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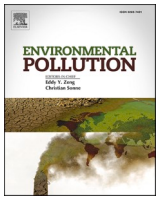

Pesticide contamination in indoor home dust: A pilot study of non-occupational exposure in Argentina☆

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ABSTRACT

Agricultural use of pesticides continues to rise globally. Argentina ranks fifth in use. While pesticides help yields, they also pose risks to human health and the environment. Indoor dust can present high pesticide concentrations, raising concerns about chronic exposure in non-farming households. Studies of pesticides in indoor dust are few worldwide. This pioneering study aimed to identify and/or quantify for the first time pesticide occurrence in indoor dust from urban residences in the Pampas Region, southeast of Buenos Aires Province, Argentina. Pesticide residues in indoor dust from 48 non-agricultural homes in the Pampas plain region were analysed. Study participants completed questionnaires on household demographics, pet ownership, pesticide use, gardening, and habits like leaving shoes outside. We detected 41 out of 49 targeted pesticides, including metabolites and banned compounds. Seven of the 49 tested are dual-use compounds (i.e. pesticide & biocide or veterinary applications). The synergist piperonyl butoxide, the dual-use imidacloprid, and "agricultural only" pesticides carbaryl, glyphosate, and atrazine were detected in all dust samples. Glyphosate, 2,4-D, atrazine, imidacloprid, carbaryl, tetramethrin, and piperonyl butoxide had maximum concentrations exceeding 1, 000 μg kg^{-1}. Complex mixtures of up to 32 residues were found per sample. Questionnaire responses revealed that most participants brought shoes inside (60 %), almost all had pets (93 %), and 51 % had used flea repellents (mainly imidacloprid and fipronil). Approximately 48 % reported pesticide use in the past year, and 19 % reported exposure via their (non-farmer) jobs, e.g., via disinfection and weeding. These findings highlight the prevalence of pesticide residues in residential settings and the need for further research on long-term exposure and risks. Improved tracking of agricultural, household, and mixed-use pesticide applications is crucial, particularly in regions heavily reliant on agriculture.

1. Introduction

The global use of pesticides surpassed 3.5 million tons in 2021, marking an approximate 4 % increase from the previous year and about 17 % higher than a decade ago (FAOSTAT, 2024). In Argentina, 241,520 tons of pesticides were used in 2021 (FAOSTAT, 2024). The National Registry of Plant Therapeutics (SENASA, 2024) lists 2060 pesticide-containing products in Argentina. Glyphosate holds the highest number of registrations (104), followed by 2,4-D and imidacloprid (44), tebuconazole (35), dicamba (35), imazethapyr (33), and atrazine (32). Most of these relate to agricultural use, but pesticides are also applied in urban settings to manage pests in gardens and homes (Meftaul et al., 2020). Some pesticides are applied in both settings, called dual-use compounds. Assessing how agricultural pesticide applications

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contribute to residential exposure is challenging due to insufficient reporting of pesticide use (Madrigal et al., 2023). Pesticides are widely used across all crops, including vegetables, vines, cereals, olives, and soft fruit (Mark et al., 2024). There is increasing evidence that they can accumulate in different environmental compartments (Figueiredo et al., 2022; Close et al., 2021; Tauchnitz et al., 2020; Silva et al., 2023). Researchers have detected residues in the homes of farmers, their neighbours and other populations who are neither involved in nor living close to agricultural production areas (Navarro et al., 2023).

In Argentina, pesticides occur widely in soil (Aparicio et al., 2023), water (Aparicio and De Gerónimo, 2024; Giacobone et al., 2022; Lutri et al., 2020), sediments (Khurshid et al., 2024), airborne particles (Aparicio et al., 2018), rainfall (Alonso et al., 2018), and food (Mac Loughlin et al., 2018). However, little is known about pesticide residues in indoor dust. The scientific community has suggested Argentina restricts or bans the use of several pesticides due to their widespread presence in the environment and the recognized health risks they pose. Chlorpyrifos-ethyl, chlorpyrifos-methyl, and fipronil have been banned in agricultural production, while others, like atrazine, remain in use despite being banned in 37 countries due to endocrine disrupting effects (Gagneten et al., 2021). Imidacloprid, linked to possible mutagenic and neurotoxic effects in humans (Abdelhafez et al., 2023; Sheets, 2010), was banned in Europe in 2020 but remains widely used elsewhere. Glyphosate, which is an eye irritant (according to EFSA and ECHA) and is associated with endocrine disruption, reproductive toxicity, and probable carcinogenicity (IARC, 2015), continues to be freely marketed.

Atmospheric particulate matter can contain numerous pesticides (Ramirez Haberkon et al., 2021, 2024; Nascimento et al., 2017; Coscollà et al., 2014). Pesticides can travel considerable distances by as vapours and air borne contaminated soil (Kalyabina et al., 2021). These processes are strongly influenced by climatic and atmospheric conditions (Farha et al., 2016; Bish et al., 2021). Airborne pesticides may reach agricultural and non-agricultural land, exacerbating primary contamination. Residential areas adjacent to agricultural fields are particularly vulnerable to secondary pesticide contamination. Non-occupational pesticide exposure of individuals residing close to farmlands experience higher exposure than those living farther away from these areas (Dereumeaux et al., 2020). Factors influencing exposure included the proximity of homes to treated fields, the extent of nearby cultivated land, and the time of the year (Dereumeaux et al., 2020). Pesticide residues in household dust have been reported globally. For example, tetramethrin, cypermethrin, and chlorpyrifos-ethyl were the most frequently detected pesticides (79, 72, and 68 %, respectively) in indoor dust samples in rural Taiwan (Simaremare et al., 2021). In Africa, chlorpyrifos-ethyl and terbuthylazine were the most prevalent (96 and 91 %, respectively), followed by carbaryl, diazinon, carbendazim, and tebuconazole (59–74 %) (Degrendele et al., 2022). The authors observed that agricultural residents were exposed to multiple pesticides via inhalation/ingestion of indoor dust. However, this exposure route was considered to be minor, with daily pesticide absorption through dust ingestion accounting for less than 10 % of inhalation and soil ingestion, for 14 of the 19 pesticides detected in dust, air, or soil (Degrendele et al., 2022).

Available indoor dust studies focus mostly on rural/agricultural settings, studying populations with and without occupational exposure to pesticides. Navarro et al. (2023), in one of the most comprehensive studies available, conducted across Europe and Argentina, covering mostly farmers and rural households, report the widespread occurrence of mixtures of pesticide residues in indoor dust samples, especially fipronil, fipronil sulfone, imidacloprid, fludioxonil, hexachlorobenzene, azoxystrobin, carbendazim, tebuconazole, and the synergist piperonyl butoxide. Others, namely chlorpyrifos-ethyl (96 %) and diazinon (72 %) were commonly detected in indoor dust from children's bedrooms, in two agricultural areas (Grabouw/Hex River Valley) and settings (farm/village) (Veludo et al., 2024). While some data exist for farmers' homes, including for this region of Argentina (Navarro et al., 2023), there are no data for non-farmer, urban homes. Navarro et al. (2023) report some control/consumers/rural households in Denmark and France were sampled besides the farmer and their neighbours' households. In these consumer households between 36 and 80 pesticide residues per indoor dust sample were found (Navarro et al., 2023). Impact of different pesticide use between that and our Argentinian study are to be explored as well.

The number and concentrations of pesticides in indoor dust can be significantly higher than in outdoor dust (Mu et al., 2022, 2024), and air (Debler et al., 2024), and that contaminated indoor dust is likely a result of multiple processes and sources. Pesticides can persist indoors for extended periods, unlike in outdoor environments, where sunlight and humidity accelerate biotic and abiotic degradation. Therefore, measures should be taken to mitigate the risk of pesticide exposure associated with indoor dust. Assessing exposure to chemicals via dust, whether through ingestion or inhalation, requires estimating total dust intake (Oomen et al., 2008). It is assumed that children generally ingest more dust than adults, primarily due to hand-to-mouth behaviour (Lijzen et al., 2001). Young children have a higher respiratory rate than adults, and are therefore more vulnerable to pesticide inhalation, even though this route represents a relatively small contribution to total dust intake (Pascale and Laborde, 2017). Salameh et al. (2003) found that children exposed to pesticides during their first year of life face a 2.5-fold increased risk of developing asthma compared to those with no pesticide exposure. Furthermore, the potential risk of exposure to toxic chemicals via ingestion of contaminated dust might be equal to or greater than exposure through food consumption, especially for younger children (Hwang et al., 2008a).

In Argentina, residing in rural towns near agricultural pesticide applications is associated with higher cancer rates (Verzeñassi et al., 2023). Husaini et al. (2024) highlighted the detrimental effects of pesticide and other indoor and outdoor air pollutants on public health and noted the limited research on the impacts of pollutants in Latin American and Caribbean countries, primarily due to resource limitations. This research gap, along with the lack of studies on pesticide residues in indoor dust from non-occupational homes, prompted this pilot study in south-eastern Buenos Aires, Argentina. This study aims to identify the types and levels of pesticides (herbicides, insecticides, fungicides) present in indoor dust from non-farmer homes located in the Pampas Plain region of southeastern Buenos Aires province, Argentina.

2. Materials and methods

2.1. Edaphoclimatic characterization of the pampas plain (Argentina) and land use distribution

The southeastern region of Buenos Aires province (Fig. 1) is located within the Pampas Plain, a semi-rural area characterized by a subhumid to humid temperate climate, with seasonal water deficiencies. Land use in the region is primarily agricultural, with 70–80 % of the area dedicated to farming activities. The main cropping systems include soybeans, maize, wheat, and sunflower, along with livestock farming, particularly cattle. Agricultural fields are distributed throughout the region, with larger farms typically located toward the western part of the area. About 20–30 % of the land is used for, cities and small villages. These urban areas are interspersed with agricultural lands, creating a mixed-use landscape. Farming systems in this region follow predominantly conventional agricultural practices, including substantial use of pesticides, sprayed with self-propelled machinery. Crop-livestock mixed systems are common, with rotations between grain production and pastureland being a typical feature of local agricultural practices.

2.2. Interviews with participants and sample collection

In a 2,634,000-ha area in the southern Pampas plain, residents from small villages (populations between 69 and 1241 inhabitants) and cities

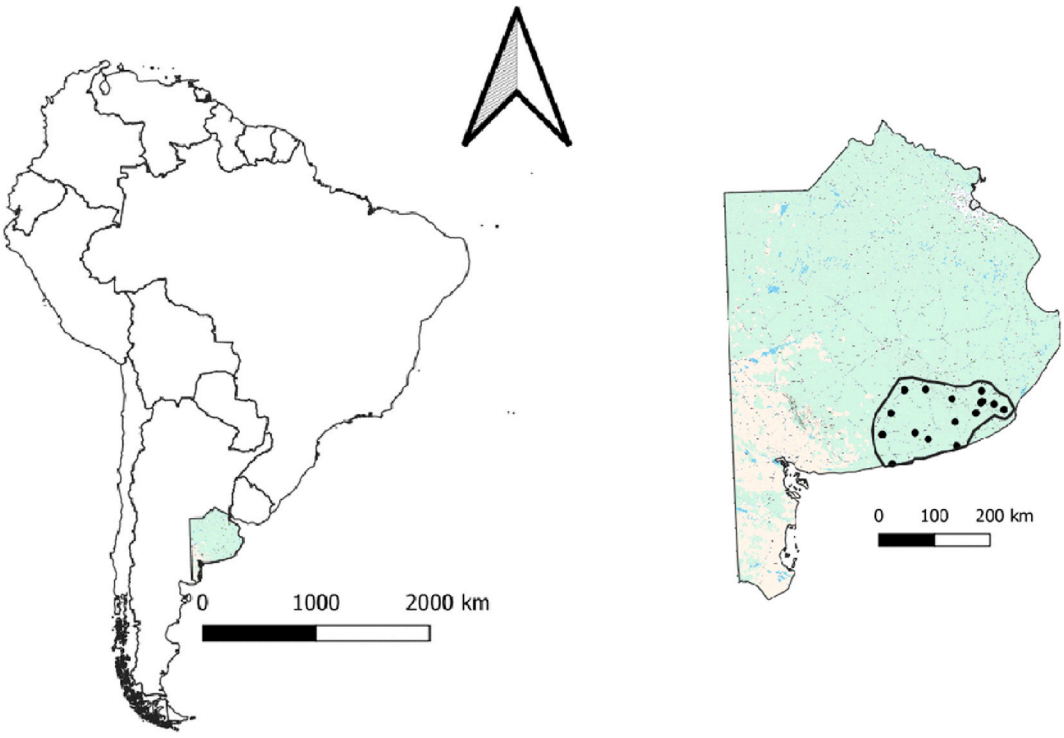

Fig. 1. Study area: left panel) South America, with political division of countries; right panel) sampling area: Pampas plain region, southeast of Buenos Aires Province, Argentina. The dots indicate the sampled cities or towns.

(populations between 7354 and 73,054 inhabitants) were invited to participate in this study (Table 1). The study population consists of 53 participants (60 % women, 40 % men), with 81 % of them working in professions such as teaching, municipal and national government employment, business, medicine, law, ceramics, librarianship, and ambulance driving, among others. The remaining participants were retirees, university students, or (grand)parents taking care of their children at home.

Participants living in small towns (46 %) were categorized as 'farmers' neighbours,' while those residing in cities (54 %) were classified as 'consumers/control'. This is an attempt to establish a gradient across professional agricultural use, non-professional rural households, and households in an urban setting.

Table 1
Overview of study area: Categorical variable, name, number of inhabitants and number of participants.

Categorical variable	Name	Number inhabitants	Number participants
City (consumers/ control)	Necochea	73,054	2
	Tres Arroyos	62,000	7
	Balcarce	44,000	6
	Benito Juárez	14,279	9
	Lobería	13,000	3
	González Chávez	9066	1
	San Cayetano	7354	2
Small villages (farmers' neighbours)	Barker	1241	2
	San Manuel	1126	3
	San Agustin	498	1
	Ramón Santamarina	430	1
	Sierra de los Padres	415	8
	Villa Cruce	200	2
	Villa La Brava	115	3
	Bosh	96	2
	Claromecó	69	1

2.2.1. Collection of contextual data

A questionnaire was used to collect information from all participants on pesticide use, household environment, family size, presence of pets, gardens or orchards, and whether shoes were removed upon entering the house (Table S1). In addition, they were asked about the distance from their home to crop fields where pesticides are used.

2.2.2. Collection of indoor dust samples

The participants were asked to collect indoor dust by sweeping the floors of different rooms of their homes (living room, kitchen, hallway, sleeping room, bathroom), maintaining their habits and frequency of home cleaning. A dust sample was collected per household, in November 2021. This was conducted at the same time as the SPRINT sampling campaign (Silva et al., 2021). All dust collected in the house over a 10 day period was combined into one, composite dust sample.

Since some participants shared housing, 48 indoor dust samples were collected: 22 from the "farmers' neighbours" group and 26 from the "consumers/control" group. Since not t all homes had a vacuum cleaner, and this is a pilot study, it was decided to homogenize the methodology using brooms. Indoor dust was then collected by the study participants using a new broom and dustpan used only inside the homes (like in Birn et al., 2012). Floors were typically of smooth cement or ceramic.

2.2.3. Sample pre-processing

These composite samples were wrapped in aluminium foil, sealed in polyethylene bags and stored at −20 °C before being transported to the INTA Balcarce Laboratory. Once there, each composite sample was sieved using a 500 μm stainless steel sieve before analysis.

2.3. Chemical analysis

A total of 49 pesticide residues were analysed, comprising 45 active substances and four metabolites. Seven out of these are identified as

dual-use substances in Argentina: imidacloprid (not approved in Europe), piperonyl butoxide (synergist in pyrethroid-based plant protection products and biocides), tetramethrin (not approved in Europe), pirimiphos-methyl (approved in Europe), fipronil (not approved in Europe), chlorpyrifos (not approved in Europe), and allethrin (not approved in Europe; see Table 2 Argentinian approval status and further details on all tested substances).

The target list was based on regional agricultural practices, and on products which agronomists, farmers, pesticide applicators, and local pesticide retailers have reported. Pesticide analysis was performed at the Pesticide Laboratory of the Instituto Nacional de Tecnología Agropecuaria (INTA) in Balcarce, Argentina, using ultra-high performance liquid chromatography UHPLC–MS/MS on an ACQUITY UPLC™ system coupled to a Quattro Premier™ XE triple quadrupole mass spectrometer (Waters). A multi-residue method was applied for most pesticides, while a dedicated additional method was used for glufosinate, glyphosate and its metabolite AMPA.

For multi-residue analysis of pesticides, a gradient mobile phase was used, consisting of water (Phase A) and methanol (Phase B), both modified with 0.1 mM ammonium acetate and 0.01 % of formic acid. For glyphosate and AMPA, the mobile phase was composed of water with 5 mM ammonium acetate (Phase A) and methanol with 5 mM ammonium acetate (Phase B). In both cases, the injection volume was 20 μL. Nitrogen, generated in-house, was used as the drying and nebulizing gas, and 99.995 % argon served as the collision gas at a pressure of 4.04×10^{-3} mbar in the T-Wave cell. For multi-residue analysis, indoor dust samples (1 g of the sieved material) were spiked with 50 μL of atrazine-d5 (1 μg mL^{-1}), followed by the addition of 1 mL of nanopure water and 4 mL of methanol with 1 % of formic acid. The mixture was sonicated for 30 min and centrifuged at 3000 rpm for 10 min. The supernatant was filtered through a 0.22 μm nylon filter and injected into the UPLC-MS/MS.

For glufosinate, glyphosate and AMPA, indoor dust samples (1 g) were spiked with 50 μL of labelled glyphosate solution (1 μg mL^{-1}; 1,2

Table 2
Pesticides, group, approval status at sampling date in Argentina, domestic pesticide (household use, biocide), agricultural pesticide (plant protection product), detection percent, median concentration and interquartile range (IQR) in indoor dust. All pesticides were tested in 48 indoor dust samples.

Pesticides	Group	Status	Domestic pesticide	Agricultural pesticide	Detection	Median concentration	IQR
					%	μg kg^{-1}	
Imidacloprid	I	A.	Y	Y	100	105.6	669
Glyphosate	H	A.	N	Y	100	81.9	188
Piperonyl Butoxide	NP	A.	Y	Y	100	18.1	23
Atrazine	H	A.	N	Y	100	10.8	11
Carbaryl	I	A.	N	Y	100	2.3	6
2,4-D	H	A.	N	Y	98	14.0	12
Tetramethrin	I	A.	Y	Y	98	12.4	48
Pirimiphos Methyl	I	A.	Y	Y	96	1.4	4
Flurochloridone	H	A.	N	Y	88	4.7	7
Fipronil	I	A.	Y	Y	83	6.0	30
AMPA (*)	*M*	–	–	–	77	31.8	48.5
Chlorpyrifos	I	A.	Y	Y	77	4.0	20.5
Allethrin	I	A.	Y	Y	73	5.0	10
Epoxiconazole	F	A.	N	Y	73	1.4	1
Atz-OH (*)	*M*	–	–	–	69	1.7	2
Atz-desethyl (*)	*M*	–	–	–	58	1.6	1
Glufosinate	H	A.	N	Y	54	7.8	19
Metalaxyl	F	A.	N	Y	46	0.4	2
Tebuconazole	F	A.	N	Y	42	6.9	21.5
Metribuzin	H	A.	N	Y	40	1.2	1
Dimethoate	I	A.	N	Y	33	0.6	0
Diazinon	I	**N.A.**	N	Y	31	0.4	0
Kresoxim Methyl	F	A.	N	Y	31	0.3	1
Dicamba	H	A.	N	Y	29	7.0	9
Sulfentrazone	H	A.	N	Y	25	5.1	7
Simazine	H	A.	N	Y	21	2.1	1
Chlorpyrifos-Methyl	I	A.	N	Y	19	1.4	1
2,4-DB	H	**N.A.**	N	Y	15	1.5	0
Metsulfuron Methyl	H	A.	N	Y	13	6.9	7.5
Carbofuran	I	**N.A.**	N	Y	13	0.9	0
Fomesafen	H	A.	N	Y	10	2.6	2.5
Diclosulam	H	A.	N	Y	10	2.4	6
Ethyl Chlorimuron	H	A.	N	Y	10	0.5	5
Imazethapyr	H	A.	N	Y	8	8.0	15.5
Pirimicarb	I	A.	N	Y	6	1.9	–
Imazapic	H	A.	N	Y	6	1.6	–
Imazapyr	H	A.	N	Y	6	1.1	2
Metconazole	F	A.	N	Y	6	0.3	–
Imazaquin	H	A.	N	Y	4	0.5	–
Triticonazole	F	A.	N	Y	2	56.5	–
Halauxifen-methyl	H	A.	N	Y	2	1.3	–
Atz-desisopropyl (*)	*M*	–	–	–	–	0.0	–
Methomyl	I	A.	N	Y	–	0.0	–
Aldicarb	H	**N.A.**	N	Y	–	0.0	–
Ametrine	H	A.	N	Y	–	0.0	–
Flumioxazin	H	A.	N	Y	–	0.0	–
Metolachlor	H	A.	N	Y	–	0.0	–
Pendimethalin	H	A.	N	Y	–	0.0	–
Picloran	H	A.	N	Y	–	0.0	–

I: Insecticide; H: Herbicide; F: Fungicide; (*) *M: Metabolite*; NP: Not Pesticide; Y: yes; N: no; A: approved; N.A: not approved.

13C, 15N). After stabilizing for 30 min, 5 mL of $KH_2PO_4/Na_2B_4O_7$ buffer solution (0.1 M, pH = 9) were added to the samples and then sonicated for 30 min in an ultrasonic bath. Then, samples were centrifuged at 3000 rpm for 10 min. A 1 mL aliquot of the supernatant was mixed with 1 mL of nanopure water and 2 mL of fluorenylmethyloxycarbonyl chloride (FMOC-Cl) reagent in acetonitrile (1 mg mL^{-1}). The solution was vigorously for 2 min with a vortex and left overnight (12–15 h) at room temperature in the dark. A liquid-liquid extraction with 4 mL of CH_2Cl_2 followed by centrifugation at 3000 rpm for 10 min was performed. The aqueous phase was then filtered through a 0.22 μm nylon filter for analysis.

For calibration standard solutions in solvent at concentrations of 0, 1, 5, 10 and 50 μg L−1, were used. These standards were analysed in triplicate. Satisfactory linearity was assumed using weighted least squares regression (1/X) when the correlation coefficient (r^2) was greater than 0.99, based on the measurement of analyte peak areas, and residues were less than 30 %. In the multi-residue method, an amount equivalent to that expected in the analysed samples of isotopically labelled atrazine was added, while in the special method for glyphosate, glufosinate and AMPA, an amount of isotopically labelled glyphosate was added to the standard solutions to evaluate the effect of the matrix in both methods. The limit of detection (LOD), defined as the lowest concentration that the analytical process can reliably differentiate from background levels, and the limit of quantification (LOQ), defined as the smallest value of analyte that can be quantitatively determined, are presented in Table S2.

Sample extracts with high concentrations were diluted for injection into the UPLC MS/MS. Blanks were the “consumer/control” indoor dust samples, as we did not expect to find pesticides. Considering the composition variability of indoor dust samples in general, and the pilot nature of the study, using blank samples seemed the best approach. This approach had been used already in literature (De Gerónimo et al., 2015). Instrumental blanks were a mix of water and solvent. Data processing was carried out using Masslynx NT v 4.1 software (Waters).

2.4. Method validation and quality control

The analytical methods were validated according to the SANTE/2020/12830 (SANTE, 2021a) and SANTE/11312/2021 (SANTE, 2021b) guidelines. Recoveries ranged from 70 to 120 %, with a relative standard deviation of(RSD) of ≤20 % for intraday repeatability. Method specificity was verified by confirming two MS/MS transitions, with q/Q ratios meeting a tolerance of <30 % and retention time deviations of <0.2 min.

2.5. Data processing and statistical analysis

Survey data were analysed in percentage terms. For pesticide analysis, descriptive statistics (mean, median, and range) were performed for positive samples (>LOD) using boxplots to illustrate data distribution. Graphs were created in Microsoft Excel to show central tendencies and variability. Statistical analyses were conducted using Infostat (version 2008, National University of Córdoba, Argentina). The normality of the variables "number of pesticides" and "sum of pesticide concentrations" was assessed using the Shapiro-Wilk test. As these data were non-normally distributed ($p < 0.05$), logarithmic transformations were applied. ANOVA was used to assess significant differences between the categorical variable "locality" and the transformed numerical variables: "number of pesticides" and "sum of pesticide concentrations".

3. Results

3.1. The questionnaires/determinants of exposure

Five households had two responses per household. The responses between inhabitants of the same dwelling were as expected rather similar (e.g. if you work, if you have pets, if you leave your shoes outside the house if you applied pesticides in the house or the garden), being treated as one in the data analysis step. The questionnaire outcomes indicated that participants typically spend between 8 and 24 h at home and most did not take off their shoes when entering (60 %). Many participants owned pet dogs, cats, or birds (93 %) with roaming habits (excluding birds). Around half of the participants51 % had used flea repellents on their pets (mainly imidacloprid and fipronil), and 15 % had used a veterinary product in the past 12 months (e.g., dewormer). Additionally, for approximately half (48 %) of the households reported pesticide use in the last 12 months, and 19 % of participants reported being exposed to pesticides at work (Table S1).

3.2. The pesticide analyses

All indoor dust samples contained mixtures of pesticides, with an average of 19 and a maximum of 32 pesticides per sample. Of the 49 pesticides analysed in the indoor dust samples, only eight were not detected (atrazine-desisopropyl, methomyl, aldicarb, ametrine, flumioxazin, metolachlor, pendimethalin, and picloram). Sixteen pesticides were found in less than 25 % of the samples, 13 were detected in 25–75 % of the samples, and 12 were detected in more than 75 % of the samples. Notably, the synergist piperonyl butoxide, imidacloprid, carbaryl, glyphosate, and atrazine were detected in all samples (Table 2). Among the four herbicide metabolites examined, only Atz-desisopropyl was not detected in any of the analysed samples, while the others were present in more than 55 % of the indoor dust samples. Insecticides and herbicides exhibited the largest range of detection percentages (0–100 %) (Table 2), while fungicides showed detection frequencies between 2 and 73 %.

Regarding the market-approval status, three out of the four tested Argentinian banned compounds at sampling time were detected at least once (diazinon, 2,4DB, and carbofuran; Table 2). aldicarb, banned in 2018 was not detected. All pesticides authorised for domestic use monitored in this study were insecticides and were present in indoor dust at detection rates above 70 % (imidacloprid, piperonyl butoxide [synergist], tetramethrin, pirimiphos-methyl, and allethrin). Two recently banned pesticides used in both agricultural and domestic settings, fipronil and chlorpyrifos-ethyl, were also present in indoor dust with high detection rates of 83 % and 77 %, respectively (Table 2).

The highest indoor dust pesticide concentrations were found for glyphosate (36,501 μg kg^{-1}), imidacloprid (15,340 μg kg^{-1}), tetramethrin (10,155 μg kg^{-1}), tebuconazole (6190 μg kg^{-1}), chlorpyrifos-ethyl (2536 μg kg^{-1}) and fipronil (1631 μg kg^{-1}). Table 2 presents the median concentrations of each pesticide analysed in indoor dust as well as the group by general use (insecticide, herbicide, fungicide). When considering the proximity of homes to farms, there were no significant differences in terms of the number of pesticide residues or the total concentration detected (Fig. 2a and b).

4. Discussion

4.1. The objective of the study

This study looked into the occurrence, types and levels of pesticides present in indoor dust from non-farmer homes in small villages and cities in the Pampas Plain, Argentina. It was a pioneering study for the region and one of the few focusing on indoor dust from urban residences. As such interpretation and comparisons are somehow restricted. We found nevertheless strong evidence of widespread contamination, which stresses the need for exposure and risk-focused follow-up studies, especially accounting for the complex mixtures found (mix of approved and not approved substances, of active substances and metabolites, of dual-use substances and agriculture-specific compounds). This study contributes to knowledge of residential pesticide use in Argentina and highlights the need for further research on non-occupational pesticide exposure, and the importance of accounting for non-agricultural

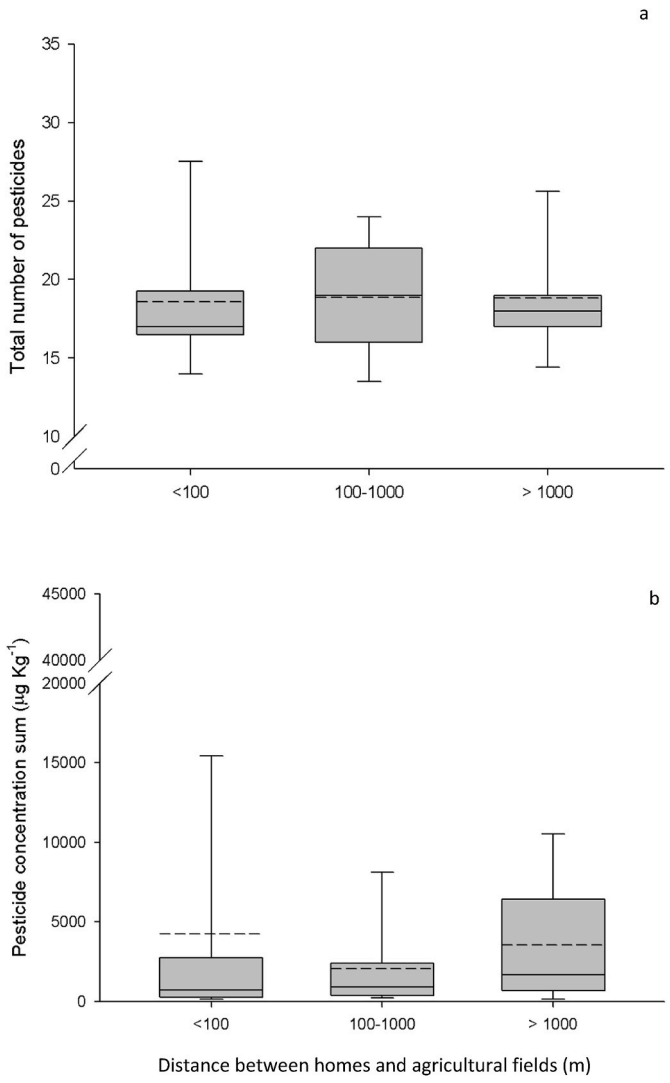

Fig. 2. Total number of pesticides (a) and sum of pesticide concentration (b) as a function of the distance between homes and agricultural fields. The boxplots represent core data (25 % percentile, median, 75 % percentile; whiskers = minimum/maximum values). Dashed lines represent mean values.

households in comprehensive risk assessments.

4.2. Determinants of exposure & potential sources of the residues found

We performed an accompanying questionnaire to participants on determinants of exposure that provides some insights on these, but that due to the reduced sample size of such a pilot study, did not allow stratification and statistical analyses between findings and covered variables. However, the questionnaires showed that half of the non-farmer participants reported using pesticides within the past 12 months, mainly to control flies, mosquitoes, slugs and ants in their homes and gardens. In France, the *Pesti'home* survey reported similar results, with three-quarters of participants using pesticides at home, primarily insecticides (84 %), followed by anti-mite agents (28 %) and herbicides (24 %) (Tessier et al., 2023). Residential pesticide use seems therefore to be a potential source of exposure, with multiple opportunities for contact within homes and gardens. Most respondents reported having pets in their homes (Table S1) and half used pesticides for flea control. Imidacloprid and fipronil were found in 100 % of dog hair samples in the Netherlands (Diepens et al., 2023). These pesticides could be transferred to indoor dust through the shedding of animal hair. Our pilot study did not establish which products were applied to domestic pets but fipronil, permethrin, imidacloprid, pirimiphos methyl, piperonyl butoxide are known active ingredients to control fleas and ticks in domestic animals. Insecticidal products were detected in more than 80 % of indoor dust samples.

Pesticides not intended for household use but found in indoor dust are likely derived from applications in nearby public green spaces or agricultural fields. In European farmers' homes, residues of 197 pesticides out of the 198 tested were detected in 115 indoor dust samples (the exception being chlorpyrifos-methyl-desmethyl). All 115 samples contained mixtures of pesticide residues (conventional farms >47 residues and in organic farms >24 residues) (Navarro et al., 2023). Despite differences in sampling methods, analytes, and the rural vs urban setting, some pesticide residues reported by Navarro et al. (2023) were also detected in our study. Navarro et al. (2023) also explores, in great detail, the hazard profile of the found substances – reason why it is not done here.

4.3. The pesticide findings

The levels in our indoor dust pesticide samples belonged to glyphosate. The high concentrations of glyphosate found in many dust samples can be explained by its extensive use in both agricultural and urban areas. Glyphosate is frequently used for weed control in the public domain, such as sidewalks. Glyphosate has also been recorded in relatively high concentrations in indoor dust (Saurat et al., 2023), even in urban homes (Li et al., 2024; Ward et al., 2023). In indoor dust from rural Argentina, Navarro et al. (2023) reported a maximum concentration of 49,500 µg kg^{-1} its presence and high levels in indoor dust reflects a significant lack of awareness, or concern, about its environmental and health risks. Glyphosate's wide availability, coupled with possible inadequate usage guidelines, facilitates unintentional exposure among residents.

The median concentrations of other compounds reported in our work, in non-agricultural households, ranged between non detected and 106 µg kg^{-1} (imidacloprid). Our values were lower than those reported by other authors, such as Degrendele et al. (2022), whose concentrations ranged between 4.4 µg kg^{-1} (tebuconazole) and 365 µg kg^{-1} (chlorpyrifos), but where half of the households were located on farms and the other half in the nearby village. For their part, Veludo et al. (2024) reported a maximum median concentration of 367 µg kg^{-1} (chlorpyrifos). In a study conducted in Europe and Argentina, median pesticide concentrations in indoor dust from rural homes of organic and non-organic farmers had a wide range (<0.01 µg kg^{-1} to 206,000 µg kg^{-1}), with glyphosate and its degradation product AMPA, permethrin, cypermethrin, and piperonyl butoxide found at the highest levels (Navarro et al., 2023).

4.4. The field distance factor

Indoor dust data reflect agricultural practices in the vicinity of homes, especially when looking at the large number of compounds found that are not approved as household biocides. A meta-regression by Deziel et al. (2017) showed that pesticide concentrations in house dust tend to decrease with increasing distance from treated fields. In California, for example, pesticide use within 1250 m of homes was found to be a significant determinant of pesticide concentrations for two herbicides (chlorthal-dimethyl and simazine), one fungicide (iprodione), and two insecticides (carbaryl, chlorpyrifos) (Gunier et al., 2011). Ward et al. (2006) collected indoor dust from 112 homes, of which 58 % had crops within 500 m of their home and detected six herbicides used almost exclusively in agriculture in 28 % of homes; when they analysed an increase in the surface area of corn and soybean fields within 750 m of homes, the probability of detecting agricultural herbicides was higher, compared to homes without crops within 750 m.

In our study, there were no statistically significant differences in

cumulative concentration or total number of pesticides present in indoor dust among the three distance classes (<100, 100–1000, >1000m). This may be a consequence of small sample size. A different construction around participant recruitment and distance assessment, a more complete assessment on participants determinants of exposure, and a robust assessment of local pesticide behaviour (via for instance OBOmod model simulations, Figueiredo et al., 2022), could provide further insights into different sub-populations' exposures. This exploratory analysis reaffirmed the need to plan for rigorous monitoring of pesticide content in indoor dust, especially when it comes to determining a large number of pesticides, some of which can be of dual-use (plant protection product and biocide).

4.5. Limitations and recommendations for further studies

As somehow introduced above, one of the main challenges encountered in this study relates to the lack of (spatial and temporal) pesticide use data. A pesticide use database based on for example the California Pesticide Use Reporting Database (https://www.cdpr.ca.gov/). can help identifying the sources of compounds, explore distance-related questions, etc. The California Pesticide Use Reporting Database is recognized as a complete database available to academic and government scientists, pesticide producers and the general public who require complete and detailed reports on agricultural and non-agricultural pesticide use. Some inferences could be made from the crops in the region but it would come not without uncertainties. During the 2020–2021 season, corn and soybeans accounted for approximately 50 % of the local cultivated area, followed by a proportion dedicated to fallow(Aparicio and De Gerónimo, 2024). Of the total pesticides used in 2015, 41 % [by mass or by type off pesticide] were applied in fallow, 36 % in soybeans, and 10 % in corn (Aparicio et al., 2015), with the most commonly used pesticides being glyphosate, 2,4-D, atrazine, metolachlor, imidacloprid, and chlorpyrifos. Agricultural practices in the area and communications with private consultants suggest that there have been no major changes in input management between 2015 and 2021. Access to a database on pesticide use would significantly improve these approaches. The information provided from a pesticide use database would allow us to guide their identification and/or quantification according to use and other criteria of interest (e.g. toxicity, synergistic effects in mixtures, effect on organisms including humans, environmental persistence, etc.).

Other limitations were: the small sample size and the selected collection method. Sweeping offers an alternative to collect household dust in areas where vacuum collection is not feasible (Birn et al., 2012). However, for inhalation exposure to indoor dust, it is necessary to collect dust according to international standards for inhalation, thoracic dust and/or respirable dust using validated air sampling equipment. Despite these limitations, this study provides valuable information on pesticide occurrence in homes with limited occupational exposure in a temperate agricultural region.

Indoor dust, acting as a reservoir/secondary source of pollutants, can lead to prolonged exposure, particularly in the absence of degradation processes such as microbial activity or photolysis (Hwang et al., 2008b; Hu et al., 2024).

Further investigations with a public health emphasis are needed to understand how universal fate/transport models using pesticides measured can serve as exposure metrics in environmental health risk analysis. Given that Argentina has only banned 18 pesticides, and the market is dominated by a few active ingredients—primarily herbicides—it is crucial to conduct a risk assessment of non-occupational exposure for both rural and urban populations (Aparicio and De Gerónimo, 2024). These findings provide a foundation for future research on pesticide mixtures, incorporating both agricultural and domestic pesticide use, to better understand and mitigate exposure risks.

5. Conclusions

In this pilot study, we identified and quantified mixtures of multiple pesticides in indoor dust samples in urban areas. Pesticide mixtures in indoor dust samples included insecticides (imidacloprid and carbaryl), herbicides (glyphosate and atrazine), and the synergist piperonyl butoxide with mean concentrations, ranging from 2 to >100 μg kg^{-1}. The findings confirm the presence of mixtures of multiple pesticides in the indoor environment of non-agricultural homes located in the Pampas plain region of southeastern Buenos Aires Province, Argentina. Our study highlights the need for further research on potential risks to human health from long-term exposure to pesticide mixtures in indoor dust. Further more detailed studies are needed to understand better the exposure and long-term health effects of non-occupational exposure to pesticides, particularly in regions where agriculture is a the dominant activity.

CRediT authorship contribution statement

Virginia Aparicio: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jessica Kaseker:** Writing – review & editing, Writing – original draft, Formal analysis. **Paul T.J. Scheepers:** Writing – review & editing, Methodology. **Abdallah Alaoui:** Writing – review & editing, Methodology. **Daniel M. Figueiredo:** Writing – review & editing, Methodology. **Hans Mol:** Writing – review & editing, Methodology. **Vera Silva:** Writing – review & editing, Methodology. **Paula Harkes:** Writing – review & editing, Visualization, Methodology. **Danilo Rheinheimer Dos Santos:** Writing – review & editing. **Violette Geissen:** Writing – review & editing, Methodology. **José Luis Costa:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2025.126208.

Data availability

Data will be made available on request.

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