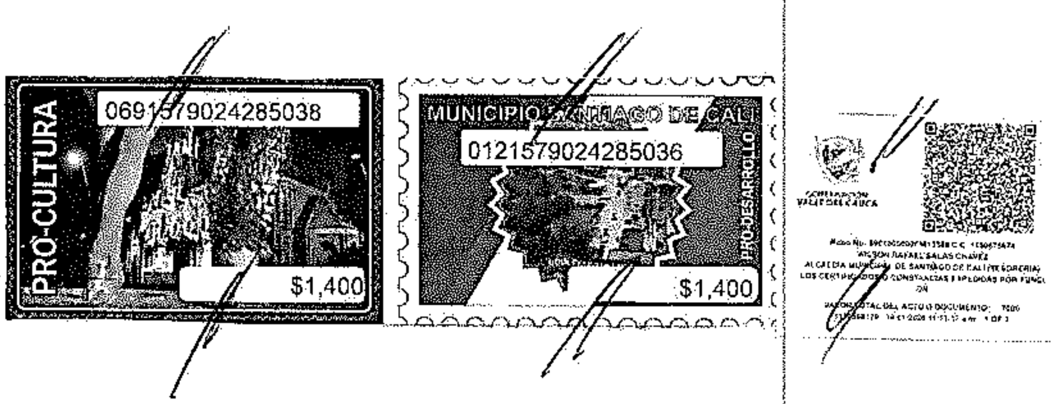
ALCALDÍA DE SANTIAGO DE CALI GESTIÓN JURÍDICO ADMINISTRATIVA GESTIÓN CONTRACTUAL	SISTEMAS DE GESTIÓN Y CONTROL INTEGRADOS (SISTEDA, SGC y MECI)	MAJA01.04.03.18.P05.F01	
		VERSIÓN	1
	CERTIFICACION DE CONTRATO / CONVENIO	FECHA DE ENTRADA EN VIGENCIA	01/oct/2019

Esta certificación no tiene validez sin las estampillas de ley (Teniendo en cuenta e Concepto de cobro jurídico del cobro de estampillas Pro-Desarrollo Urbano Radicado No. 201741210100043214 del 01/11/2017 de la Dirección del Departamento Administrativo de Gestión Jurídica Pública, recibido en esta Oficina el 07/11/2017 y la Resolución 000063 del 14 de Noviembre de 2017, se adjunta y se anulan estampillas Pro-Hospitales Universitarios del Valle de $3000, Pro Salud Departamental de $3000, Pro Desarrollo Urbano $1300 y Pro cultura de $1300).

Para constancia se firma en Santiago de Cali, a los catorce (14) días del mes de enero del año dos mil veinte (2020).

CARLOS EDUARDO CALDERÓN LLANTÉN
DEPARTAMENTO ADMINISTRATIVO DE GESTIÓN DEL MEDIO AMBIENTE - DAGMA

Elaboró: Mónica Isabel Lozada Montilla – Secretaria Ejecutiva – Área Administrativa Mónica



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USC UNIVERSIDAD SANTIAGO DE CALI

LA DIRECCION DEL DEPARTAMENTO DE GESTION HUMANA DE LA UNIVERSIDAD SANTIAGO DE CALI

HACE CONSTAR:

Que el(a) señor(a) SALAS CHAVEZ WILSON RAFAEL, identificado(a) con cedula de ciudadanía No. 1130675674, prestó sus servicios profesionales a esta institución, como docente, mediante honorarios por prestación de servicios:

FECHA: Octubre 15 al 06 de noviembre de 2021
PROGRAMA: Especializacion en Control de la Contaminacion Ambiental
MODULO: Calidad y Control de la Contaminacion Atmosferica
DURACION: 48 Horas

FECHA: Noviembre 4 al 19 de Noviembre de 2022
PROGRAMA: Especializacion en Control de la Contaminacion Ambiental
MODULO: Modelacion de la Calidad del aire- Electiva II
DURACION: 32 Horas

Para constancia de lo anterior, se firma y sella en la ciudad de Santiago de Cali, a los 27 días del mes de mayo de 2024.

LINA MARIA GALINDO CARDOZO
DIRECTORA DEPARTAMENTO DE GESTION HUMANA
Proyectó: Carolina Durán
Aprobó: Lina María Galindo Cardozo

USC UNIVERSIDAD SANTIAGO DE CALI
DIRECCIÓN GESTIÓN HUMANA

ACREDITACIÓN INSTITUCIONAL EN ALTA CALIDAD

Environmental Modeling & Assessment (2024) 29:915–932
https://doi.org/10.1007/s10666-024-09969-7

RESEARCH

Characterization of Non-Conventional Airborne Pollutants (BTEX) by means of Chemometric Techniques

Rubén Albeiro Sánchez-Andica[1] · Wilson Rafael Salas-Chávez[1] · Martha Isabel Páez-Melo[1]

Received: 23 February 2023 / Accepted: 6 March 2024 / Published online: 21 March 2024

Abstract

In this study, chemometric and spatial interpolation methods were employed to characterize non-conventional pollutants in the atmosphere of Santiago de Cali, Colombia. The pollutants were monitored using passive diffusion samplers during two distinct periods (January to February and March to April) in the two years after the pandemic (2021 and 2022). None of the monitored cases exceeded the concentration limits established by the National Air Quality Standard. Cluster analysis revealed distinct groups, categorizing sites into low, medium, and high pollutant influence. Principal Components Analysis (PCA) was employed to condense all variables into two primary constituents. The first component (PC1) serves as an indicator of mobile pollutant sources due to the consistent contribution of pollutants. Conversely, the second component (PC2) indicates punctual emissions of toluene, which made the most significant contribution. Spatial analysis demonstrated that downtown and the northern region of the city were highly influenced by PC1, with a substantial decrease in its effects towards the periphery, particularly the south. Utilizing Inverse Distance Weighting (IDW), we identified hotspots for both PCs, notably in areas undergoing real estate construction and the downtown industrial sector. Finally, our analysis revealed a cancer risk in the downtown and northeast areas of the city, associated with exposure to benzene and ethylbenzene. This observation aligns with the region of incidence indicated by PC1.

Keywords Atmospheric pollution · Volatile organic compounds · Chemometrics

1 Introduction

Air pollution in cities and towns is an escalating concern due to the continuous emission of a diverse range of pollutants. According to the World Health Organization (WHO) in 2012, air quality issues were linked to an estimated 6.5 million deaths, out of which 3.5 million were premature [1]. Urban centers primarily face atmospheric contamination from vehicle emissions, combustion processes, and industrial activities. Priority pollutants in atmospheric contamination studies include particulate matter, nitrogen and sulfur oxides, heavy metals, and various volatile organic compounds (VOCs), notably BTEX (benzene, toluene, ethylbenzene, and xylenes) [2, 3]. These pollutants have diverse impacts on human health. For instance, benzene affects the nervous system and is carcinogenic, linked to leukemia [4]. Toluene primarily impacts the nervous system, and prolonged exposure can lead to vision loss and permanent brain damage [5]. Ethylbenzene, when present in high levels, can cause vertigo, eye and throat irritation, and is considered a potential carcinogen [6]. Xylenes affect the nervous system (e.g., short-term memory) and the airways, potentially causing kidney and liver problems at high concentrations [7]. Various methodologies have been employed to determine contamination sources, enabling the establishment of preventive plans. Among these, chemometrics, a set of statistical methods, stands out [8]. Cluster Analysis (CA) is a prominent chemometric method enabling the classification of elements or variables [9–12]. Principal Component Analysis (PCA) is another vital method, summarizing variables

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to a smaller set and facilitating the identification of pollution sources [13–19]. To correlate geographic information with pollutant concentration in hard-to-reach areas, spatial representation of pollution phenomena has been essential. Spatial interpolation methods like Inverse Distance Weighting (IDW) interpolation [20, 21] and kriging [22–27] have been utilized for this purpose. Risk assessment, a methodology estimating risk levels for living beings based on possible exposure scenarios, is also crucial. Due to the persistence of VOCs in urban areas, several authors suggest that the characterization of pollutants and spatial representation should be accompanied by risk assessment studies, considering the toxicological characteristics of polluting chemical compounds [28–32].

The primary objective of this study was to apply chemometric techniques to characterize and spatially represent VOCs, as well as to assess the carcinogenic risk based on data from passive pollutant sampling in Santiago de Cali, Colombia.

2 Methodology

2.1 Study Area

The pollutants were monitored within the city of Santiago de Cali, Colombia. Geographically, the city is positioned at 3°27’26” North latitude and 76°31’42” West longitude, situated at an elevation of 1,070 m above sea level (masl). Santiago de Cali is nestled between the Western Cordillera and the Central Cordillera. Serving as the capital of the Valle del Cauca department, it ranks as the third most populous city in Colombia, housing approximately 2,394,870 inhabitants (refer to Fig. 1).

The city spans an approximate area of 561.6 km², with the urban area constituting 120.9 km². Administratively, it is organized into 22 communes and 248 neighborhoods. The city shares its boundaries; to the north with the municipalities of Yumbo, La Cumbre, and Palmira, to the east with the municipality of Candelaria, to the west with the municipalities of Buenaventura and Dagua, and to the south with the municipality of Jamundí. The administrative division comprises 22 communes and 248 neighborhoods [33].

2.2 Sampling and Analysis

The sampling of contaminants was conducted by the passive sampling technique using Carbopack B as an adsorbent material (procured from the Swedish Environmental Research Institute).

A total of four (4) monitoring campaigns for two months (according to the Swedish Environmental Research Institute IVL recommendations) were conducted as follows: s1 (February-March 2021), s2 (March-April 2021), s3 (February-March 2022), and s4 (March-April 2022) in Santiago de Cali city. Across the city, 41 monitoring points were strategically located along streets and road corridors, covering all 22 communes (refer to Table 1).

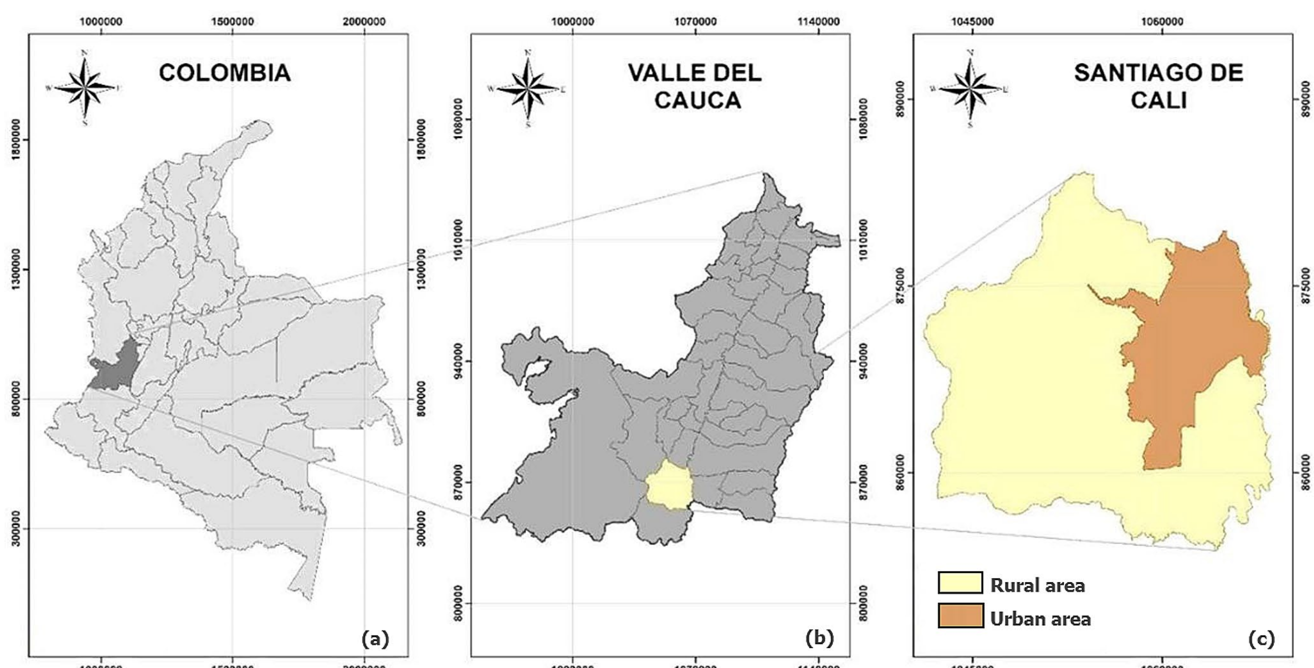


Fig. 1 Spatial geographical location in (a) Colombia of (b) Departamento del Valle and (c) the municipality of Santiago de Cali and the city of Santiago de Cali (urban area)

Notably, some of these sampling stations are operated by the *Departamento Administrativo de Gestión del Medio Ambiente* (DAGMA) as part of the Santiago Cali Air Quality Surveillance System. The spatial distribution of these stations within the city is illustrated in Fig. 2.

During the sampling campaigns, the average weather conditions were recorded as follows:

Period s1 (February-March 2021): Minimum temperature (Tmin) of 19.2 °C, maximum temperature (Tmax) of 28.6 °C, and rainfall of 5.7 mm [34].

Period s2 (March-April 2021): Tmin of 19.7 °C, Tmax of 28.4 °C, and rainfall of 2.7 mm [34].

Period s3 (February-March 2022): Tmin of 18.7 °C, Tmax of 29.2 °C, and rainfall of 3.4 mm [34].

Period s4 (March-April 2022): Tmin of 19.4 °C, Tmax of 29.6 °C, and rainfall of 6.1 mm [34].

According to data from the *Instituto de Hidrología, Meteorología y Estudios Ambientales* (IDEAM), the foremost hydroclimatology authority in Colombia, no significant deviations were observed in temperature fluctuations between the sampling periods and the respective years in 2021 and 2022.

The samplers were anchored to posts alongside the road at an average height of 6 m and left for a period of two months. After this time, the samplers were removed and taken to the laboratory for the respective quantification.

Analytical determination of volatile organic compounds (VOCs) was carried out at IVL laboratories following the standardized method EN 13528-2 2003 [35]. In short, this method involves thermal desorption of the compounds at 250 °C for 5 min, followed by sample concentration in a cold trap maintained at -30 °C and quantification by Gas Chromatography with flame ionization detector (GC-FID).

2.3 Analytical Performance

Stock solution of COVs were prepared from benzene, toluene, ethylbenzene, m,p-xylene, o-xylene, n-octane, and nonane (Sigma-Aldrich, USA) analytical standards. Chromatographic quantification of VOCs was conducted in a GC-FID Hewlett Packard 6890 series. A CP-Sil 5 CB GC column (0.32 mm id., 1.2 µm x 50 m) was used in the chromatographic separation. The oven temperature was raised from 35 to 300 °C with a rate of 20 °C/s. The measurements were acquired by external calibration in triplicate and reported as mean values. Precision was calculated as standard deviation (SD). The accuracy of the analytical method was determined by the recovery method by spiking a known concentration of VOCs at three levels (20, 50 y 90 µg/L) to the extracts and the recovery percentage (% R) for each VOC was calculated. The average of recovery percentages of all compounds was 90%. The Lineal range of the calibration plots were between 5 µg/L and 120 µg/L on average. The linearity of each plot was evaluated by the correlation coefficient (r) giving 0,995 (p-value $<$ 0,05) on average. The instrumental limit of detection (LOD) and limit of quantification (LOQ) were calculated for each compound based on 3 and 10 times the Signal Noise ratio (S/N) respectively. The LOD and LOQ were 3.0 µg/L and 5.0 µg/L on average, respectively. Excel® was used for mathematical and statistical calculations when necessary.

2.4 Chemometric Characterization

2.4.1 Data Exploratory Analysis

For the exploratory statistical analysis, R® software was employed, utilizing the graphical interface of R Studio. Box plots were generated for each pollutant in every sampling period to identify potential trends. A statistical significance level of $p < 0.05$ was established. Additionally, each variable was normalized to a statistical value of Z_i calculated by

$$Z_i = \frac{x_i - \mu}{\sigma}, \tag{1}$$

Table 1 Codes for the places where the Volatile Organic Compounds (VOCs) were monitored

Code	Name	Code	Name	Code	Name	Code	Name
1	Icesi†	12	Nueva Floresta	23	Av 3ª C44†	34	Ermita Dagma* †
2	Pance Dagma*	13	Chapinero†	24	Chipichape	35	Luna*†
3	Calicanto	14	B Herrera	25	Primavera	36	Univalle Dagma*
4	MI Urrutia†	15	Comfandi Delicias	26	Guabal	37	Madrigal
5	Vallado	16	Maizena	27	Autopista K44†	38	Premier†
6	ET Dagma*	17	Flora Dagma*†	28	Club Noel†	39	Siloé
7	Calipso†	18	Floralia	29	Aguacatal†	40	Cañaveralejo Dagma*†
8	Mojica	19	Calima†	30	Terrón†	41	Parque Banderas†
9	Compartir Dagma*	20	Ciudad de Cali †	31	San Cayetano		
10	Puente Mil Días †	21	Cl 44 K1 †	32	CC Caleño †		
11	Base Area †	22	Bolivariano	33	ERA Dagma *†		

* = SVCASC's stations; † = Near to main streets

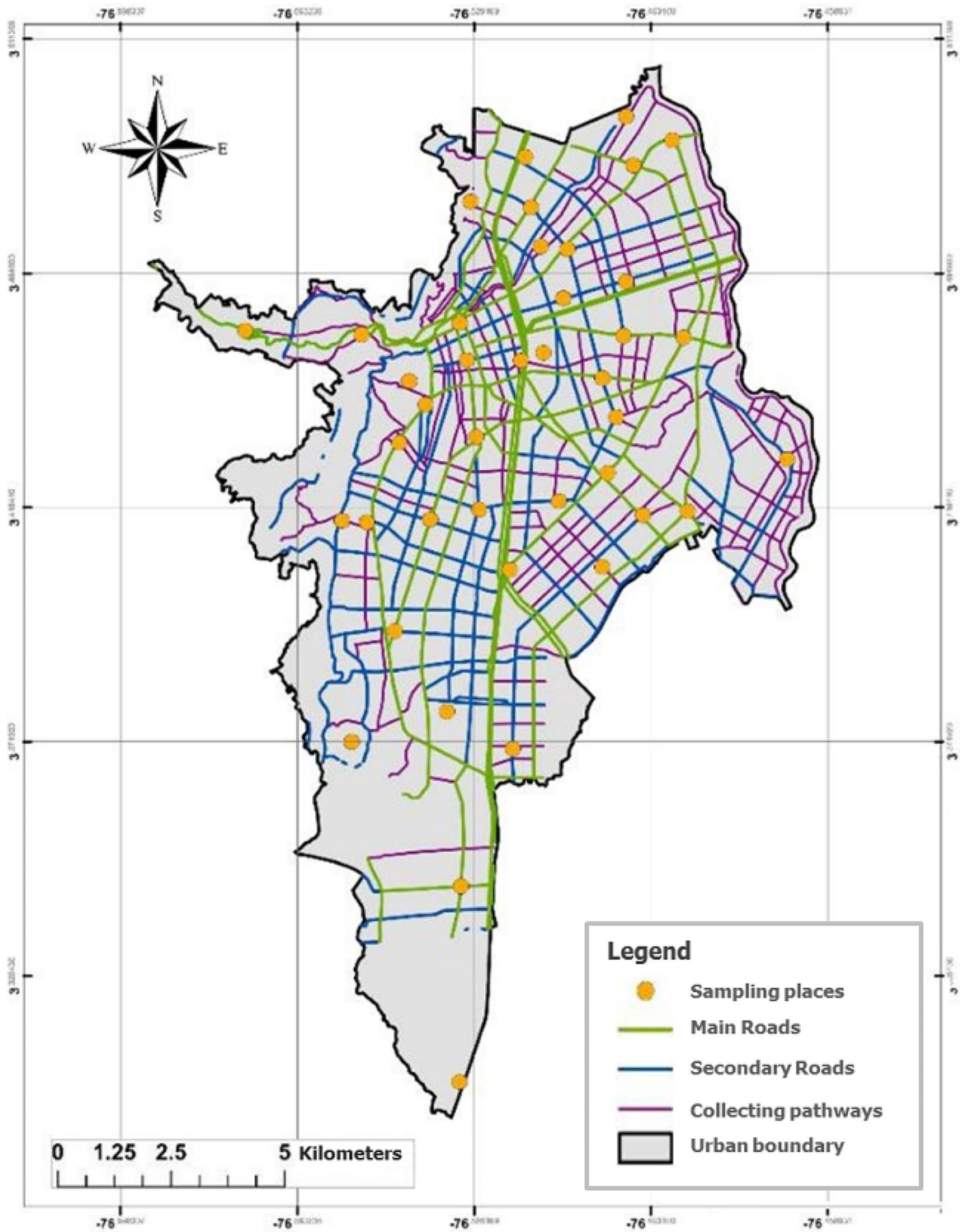


Fig. 2 Spatial location of the samplers in the VOCs monitoring in the urban area of the city of Santiago de Cali

where x_i represents the concentration, μ stands for the mean, and σ represents the standard deviation of the compound [36].

Furthermore, the correlation between different compounds was assessed using the Pearson correlation test. The correlation charts were created using the *cor* function and the *corrplot* package, enabling the examination of potential linear relationships among the VOCs, thus serving as an indicator of common emission sources [36].

2.4.2 Cluster Analysis

The cluster analysis is an unsupervised grouping method in such a way that objects are classified according to their similarities and differences [36]. Euclidean distance and Ward's agglomeration method have been reported as those that present the best structure for environmental data, for this reason, they were the methods that were used in the cluster analysis, to this end, it was set as criteria of similarity between two points i and j, Euclidian distance d_{ij}, was calculated using the Eq. 2.

Cluster analysis is an unsupervised grouping method used to classify objects based on their similarities and differences [36]. In this study, the Euclidean distance and Ward's agglomeration method were selected as they are known to provide the most effective structure for environmental data. For this purpose, the Euclidean distance, d_{ij}, between two points i and j was calculated by the following expression:

$$d_{ij} = \sqrt{\sum_{n=1}^{7} \left(x_{i,n} - x_{j,n}\right)^2}, \tag{2}$$

where x_i and x_j represent the n characteristics of those points, in this case the 7 VOC concentrations. Initially, each object was considered as its own cluster, and iteratively, the most similar objects were linked. Using Ward's method, clusters were formed until a single total cluster composition was achieved [36]. The cluster analysis was conducted using the *hclust* function within the *stats* package.

2.4.3 Principal Components Analysis

Principal Components Analysis (PCA) is a multivariate analysis method commonly employed to reduce the dimensionality of a data array comprising interrelated variables. It effectively preserves most of the original information while simplifying the interpretation of variation sources [36, 37]. The method involves decomposing the original data matrix (X) as expressed by

$$\mathrm{X} = TL^T, \tag{3}$$

where X is a matrix of dimensions (n,p), T is the matrix of *scores* (n,d), L is the matrix of *loadings* (p,d) and the superscript T indicates the transpose of the matrix.

The resulting new variables, known as principal components (PC), are derived from the projection of X onto the matrix of scores (L), yielding T (Eq. 4), where columns represent the principal components [12, 36, 37]

$$\mathrm{T} = \mathrm{XL} \tag{4}$$

.The PCA was conducted using the PCA function from the *FactoMineR* package.

2.4.4 Spatial Analysis

Two interpolation methods were employed for spatial analysis: Inverse Distance Weighting (IDW) [19, 38] and kriging [38, 39].

Inverse Distance Weighting (IDW) This method assumes that each sampled point has a local influence, which decreases with the distance, giving more weight to closer points. IDW estimates a property $\hat{x}$ at a point in space s_0 through the following expression.

$$\widehat{x}\left(s_0\right) = \frac{\sum_{i=1}^{N}\left(x\left(s_i\right)/d_i^p\right)}{\sum_{i=1}^{N}\left(1/d_i^p\right)}, \tag{5}$$

where N is the number of neighbors, $x(s_i)$ is the property at point s_i, d_i is the distance from s_i to s_0, and p is the power to which the distance raised. Here, $N = 12$ neighbors and $p = 2$, were used.

Kriging Kriging is based on the statistical principle of spatial autocorrelation, suggesting greater similarity between nearby points. Similar to IDW, it estimates the value of a property, $\hat{x}$, at s_0 using the following expression.

$$\widehat{x}\left(s_0\right) = \sum_{i=1}^{N} \lambda_i x\left(s_i\right). \tag{6}$$

Here, N is the number of measured values, $x(s_i)$ is the property at a point, and λ_i, represents the weighting of the measured value at the location i. The weighting factor, λ, is known as the semi-variance, and was calculated by

$$\lambda\left(d_{ij}\right) = \frac{1}{2}\sum_{i=1}^{N}\left(x\left(s_i\right) - x(s_j)\right)^2, \tag{7}$$

where d_{ij} is the distance between 2 points s_i and s_j and $x(s_i)$ and $x(s_j)$ are the values at those points. This yields a semi-variogram representing the degree of spatial correlation. In this study, ordinary kriging with a spherical semi-variogram model was employed. The calculations and cartographic representations were conducted using ArcGIS® 10.1.

2.4.5 Carcinogenic Risk Assessment

Carcinogenic risk (R) assessment was conducted for benzene and ethylbenzene using the EPA model [14, 28], as depicted as

$$R = SF\frac{CxIRxEFxETxED}{BWxAT}, \tag{8}$$

where SF represents the slope factor (2,73 × 10-2 y 3,85 × 10-3 mg/kg/day for benzene and ethylbenzene, respectively), C(si) is the pollutant concentration at the point si (mg/m3), IR is the inhalation rate (0,875 m3/h for adults), ET is the exposure time (4 h/day), EF is the exposure frequency (350 days/year), ED is the exposure duration (30 years), BW is the body weight (70 kg) and AT is the averaging Time (70 years). The study framework considered an adult spending a minimum of 4 h per day outdoors, for 350 days each year, over a minimum of 30 years [30]. Risk values were calculated for each sampling period *i* and both pollutants as the total carcinogenic risk TR_i (Eq. 9):

$$TR_i = BR_i + ER_i, \tag{9}$$

where BR_i and ER_i represent the benzene and ethylbenzene risk for the sampling period i. This model assumes non-interaction among pollutants and was represented cartographically using the kriging method to generate carcinogenic risk maps for the city of Santiago de Cali.

3 Results and Discussion

3.1 Exploratory Analysis

The box plots, depicted in Fig. 3, illustrate the concentrations of each analyte across the four sampling campaigns. Notably, there is a noticeable congruency between the s1-s3 and s2-s4 samplings, indicating a certain temporal stability in the monitored contaminants. The average VOC concentrations obtained from the four campaigns underwent One-way ANOVA, yielding a significance level (p-value) of 0.246, exceeding 0.05. Therefore, no significant difference was observed between each group.

The specific concentrations of each analyte during each sampling period are summarized in Table 2. Notably, the first campaign exhibited the highest average concentrations for all the VOCs analyzed and displayed the greatest dispersion of data.

In comparison with data from various cities worldwide (see Table 3) [40], the average benzene concentrations in this study are comparable to most cities, except for Rome and Bombay, where they are an order of magnitude lower. For toluene, the concentration in Cali is higher than that of benzene. However, the concentration ranges align with those of the cities mentioned in Table 3. The xylene isomers' concentrations in Cali were an order of magnitude higher than benzene, akin to the data from the Sao Paulo study.

Several studies suggest that the m,p-xylene/ethylbenzene (mpX/E) ratio can serve as an emissions indicator, primarily from mobile sources. In this study, the mpX/E ratio averages 4.8, closely resembling ratios reported by other authors

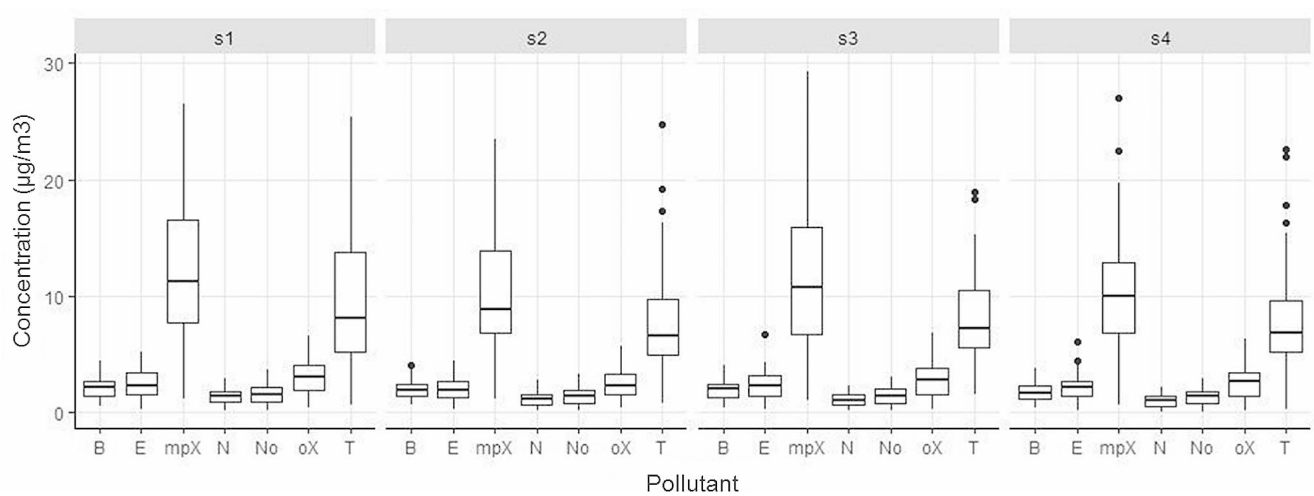


Fig. 3 Box plot of VOC concentrations for the comparison of pollutants in the 4 monitoring (s1, s2, s3 and s4)

Table 2 Summary of VOC concentrations (μgm^{-3}) for each sampling period (S_1, S_2, S_3 and S_4)

Analite (μg/m^3)	S_1			S_2			S_3			S_4		
	m ± s	min	max	m ± s	min	max	m ± s	min	max	m ± s	min	max
Benzene	2.3 ± 1.0	0.51	4.40	2.0 ± 0.9	0.68	4.08	2.1 ± 0.9	0.41	4.05	1.8 ± 0.8	0.39	3.81
Toluene	9.5 ± 5.8	0.63	25.4	8.0 ± 5.0	0.85	24.8	8.3 ± 4.1	1.59	18.9	8.4 ± 5.0	0.28	22.5
Ethylbenzene	2.6 ± 1.2	0.29	5.15	2.1 ± 1.0	0.30	4.46	2.4 ± 1.2	0.29	6.72	2.2 ± 1.2	0.19	6.10
m,p-Xylene	12.6 ± 6.3	1.13	26.6	10.5 ± 5.2	1.14	23.5	11.5 ± 6.0	1.10	29.3	10.8 ± 5.6	0.70	27.0
o-Xylene	3.2 ± 1.5	0.40	6.59	2.6 ± 1.2	0.38	5.68	2.9 ± 1.5	0.3	6.8	2.7 ± 1.3	0.23	6.29
n-Octane	1.6 ± 0.9	0.15	3.72	1.5 ± 0.8	0.14	3.31	1.5 ± 0.8	0.17	3.05	1.5 ± 0.7	0.08	2.99
Nonane	1.4 ± 0.7	0.15	2.97	1.3 ± 0.6	0.13	2.81	1.1 ± 0.6	0.12	2.37	1.1 ± 0.5	0.08	2.16

m = mean; s = standard deviation; min = minimum concentration; max = maximum concentration; s1 = sampling on February-March 2021, s2 = sampling on March-April 2021, s3 = sampling on February-March 2022 and s4 = sampling on March-April 2022

Table 3 BTEX concentrations in different cities worldwide (μg.m^{-3}) compared from those obtained in this study. Values adapted from Kerchich & Kerbachi [41]*

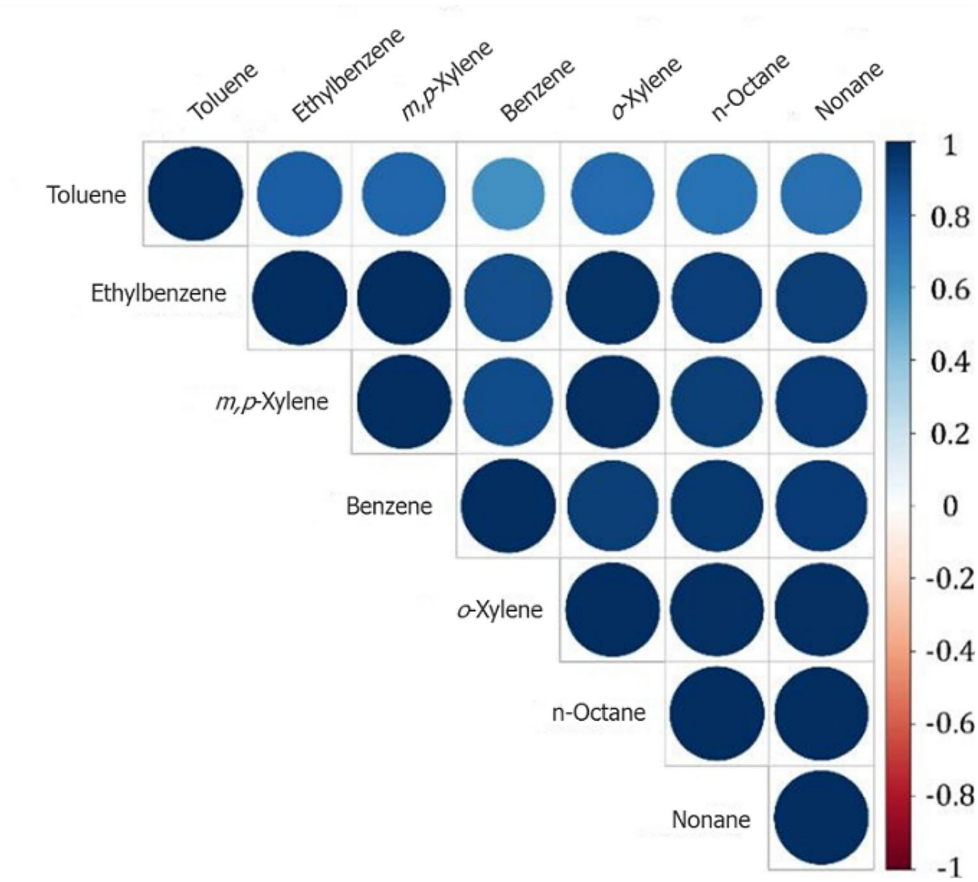
City	Benzene	Toluene	Ethylbenzene	m,p-Xylene	o-Xylene
Argiel	1.94	4.57	1.20	1.07	0.55
Rome	33.5	99.7	17.6	54.1	25.1
Yokohama	1.7–3.7	4.7–34.3	0.5–3.8	1.0–2.0	0.1–0.8
London	2.7	7.2	1.4	3.7	2.9
Mumbai	13.7	11.1	0.4	1.3	2.2
São Paulo	4.6	44.8	13.3	26.1	6.9
La Coruña	3.4	23.6	3.3	5.1	2.7
Toulouse	2	6.6	NA	1.2	3.7
Pamplona	2.8	13.3	2.15	6.01**	NA
Seoul	3.2	24.5	3.0	10.0	3.5
Hong Kong	30.51	200.82	15.07	15.67**	N.A.
Cali (This study)	**2.1**	**8.6**	**2.3**	**11.4**	**2.8**

*Data collected between 1997 to 2012. ** (o + m + p)-xylenes

(ranging between 2 and 5) [41–43 Given that the air quality standard in Colombia only establishes a threshold limit for benzene (5 μg/m3 annual average) [3] and considering the global standard values ranging from 1.3 to 10 μg/m3 (annual averages) [44], the measured values fall within compliance with Colombian legislation and are within the concentration range of the majority of legislations worldwide.

The correlation graph (Fig. 4) reveals that toluene has the lowest correlations with all VOCs, particularly benzene, while displaying a high correlation with the rest of the VOCs. Previous research investigating the correlation between these compounds has also noted that high correlations between VOCs suggest similar emission sources, particularly mobile sources [41–43], as observed for benzene, xylenes, ethylbenzene, n-octane, and nonane. The low correlation between benzene and toluene (BT) can be explained by the (B/T) ratio, which can be considered an indicator of vehicle emissions. In this study, B/T ratio values between 4 and 5 were obtained, closely resembling ratios reported in other works [41–43]. However, upon detailed analysis of the B/T ratio, it was observed that for the highest concentrations of both pollutants, the ratio increases. Kerchich and Kerbachi (2012) suggested that this phenomenon might be attributed to the presence of point emission sources of toluene, since the (BT) correlation is high in road corridors [40].

Fig. 4 Pair-wise correlation analysis for the 7 VOCs monitored using 'corrplot' package. In the right side of the correlogram, the legend color shows the correlation coefficients and the corresponding colors, blue for positive correlations and red for negative correlations. All samples showed positive correlation with each other, and the size of the circle were proportional to correlation coefficients



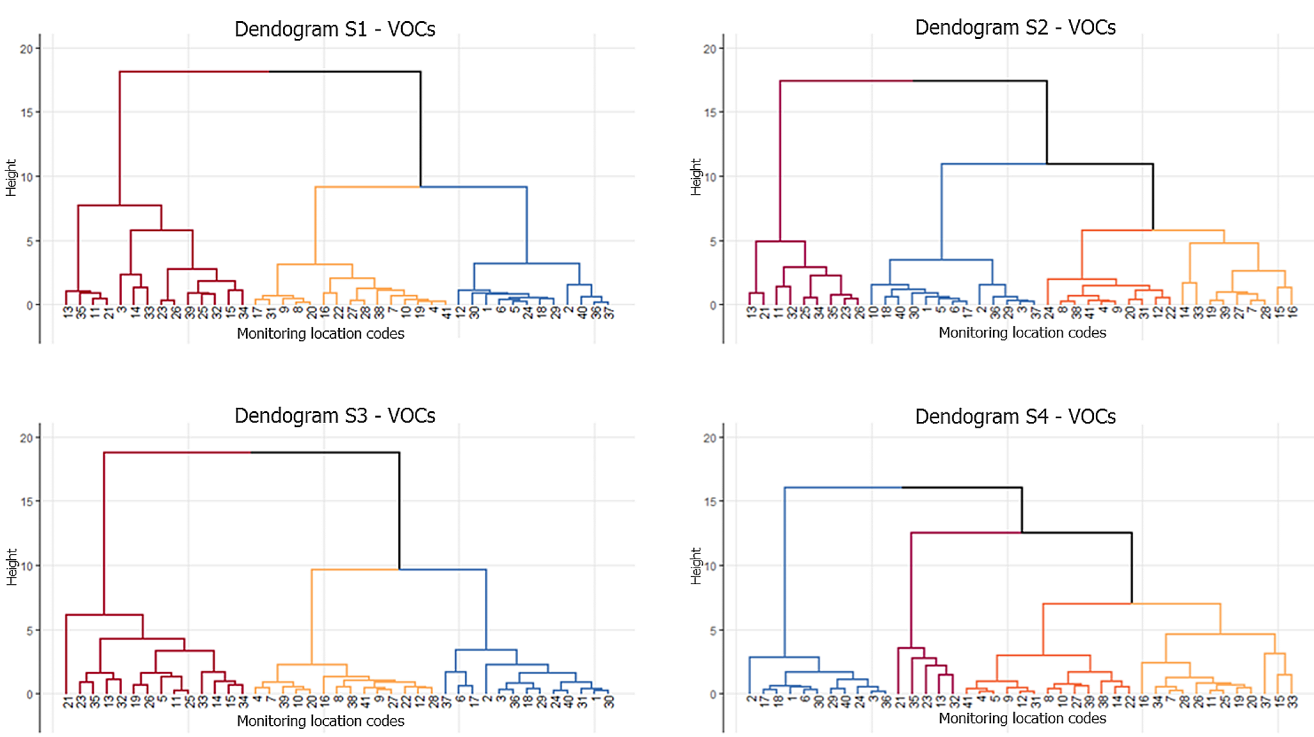


Fig. 5 Mean similarity dendrograms for the pollutants assemblages (VOCs) of the four sampling periods (s1, s2, s3 and s4). Each group formed cluster is denoted by the red, blue, orange and yellow colors, which agglomerate pollutants according to the characteristics of the sampling place

3.2 Cluster Analysis

The cluster analysis was employed to characterize monitoring locations based on the concentrations of VOCs found. This method involves a global-type multivariate classification considering all measured variables [45].

Figure 5 displays the dendrograms resulting from the cluster analysis for each sampling (s1, s2, s3, and s4). The graphic illustrates distinct clustering patterns of contaminants for s1-s3 (3 clusters) and s2-s4 (4 clusters), which aligns with the expectation as s1-s3 and s2-s4 represent samplings from the same period in different years. The resulting clusters in the four periods are as follows, categorized by sampling sites:

a) *Cluster H (Red)*: (13) Chapinero, (21) C44K1, (23) Av3 C44, (32) CC Caleño, (35) Luna. These locations are characterized by high vehicular traffic, particularly emissions from two-stroke motorcycle engines [44].
b) *Cluster L (Blue)*: (1) Icesi, (2) Pance Dagma, (6) ET Dagma, (18) Floralia, (29) Aguacatal, (36) Univalle Dagma, (40) Cañaveralejo Dagma. These places correspond to residential areas close to low-traffic roads or spacious areas with better airflow.
c) *Clusters M and ML (Orange and Yellow respectively)*: (4) MI Urrutia, (7) Calipso, (8) Mojica, (9) Compartir Dagma, (16) Maizena, (20) Ciudad Cali, (22) Bolivariano, (27) Autop 44, (28) Club Noel, (38) Premier, (41) P Banderas. These clusters comprise locations near high-traffic areas with significant mobility and high motorcycle circulation. Although individual motorcycles have low VOC emissions, their sheer number results in high VOC concentrations.

Table 4 presents the average VOC concentrations for each cluster group during the four campaigns. ANOVA analysis indicates no statistical difference among all the cluster groups (p-value $(0.58) > 0.05$). The model's sensitivity to variations in pollutant concentrations can cause sampling points to shift from one cluster to another. Certain cases are highlighted, such as calicanto, which responds to an increase in toluene concentrations (likely due to residential buildings), and terron, where low VOCs are in similar proportions to those with high pollutant levels. For the latter, a noticeable transition occurs from the marked cluster L to cluster H, representing high-traffic areas. For the remaining locations, variations are attributed to proximity to road corridors, resulting in smoother transitions.

Table 4 Average VOC concentrations (µg/m^3) for each cluster group during the four campaigns

Sampling campaign	Period time	Clusters			
		H	L	M	ML
S1	Feb – Mar (2021)	2,23	5,27	8,29	N.A.
S2	Mar – Abr (2021)	1,95	6,86	3,53	5,49
S3	Feb – Mar (2022)	6,60	3,87	1,81	N.A.
S4	Mar – Abr (2022)	1,81	3,14	7,70	4,69

3.3 Principal Components Analysis (PCA)

The aim of this technique was to condense the dimensionality of the original variables into a smaller number of elements, known as principal components (PCs), to facilitate data interpretation while preserving the contained information. A scree plot was initially constructed, a tool to determine the number of principal components based on the percentage of variance explained and the abrupt change in the slope of the curve [12, 37].

This change becomes apparent from the second PC, as depicted in Fig. 6a. The total variance explained by the first two PCs amounts to over 95% of the total variance across all samples. For these reasons, it was concluded that these two PCs sufficiently explain the original set of variables [36, 37].

Figure 6b displays correlation circles, representing each variable's contribution to each PC [12, 36, 37]. These graphs illustrate the qualitative and semi-quantitative contribution of each variable to PCs. Notably, all compounds, except toluene, primarily contribute to PC1, aligning with its horizontal axis. Moreover, the small angle between these compounds indicates their high correlation [12], consistent with the results of the correlation analysis. Concerning PC2, toluene emerges as the major contributor. It's worth noting the behavior of benzene, showing a negative association with PC2 and being nearly orthogonal to toluene, signifying the low correlation between these contaminants [12, 37]. Despite toluene's positive contribution to PC1, its greatest impact is on PC2. The strong correlation and contribution of all VOCs to PC1 suggest a common emission source, aligning with previous reports by Laowagul et al. (2008) and Bruno et al. (2001) [43, 45]. In contrast, toluene, being the primary contributor to PC2, is linked to specific emission sources of this pollutant [47], such as paints and dyes.

Similarly, monitoring points can be depicted as a function of the variables in a biplot [12, 36], shown in Fig. 7. To enhance comprehension, colors corresponding to the clusters obtained from CA have been utilized. In general, the distribution of points with respect to PC1 for each sampling period suggests mobile sources, with limited instances related to point sources (PC2). Notably, the previously obtained clusters are mainly conserved concerning PC1. The cluster L (blue) exhibits low PC1 influence, transitioning to

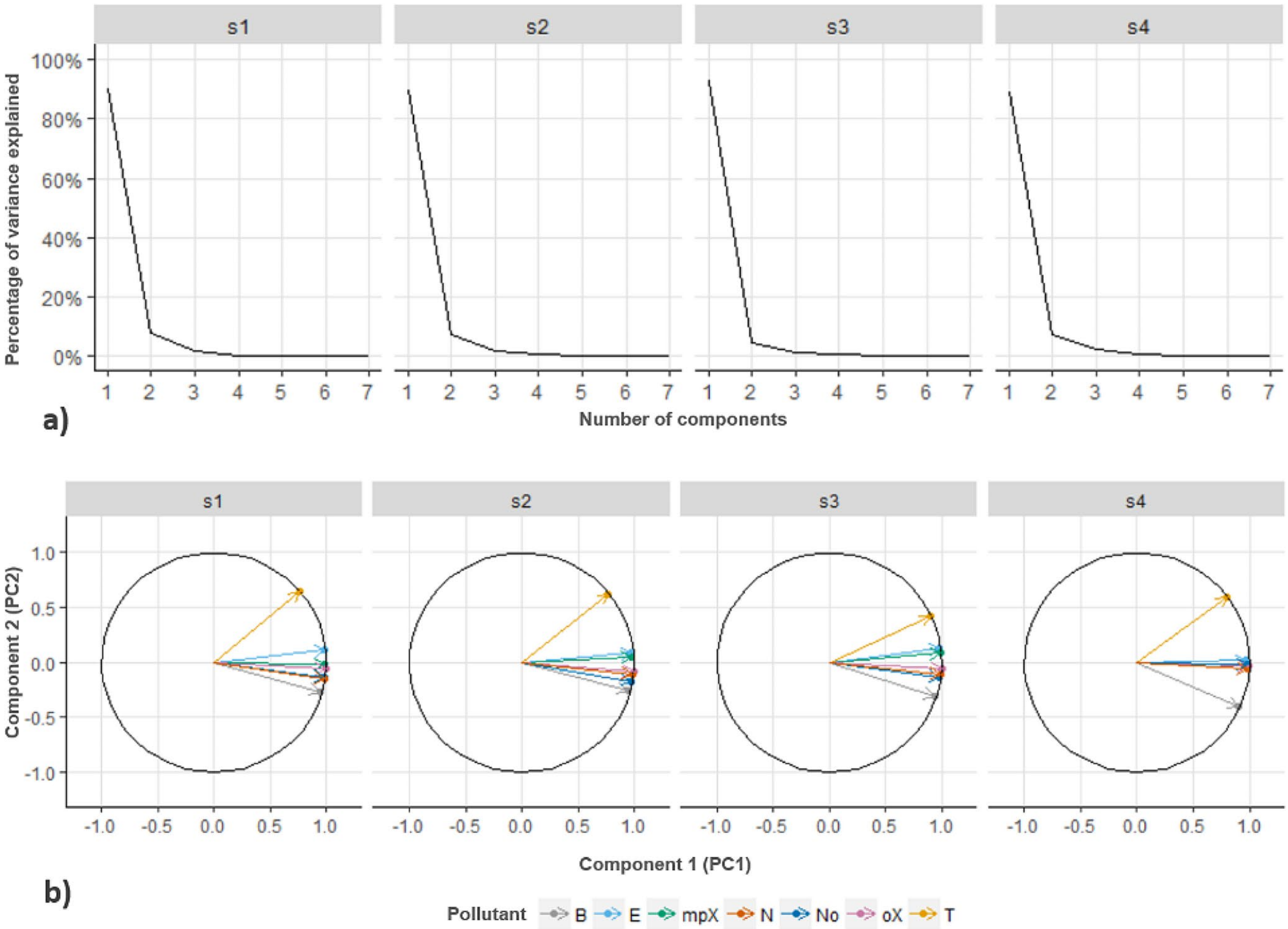


Fig. 6 (a) Scree plots of the variance explained and the corresponding principal components (PC) number for the four sampling periods of VOCs, (b) Correlation circles plots of the two Principal Components (PC1 and PC2) where the qualitative and semi-quantitative contribution of each pollutant (denoted by the color in the legend) is observed

clusters ML (yellow), M (orange), and finally H (red) as the PC1 effect intensifies. This indicates that the mobile sources indicator (PC1) is primarily responsible for organizing the clusters.

Additionally, sampling sites 3 and 37 (Calicanto and Madrigal respectively) demonstrate a low PC1 contribution (indicating a minor influence of mobile sources in minor road areas and the residential sector) but a high PC2 contribution, likely due to point sources of toluene stemming from construction activities (paints, solvents, etc.) in both zones. Likewise, places like Benjamín Herrera and ERA Dagma (sampling sites 14 and 33) situated in industrial sectors and near automotive workshops exhibit a significant PC2 effect despite their proximity to high-traffic roads. Finally, it is evident that the concentrations of VOCs in cluster H places predominantly stem from mobile sources.

3.4 Spatial Characterization

Figures 8 and 9 depict spatial interpolation maps for PC1 (a mobile sources indicator) during the s1 sampling period (February – March 2021), generated using Inverse Distance Weighting (IDW) and ordinary Kriging methodologies, respectively. The spatial interpolation of PC1 of the remaining periods (s2 period (March – April 2021), s3 period (February – March 2022), s4 period (March – April 2022)), generated by IDW and Kriging methods can be found in figures S1 to S6, respectively, available in online resources. Both IDW and Kriging are spatial interpolation methods used to estimate values between data points in unsampled geographic spaces. While IDW assigns weights to data points based on their distances to the point of estimation, Kriging employs a statistical model that considers spatial correlation structures among the points. It encompasses both overall trend and spatial correlation, making both models complementary [48]. For instance, in an epidemiological

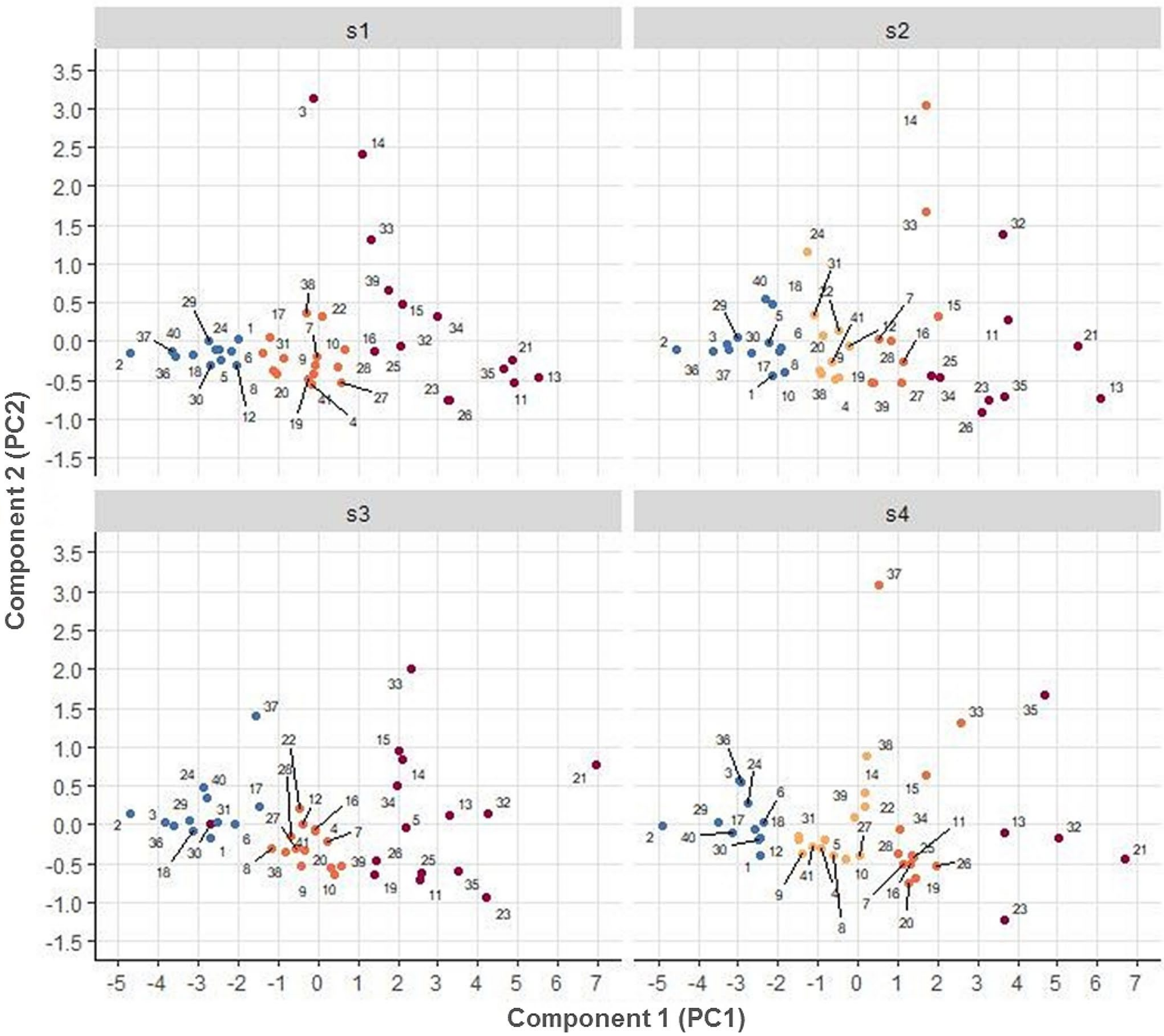


Fig. 7 Principal component biplot (PC1 and PC2) of the sampling sites and pollutants in the air of Santiago de Cali. The numbers correspond to the sampling site codes listed in Table 1

malaria study, IDW highlighted areas with the highest incidence of cases, while Kriging provided an estimate of the overall impact in a city region [20].

In both cases, the spatial behavior of PC1 is predominantly centered in the downtown area where streets are narrow, and traffic is slow. This situation hampers air mass recirculation, consequently delaying the dilution of VOCs in the atmosphere. The phenomenon also extends to the north and east of the city, corresponding to areas of high population density. These population groups primarily belong to a low socio-economic background [33], often relying on motorcycles as their mode of transportation (a significant source of VOCs) [46, 48, 50].

The effects of PC1 diminish in the western (hillside sector) and southern directions, characterized by less dense road corridors and greater amplitude, allowing for better circulation of VOCs. Temporally, few differences are observed between each of the sampling periods. In the case of PC1, both methods identify specific events with a high vehicular impact (as observed in the Siloé area), as well as the broader affected region (center-northern-eastern area). It's important to note that due to the low density of sampling points, the resolution of the Kriging method is affected, as seen in the northern sector (Flora, Chipichape, and Floralia), where PC1 levels are low but the method overestimates its effect.

Exploiting the properties of IDW and the characteristics of PC2, spatial interpolation of this component was

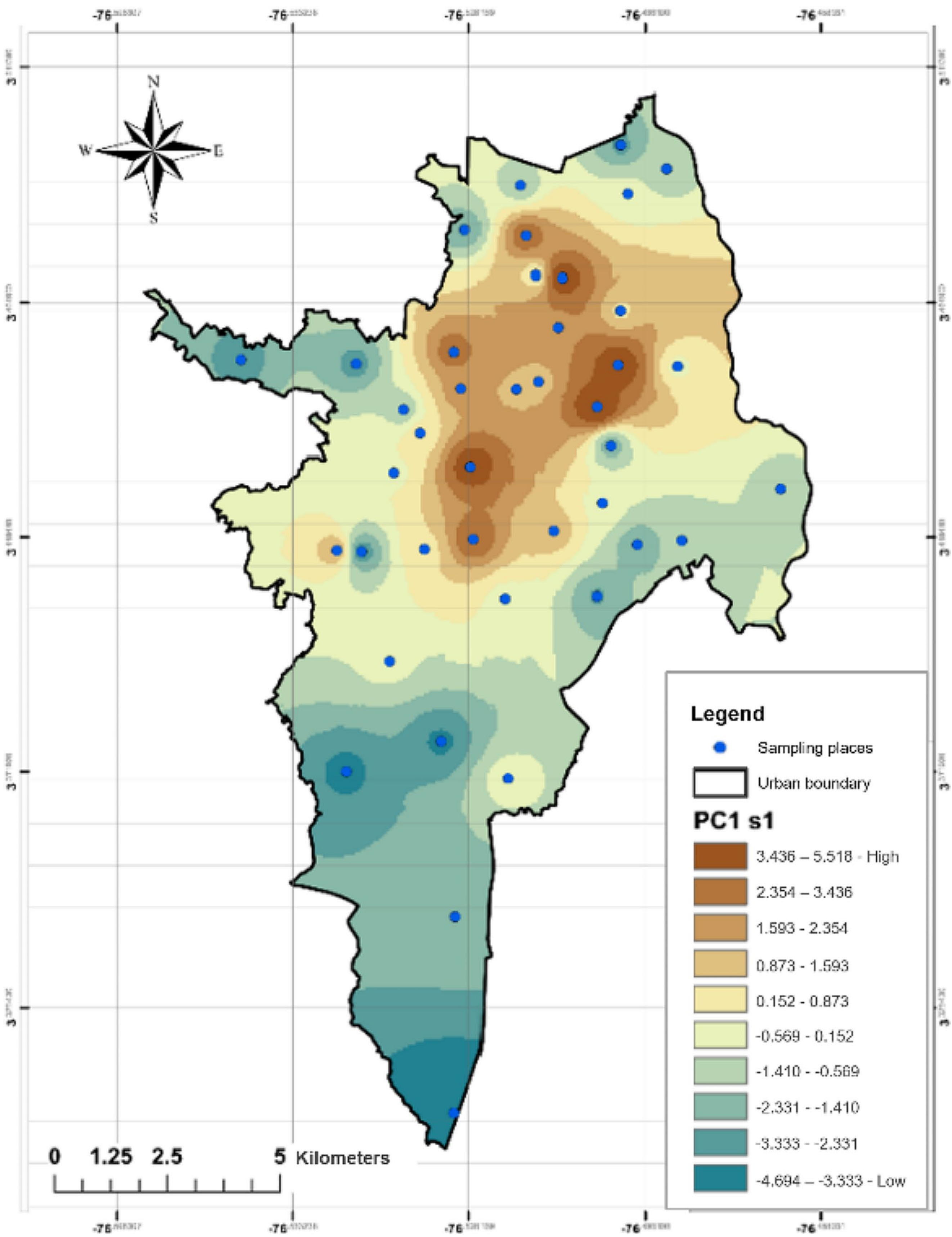


Fig. 8 Inverse distance weighting (IDW) map for the spatial distribution of PC1 in the city of Santiago de Cali for s1 sampling campaign (February to March 2021)

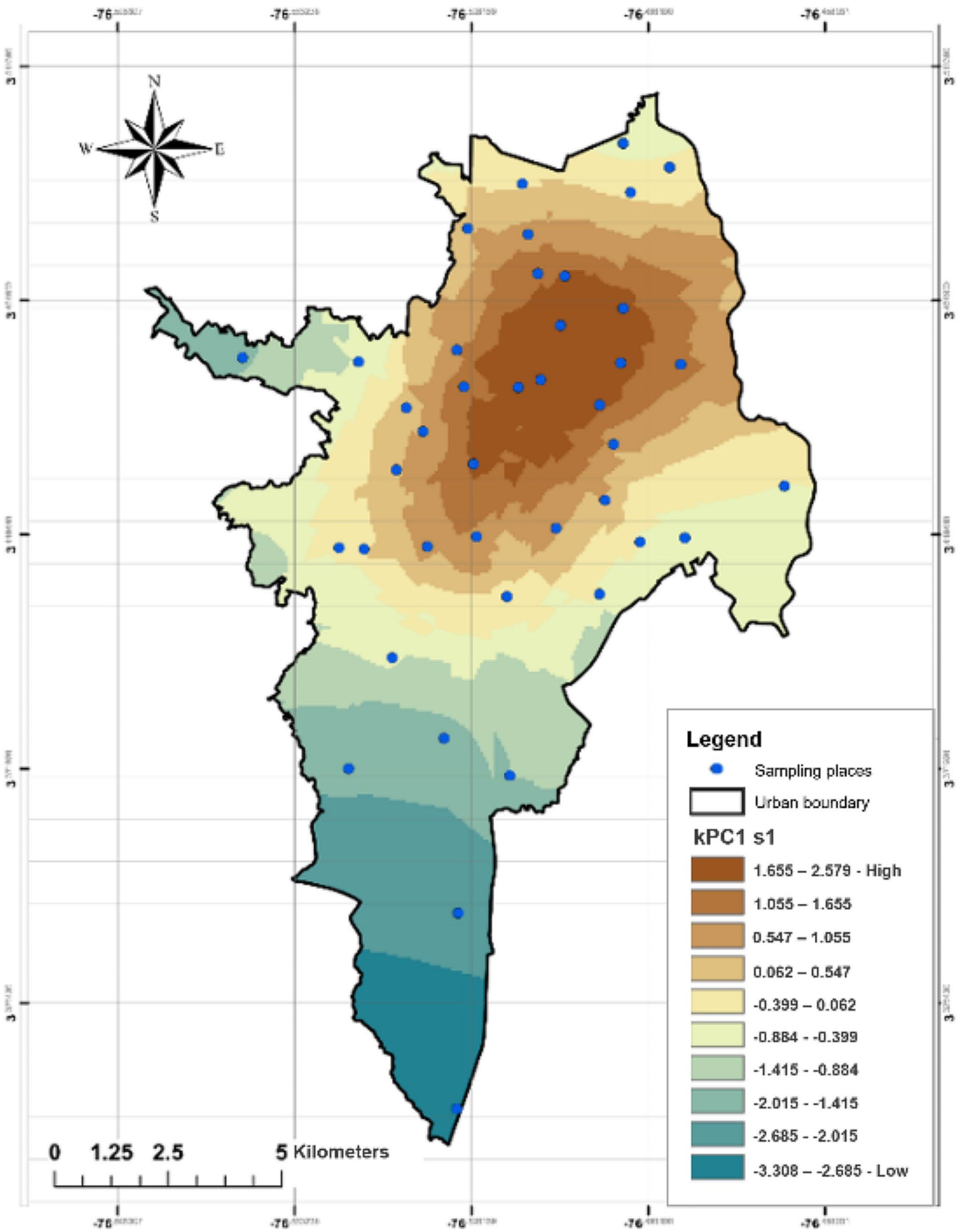


Fig. 9 Spatial interpolation map prepared by kriging method of PC1 in the city of Santiago de Cali for s1 sampling campaign (February to March 2021)

conducted (Fig. 10). As depicted in the Principal Component Biplot (Fig. 7), PC2's incidence on most points throughout the city is very low, thus resulting in low spatial predominance values. However, specific sources of toluene emission are emphasized. Notably, the Calicanto site stands out in samplings s1, s3, and s4, as does the Chipichape area in samplings s3 and s4, both of which are associated with ongoing construction of residential complexes. Conversely, in all samplings, downtown and its surrounding areas predominate as sources. These areas correspond to industrial zones with automotive activities, tanneries, paper industries, textiles, and common usage of toluene [33]. IDW maps for the spatial interpolation of PC2 of the remaining periods (s2 period (March – April 2021), s3 period (February – March 2022), s4 period (March – April 2022)) can be found in figures S7 to S9, respectively, available in online resources. Both for PC1 and PC2, the employed spatial interpolation methods effectively elucidate the phenomena, enabling an estimate of the impact of pollutants in non-monitored areas.

3.5 Carcinogenic Risk Assessment

Given the detrimental impact of VOCs identified in the city's air and acknowledging benzene as a known carcinogen [4, 49] and ethylbenzene as a potential carcinogen, it was imperative to evaluate the inhalation-based carcinogenic risk in the population, aligning with the guidelines set forth by the Environmental Protection Agency of the United States (EPA) [31].

The scenario considered for this assessment was geared towards adults. Deliberations on exposure time (ET) led to an estimation of 4 h, encompassing the representative duration an individual typically spends outdoors, either commuting to work or engaging in leisure activities. A standard average time (AT) of 70 years was established, with an exposure period of 35 years. Other exposure factors were adopted in accordance with EPA recommendations [30, 51]. The carcinogenic risk results pertaining to benzene and ethylbenzene, calculated utilizing Eq. 9, are succinctly presented in Table 5.

The EPA has set carcinogenic risk reference values greater than 1×10^{-6} as the acceptable threshold. Based on this criterion, it is evident that none of the ethylbenzene concentrations pose a carcinogenic risk under the stipulated exposure conditions. Conversely, for benzene, across samplings s1 to s3, at least half of the measured concentrations surpass the 1×10^{-6} median, indicating a potential cancer risk.

Moreover, in sampling s4, the average concentration exceeds the permissible risk level. The calculation of the total carcinogenic risk (Eq. 9) was performed, assuming a lack of additive effects between the health impacts of both pollutants, indicating no synergy or antagonism [52]. Consequently, cancer risk maps were generated for all four samplings, as illustrated in Fig. 11.

The spatial distribution of the risk aligns predominantly with the behavior of PC1, attributable to the substantial contribution of benzene and ethylbenzene concentrations in this principal component. The prevailing trend underscores a heightened carcinogenic risk in the downtown area and, to a lesser extent, in the northern and eastern regions of the city during all sampling periods. In contrast, both the hillside areas and the southern region of the city exhibit negligible risks to human health.

4 Conclusions

This study successfully determined the concentrations of volatile organic compounds (VOCs) in the air of Santiago de Cali using passive diffusion samplers. Notably, none of the monitored compounds exceeded the national air quality standards. The observed pollutant concentrations were comparable to those found in other major cities. The correlation analysis provided valuable insights, revealing an unusual behavior in toluene concentrations compared to the other VOCs, which exhibited strong correlations. Utilizing Cluster Analysis (CA), monitoring sites were effectively grouped based on similarities, demonstrating relative homogeneity among different sampling periods. Principal Component Analysis (PCA) further summarized the original 7 variables into 2 principal components. The first component suggested a potential indicator of mobile emissions, while the second highlighted specific toluene emissions. The synergy between CA and PCA was evident, emphasizing the dependency of conglomerates on the behavior of PC1.

Spatial interpolation through Inverse Distance Weighting (IDW) and kriging facilitated the representation and prediction of VOC concentrations in non-monitored areas. PC1 analysis identified critical areas, including the downtown, east, and north of the city, as regions of heightened concern. Additionally, PC2 representation by IDW confirmed punctual emissions primarily associated with toluene. Furthermore, the carcinogenic risk assessment for benzene and ethylbenzene shed light on inhalation-induced carcinogenic risk within the proposed scenario. The generated risk maps proved to be invaluable tools for identifying critical areas concerning human health, notably the downtown and northeast sectors of the city.

In conclusion, this comprehensive study employing chemometric techniques and spatial analysis provided a holistic understanding of VOC concentrations, their sources, and associated health risks. The findings contribute significantly to environmental monitoring efforts and lay a foundation for

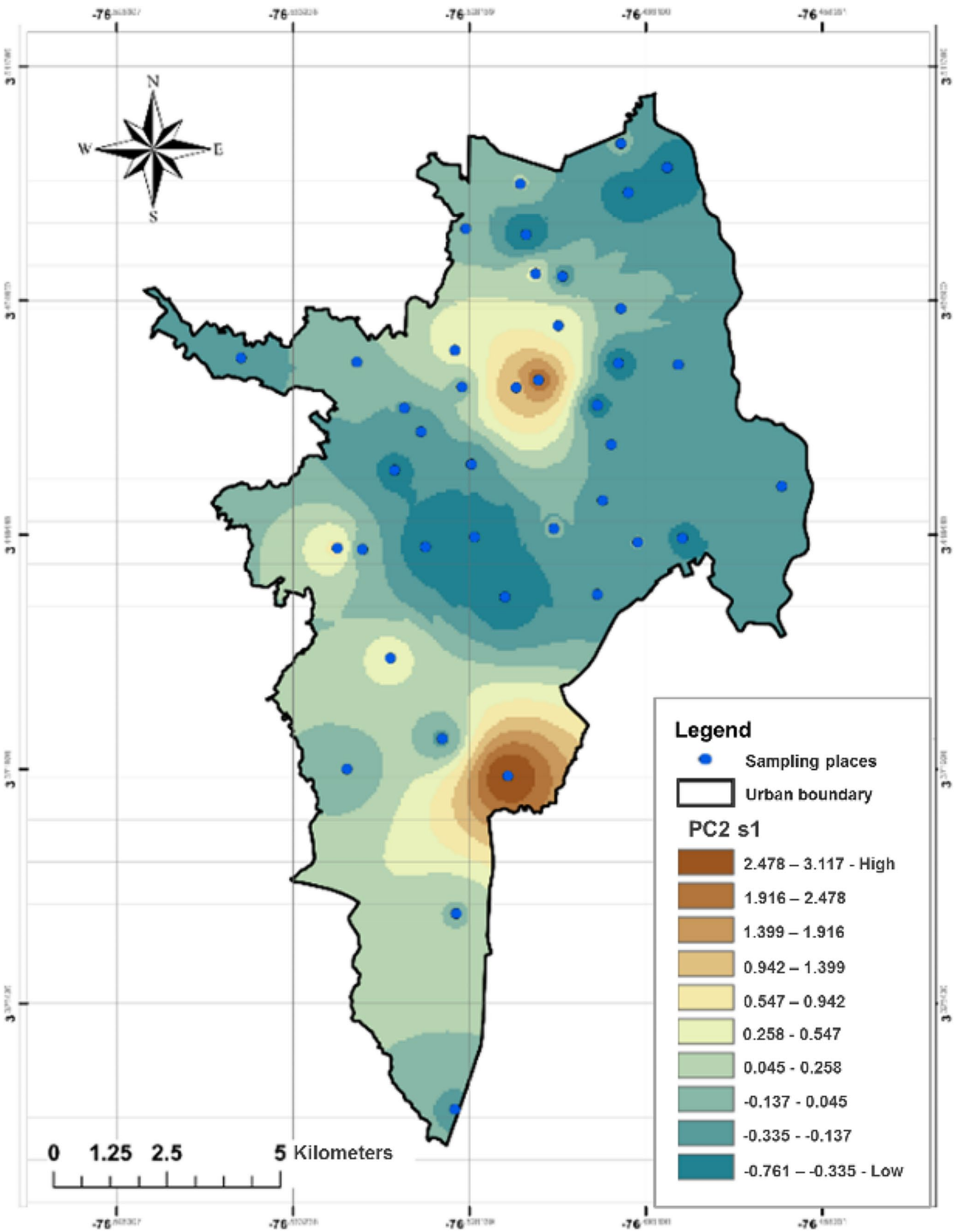


Fig. 10 Inverse distance weighting (IDW) map for the spatial distribution of PC2 in the city of Santiago de Cali for s1 sampling campaign (February to March 2021)

Table 5 Summary of cancer risk for adults from inhalation benzene and ethylbenzene

	Cancer risk (x 10^{-6})							
	S1		S2		S3		S^4	
	Benzene	Ethylbenzene	Benzene	Ethylbenzene	Benzene	Ethylbenzene	Benzene	Ethylbenzene
Minimum	0.29	0.02	0.38	0.02	0.23	0.02	0.22	0.02
Maximum	2.47*	0.41	2.29*	0.35	2.27*	0.53	2.14*	0.48
Average	1.29*	0.20	1.14*	0.17	1.16*	0.19	1.01*	0.18
Median	1.20*	0.19	1.10*	0.15	1.18*	0.18	0.94	0.17

*Values above 1×10^{-6} are considering with cancer risk

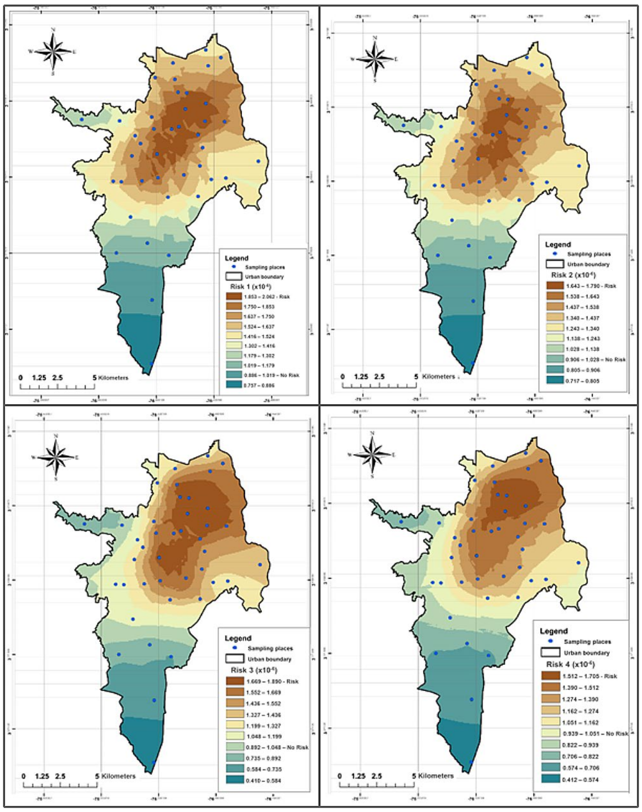


Fig. 11 Spatial interpolation map prepared by kriging method for cancer risk caused by benzene and ethylbenzene in the city of Santiago de Cali in each of the four sampled periods: Risk 1 = s1, Risk 2 = s2, Risk 3 = s3 and Risk 4 = s4

potential targeted interventions to mitigate air pollution in Santiago de Cali.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10666-024-09969-7.

Acknowledgements The authors thank Engineer Gisela Arizabaleta and Mr. Jairo Copete from the Air Quality group of the *Departmento Administrativo de Gestión Ambiental* (DAGMA), for allowing the use of the Santiago de Cali Air Quality Surveillance System stations.

Author Contributions Rubén Albeiro Sánchez-Andica: Designed and Supervised analytical measurements also wrote and revised the manuscript. Wilson Rafael Salas-Chávez: Monitoring coordination, performed analytical measurements and wrote and reviewed manuscript. Martha Isabel Páez-Melo: Searched for resources, supervised the experiments and reviewed and approved the manuscript.

Funding This work was funded by *Corporación Autónoma del Valle* (CVC) and *Universidad del Valle* with 059 and 077 Grant numbers.

Data Availability The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Ethical Approval Not aplicable.

WRS-C Monitoring coordination, performed analytical measurements and wrote and reviewed manuscript.

MIP-M Searched for resources, supervised the experiments and reviewed and approved the manuscript.

Competing Interests The authors declare no competing interests.

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Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-023-31306-w

RESEARCH ARTICLE

Intra-urban variability of long-term exposure to $PM_{2.5}$ and NO_2 in five cities in Colombia

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Received: 31 May 2023 / Accepted: 26 November 2023

Abstract
Rapidly urbanizing cities in Latin America experience high levels of air pollution which are known risk factors for population health. However, the estimates of long-term exposure to air pollution are scarce in the region. We developed intraurban land use regression (LUR) models to map long-term exposure to fine particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2) in the five largest cities in Colombia. We conducted air pollution measurement campaigns using gravimetric $PM_{2.5}$ and passive NO_2 sensors for 2 weeks during both the dry and rainy seasons in 2021 in the cities of Barranquilla, Bucaramanga, Bogotá, Cali, and Medellín, and combined these data with geospatial and meteorological variables. Annual models were developed using multivariable spatial regression models. The city annual $PM_{2.5}$ mean concentrations measured ranged between 12.32 and 15.99 μg/m^3 while NO_2 concentrations ranged between 24.92 and 49.15 μg/m^3. The $PM_{2.5}$ annual models explained 82% of the variance (R^2) in Medellín, 77% in Bucaramanga, 73% in Barranquilla, 70% in Cali, and 44% in Bogotá. The NO_2 models explained 65% of the variance in Bucaramanga, 57% in Medellín, 44% in Cali, 40% in Bogotá, and 30% in Barranquilla. Most of the predictor variables included in the models were a combination of specific land use characteristics and roadway variables. Cross-validation suggests that $PM_{2.5}$ outperformed NO_2 models. The developed models can be used as exposure estimate in epidemiological studies, as input in hybrid models to improve personal exposure assessment, and for policy evaluation.

Keywords Air pollution · Fine particulate matter · Nitrogen dioxide · Land use regression models · Colombia

Introduction

Air pollution is recognized as one of the leading environmental risk factors for population health (GBD 2019 Risk Factors Collaborators 2020). It is estimated that 99% of the world population is living in places where air pollution levels for fine particulate matter ($PM_{2.5}$) exceed the current safe guideline level defined by the World Health Organization (WHO), and populations from low- and middle-income countries are exposed to the highest levels (World Health Organization 2021). In 2019, it was estimated that a total of 2.92 million deaths in females and 3.75 million deaths in males were attributable to ambient particulate matter and ozone air pollution. For Latin America and the Caribbean (LAC) region, and overall for low- and low-middle income countries, air pollution was the second most important risk factor (after malnutrition) that accounted for attributable disability-adjusted life-years (DALYs) rates over the past decade (GBD 2019 Risk Factors Collaborators 2020).

Particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and ozone (O_3) are the ambient air pollutants most strongly associated with adverse health adverse effects in the short- and long-term (World Health Organization 2021). The health effects from long-term exposure to air pollution are tenfold higher than the short-term effects represented by daily variations (Pope 2007). For long-term exposure there is also evidence that there are large within-city contrasts and their effects are probably higher than the effects related to variations between cities

Responsible Editor: Gerhard Lammel

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(Crouse et al. 2015). Therefore, high-resolution spatial estimations of long-term exposure to air pollutants, particularly in urban setting, are critical for epidemiological research studying the association between air pollution and health and an important input for air quality management plans aimed to reduce air pollution adverse effects (Fann et al. 2011). There are different methods for estimating intraurban spatial variability of air pollutants. These methods include models based on proximity to monitoring stations, interpolation methods, land use regression models (LUR), and dispersion and chemical transport models combined with satellite remote sensing (Dijkema et al. 2011; Hoek 2017; Hoek et al. 2008; Michael Jerrett et al. 2005; van Donkelaar et al. 2021).

LUR models combined monitoring of air pollutants with the development of stochastic models using physical landscape characteristics, meteorology, and population as predictor variables (Hoek et al. 2008). LUR models use standard multivariable spatial regression techniques that have lower computational requirements compared with dispersion or chemical transport models and are relatively easy to implement using geographic information systems (GIS), which made them a method of preference in developing intraurban surfaces of air pollutant exposure (Hoek et al. 2008). LUR models have shown to have a high predictive value and to be a cost-effective method to estimate intraurban variations of air pollutants in different regions including North America, Europe, and Asia (Allen et al. 2011; Chen et al. 2013; de Hoogh et al. 2016; Eeftens et al. 2012; Gurung et al. 2017; Kashima et al. 2018; Lee et al. 2017; Stafoggia et al. 2022). Recently LUR has been used in these regions as input data for hybrid models combining dispersion models, satellite-based observations, land use, and surface monitoring data for $PM_{2.5}$ and NO_2 (Hoek 2017). Also, annual and monthly global estimates of ground level $PM_{2.5}$ and NO_2 have been developed, combining satellite remote sensing with the GEOS-Chem chemical transport model and calibration using ground-level observations (van Donkelaar et al. 2021). These models provide spatially fine resolutions at $0.01° \times 0.01°$ and have shown to have a very good performance in North America and Europe but have very high uncertainty for tropical areas particularly in South America (Hoek 2017; van Donkelaar et al. 2021).

Despite LAC cities are growing rapidly and experiencing high levels of air pollution, the estimates of long-term exposure to air pollution are scarce in the region. In most cities, the ground-level measurements of atmospheric pollutants have poor consistency and coverage (Cunha-Zeri and Ometto 2021). Limitations include that traditional air quality stations require high financial funding in resource-limited countries which make them logistically prohibitive since it is not cost-effective. Consequently, given the limited resources of good air quality data, modeling emerges as a possible tool to derive management measures (Agudelo-Castañeda et al. 2023). However, high-resolution spatial estimations of long-term exposure to air pollutants are scarce in LAC and development of LUR models for some pollutants have been reported only for the cities of Mexico, Sao Paulo, Quito, and Medellín (Alvarez-Mendoza et al. 2019; Habbermann and Gouveia 2007; Londoño and Cañon 2015; Luminati et al. 2021; Son et al. 2018).

Colombia is located at the extreme north of South America with an estimated population of 52 million inhabitants (Departamento Nacional de Estadística (DANE) 2020b) distributed across 32 departments and 1122 municipalities. The national air quality surveillance network has operated since 1993 and currently includes 22 regional surveillance systems that are distributed in 77 municipalities of 19 departments. In 2021, the national monitoring network included 131 monitoring stations for $PM_{2.5}$ and 57 for NO_2 (Instituto de Hidrologia Meteorología y Estudios Ambientales-IDEAM 2022). Data from monitoring stations provide useful information for temporal daily variations of pollutants but provide limited information on the spatial variability of pollution especially in densely populated urban settings that concentrate 77% of the country's population (Departamento Nacional de Estadística (DANE) 2020b). Data from monitoring surveillance systems have been used in epidemiological studies assessing the short-term effects of pollutant concentrations on mortality and morbidity in the largest cities in Colombia (Blanco-Becerra et al. 2014; Rodriguez-Villamizar et al. 2018). However, there is a need for estimations of long-term spatial variation of pollutants within cities. LUR models have provided high performance and less computational requirements compared to other methods for assessing long-term exposures to air pollutants. Therefore, our objective was to develop intraurban LUR models for $PM_{2.5}$ and NO_2 in the five largest cities in Colombia to estimate of long-term population exposure to air pollution for use in air quality health assessment and mitigation.

Methods

Study areas

The study was conducted in the urban areas of the five largest cities in Colombia: Barranquilla, Bucaramanga, Bogotá, Cali, and Medellín (Fig. 1). The population varies across cities, Bogotá being the most populated city with an estimated population of 7,834,167 million inhabitants in 2021. The estimated total population during 2021 was 1,297,082 for Barranquilla; 614,269 for Bucaramanga; 2,264,748 for Cali; and 2,573,220 inhabitants for Medellín (Departamento Nacional de Estadística (DANE) 2020b). The altitude and average temperature also vary across cities, with Barranquilla being the warmer and closest to the sea level and Bogotá being the coldest and highest elevation. The physical

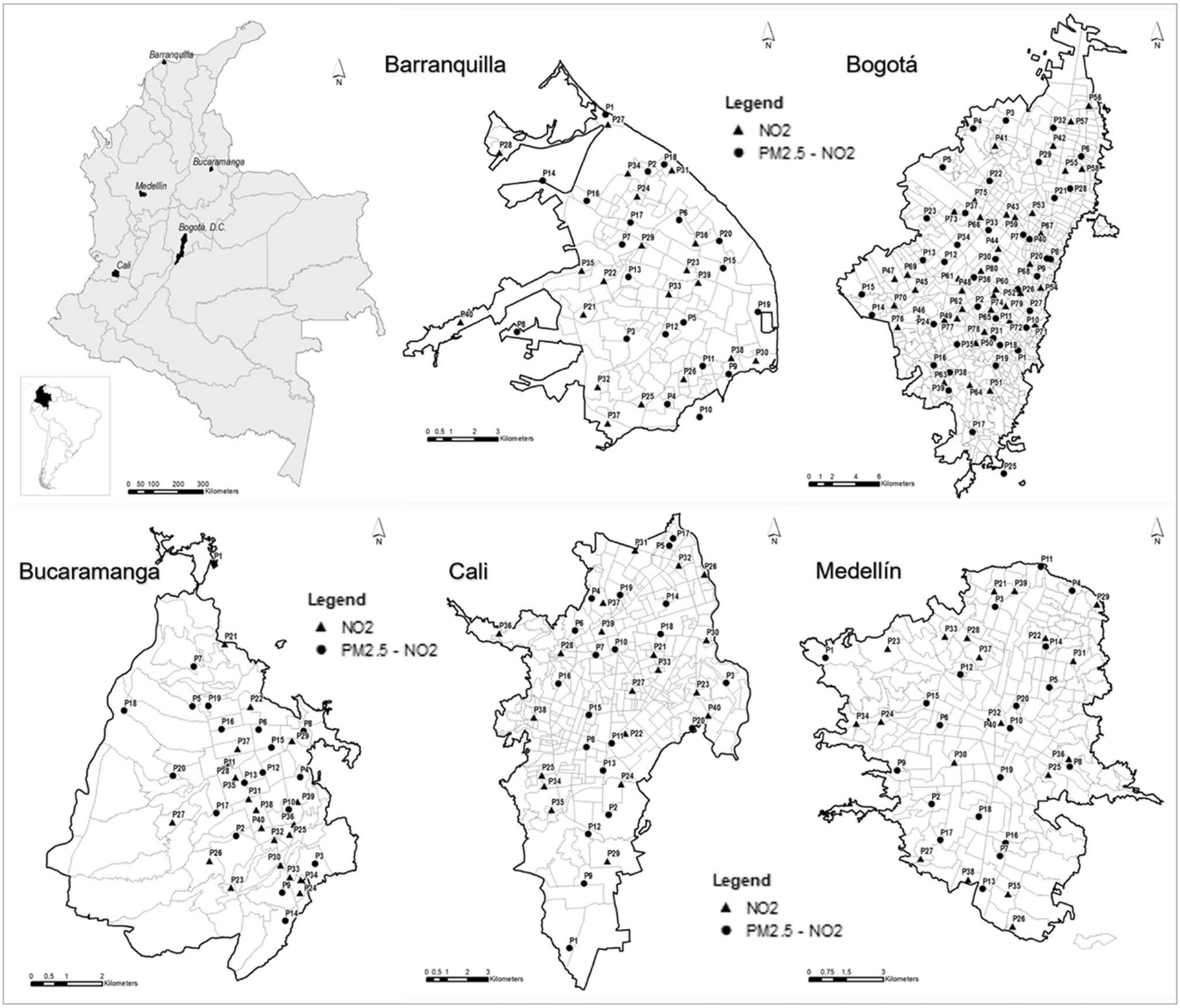

Fig. 1 Study areas and monitoring location within cities in Colombia. Note: Circles represent monitoring sites for both pollutants, $PM_{2.5}$ and NO_2, and triangles represent monitoring sites for NO2 only

characteristics of these cities are presented in Table S1 in Supplementary material. Similar to other capital cities in South America, the roadways networks in these cities are complex and dense, and both industrial and residential neighborhoods coexist.

Air pollution measurement data

$PM_{2.5}$ and NO_2 concentrations were measured in the five cities for two consecutive weeks during both the dry and the rainy season in 2021. The selection of the dry and rainy seasons for each city was defined based on the total precipitation registered in local meteorological stations between 2010 and 2019. The driest months correspond to January to March while the months with higher precipitation were April to May for most cities. The details of the sampling period for each city are presented in Table S1 in Supplementary material.

For NO_2, there were 80 sampling sites for Bogotá and 40 for the other cities; while for $PM_{2.5}$, there were 40 sampling sites for Bogotá and 20 for the other cities. Figure 1 shows the location of sampling sites distributed across the urban area of the cities. The density of sampling sites in the urban areas for NO_2 measurements (samplers per km^2) was 2.3 for Barranquilla, 0.8 for Bucaramanga, 4.4 for Bogotá, 3.5 for Cali, and 3.6 for Medellín; the density of sampling for $PM_{2.5}$ was twice these values as we used half the number of monitors. The selection of sampling sites was conducted with participation of the study team and experts from the environmental and health departments of each city. The criteria for selecting the monitoring sites included (1) the representation of traffic, residential, industrial or other areas within the cities, and (2) the heterogeneity in the characteristics of the selected sites (i.e., in terms of types of traffic, density of residential areas or particular areas for cities such as port or industrial areas). The sampling sites included one background urban site per city. The background site was located in the area of the city with the lowest concentrations of pollutants based on measurements, if they were available, or based on the experts' knowledge of pollution within the city. In addition, sampling included 3–4 sites per city that were installed in the same location as monitoring stations from the local air quality network to facilitate instrument intercomparisons. For quality control, two blank filters were used for each city.

Measurement campaigns were simultaneously conducted across all sampling sites in each city for 2 weeks. Two trained teams of field staff were responsible for installing and uninstalling monitoring samplers across the study cities. We measured gravimetric $PM_{2.5}$ using Ultrasonic Personal Aerosol Sampler (UPAS) samplers (V2.0 Access Sensor Technologies, Fort Collins, CO, USA) that were installed between 2.5 and 3 m above ground in all monitoring sites. The UPAS monitors have been widely used for measuring gravimetric $PM_{2.5}$ in similar and higher pollution settings (Arku et al. 2020) and have shown good performance for collecting airborne PM for gravimetric analysis (Leith et al. 2020). We adapted an environmental enclosure to protect the device during outdoor sampling and added an external battery to increase the sampling time to 7 days at 25% duty cycle at a flow rate of 1 lpm. Each monitor was loaded with a 37-mm Teflon filter at the start of each measurement period. We replaced the UPAS and filters at each sampling site after 7 days to complete the 2 weeks monitoring period. Gravimetric analysis was conducted for all cities in a single laboratory certified for this competence (ISO/IEC 17025:1999) by the Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM). Each filter and blank were weighted three times, and the average measurement was reported for each filter. The reported limit of quantification was 0.68 µg, and the limit of detection was 1.36 µg. The average $PM_{2.5}$ concentration of the two weekly filters from the same site, and campaign was reported as the site concentration for statistical analysis.

For measuring NO_2, we used passive diffusion Palmes Tubes (Gradko environmental, Hampshire, UK) that were installed for 2 weeks with a height of 2.5–3 m above ground in all monitoring sites. For quality control, an extra two blank tubes were deployed in each city. The processing of all tubes was conducted in the manufacturers' laboratory, and concentration measurements were reported as the average of duplicate measurements. The reported limit of detection was 0.031 µg of NO_2 in tubes. The installation, operation, and deinstallation of the $PM_{2.5}$ and NO_2 monitoring devices including refrigeration of samples were conducted by trained personnel following the manufacturer's instructions.

GIS predictor variables

Predictor variables were grouped into five categories: (1) land use (areas of different land uses); (2) population (including population counts and population density); (3) roads (including total length of roads and distance from sampling sites to arterial roads); (4) traffic (including estimated average speed and traffic volume); (5) physical geography (altitude); and (6) meteorology (including average temperature, precipitation, relative humidity, and wind direction). All predictor variables were created for circular buffers with radii of 100 m, 200 m, and 500 m and centered at the monitoring sites. These predictor variables were obtained from the intersection between buffers and GIS layers. In total, 78 independent variables were generated including variations of roadways variables. Maps were created using ESRI ArcGIS® 10.8.1 and ArcMap™ under license (ESRI® version, US). Table 1 provides the details of the predictor variables used to generate the LUR models.

Land use data were obtained from the local government's planning office based on the most recent land use distribution available. Altitude was measured in sampling sites directly using an altimeter during the first deployment of monitoring devices. Population data and roads classification were obtained from the demographic and cartographic information of the census 2018 (Departamento Nacional de Estadística (DANE) 2020a). Meteorology data were obtained from meteorological monitoring stations from the local environmental authority including 16 stations in Bogotá, 22 stations in Medellín, and 8 stations in Cali. Precipitation and temperature raster surfaces were calculated using the Regnie model (Rauthe et al. 2013). Briefly, we used data from stations coupled with altitude from the digital terrain model (DTM) with 30 m resolution, the slope and land exposure (the direction or azimuth angle of the inclination of the slope) to calculate spatial precipitation and temperature mean values using a linear regression model. Barranquilla and Bucaramanga had less than four local meteorological stations that did not allow for a valid spatial estimation, and therefore, meteorological data was not included in LUR models for these two cities.

Traffic predictor variables were measured and estimated for the project. The traffic speed measurements were obtained during the same monitoring campaigns periods by using a cloud-based data method that included data pre-processing, speed computation, and output data formatting. During the pre-processing, the street network vector data from Openstreetmap was edited to match the same network used by the Google Maps platform. Then, the network streets were split into 100-m links considering the road intersections setup. Then, the speed was computed for those links using their length and travel time. Travel times at the link level were obtained from the Google Maps platform using the distance

Table 1 Land use regression predictor variables[a]

Category	Source	Year	Unit	Variable names
Land use	Land use plan for each city	2014	% of land use type (square meters)	Industrial-IND Residencial-RES Dotacional-DOT Central-CEN Commercial-COM Port-PORT Mixed-MIX
Population	National Census	2018	People per square meter	Total population-POB Population density-DEN
Roads	Open Street Maps	2020	Kilometers	Length by road type Trunk road-TRUNK Primary road-PRIM Secondary road-SEC Tertiary road-TER Local road-LOC Distance from site to road by road type DTRUNK DPRIM DSEC DTER DLOC
Traffic	Speed Distance Matrix API—Google Speed-density-flow functions	2021	Kilometers per hour Vehicles per hour	Traffic speed-VEL Traffic volume-VOL
Physical geography Altitude		2021	Meters above sea level (MASL)	Altitude-ALT
Meteorology	Monitoring Station	2021	Temperature °C Precipitation mm Relative humidity % Wind direction	Temperature TPROM Precipitation PPROM Humidity (%) HR Wind direction WD

[a]All predicted variables were created for buffers of 100 m, 200 m, and 500 m

matrix API service, which provides predicted values at the time the service was used. Finally, the speed of each link was added to its attributes set, and the whole collection of links was used to create a GIS layer using Python scripts.

To estimate traffic volumes, we used speed-density-flow functions, which describe the relationships between traffic speed, density, and flow rate on a road segment. These functions were obtained and used to estimate traffic conditions (National Research Council 2010). We computed speed-density-flow functions for urban traffic for Bogota (73 road segments) and Medellín (199 road segments) using data from sensors and traffic cameras provided by the transportation authorities. We computed and validated the functions for three different traffic regimes: interrupted, semi-interrupted, and uninterrupted flow. We tested six theoretical functional forms (Greenshields, Drew, Pipes, May&Keller, Greenberg, and Underwood Model) (Gaddam and Rao 2019) by using random sampling with replacement. The best model was selected based on the root mean square error (RMSE). The resulting functional forms were then used to estimate traffic volumes in the road network of Barranquilla, Cali, and Bucaramanga, taking into account the traffic regimes, and the number of lanes in each road segment.

Statistical analysis

We averaged pollutants' concentrations measured during both sampling campaigns to obtain annual means for each city. The comparison of measurements of the $PM_{2.5}$ sampling device with local monitoring stations was conducted for 13 monitoring stations with data available (2 in Barranquilla, 4 in Bogotá, 4 in Cali, and 3 in Medellín). Comparison of concentrations was evaluated using Bland and Altman agreement coefficients and graphs (Bland and Altman 1986). The average annual measurements across the monitoring sites were also compared to the average annual estimation measurements from the real-time local monitoring stations in the cities.

We developed LUR models to estimate intraurban spatial variation of $PM_{2.5}$ and NO_2 within the five cities. We used multivariable spatial regression models that allow local estimations of a dependent variable *Z*, by implementing the ordinary least squares (OLS) method, in the presence of possible explanatory variables (Z_j) at the same point $\left(x_i, y_i\right)$ represented by the following equation (Londoño, 2018; Maantay and McLafferty 2011):

$$Z\left(x_i, y_i\right) = \beta_0 + \sum_{j=1}^{n} \beta_i Z_j\left(x_i, y_i\right) + \varepsilon_j,\ \varepsilon_j \sim N\left(0, v^2\right)$$

To represent the spatial dependency structure between the features being analyzed, the best combination of explanatory variables must be determined. In a first step, we removed highly correlated variables (> 0.7) and those variables in which zero values account for more than 90% of the sampling sites. Then, all the predictors are included in the model assessing their statistical significance (p value < 0.05) and the sign for their coefficient (βi) (observing their agreement with the expected theoretical direction of effect). In addition, the selected variables must adequately specify the regression model, by evaluating the specification criteria of the OLS method. We estimated the adjusted R-squared to assess the performance of the models and the variance inflation factor to determine multicollinearity. All models were built with a combination of all the buffer variables (Eeftens et al. 2012; Van Nunen et al. 2017).

We performed a geographically weighted regression (GWR) with the selected equation to examine the spatial heterogeneity of the relationship between air pollutants and other spatial variables and to estimate the multiple regression model parameters. Then, we created a regular point mesh with cells spaced by 200 m over the cities' surface, where the formula obtained by each annual regression model was applied, in order to predict air pollutant levels for each point. Then, a spatial interpolation method (spline) was applied to obtain the concentration surface of the pollutant in the study area. Finally, we performed a leave-one-out cross validation (Eeftens et al. 2012; Wang et al. 2016) for each LUR model in each city and compared the set of predicted values against the observed ones. Then, the cross-validated square error and R^2 were calculated for each model. The cross-validation was conducted using the "loocv" command in Stata® version 13 (Stata Corporation).

Results

Pollutants' concentrations at sampling locations

There were 116 $PM_{2.5}$ sampling sites with valid measurements for both monitoring campaigns used for the estimation of the annual average concentrations. Three sites in Cali, four sites in Bogotá, and one in Medellin were excluded because they contribute only one successful measurement. The mean $PM_{2.5}$ concentrations during the dry season were slightly higher compared to the rainy season (see supplementary material Table S1). The annual $PM_{2.5}$ mean concentration and range in sampling sites were 16.12 μg/m^3 (7.42–22.22) for Medellín, 15.90 μg/m^3 (3.64–35.30) for Barranquilla, 15.79 μg/m^3 (4.86–32.69) for Cali, 13.89 μg/m^3 (4.39–25.52) for Bogotá, and 12.93 μg/m^3 (4.90–32.23) for Bucaramanga.

For NO_2 sampling, 17 out of the 240 tubes deployed were removed due to vandalism or invalid measurements, leaving 223 observations for the analyses. The mean NO_2 concentrations during the dry season were slightly higher than those in the rainy season (see supplementary material Table S1). The annual NO_2 mean concentration and range in sampling sites were 49.09 μg/m^3 (32.38–68.31) for Medellín, 34.92 μg/m^3 (12.56–64.67) for Bucaramanga, 39.12 μg/m^3 (13.52–69.89) for Cali, 34.63 μg/m^3 (5.09–52.19) for Bogotá, and 24.92 μ/m^3 (7.38–51.81) for Barranquilla.

The average of the differences in $PM_{2.5}$ concentrations measured using the UPAS and those reported during the same sampling period by local monitoring stations was – 1.5 μg/m^3 (95%CI – 6.8 to 3.9) during the dry season campaign (11 monitoring stations) and – 0.05 μg/m^3 (95% CI – 11.5 to 11.4) during the rainy season campaign (13 monitoring stations). During the dry season campaign, higher differences were observed for two local monitoring stations, one in Medellín and one in Cali. During the rainy season campaign, higher differences were observed for the three local monitoring stations from Medellín. Figure S1 shows the levels of agreement for $PM_{2.5}$ measurements during the two monitoring campaigns. There was only one monitoring station in downtown Medellín with valid NO_2 data for comparison of measurements obtained from Palmes tubes and local monitors. For this site-station pair, the differences was 5.71 and 2.59 μg/m^3 during the dry and rainy season, respectively. In Bogotá during the second campaign (rainy season), there were four sites with valid paired measurements whose average difference was 6.70 μg/m^3, which was highly influenced by the discrepancy observed in one particular station located at Carrera 7a (excluding this station the average of the difference was 2.86 μg/m^3). The comparison of the $PM_{2.5}$ average campaign's measurements from monitoring sites with the average annual measurements from monitoring stations during 2021 resulted in differences of – 0.84 μg/m^3 for Bucaramanga, – 1.1 μg/m^3 for Medellín, – 1.7 μg/m^3 for Bogotá, 1.4 μg/m^3 for Cali, and 1.7 μg/m^3 for Barranquilla. For NO_2, the difference between passive samplers and monitoring stations in Bogotá was 5.6 μg/m^3.

LUR models

The final LUR models selected for the cities explained higher variability for $PM_{2.5}$ compared with NO_2 (Tables 2 and 3, respectively). The models for $PM_{2.5}$

explained between 44% (Bogotá) and 82% (Medellín) of pollutant's spatial variability within cities. Most models showed a RMSE of approximately 1.5 μg/m^3 except for Barranquilla where the error was approximately 4 μg/m^3. The contrasts between $PM_{2.5}$ measured and predicted concentrations at monitoring sites for all cities are presented in Supplementary material Figure S2. Most of the predictor variables included in the $PM_{2.5}$ LUR models were related to specific types of land uses and roadways' attributes with predominance of 200 and 500 m buffers. In Bucaramanga, the LUR model only included roadways variables while Medellín was the only city where the model included a meteorological variable (see Table 2). There was no evidence of multicollinearity in the LUR models for both pollutants as the VIF values were all below 2.1. The maps of the predicted concentrations for $PM_{2.5}$ in the urban areas of the five cities are presented in Fig. 2.

The final selected models for NO_2 explained between 30% (Barranquilla) and 65% (Bucaramanga) of the pollutant's spatial variability within cities. Most cities models showed a RMSE around 6 to 8 μg/m^3 except for Cali where the error was close to 1.5 μg/m^3. The measured values versus the predicted values of the models in the monitoring sites for NO_2 in all cities are presented in Supplementary material Figures S3. As expected, most of the predictor variables included in the NO_2 LUR models were a combination of roadways variables with different buffers. In Bucaramanga, the LUR model included population variables and, in Medellín, one meteorological variable (see Table 2). There was no collinearity in the LUR models for both pollutants as the VIF values were all below 1.7. The maps of the predicted concentrations for NO_2 in the urban areas of the five cities are presented in Fig. 3.

Cross validation

Overall, the leave-one-out cross-validation R^2s showed good stability, particularly for $PM_{2.5}$. For $PM_{2.5}$, the

Table 2 Description of developed LUR models for $PM_{2.5}$ in five cities in Colombia, 2021

City	LUR model	No. sites	Model R^2	RMSE	VIF	R^2 cross validation
Barranquilla	$PM_{2.5}$ = 19.83344–0.1489524*ALT–0.0230902*DTRON500 + 44.43591*IND200 + 21.93109*CEN500 + 23.10317*PORT500	20	0.73	3.98	1.90	0.54
Bogotá	Ln ($PM_{2.5}$) = 2.4713 + 3.1439*DEN100 + 1.8045*IND200–0.8418*RES500	40	0.44	1.39	1.63	0.38
Bucaramanga	Ln ($PM_{2.5}$) = 2.199057 + 0.0014062 ∗ SEC100 + 0.0000327 ∗ LOC500–0.0012659 ∗ DPRIM500 + 0.0215501 ∗ VEL100–0.000242 ∗ VOL200	20	0.77	1.23	1.78	0.46
Cali	Ln ($PM_{2.5}$) = 2.3387 + 0.00001 ∗ DOT200 + 1.0713 ∗ PRIM200 + 0.5943 ∗ SEC200–0.0004 ∗ VOL100	17	0.70	1.28	2.06	0.51
Medellín	$PM_{2.5}$ = 13.77207–1.357455 ∗ PPROM–5.589831 ∗ DOT100 + 2.269679 ∗ DEN200 + 70.23039 ∗ MIX500 + 0.0043842 ∗ VOL500	19	0.82	1.71	1.48	0.79

RMSE Root mean square error, *VIF* variance inflation factor, *ALT* altitude, *CEN*, central land use, *DEN* population density; *DOT* Dotacional land use; *DPRIM* distance to primary roadway; *DTRON* distance to trunk roadway; *IND* industrial land use; *LOC* length local roadways; *MIX* mixed land use; *PORT* Port land use; *PPROM* precipitation average; *PRIM* length primary roadways; *RES* residential land use; *SEC* length secondary roadways; *VEL* vehicular speed; *VOL* vehicular volume. Numbers correspond to buffers of 100 m, 200 m, and 500 m

Table 3 Description of developed LUR models NO_2 in five cities in Colombia, 2021

City	LUR model	No. sites	Model R^2	RMSE	VIF	R^2 cross validation
Barranquilla	NO_2 = 12.89591 + 25.45936 ∗ PRIM100–0.1583713 ∗ VEL100 + 0.0061518 ∗ VOL500	36	0.30	8.02	1.28	0.19
Bogotá	Ln (NO_2) = 2.8714 + 0.0001*PRIM500 + 0.0058*VEL100 + 0.2599*WPROM	73	0.40	1.26	1.19	0.34
Bucaramanga	NO_2 = 13.00243 + 291.5302 ∗ DEN100–0.0013283 ∗ POB500 + 0.0025503 ∗ TER500 + 0.0020514 ∗ LOC500 + 0.0057464 ∗ VOL100	40	0.65	8.08	1.66	0.55
Cali	Ln (NO_2) = 3.47834312 + 0.49126931*PRIM200 + 0.39823891 ∗ SEC200 + 0.36505469 ∗ TER200–0.01475995 ∗ VEL200	40	0.44	1.28	1.56	0.36
Medellín	NO_2 = 46.06516–3.625967 ∗ PPROM–0.0299678 ∗ DSEC200 + 0.0225605 ∗ VOL500	34	0.57	5.53	1.06	0.45

RMSE Root mean square error, *VIF* variance inflation factor, *DEN* population density, *DOT* Dotacional land use, *DSEC* distance to secondary roadway; *LOC* length local roadways; *POB* population size; *PPROM* precipitation average; *PRIM* length primary roadways; *SEC* length secondary roadways; *TER* length tertiary roadways; *VEL* vehicular speed; *VOL* vehicular volume, *WPROM* wind speed (mean). Numbers correspond to buffers of 100 m, 200 m, and 500 m

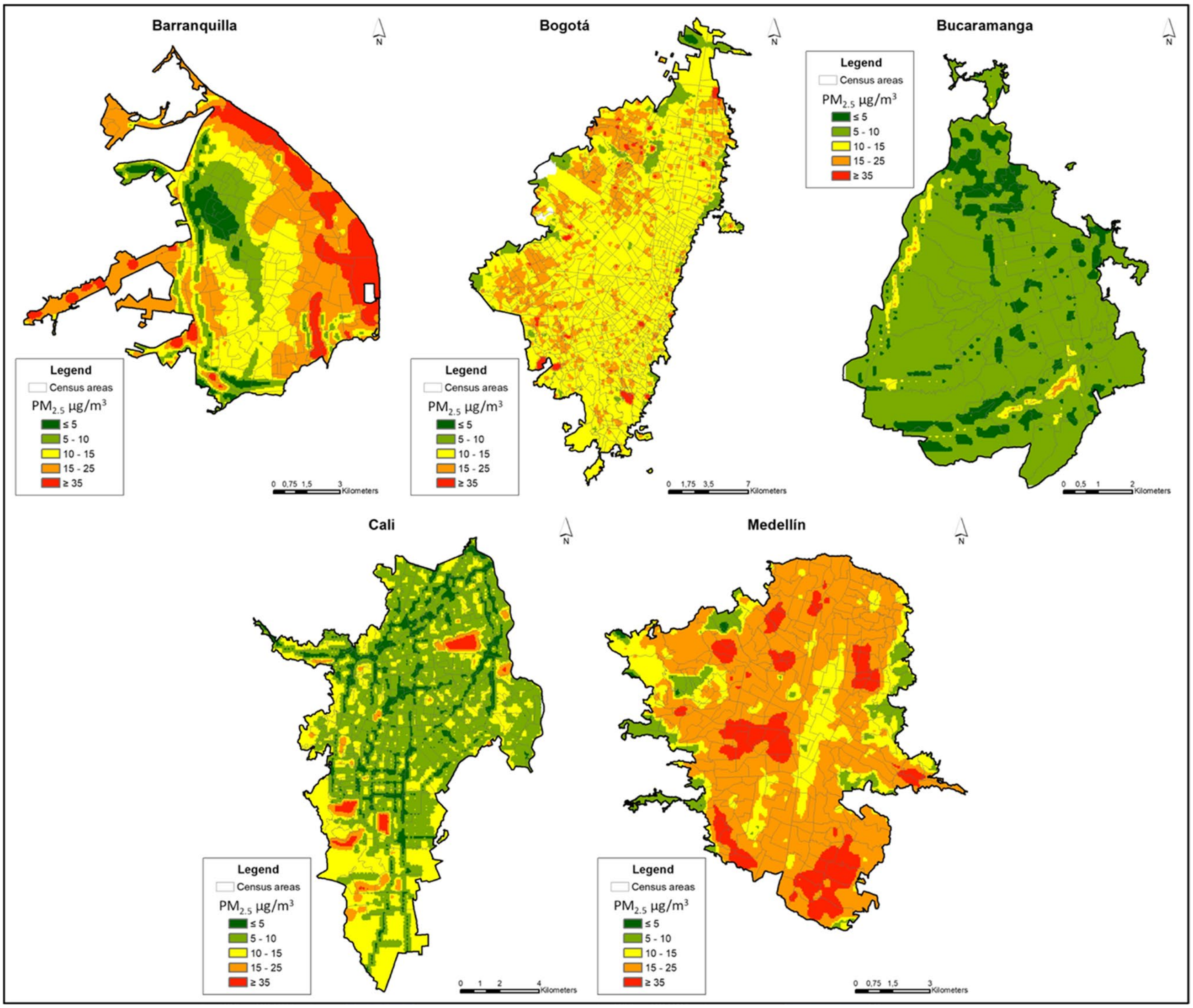

Fig. 2 Annual predicted concentrations for $PM_{2.5}$ in five cities in Colombia, 2021

difference between the model R^2 and the validation R^2 was 19% for Barranquilla, 31% for Bucaramanga, 6% for Bogotá, 19% for Cali, and 3% for Medellín. For NO_2, the difference between the model R^2 and the validation R^2 was 11% for Barranquilla, 10% for Bucaramanga, 6% for Bogotá, 8% for Cali, and 12% for Medellín. Validation R^2s are presented in Tables 2 and 3 for $PM_{2.5}$ and NO_2, respectively.

Discussion

This is the first study to develop LUR models for multiple cities in a Latin American country, providing small-area estimations of air pollutants for use in health risk assessments, epidemiological studies of long-term exposure to air pollution, and mitigation evaluation. The development of LUR models to estimate concentrations for $PM_{2.5}$ and NO_2 in five of the largest Colombian cities showed moderate to high explained variance, respectively. Generally, the models showed higher explained variance of $PM_{2.5}$ compared with NO_2. Among the cities, the lowest explained variance was obtained for Bogotá, while the highest was recorded for Medellín and Bucaramanga.

The LUR models for $PM_{2.5}$ showed relatively small errors of the predicted concentrations (RMSE < 1.7 µg/m^3) in the cities, except for Barranquilla. Moreover, the performance of the LUR models developed for $PM_{2.5}$ was higher than that reported in previous studies in Colombia. Previous LUR models were available only for PM_{10} and $PM_{2.5}$ in the city

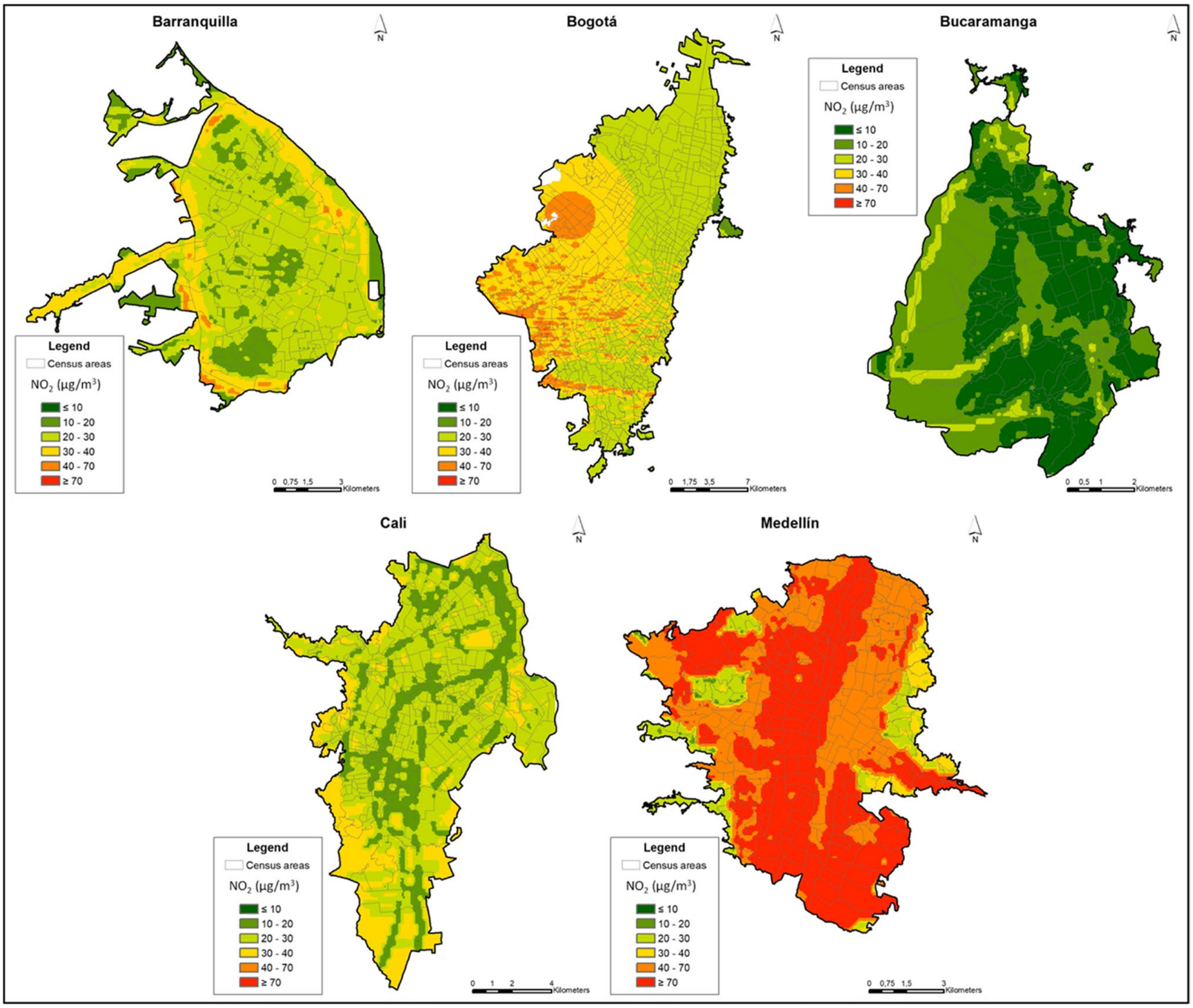

Fig. 3 Annual predicted concentrations for NO_2 in five cities in Colombia, 2021

of Medellín with an explained variability of 79% for PM_{10} (Londoño and Cañon 2015) and monthly variations between 26 and 79% for $PM_{2.5}$ (Grisales 2020), using data from 2007 and 2018, respectively. Our selected LUR model for $PM_{2.5}$ in Medellín explained 82% of the variability, the highest of the five cities, using a combination of meteorological, land use, population density, and traffic volume variables. The high performance of the LUR models for $PM_{2.5}$ in Medellín compared to other cities might be explained by the wide range of estimated concentrations in the city and the influence of the topography and meteorology in the Valley of Aburrá where Medellín is located, as well as the important contribution of vehicular emissions to local concentrations as have been described in studies of $PM_{2.5}$ characterization in the city (Area Metropolitana del Valle de Aburrá and Politecnico Colombiano Jaime Isaza Cadavid 2021). In contrast, the low performance of the LUR models for $PM_{2.5}$ in Bogotá compared to other cities might be explained partially by the lower contribution of vehicular emissions and the increased contribution of enriched fugitive dust (resuspension of crustal material and soil dust) and secondary PM (Ramírez et al. 2018). A similar profile has also been documented for Barranquilla with an important contribution of ocean aerosols (Nuñez Blanco 2019), secondary organic aerosols and the effect of exposed land resuspension and road dust (Gómez-Plata et al. 2022), which was represented in the developed LUR model for this city. Additional unexplained variability in $PM_{2.5}$ concentrations in the cities might be related to regional wildfires contributions which have been substantial in northern South America and particularly in Bogotá (Ballesteros-González et al. 2020) (Casallas et al. 2022).

The variation in explained variability reported for the Colombian cities is comparable to that of $PM_{2.5}$ in other Latin American and European countries. In Ecuador, Alvarez et al. (Alvarez-Mendoza et al. 2019) developed LUR models for PM_{10} using remote sensing data, and the models showed an explained variability of 68% at its highest. Sangrador et al. (2008) developed LUR models for $PM_{2.5}$ during the rainy season in 2003 for Mexico City, which showed an explained variability of 60%. Later, Son et al. (2018) developed LUR models for the same city for different temporal scales, and the best explained variability for monthly $PM_{2.5}$ models was 76%. In Europe, the ESCAPE project developed LUR models for $PM_{2.5}$ in 20 study areas, where the explained variability varied from 35% in Manchester, UK, to 89% in Paris, France (Eeftens et al. 2012).

As expected, the best predictor variables in our LUR models for NO_2 were road and traffic variables. However, the performance of the LUR models developed for NO_2, however, was lower than that for $PM_{2.5}$ and the reported from previous studies in other countries. In Sao Paulo, an annual LUR developed for NO_2 explained 66% of the variability in urban concentrations, with variations for summer (75%) and winter (52%) seasons (Luminati et al. 2021). For the Western European countries, Vienneau et al. (2013) developed LUR models for NO_2 with and without satellite-based NO_2 and obtained explained variability between 48 and 58% without satellite-based NO_2 and a modest additional improvement of 5% when adding satellite-based data. In our models for NO_2, despite including different variables and metrics of traffic and roads, the models could not capture a higher variability in concentrations, which suggests secondary reactions might be an important source of NO_2 in the cities. Although our NO_2 LUR explained less variability compared to other reported models in cities, the LUR models explain more variability than simple road proximity metrics or interpolation methods based on data from monitoring stations and similar variability than dispersion models, which have been demonstrated in previous studies assessing exposure assessment for epidemiological studies (Allen et al. 2011; de Hoogh et al. 2014; Jerrett et al. 2007).

The LUR models have been used in exposure assessment and health research related to long-term exposure to air pollutants. By incorporating data on local sources of pollution, such as traffic or industrial activity, these models can provide more accurate and precise exposure estimates than traditional monitoring methods (Hoek et al. 2008). This is particularly important for assessing the health effects of chronic exposure to air pollution, which has been linked to a range of adverse health outcomes, including respiratory and cardiovascular disease, cancer, and neurological disorders (Chen et al. 2013; Herting et al. 2019; Knibbs et al. 2018; Lamichhane et al. 2017; Stafoggia et al. 2022). LUR models can also identify areas of high pollution levels and vulnerable populations, helping to inform policy and intervention strategies to reduce exposure and improve public health (Vienneau et al. 2013).

Alternative methods for estimating surface concentrations of air pollutants have been developed recently using satellite-based models and models using mobile air pollutant measurements. A study conducted at the municipality level in Colombia compared air quality models based on satellite measurements for $PM_{2.5}$ between 2014 and 2019. It showed that the Copernicus Atmospheric Monitoring Service Reanalysis (CAMRA) and the Atmospheric Composition Analysis Group (ACAG) models had a low correlation and tended to overestimated surface concentrations when both models were compared to surface data from 28 cities in 2019. However, ACAG outperformed CAMSRA in terms of mean bias of the model and the spatial representation of the highest concentrations (Rodriguez-Villamizar et al. 2022). Using a mobile monitoring campaign in the city of Bucaramanga in 2019, estimations of within-city spatial variations in ultrafine particle and black carbon concentrations were predicted using a combination of LUR and convolutional neural networks trained using satellite and street-level images, showing the improvement of prediction when using a hybrid approach (Lloyd et al. 2021). Following this hybrid approach, our locally developed LUR models can be further used to develop hybrid models with satellite or mobile data and produce better spatially calibrated models for estimating long-term exposure for $PM_{2.5}$ and NO_2 in the main cities in Colombia and explore their potential transferability across cities.

There are some strengths in our study that are worth mentioning. First, there was a good agreement between $PM_{2.5}$ measurements made with UPAS compared to the concentrations reported by the local monitoring stations in the cities. For NO_2, there were few monitoring sites to conduct a valid comparison in all cities, but data from local government stations in Bogotá had a good agreement with concentrations reported from measurements with the Palmes tubes. Second, we followed the same standardized procedure for conducting measuring pollutants during the two campaigns in each city and the simultaneous measurement within cities avoid the potential error related to using measures in different time scales. Third, we included basic predictor variables for developing LUR models in the cities (land use, roads, traffic, population, and meteorology) available in the cities in Colombia and might be used further to developed multi-city models as those developed for Europe (Wang et al. 2014).

One limitation of the LUR models developed for the cities is the limited number of sampling sites which was 20 for $PM_{2.5}$ and 40 for NO_2, except for Bogotá which doubled the number. These numbers are below the lower range of recommended monitoring sites (between 80 and 100) for modeling intraurban variations in complex urban settings using LUR

(Basagaña et al. 2012). As a result, the models developed using many predictors might have resulted in more unstable performance as was observed in the cross-validation. A second limitation of this study is the absence of valid traffic data for the cities during the campaign measurement, which has shown to improve the LUR model performance, particularly for NO_2 (Beelen et al. 2013). To overcome this limitation, we measured traffic speed derived from satellite instruments and used previously available traffic count data for the largest cities to calculate density functions which were then transferred to the other cities to estimated traffic density. Despite the density functions in the cities seemed to reflect the traffic patterns in the cities and were included as significant predictive variables, their inclusion did not help to explain a higher variability in the models for NO_2. Third, we did not include meteorological variables in the development of LUR models for the cities of Bucaramanga and Barranquilla due to limited number of meteorological stations and data to produce a valid estimated surface. Although the models' performance for $PM_{2.5}$ were good particularly for Bucaramanga, including meteorological variables might have increased the models' performance as they have been reported as important predictors for intraurban variations in other countries (Cheewinsiriwat et al. 2022; Olvera Alvarez et al. 2018). Another limitation of our study is that we did not include local emission sources and regional sources (such as forest fires) in the prediction models. These variables have shown to influence the concentration of particles in the cities (Casallas et al. 2022). Moreover, street NO_2 levels may vary in building density or location, influencing their dispersion. Also, some atmospheric chemical reactions may reduce or transform NO_2 concentrations. In urban areas, NO_2 emitted mostly from traffic within a radius of 100–300 m showed a correlation, although the high reactivity of NO_2 and rapid photodissociation may transform this pollutant in a reduced period (Agudelo-castañeda et al. 2020).

Conclusion

In this study, we developed LUR models to predict $PM_{2.5}$ and NO_2 exposure in five main cities in Colombia. The LUR models showed a large intraurban variability of pollutant concentrations in all cities. The annual models for $PM_{2.5}$ outperformed the models for NO_2 and provided robust models that can be used in epidemiological studies, particularly cohort studies, assessing the effects of long-term air pollution on human health. The newly developed LUR models might be further used to create hybrid models in combination with other data sources to improve personal exposure assessment.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-023-31306-w.

Acknowledgements The authors thank Oscar Jiménez, Hermes Betancur, Jefferson Fernánez, Angie Rojas, Paola Barbosa, Kelly Burbano, Ronald Correa, Daniela Ortiz, Martha Mendoza, Wilmer Urango, Luz Obando, and Orlando Guaduña for their contributions during the monitoring field work in the cities.

Author contribution Conceptualization and methodology: LR-V, SM, JC, DA-C, VH, DM, JPJ, LB-C, OR-S, JOV, SW, JB, NR; field work and data collection: LL, OMR, MV, WS, AZO, MC, HS; formal analysis and investigation: LR-V, YR, and SCG; writing—original draft preparation: LR-V, YR, and SCG; writing—review and editing: DA-C, VH, DM, JPJ, LB-C, OR-S, JOV, SW, JB, NR, LL, OMR, MV, WS, AZO, MC, HS; funding acquisition: LR-V, SM, JC, DA-C, VH, DM, JPJ, LB-C, OR-S, JOV, NR.

Funding Open Access funding provided by Colombia Consortium This research was funded by the Ministry of Science and Technology MINCIENCIAS in Colombia, grant number 905–2019.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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