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Review

Legacy and emerging pollutants in Latin America: A critical review of occurrence and levels in environmental and food samples

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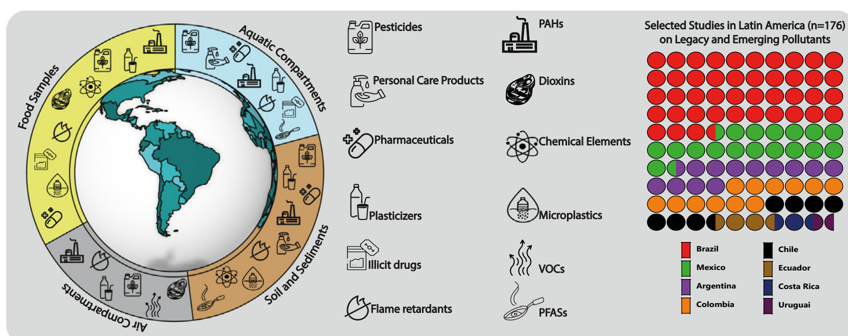
HIGHLIGHTS

- Brazil has the higher number of articles in LA, corresponding to 45 % of the total.
- PAHs are the major group of anthropogenic environmental pollutants studied in Brazil.
- Pesticides and pharmaceutical compounds are the prevalent EPs in water samples.
- There are still gaps in Latin America's PFAS, EDCs, and illicit drug studies.
- The lack of analytical instrumentation limits many countries from getting data on EPs.

GRAPHICAL ABSTRACT



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ABSTRACT

The increase and indiscriminate use of personal care products, food products, fertilizers, pesticides, and health products, among others, have resulted/are resulting in extensive environmental contamination. Most of these products contain traces of widespread chemicals, usually known as emerging pollutants (EPs) or pollutants of emerging concern (PEC). The Latin American (LA) region comprises 20 countries with different social and cultural aspects, with 81 % of the population living in urban areas. The LA region has some countries on the top list of users/consumers of EPs, from pesticides and fertilizers to personal care products. However, there is a gap in information related to the distribution of EPs in the environment of this region, with very few existing review texts exploring this issue. Therefore, this present paper advances this approach. An exhaustive literature review, with the selection of 176 documents, provided unique up-to-date information on the presence/distribution of 17 classes of legacy or emerging pollutants in different food and environmental matrices (soil, sediment, water, and air). The study shows that the wide distribution and recorded levels of these pollutants in the continental environment are potential risks to human health, mainly through food and drinking water ingestion. Polycyclic aromatic hydrocarbons are pollutants of deep public concern since they show carcinogenic properties. Several classes of pollutants, like endocrine disruptors, have caused harmful effects on humans and the environment. Besides that, pharmaceutical products and pesticides are compounds of high con-

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sumption worldwide, being environmental contamination a real and ongoing possibility. Finally, gaps and future research needs are deeply pointed out.

Contents

1. Introduction

In recent years, the increase in industrial manufacturing processes, agricultural practices, and new technological development, have exposed the environment and humans to many new chemical compounds, defined as emerging pollutants (EPs) or pollutants of emerging concern (PEC). Such chemicals include pharmaceuticals, pesticides, cosmetics, personal care products, hormones, plasticizers, flame retardants, microplastics, additives, illicit drugs, and rare earth elements (REEs), among others. Since the knowledge of their environmental impacts is increasing and the toxic effects on humans are becoming evident, national/international agencies are regulating and controlling their use (Deblonde et al., 2011; Gavrilescu et al., 2015; Llorca et al., 2016; Arismendi et al., 2019; Peña-Guzmán et al., 2019; Starling et al., 2019; Saldaña-Duran et al., 2020).

Some organic EPs are also classified as endocrine-disrupting compounds (EDCs) (Montagner et al., 2017; Peña-Guzmán et al., 2019; Lopez-Velázquez et al., 2021). EDC is defined by the European Chemicals Agency (ECHA) and the European Food Safety Authority (EFSA) as an exogenous substance or mixture that alters the functions of the endocrine system. Consequently, it causes adverse effects on the health of the organisms, their progeny, or (sub)populations. On the other hand, legacy pollutants are a public health concern due to their persistence in the environment, their toxicity to ecosystems and organisms, and the potential for long-range transport. Organochlorine pesticides (OCPs), polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) are classified as legacy pollutants (WHO, 2011; UNEP, 2010; Tombesi et al., 2014; Brovini et al., 2021).

Although almost all legacy and emerging pollutants come from anthropogenic activities, they can reach the environment and be distributed throughout the food and environmental matrices (water, soil, marine sediment, and indoor/outdoor dust) (Lapworth et al., 2012; Cesar et al., 2014; Gavrilescu et al., 2015; Arismendi et al., 2019; Souza et al., 2021). Several studies have reported potential exposure sources, occurrences, and ways of legacy and EPs behaving in the environment, including persistence and bioaccumulation in animal tissues. For this, it is essential to assess the risk of human exposure to these pollutants (Llorca et al., 2016; Souza et al., 2021). Furthermore, analytical instrumentation and methodologies have been constantly being aphorized to improve the ability to detect and determine lower levels of legacy and EPs in various matrices. However, most of the innovative instrumentation to detect low concentrations of them in environmental samples are not currently accessible in developing countries and regions. Therefore, there is very limited information on the distribution and incidence of legacy and EPs in the environment of these countries. Despite this, some investigations suggest that their environmental levels could be even higher than in more developed regions (Reichert et al., 2019; Vargas-Berrones et al., 2020; Souza et al., 2021).

Latin American (LA) countries present a natural and cultural diversity beyond several social inequalities. Moreover, the LA region is the second most urbanized of the planet, with 81 % of the population living in urban areas (Llorca et al., 2016; Duque et al., 2019; Peña-Guzmán et al., 2019; Bonilla-Bedoya et al., 2020). While urbanization promotes economic growth, it also generates serious environmental problems. As a consequence, some studies confirm significant associations between the environmental burdens of legacy and EPs and the socioeconomic status of the population (Liang and Yang, 2019; Peña-Guzmán et al., 2019; Hao et al., 2020; Caro-Borrero et al., 2021; Souza et al., 2020).

LA is an important global food producer, concentrating on the production of several grains, fruits, and vegetables. In recent years, there has been a great expansion of arable areas throughout the region, with a huge and growing consumption of fertilizers and pesticides. This practice has had major consequences for the environment, with extensive areas affected. For example, Brazil has become the highest global pesticide consumer, with 1 million and 52 thousand tons in 2020 (IBGE, 2021; Silva et al., 2021a, 2021b). The intensification in the use of pesticides is currently a public health concern, as some of these compounds are environmentally persistent. Their unrestricted and repeated application to soils is associated with a loss of biodiversity and an increased resistance to target pests (Hernández et al., 2013; Holme et al., 2016; Kim et al., 2017; Machado and Martins, 2018; Sinha and Banda, 2018; Gonçalves-Filho et al., 2020; Paumgartten, 2020). Nevertheless, despite the global concern by the crescent demand for pesticides, some LA countries are changing laws to flexible their use. For example, in February 2022, the Brazilian Chamber of Deputies approved a new bill (6299/02) that makes the control and approval of pesticides more flexible in Brazil. This bill intends to focus decisions on the approval of new products with the Ministry of Agriculture and remove the powers of national regulatory bodies, including the National Health Surveillance Agency (ANVISA), the Brazilian Institute of the Environment, the Renewable Natural Resources (IBAMA), and the Ministry of Health. The United Nations has already spoken out against this project. In 2021, 560 new pesticides were registered for use in Brazilian crops. Therefore, the removal of Brazilian regulatory agencies from pesticides control will probably rise even the presence and levels of substances considered dangerous to the environment and human health.

Pesticides are not the only EPs for which the demand and consumption are increasing in the LA region. Flame retardants like polybrominated diphenyl ethers (PBDEs), are widely used in various materials due to their low cost and high efficiency against flame propagation. Some PBDE congeners have been banned in several countries. Notwithstanding, LA does not present specifications for the current usage and commercialization of these chemicals, ultimately giving place to a significant presence of these chemicals in the LA environment (Cristale et al., 2019; Souza et al., 2019; Souza et al., 2021).

Despite the widespread manipulation, distribution, and release of EPs in different LA countries, these chemicals are not routinely monitored in environmental and food samples of the region. In addition, the absence of structured legislation represents a potential hazard to the environment and the local population's health (Lopes et al., 2016). Based on the above, this review compiles the current knowledge of the levels of different classes of EPs and legacy pollutants in food and environmental matrices (soil, sediment, water, and air) of the LA region. Moreover, the current gaps in the studies related to this issue are discussed.

The current review intends to cover the literature data on the observed levels of the most representative legacy and EPs in several environmental and food samples. The distribution/occurrence of these pollutants in the LA region was studied by: (i)-identifying the predominant classes of pollutants in each country and/or region, (ii)-quantifying their levels found in environmental matrices in the region, and (iii)-comparing the reported concentrations with those corresponding to other geographic regions, with a different legislative control, and (iv)-filling the research gaps and identifying further research needs.

2. Databases

The search strategy was conducted by choosing specific keywords and some terms in the databases of Scopus, ScienceDirect, PubMed, and Web of Science. The selected papers for this review were published in the last 20 years, between 2002 and 2021. A considerable time range was selected to cover a significant number of studies and to verify possible changes in pollutant concentrations over time. Groups of keywords were combined by the Boolean operator "OR," including "emerging pollutants" OR "emerging contaminants" OR "environmental contaminants" OR "endocrine-disrupting compounds" OR "legacy pollutants" OR "specific name of the EP." This review encompasses 17 classes of compounds classified as legacy and emerging pollutants, from organic compounds to chemical elements. These groups were combined using the Boolean operator "AND" with "the specific Latin America country" and "environmental samples or food samples." For example, "pesticides + water + Mexico."

The specific keywords were based on the environmental matrices, including water (drinking water, groundwater, river/lake water, raw/treated water, seawater, surface water, and wastewater), soil, sediment (marine, urban and remote area), air (passive air, indoor dust, outdoor levels). On the other hand, food samples such as fruit and vegetables, animal origin food (milk, dairy products, meat, eggs, fish, seafood), and processed food are also included. Tables S1 and S2 (Supplementary Information) show the distribution of the selected studies according to the type of the sample and the classes of legacy and EPs, respectively.

The selection of articles for this review was carried out according to the following relevant points: i) a complete description of the matrices, like geographical localization, collection, and storage of samples; ii) an adequate number of analyzed samples, according to the type of the sample (the amount depends on the sample type); iii) analytical methods described with appropriate quality control (QA/QC) methodology. Conference documents, review papers, and manuscripts not published in English were not included in the present review since they did not follow the above-mentioned points.

3. Results

For this review, up to 350 publications were identified in the initial search. Among them, only 176 studies were selected and included in this

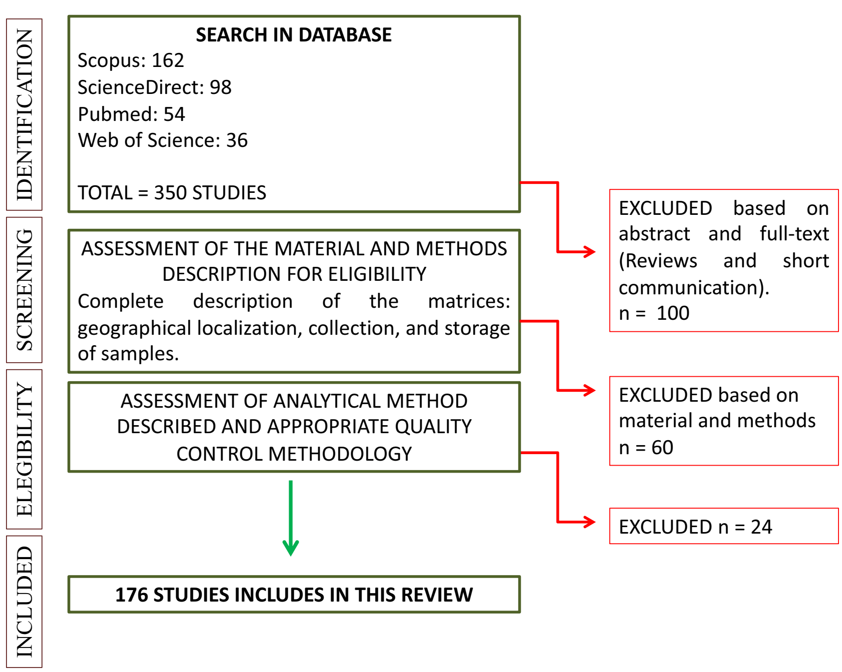

Fig. 1. Simplified schematic diagram of the selection of articles in the databases for this review.

Table 1
Levels of legacy and emerging pollutants in different water samples from Latin American countries, including drinking water, surface water, groundwater, river/lake water, and wastewater.

Classification	Emerging pollutants	Country	Sample	n[a]	Median (ng/mL)	Min–Max	Reference
Additives	ClO_4^-	Chile	Drinking water	55	3.0	–	Calderón et al. (2020)
			Surface water		1.8	0.8–15.9	
			Groundwater		12.1	–	
			River water		3.7	2.5–4.9	
	BrO_3^-		Drinking water	55	18.5	1.7–22.9	Calderón et al. (2019)
			Surface water				
			Groundwater				
Bisphenols	BPA	Brazil	Surface raw	12	0.53	0.09–1.46	Ramos et al. (2021)
			Surface treated		1.88	0.36–3.57	
Endocrine-disrupting compounds (EDCs)	BPA	Mexico	Wastewater	12	–	Winter: 0.5–450 Summer: 0.5–12.1	Lopez-Velázquez et al. (2021)
	4 *Tert*-octylphenol				–	Winter: 0.3–7.0 Summer: 0.8–58.8	
	17β-Estradiol (E2)			12 (ng/L)	–	Winter: 2.7–15.1 Summer: 0.4–9.5	
	17α-Ethinylestradiol				–	Winter: 1.3–407.5 Summer: 1.9–26.8	
Estrogens	17β-Estradiol (E2)	Argentina	Wastewater	(ng/L)		1.62–7.0	González et al. (2020a, b)
	17α-Ethinylestradiol					3.2–64	
Microplastics	–	Brazil	Surface water	–	7.62 items/kg	–	Castro et al. (2020)
Illicit drugs	COC/BE	(Colombia)	Wasterwater	28	–	>1000	Bijlsma et al. (2016)
		Bogotá	(ng/L)			>4000	
	THC-COOH	Medelin				200	
						300	
	MDMA					18–68	
						10	
	Ketamine					<32 (both)	
Illicit drugs	COC	Brazil	Wastewater	48	–	12.18–203.6	Fontes et al. (2019)
	BE		(ng/L)			8.20–38.59	
Parabens	MetP	Chile	Wastewater	–	0.73	–	Becerra-Herrera et al. (2018)
	EtP				0.87		
	PrP				0.61		
	BuP				0.53		
Parabens/TCS	MetP	Brazil	Urban River	11	–	<LQ–265.0	Reichert et al. (2020)
	EtP					Nd–144.6	
	PrP					<LQ–486.6	
	BuP					Nd–133.1	
	TCS					50.3–788.8	
Parabens	MetP	Brazil	Surface water	28	–	<20–660	Chaves et al. (2020)
	EtP		(ng/L)			<52	
PAHs	Σ-PAHs	Brazil	(pg/L)	–	–	10–110	Meire et al. (2019)
PAHs	Σ-PAHs	Colombia	(ng/mL)	5	–	0.03–0.34	Burgos-Núñez et al. (2017)
PAHs	Σ-PAHs	Brazil	Surface water (ng/L)	46	18	4,4–119	Santos et al. (2018)
PAHs	PAHs	Brazil	River water (μg/L)	–	–	ND–2.96	Brum and Netto (2009)
PAHs	Σ-17PAHs	Argentina	Surface water (μg/L)	40	–	ND–>4.0	Arias et al. (2009)
Per- and polyfluoro alkyl substances	Σ-PFAS	Brazil	Coastal water (pg/L)	10	–	<312–1020	Nascimento et al. (2018)
PFAS	PFBA	Mexico	Sewerage	–	176.9	–	Rodríguez-Varela et al. (2021)
	PFHxA		(ng/L)		133.4		
	PFHpA				116.6		
	PFOA				133.1		
	PFUnA				23.5		
PFASs	PFBA	Brazil	Drinking water (ng/L)	30	3.4	3.1–3.6	Schwanz et al. (2016)
	PFHpA				6.8	5.7–8.9	
	PFOA				7.6	3.4–12	
	PFNA				10	–	
	PFDA				15	–	
	PFHxDA				5.48	2.6–8.4	
	PFOSA				8.7	–	
	PFODA				15	–	
Pesticides	Aldrin	Argentina	Surface water	110	$1.55E^{-6}$	$2.00\,E^{-7}$–$4.94\,E^{-6}$	Dubny et al. (2018)
			Groundwater	300	$2.52E^{-7}$	$2.09\,E^{-7}$–$3.46\,E^{-7}$	
	Chlordane		(mg/L)		$9.74E^{-6}$	$4.00\,E^{-7}$–$2.55\,E^{-6}$	
					$5.13E^{-7}$	$4.23\,E^{-7}$–$7.25\,E^{-7}$	
	Dieldrin				$9.96\,E^{-7}$	$1.00\,E^{-6}$–$1.60\,E^{-6}$	
					$4.20\,E^{-6}$	$4.23\,E^{-7}$–$7.25\,E^{-7}$	
	Endosulfan				$4.85\,E^{-7}$	$1.00\,E^{-7}$–$1.47\,E^{-6}$	
					$5.70\,E^{-7}$	$4.30\,E^{-7}$–$1.71\,E^{-6}$	
	Endosulfan Sulphate				$5.84\,E^{-6}$	$2.50\,E^{-6}$–$1.16\,E^{-5}$	
					$4.21\,E^{-6}$	$2.82\,E^{-6}$–$7.32\,E^{-6}$	
	α-HCH				$8.06\,E^{-6}$	$6.00\,E^{-7}$–$2.78\,E^{-5}$	

Table 1 (*continued*)

Classification	Emerging pollutants	Country	Sample	n[a]	Median (ng/mL)	Min–Max	Reference
					1.09 E^{-4}	3.21 E^{-5}–2.78 E^{-4}	
	Heptachlor				1.37 E^{-5}	1.17 E^{-5}–2.81 E^{-5}	
					–	–	
	Deltamethrin				6.17 E^{-5}	8.89 E^{-5}–8.91 E^{-5}	
					–	–	
	Cypermethrin				2.75 E^{-2}	3.00 E^{-2}–6.94 E^{-2}	
					–	–	
Pesticides	Atrazine	Brazil	Surface water (μg/L)	17	–	<LOQ–2.89	Della-Flore et al. (2019)
Pesticides	ΣPriority pesticides	Argentina	River water (ng/L)	5 sites	–	131.6–457.3	Bonansea et al. (2013)
Pesticides	Dimethoate	Brazil	Fresh and seawater	7	–	< LOQ – 12.0	Nascimento et al. (2021)
	Malathion		(ng/L)			< LOQ – 85.7	
Pesticides	Acetochlor	Argentina	Surface water	12	0.008	–	Péres et al. (2021)
	Glyphosate		(μg/L)		1.88	0.50–4.36	
	AMPA				0.66	0.50–1.03	
	Metolachlor				0.004	0.002–0.006	
	Imidacloprid				0.054	0.008–0.19	
	Tebuconazole				0.002	0.001–0.003	
Pesticides	Atrazine	Argentina	Surface water	56	1.02	–	Gerónimo et al. (2014)
	Metconazole		(μg/L)		0.048		
	Imazapic				0.035		
	Metsulfuron				0.028		
	Dimethoate				0.035		
	Carbofuran				0.025		
	Diethyltoluamide				0.19		
	Epoxiconazole				0.037		
	Tebuconazole				0.033		
Pesticides	Butachlor	Ecuador	Freshwater	181	–	<LOQ–2.006	Deknock et al. (2019)
	Cadusafos		(μg/L)			<LOQ–0.081	
	Chlorpyrifos					<LOQ–0.035	
	Fenpropimorph					0.022–0.241	
	Malathion					<LOQ–0.687	
	Oxadiazon					0.068–0.120	
	Pendimethalin					0.170–0.557	
	Pyrimethanil					<LOQ–0.080	
	Spiroxamine					0.099	
	Tebucozanole					0.316	
	Triadimenol					0.092	
Pesticides/FRs	PCB	Brazil	Surface water	–	–	0.02–0.5	Rissato et al. (2006)
	DDT		(ng/L)			0.02–0.58	
	HCH					0.02–0.6	
Pesticides	Carbendazin	Costa Rica	Water	26	2.97	0.10–13.5	Ramírez-Morales et al. (2021)
	Carbofuran		(μg/L)		0.11	0.10–014	
	Chlorpyrifos				0.055	0014–0.094	
	Diuron				0.79	0.08–2.66	
	Ethion				1.92	–	
	Oxamyl				0.24	0.12–0.36	
	Oxyfluorfen				0.042	0.024–0.061	
	Thiabendazole				0.055	0.037–0.075	
Pesticides/FR	PCB	Mexico	Filtered water	22	–	70–3405	Carvalho et al. (2009)
	HCB		(pg/L)		<1.5	–	
	Σ-HCH				–	8–76	
	Σ-DDT				–	73–605	
	Σ-Chlordane					3–33	
	Heptachlor				<3.0	–	
	Aldrin				<2.0	–	
	Dieldrin				–	<3–12	
	Endrin				<16	–	
	Σ-Endosulfan				–	0–37	
	Chlorpyrifos				–	<4–72	
Pesticides	Aldrin	Ecuador	Coastal water	8	0.37	–	Riascos-Flores et al. (2021)
	Cadusafos		(μg/L)		0.80		
	Carbendazim				4.12		
	Chlorpyrifos				0.09		
	DDT				0.21		
	Dimethoate				0.28		
	Diuron				0.55		
	Ethoprophos				0.04		
	Fenpropimoph				0.11		
	Flazasulfuron				0.24		
	Heptachlor				0.21		
	Linuron				0.02		
	Malathion				0.15		
	Metalaxyl				0.17		

(continued on next page)

Table 1 (*continued*)

Classification	Emerging pollutants	Country	Sample	n[a]	Median (ng/mL)	Min–Max	Reference
	Propiconazole				0.03		
Phenolic compounds	2 Chlorophenol	Brazil	Surface – Raw/ Treated	12	2.43 1.74	–	Ramos et al. (2021)
	2 Methyl phenol				2.23 3.08	0.06–6.55 0.66–5.46	
	2 Nitrophenol				0.27 0.43	0.19–0.37 –	
	4 Nitrophenol				13.4 2.99	4.47–25.4 0.22–8.22	
Pharmaceutical, antibiotics	Diclofenac Ibuprofen TCS	Colombia	Seawater (μg/L)	99	–	0.12–1.54 0.12–0.46 0.1–0.79	Pemberthy et al. (2020)
Pharmaceutical, antibiotics	Caffeine Acetaminophen Albendazole Carbamazepine Diclofenac Furosemide Ibuprofen Lidocaine Mebendazole Sulfamethoxazole	Brazil	Surface water (ng/L)	28	–	84–24,961 <200–1716 <4–22 7–83 <100–463 <52–112 <100–320 <20–41 <4–18 <20–120	Chaves et al. (2020)
Pharmaceutical, antibiotics	Acetaminophen Diclofenac Carbamazepine Venlafaxine Loratadine Sulfamethoxazole Trimethoprim Norfloxacin Ciprofloxacin Irbesartan Valsartan Erythromycin Azithromycin Clarithromycin Clindamycin	Colombia	Wastewater (μg/L)	–	293.8 0.04 1.9 0.0015 8.1 0.001 0.03 3.9 10.7 0.05 17.7 0.36 27.9 23.4 25.4	–	Serna-Galvis et al. (2019)
Pharmaceutical, antibiotics	Escitalopram Sertraline Amitriptyline Fluoxetine Carbamazepine Bupropion Trazadone Nortriptyline	Brazil	Wastewater (ng/L)	24		25–466 25–417 25–200 25–147 240–3000 25–137 25–207 159	Pivetta et al. (2020)
	Escitalopram Amtriptyline Fluoxetine Carbamazepina Bupropion Trazadone		Surface water (ng/L)	40		25–520 157–196 60 25–3530 25–1880 25–230	
Pharmaceutical, antibiotics	Salicylic acid	Mexico	Groundwater Surface water (ng/L)	26	–	1–464 29–309	Félix-Cañedo et al. (2013)
	Diclofenac					1,0 28–32	
	TCS					1–345 16–19	
Bisphenol	BPA					1–10 7,0	
Phthalates	BBP					1–82 5–201	
	DEHP					19–232 75–2282	
Surfactant	Nonylphenol					1–47 89–655	
Surfactant	Nonylphenol	Mexico	Surface water Wastewater Drinking water	25	3.05 3.79 2.48	0.83–12.61 <LOD–12.20 <LOD–6.08	Vargas-Berrones et al. (2020)
Surfactant	Nonylphenol	Mexico	Wastewater	12	–	Winter: 0.3–5.4 Summer: 0.2–18.9	Lopez-Velázquez et al. (2021)

[a] n: correspond to sample the number of the study.

critical review (Fig. 1). As a preliminary finding, we noted that research with legacy and EPs in LA is concentrated in only a few countries. The following nine LA countries presented at least one publication among the selected papers: Brazil, Mexico, Costa Rica, Chile, Colombia, Argentina, Uruguay, Ecuador, and Puerto Rico. For every selected matrix, a table was created with the description of all classes of environmental pollutants and the respective region of the studies, corresponding to Tables 1 to 4. Furthermore, the distribution profile of the environmental and food samples selected in this review is summarized in Fig. 2. Brazil and Mexico were the countries with the largest number of publications (77 and 31, respectively). The distribution of the legacy and EPs in the papers published by Brazilian researchers is depicted in Fig. 3.

3.1. Legacy and EPs selection

The current review encompassed both organic and inorganic pollutants. The organic chemicals, classified as legacy or emerging pollutants, have included additives, benzophenones, bisphenol, polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs), estrogens (17α-ethinylestradiol and 17β-estradiol), flame retardants, illicit drugs, microplastics, parabens, per-, and polyfluorinated alkyl substances (PFASs), pesticides, pharmaceutical, personal care products, antibiotics, phenolic compounds, phthalates, polycyclic aromatic hydrocarbons (PAHs), surfactants, and volatile organic compounds (VOCs). Since there is a considerable increase in demand and use, but little information about the environmental occurrence/levels of REEs and noble metals, they were also included as EPs. These pollutants could be classified as emerging chemical elements. The REEs here included were the following: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), scandium (Sc), and yttrium (Y). Three noble metals, platinum (Pt), palladium (*Pd*), and rhodium (Rb), were also included.

As above-mentioned, Brazil (45 %), Mexico (18 %), and Argentina (13 %) were the LA countries with the highest number of published articles. Interestingly, most papers report concentrations of the pollutants in food samples of animal origin, air, and sediments. On the other hand, Brazil and Colombia are the only countries with published papers on legacy and EPs levels in all the selected samples. The most prevalent compounds studied were pesticides, PAHs, and flame retardants. PAHs are legacy pollutants and the primary group of anthropogenic environmental pollutants studied in Brazil, followed by flame retardants and pesticides.

The determination of microplastics in the environment is a new issue of concern. A proof is the fact that the most recent article on this issue was published in 2019. In turn, in Mexico and Argentina, most publications were related to pesticides. In addition, the levels of phthalates were reported only in Mexico. Brazil is one of the largest agricultural producers globally, whose extensive planting area has increased the consumption of pesticides. The cultivation of soybean, sugarcane, and corn represents 76 % of the entire planted area, with a consumption of 70 % of the pesticides used, including atrazine, glyphosate, and 2,4-dichlorophenoxyacetic acid (Oliveira et al., 2013; Pignati et al., 2017; Brovini et al., 2021).

Some reviews on EPs levels in environmental or food samples have been already published in the scientific literature. However, they are mainly focused on some particular chemicals and/or specific matrices, like water. For example, Llorca et al. (2016) published an overview regarding organic EPs in freshwater and marine biota from LA between 2002 and 2016, including 23 papers. Peña-Guzmán et al. (2019) reported information on EP levels in the urban water cycle from 11 countries of LA between 1999 and 2018, while Kutralam-Muniasamy et al. (2020) reported the trends of microplastic occurrence in different environmental compartments in LA countries. Concerning data on microplastic pollution, Castro et al. (2018) reported their levels in some Brazilian aquatic ecosystems. In turn, Vargas-Berrones et al. (2020) published a critical review about nonylphenol levels in LA waters. Finally, although there are some reviews regarding pesticides residues in some food samples, they are limited to chlorpyrifos levels in fruit and vegetables (Foong et al., 2020), pesticides concentrations in bananas (Gomes et al., 2020), and the impact of wastewater on the pesticides fate in soils (Peña et al., 2020). Other studies were conducted in a single country, not covering the entire LA region (Deblonde et al., 2011; Lapworth et al., 2012; Gavrilescu et al., 2015; Calderón et al., 2017; Vargas-Berrones et al., 2020).

3.2. Legacy and emerging pollutants in environmental samples

3.2.1. Aquatic compartments

The studies of legacy and EPs in aquatic compartments were conducted by employing specifically, water from rivers, sea, and coastal, drinking water, surface water, groundwater, wastewater, and sewerage. According to the data shown in Table 1, it can be observed that most general studies in Latin America provided data on pollutants in surface water (38 %) and wastewater (19 %) samples, being Brazil (46 %) and Mexico (16 %) the countries with more studies. Pesticides and pharmaceutical compounds are the prevalent pollutants in water samples. Atrazine, organophosphates, organochlorines, and glyphosate were some of the pesticides included in this review. Atrazine and glyphosate, classified as herbicides, are the most used pesticides in Brazil. In 2004, atrazine was banned in the European Union since it is the pesticide most prevalent in water. In 2015, the World Health Organization (WHO) reclassified this herbicide as probably carcinogenic. Glyphosate (N-(phosphonomethyl)glycine), a large-spectrum herbicide, is ubiquitous in the environment. This herbicide has been detected in all major food categories and also in various biological samples of the general population (Oliveira et al., 2013; Pignati et al., 2017; Brovini et al., 2021). The values of atrazine ranged <LOQ (limit of quantitation) – to 2.89 ng/mL in Brazil, while a median concentration of 1.02 ng/mL was found in Argentina (Della-Flore et al., 2019; Gerónimo et al., 2014). Péres et al. (2021) reported concentrations of 1.88 ng/mL (range: 0.50–4.36 ng/mL) of glyphosate in surface water from Argentina, and 0.60 ng/mL (range: 0.50–1.03 ng/mL) of its metabolite, aminomethylphosphonic acid (AMPA). The concentrations of malathion, an organophosphate pesticide, were reported by Nascimento et al. (2021) in seawater of Brazil (<LOQ–85.7), as well as by Deknock et al. (2019) and Riascos-Flores et al. (2021) in Ecuador (<LOQ–0.687 ng/mL and 0.15 ng/mL, respectively). Organochlorine pesticides (OCPs) are legacy pollutants whose production, use, and commercialization have been banned worldwide. Various studies have reported concentrations of OCPs in the LA region in the order of parts per million, or less. Due to their high environmental persistence, these compounds are still detected in the water. On the other hand, the improvement and the growth of agricultural production have increased the use of pesticides, with most amounts of these chemicals applied in agriculture being leached into soil and water. Thus, the greater the use, the greater the concentrations found in these matrices. Since agriculture is one of the main sources of groundwater contamination by the extended use of pesticides, the available literature is mainly focused on the determination of these chemicals in water bodies and irrigation water.

The high levels of EPs in the water column and the aquatic biota are of continued concern for public health. This contamination suggests a precarity and malfunction of the wastewater treatment system in these emerging economies. The current wastewater treatment system is not effective in the remotion of these EPs, which are not routinely monitored in these matrices. In poorer areas of emerging countries, such as some locations in Latin America, there are inadequate and precarious water treatment conditions, which increase human exposure to these compounds. The term emerging pollutant is comprehensive and it can refer to unlegislated substances with routine use such as caffeine. The great challenge in terms of public policies is to legislate several compounds. Caffeine is an excellent indicator of the anthropogenic contamination of water sources. About pharmaceutical compounds, caffeine showed high concentrations in surface waters from Brazil, with a concentration range of 84–24,961 ng/mL (Chaves et al., 2020). This substance shows resistance to sewage treatments, being associated with other compounds that show estrogenic activity. Therefore, the scientific community must identify those chemicals whose human exposure may derive in health risks. Unfortunately, such studies are still scarce in Latin America.

Another problem is the presence of antidepressants and antibiotics in surface water and wastewater. The presence of triclosan (TCS), a bacteriostatic substance, was determined by Félix-Cañedo et al. (2013) in Mexico, and by Pemberthy et al. (2020) in Colombia (Table 1). Regarding

Table 2
Levels of legacy and emerging pollutants in soil and sediment samples from Latin American countries.

Classification	Emerging pollutants	Country	Sample	n	Median	Min–max	Reference
Additives	ClO_4^-	Chile	(ng/g)	29	22.2	0.3–311	Calderón et al. (2020)
	BrO_3^-		(ng/g)	29	4.8	0.6–38.6	Calderón et al. (2019)
Chemical elements	Sc	Brazil	Topsoil	77	11.6	0.556–46.6	Paye et al. (2016)
REEs			Subsoil	67	12.8	0.724–53.3	
	Y		(mg/kg)		17.8	0.027–67.8	
					18.1	3.233–44.5	
	La				38.1	0.103–197.6	
					40.9	3.479–167.9	
	Ce				87.1	0.228–4187	
					99.9	8.186–541.5	
	Pr				8.2	0.022–38.8	
					8.6	0.612–38.3	
	Nd				27.3	0.077–114.4	
					28.5	2.091–117.7	
	Sm				5.2	0.013–21.6	
					5.3	0.463–22.4	
	Eu				1.1	0.002–6.3	
					1.0	0.081–6.8	
	Gd				3.9	0.008–15.8	
					3.9	0.517–14.6	
	Tb				0.6	0.001–2.3	
					0.6	0.141–1.6	
	Dy				3.3	0.002–6.3	
					3.4	0.427–4.2	
	Ho				0.6	0.001–0.9	
					0.7	0.071–0.7	
	Er				1.8	0.002–5.6	
					1.9	0.507–4.3	
	Tm				0.3	0.001–0.9	
					0.3	0.082–0.7	
	Yb				1.8	0.002–5.6	
					1.9	0.500–4.3	
	Lu				0.3	0.001–0.89	
					0.3	0.080–0.7	
REEs	ΣREEs	Brazil	Soil (mg/kg)	482	–	76–95	Turra et al. (2013)
FRs	Σ-PBDEs	Argentina	Soil (ng/g dw)	9	–	0.04–10.7	Tombesi et al. (2017)
Microplastics	Fibers	Mexico	Dry soil	40	2.54/g	40–60 μm and	Álvarez-Lopeztello et al. (2021)
	Fragments				2.50/g	60–150 μm	
PAHs	Acenaphthene	Brazil	(μg/kg dw)	12	2.1	–	Paraíba et al. (2010)
	Anthracene				2.2		
	Benz(*a*)anthracene				3.0		
	Benz(*b*) fluoranthene				5.7		
	Benz(*g*,*h*,*i*)perylene				3.6		
	Benz(*k*) fluoranthene				8.5		
	Chrysene				3.3		
	Dibenz(*a*,*h*) anthracene				4.4		
	Fluoranthene				3.1		
	Fluorene				1.9		
	Indeno(*1*,*2*,*3-c*,*d*) pyrene				4.5		
	Naphthalene				4.8		
	Phenanthrene				2.8		
	Pyrene				4.9		
PAHs	Σ-20PAHs	Brazil	(μg/kg)	42	–	4.8–347	Wilcke et al. (2003)
PAHs	Σ-PAHs	Brazil	Biochar amended soil (ng/g)	–	–	15.80–39.40	Resende et al. (2018)
Pesticides	OCPs	Argentina	Pampean soil	–	–	0.039–0.07	Gonzalez et al. (2010)
			Patagonia soil (μg/g)			38.1–46.5	
Pesticides	OCPs	Brazil	Atlantic Rain Forest fragments (ng/g dw)	29	–	<0.01–17	Quinete et al. (2011)
Pesticides	Acetochlor	Argentina	(μg/g)	12	9.34	2.70–14.90	Péres et al. (2021)
	Glyphosate				27.90	1.50–176	
	AMPA				270	3.00–712.5	
	Metolachlor				1.30	–	
	Metsulfuron-methyl				1.10	–	
	Chlorpyrifos				6.30	–	
	Imidacloprid				14.25	8.00–33	
	Tebuconazole				35.10	–	
Pesticides	Azoxystrobin	Colombia	Open-field soil	32	1.35	1.14–1.48	Arias et al. (2021)
	Benadryl		(mg/kg)		0.42	0.415–0.42	
	Carbendazim				7.10	0.50–22.03	

Table 2 (*continued*)

Classification	Emerging pollutants	Country	Sample	n	Median	Min–max	Reference
	Carbofuran				18.38	16.44–20.74	
	Cymoxanil				23.17	16.33–26 04	
	Difenoconazole				2.20	0.90–3.85	
	Dimethomorph				29.14	17.14–44.45	
	Indoxacarb				15.48	11.91–18.13	
	Metalaxyl				0.385	0.35–0.43	
	Methomyl				2.05	0.745–4.74	
	Pirimicarb				2.79	2.58–3.02	
	Tebuconazole				15.28	3.22–25.23	
	Thiabendazole				1.26	1.19–1.31	
Pesticides	Σ-DDT	Mexico	Mexicali and Yaqui valleys	27	22	–	Sánchez-Osorio et al. (2017)
			(ng/g dw)	25	5		
	Σ-HCH				0.80		
					0.23		
	Σ-CHL				0.88		
					0.67		
Pesticides/FRs	PCB	Brazil	(ng/g dry wt)	–	–	0.02–0.25	Rissato et al. (2006)
	DDT					0.12–11.01	
	HCH					0.05–0.92	
Pesticides	Σ-DDT	Mexico	(ng/g)	Sampling	–	0.057–360	Wong et al. (2008)
	Toxaphene			2002–2003		0.066–69	
Pesticides	Σ-DDT	Mexico	Rural, urban and agricultural soil	29	1.6	–	Wong et al. (2010)
	Toxaphene				0.16		
	Endosulfan		(ng/g)		0.64		
Benzophenones	BP3	Colombia	Sediment	13	–	< LOQ – 5.38	Barón et al. (2013)
		Chile	(ng/g dw)	17	–	1.05–2.96	
Benzophenones	BP3	Brazil	Surface sediment (ng/g)	28	–	< 3–17	Chaves et al. (2020)
Chemical Elements	Rh	Brazil	Estuary	14	–	0.08–1.7	Berbel et al. (2021)
	Pd		(ng/g)			1.05–22.0	
	Pt					0.15–40.3	
	Th	Brazil	Subtropical mangrove	20	19	–	Bosco-Santos et al. (2016)
Chemical Elements	U		(mg/kg)		17		
REEs	La				141		
	Ce				318		
	Pr				38		
	Nd				146		
	Sm				19		
	Eu				4.7		
	Gd				13		
	Tb				1.6		
	Dy				8		
	Ho				1.2		
	Er				3		
	Tm				0.35		
	Yb				2.3		
	Lu				0.35		
Chemical Elements REEs	Normalized REE patterns	Mexico	Surface sediment (mg/kg)	26	98.4	–	Marmolejo-Rodríguez et al. (2013)
Chemical Elements	La	Colombia	(μg/g dw)	50	15.7	10.3–19.0	Palacio-Torres et al. (2020)
REEs	Ce				30.4	20.0–37.6	
	Pr				4.00	2.88–4.83	
	Nd				17.2	13.1–20.9	
	Sm				3.93	3.17–4.79	
	Eu				1.10	0.85–1.36	
	Gd				3.98	3.15–4.91	
	Tb				0.62	0.49–0.76	
	Dy				3.82	3.03–4.68	
	Ho				0.79	0.63–0.97	
	Er				2.34	1.87–2.87	
	Tm				0.34	0.27–0.41	
	Yb				2.25	1.82–2.73	
	Lu				0.33	0.27–0.40	
Dioxins	PCDD/Fs	Chile	Urban lakes	–	941	Freshwater	Loyola-Sepúlveda et al. (2018)
			Remote lakes		335	sediment:	
			Marine		124	335.4–2250.5	
			(ng/kg)			115.7–131.9	
Flame retardants (FRs)	Brominated FRs	Colombia	ng/g dw	13	143	–	Barón et al. (2013)
	(BFRs)	Chile		17	–	0.03–2.43	
FRs	PCBs	Brazil	Superficial sediment (ng/g dw)	–	93.3	<LD–190.7	Souza et al. (2018)
FRs	PCBs	Puerto Rico	Surface sediment (ng/g dw)	18		0.42–1232	Alegria et al. (2016)
FRs	Σ-PBDEs	Mexico	Marine sediment (ng/g dw)	91	0.71	0.02–5.90	Macías-Zamora et al. (2016)

(continued on next page)

Table 2 (*continued*)

Classification	Emerging pollutants	Country	Sample	n	Median	Min–max	Reference
FRs	Σ-PBDEs Σ-PCBs	Argentina	Coastal surface sediments (ng/g dw)	4	–	0.16–2.02 0.61–17.6	Tombesi et al. (2017)
Microplastic	Fiber particles	Brazil	Sediment	20	247 particles	0–38 particles/per sample	Neto et al. (2019)
Microplastic	–	Brazil	Beach sand	6	85.1 % fragments	2.4–30.4 particles/m^2	Maynard et al. (2021)
Microplastic	–	Brazil	Bottom sediment Beach sediment	–	20.74 items/kg 166.50 items/kg	–	Castro et al. (2020)
Parabens	MetP	Brazil	Surface sediment (ng/g)	28	–	<5–14	Chaves et al. (2020)
Pollutants Organic Persistent (POPs) (PAH/PCB/OCP)	PAH PCB OCP	Brazil (Amazônia)	Estuary (ng/g)	–	–	331–2341 <DL–0.87 <DL–72.67	Neves et al. (2018)
PAHs	Σ-PAHs	Brazil	River sediments (ng/g dw)	4	–	143–1713	Leite et al. (2008)
PAHs	Σ-PAHs	Colombia	Shallow sediment (ng/g)	5	–	7.0–41	Burgos-Núñez et al. (2017)
PAHs	Σ-17PAHs	Argentina	Sediment (ng/g dw)	6	–	37.5–380.5	Recabarren-Villalón et al. (2019)
PAHs	Σ-16PAHs	Brazil	Sediment Amazon River Estuary (ng/g dw)	16	49.4	22.2–158.9	Rodrigues et al. (2018)
PAHs	Σ-16PAHs	Brazil	Urbanized tropical estuary (μg/g)	14	–	<DL–497.6	Maciel et al. (2015)
Pesticides	Σ-DDT Σ-HCH Σ-CHL	Mexico	Mexicali and Yaqui valleys (ng/g dw)	3 8	5.0 2;6 0.23 0.12 0.53 0.009	–	Sánchez-Osorio et al. (2017)
Pesticides	PCB HCB Σ-HCH Σ-DDT Σ-Chlordane Heptachlor Aldrin Dieldrin Endrin Σ-Endosulfan	Mexico	(pg/g dw)	22	–	15.6–355.8 0.87–5.5 0–4.92 8.3–631.2 0–22.5 <0.43 <0.42–9.9 <0.57–16 <1.5–16 0–50.3	Carvalho et al. (2009)
Pesticides/FRs	PCBs Σ-DDT Σ-HCH HCB	Brazil	Surface sediment (ng/g)	19	–	<DL–19.1 <DL–122 <DL–1.2 <DL–0.75	Rizzi et al. (2017)
Pesticides	Σ-OCPs	Brazil	Sediment of the semi-arid region (ng/g)	8	–	5.09–154.43	Oliveira et al. (2016)
Pharmaceutical, antibiotics	TCS TCC Caffeine Albendazole Avobenzone Ketoconazole Mebendazole Nifedipine Nimesulide Propranolol	Brazil	Surface sediment (ng/g)	28	–	<50–137 <1–1318 6–20 <1–13 <13–51 <5–277 <1–3 1–75 <3 2	Chaves et al. (2020)
Phthalates	Σ-Phthalates DEHP DnOP	México	Coastal sediments (μg/g dw)	36	Σ = 21.702 6.973 2.801	–	Ramirez et al. (2019)
Microplastic	–			27	1392 items/m^2	–	
Per- and polyfluoroalkyl substances	Σ-PFAS	Brazil	Coastal sediment (pg/L dw)	10	–	7–198	Nascimento et al. (2018)
Pesticides	Acetochlor Glyphosate AMPA Metolachlor Chlorpyrifós Imidacloprid Tebuconazole	Argentina	(μg/kg)	12	15.10 8.28 6.85 1.73 4.20 4.85 19.60	4.10–28.5 1.50–32 3.00–17.5 1.30–2.60 – – –	Péres et al. (2021)
Pesticides	Chlorpyrifos Cypermethrin	Costa Rica	(μg/kg)	18	10.0 1.74	1.05–12 0.44–2.49	Ramírez-Morales et al. (2021)

pharmaceuticals and antibiotics, the higher concentrations found in Colombia (μg/L) when compared to those of Brazil (ng/L), may reflect the high consumption of these substances in the country, or even their improper disposal. Comparing EP concentrations in different countries is difficult due to the lack of studies in some regions and the lack of similarity between the water matrices. Some studies have considered wastewater, while others have surface water or drinking water. Therefore, the comparison is hard.

Synthetic steroid hormones, like contraceptive methods, hormonal therapies, and growth promotion, are endocrine disruptors that are daily excreted. Since their effects occur even at tiny concentrations, these compounds have received widespread attention around the world. Like other pharmaceuticals, the presence of estrogens such as 17β-estradiol and 17α-ethinylestradiol occurs in greater proportion in wastewater, showing a deficiency in the water treatment system. The presence of estrogens in water is an important public health problem. It can cause damage to aquatic organisms and human health, as people may be constantly exposed to these substances (Gonzalez et al., 2010; Lopez-Velázquez et al., 2021). Lopez-Velázquez et al. (2021) reported the concentrations of 17β-estradiol and 17α-ethinylestradiol in wastewater from Mexico in two seasons, winter and summer. The highest concentrations of both estrogens were observed in winter (2.7–15.1 ng/L for 17β-estradiol and 1.3–407.5 ng/L for 17α-ethinylestradiol). That study showed that warm temperature in the summer season makes easier the removal of wastewater treatment plants. González et al. (2020a, 2020b) also determined these estrogens in wastewater from Argentina, founding lower concentrations of 17β-estradiol (from 1.62 to 7.0 ng/L) and 17α-ethinylestradiol (from 3.2 to 64 ng/L), than those found in Mexico.

The physical-chemical properties of the general pollutants determine their environmental fate. The partition coefficients and hydrophobicity may influence the distribution of chemicals among the different compartments, including water, sediment, and aquatic biota. Most studies on the levels of legacy and emerging pollutants in environmental matrices have been performed in US/Canada, Europe, and Asia, while there is an important scarcity of investigations reporting the spatial and temporal trends of these pollutants in the LA area. Therefore, evaluating the levels of the legacy and emerging pollutants in environmental compartments and their respective concentrations in human fluids, like urine and plasma, is an essential step to perform an accurate risk assessment of human health. The presence of these chemicals in water has exhibited ecotoxicity at low concentrations, receiving consequently much attention from regulatory agencies worldwide (Voloshenko-Rossin et al., 2014; Montagner et al., 2017; Peña-Guzmán et al., 2019; Lopez-Velázquez et al., 2021).

3.2.2. Soil

The soil quality evaluation regarding chemical substances must be based on Guiding Values of Reference for Quality, Prevention, and Investigation (CONAMA, 2009). Soil quality and the persistence of EPs are often influenced by irrigation water, agronomic practices, regional climate, and the physicochemical properties of the pollutants. Contaminants in the wastewater can achieve the soil during irrigation and affect the crops (Gonzalez et al., 2010; Peña et al., 2020). Soil constitutes an important primary contamination source of POPs for animals such as chickens and cows, and also for humans (Souza et al., 2021). In Brazil, the resolution n° 420 of December 28, 2009, of the National Council for the Environment (CONAMA) sets the criteria and guiding values for soil quality. It also establishes guidelines for the environmental management of contaminated areas, as a result of anthropic activities.

Tables 1 and 2 summarize several studies on the levels of several pesticides in soil and water samples collected in the LA region. Brazil and Mexico were again the two countries with a higher number of studies on legacy and EPs in soil (38 % and 25 %, respectively), being most of the investigations focused on pesticides (53 % of the total). Nearly one-half of the chemicals released in Brazil have been banned in the European Union. The indiscriminate use of pesticides can lead to water and soil contamination, ultimately causing drastic effects on non-target species (Nascimento et al., 2021). Argentina and Brazil are among the top ten pesticide-consuming countries globally (Gonzalez et al., 2010; Péres et al., 2021). Pesticide consumption is approximately 4 million tons per year worldwide (Rousis et al., 2016; Kim et al., 2017; Kalliora et al., 2018). According to data published in the resolution N420 of the National Council for the Environment (CONAMA, 2009), the value of reference for quality, prevention, and investigation for dichlorodiphenyltrichloroethane (DDT) is 10 ng/g dry weight (dw). However, in the Brazilian study by Rissato et al. (2006), the highest concentration for the sum of DDT (ΣDDT) in soil samples (11,01 ng/g dw) exceeded the threshold value. In Mexico, the ΣDDT levels were between 0.057 and 360 ng/g dw. Péres et al. (2021) also reported glyphosate concentrations in soil samples from Argentina, with a median value relatively higher than that reported in water samples (27.90 μg/g in soil vs. 1.88 μg/L in water).

PAHs are legacy pollutants and hydrophobic compounds that exhibit a strong affinity with complex environment solid matrices, including soils and sediments. The levels of PAHs in soils may result from natural processes, including vegetation fires, crude oil (low molecular weight-PAHs, with 2 and 3 rings), and volcanic exhalations, with values between 1 and 10 μg/kg. However, since PAHs can reach the soil via atmospheric deposition, higher concentrations of these pollutants are found in industrialized locations, high traffic areas, as well as in zones with important anthropogenic contributions, like domestic heating. PAH levels can vary according to weather conditions, with temperature and solar radiation playing a key role (Nadal et al., 2006; Marquès et al., 2016, 2017). PAHs are persistent and ubiquitous environmental pollutants since these compounds are present in soils, they can contaminate sediments and aquatic biota through the water bodies (Wilcke et al., 2003; Paraíba et al., 2010; Resende et al., 2018; Souza et al., 2022). The United States Environmental Protection Agency (USEPA) has classified 16 PAHs, including 7 carcinogenic substances, as priority pollutants (Nadal et al., 2004). Benzo[*a*]pyrene has been classified as a human carcinogen. Other toxicity profiles of PAHs include reduction of lung function and cardiovascular diseases. In some European countries, the maximum allowed concentration in soils is 3000 ng/g. In Brazil, according to the National Environmental Council (CONAMA, 2009; Resende et al., 2018), the sum of the levels of the 16 PAHs cannot exceed 8100 ng/g. All the studies found in the scientific literature in the LA region (Table 2) state values below that threshold (Resende et al., 2018).

According to the International Union of Pure and Applied Chemistry - IUPAC, REEs are a group composed of 17 chemical elements, including 15 lanthanides (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dt, Ho, Er, Tm, Yb, and Lu). Since they show physicochemical properties similar, scandium (Sc) and yttrium (Y) are also considered REEs. To date, REEs are little-studied around the world. However, because of their potentially wide application in clean energy generation, a growing interest in these elements is expected. They are mainly incorporated in agricultural soils by phosphate fertilization, increasing productivity. It has been found that applying lanthanum (La) at low concentrations can accelerate the transformation of nitrogen in soils. After application in crops, the accumulation of REEs in plants is related to their age, as well as the different accumulative properties of their organs, with higher levels in roots and lower in grains (Oliveira et al., 2014; Turra et al., 2015; Silva et al., 2021a, 2021b).

Because of their high consumption and increasing introduction into the environment, in recent years REEs have been considered EPs (Silva et al., 2021a, 2021b). Besides, their extensive use has increased concerns about their environmental impacts and human health risks. In Brazil and other LA countries, current legislation and quality reference values on REEs in fertilizers and soil correctives are scarce. The most significant mineral deposits of REEs are in China. However, according to the US Geological Survey, Brazil has 52 million tons of rare earth stock. Brazil is currently the fourth largest consumer of fertilizers in the world, with large consumption of phosphate fertilizers, an important route of entry of REEs into the soil (Oliveira et al., 2014; Silva et al., 2021a, 2021b). Paye et al. (2016) reported the concentrations of 16 REEs in soil samples from Brazil (Table 2). The highest concentrations corresponded to cerium

Table 3
Levels of legacy and emerging pollutants in different air compartments from Latin American countries, including passive air, indoor dust, and outdoor levels.

Classification	Emerging pollutants	Country	Sample	n	Median	Min–max	Reference
Bisphenols	BPA	Argentina	Total suspended particles (pg/m^3)	Temporal (55) Spatial (23)	740 403	84–2454 89–1247	Graziani et al. (2019)
Bisphenols	BPA BPS BPF BPZ BPB BPP BPAP BPAF TBBPA (FR)	Colombia	Indoor dust (ng/g)	42	420 3.7 69 <0.5 <1.0 <2.0 <0.5 4.3 21	9.6–2000 <2–35 <1–780 – – – – 0.07–34 <1–280	Wang et al. (2015)
Dioxins	PCDD/Fs	Argentina	Passive air (fg/m^3)	18/area/month	632	6–5824	Cappelleti et al. (2016)
Dioxins and dioxin-like compounds	PCDD/Fs dl-PCBs	Colombia	Passive air (fg/m^3)	Mangzales Bogotá 27	151 3727 373 4388	101–255 1953–6515 312–449 3777–5391	Cortés et al., 2016
Dioxins	PCDD/Fs	México Costa Rica Ecuador Colombia Sao Paulo, Brazil Argentina	Passive air (fg/m^3)	–	1310 14.4 213 286 1580 1680	893–1610 10.8–18.1 208–218 223–444 1470–1690 –	Schuster et al. (2015)
Flame retardants (FRs)	TBBPA	Colombia	Indoor dust (ng/g)	42	3.3	<1–280	Wang et al. (2015)
FRs	PCBs	GRULAC[a]	Passive air (pg/m^3)	–	–	0.08–128	Rauert et al. (2018)
FRs/OCPs	Σ-PBDEs Σ-OCPs	Mexico	Urban particles $PM_{2.5}$ e PM_{10}) (μg/m^3)	–	7.3 3.9 8.8 13.6	6.9–7.7 2.0–3.9 8.4–9.3 12.7–16.6	Beristain-Montiel et al. (2020)
PAHs	Phenanthrene Anthracene Fluoranthene Pyrene Benzo[*a*]anthracene Chrysene Benzo[*b*]fluoranthene Benzo[*a*]pyrene Indeno[1,2,3-*cd*] pyrene Benzo[*ghi*]perylene	Brazil	Particulate matter (PM10) Total suspended particulate (TPS) (ng/m^3)	3	0.62 0.51 0.37 0.45 0.67 0.56 1.30 1.14 0.81 0.90 0.890 .080 1.38 1.04 1.29 1.01 1.18 1.32 1.50 1.26	–	Menezes and Cardeal (2011)
PAHs	Σ-PAHs PM_{10}	Brazil	Atmospheric mass concentrations (ng/m^3)	5	16.7 72.2	4.8–28.4 21.2–100.9	Allen et al. (2008)
PAHs	Σ-PAHs	Brazil	Passive air (ng/m^3)	–	–	0.70–90	Meire et al. (2019)
PAHs	Σ-PAHs	Mexico	Total suspended particulate (ng/m^3)	Winter Spring	–	32–116 1.0–5.9	Lopez-Ayala et al. (2019)
PAHs	Σ-15PAHs	Brazil	Particulate matter (ng/m^3)	14	21.05	8.84–62.5	Ré-Poppi and Santiago-Silva (2005)
PAHs	Σ-15PAHs	Brazil	Street dust (μg/g)	17	–	0.106–8.57	Franco et al. (2017)
PAHs	Σ-16PAHs	Brazil	PM10 TPS (ng/m^3)	27	–	<LOQ–3.42 <LOQ–2.25	Franco et al. (2015)
POPs	Σ-PAHs Σ-PCBs Σ-HCH Σ-Endosulfan DDE DDT	Colombia	Atmospheric (ng/m^3)	4 sampling sites	–	25–66 220–850 <LOD–20 01–60 0.7–23 0.3–10	Álvarez et al. (2016)
POPs	Σ-15PAHs Σ-48PCBs Σ-8OCPs	Chile	Atmospheric (pg/m^3) (ng/m^3 - PAH)	6 sampling sites	100 160 –	30–230 40–350 1.5–50	Pozo et al. (2012)
Pesticides	Hexachlorobutadiene Pentachloroanisole Dichlorobenzophenone Hexachlorobenzene Chlordane	GRULAC	Passive air (pg/m^3)	–	–	<20–120 <1–8.5 <0.9–4.6 8.8–108 <1.6–7.1	Rauert et al. (2018)

Table 3 (*continued*)

Classification	Emerging pollutants	Country	Sample	n	Median	Min–max	Reference
	Heptachlor					<0.5–3.1	
	Endosulfan					<1–868	
	Dieldrin					17–112	
	DDT					<0.7–8.3	
	DDE					<0.4–25	
Pesticides	ΣChlordane	Brazil	Passive air (pg/m^3) INP/SONP[b]	–	17 73	–	Guida et al. (2018)
	Σ-Heptachlor				ND 9		
	Σ-Drin				5 49		
	Methoxychlor				9 19		
	Mirex				2 12		
	HCB				35 60		
	Σ-HCH				2 48		
	Σ-DDT				ND 83		
	Σ-Endosulfan				377 1485		
	Σ-Chlorpyrifos				24 157		
	Σ-Cypermethrin				25 504		
	Σ-Permethrin				ND 21		
Pesticides	OCPs	Chile	Passive air (pg/m^3)	6 sampling sites	–	<LOQ–13.0	Climent et al. (2019)
	Chlorpyrifos-ethyl					229.4–3470.2	
	Diazinon					<LOQ–41.6	
	Pyrimethanil					<LOQ–52.8	
Pesticides	Chlorpyrifos	Chile	Passive air (pg/m^3)	27	–	20–14,600	Pozo et al. (2016)
Pesticides/FRs	PCB	Mexico	Passive air (pg/m^3)	Sampling 2002–2004	–	34–213	Alegria et al. (2008)
	Σ-DDT					239–2360	
	Σ-Endosulfan					92–341	
	Σ-CHL					5.8–12	
	Chlodane					0.8–1.2	
	Lindane					12–52	
	Toxaphene					19–229	
	Dieldrin					0.9–11	
Pesticides	Σ-DDT	Mexico	Passive air (pg/m^3)	Sampling 2002–2003	–	240–2400	Wong et al. (2008)
	Toxaphene					6.2–230	
Phthalates	DEHP	Mexico	Urban airborne particles (PM_{10} e $PM_{2.5}$) (μg/g)	–	–	PM_{10}: 32.8–175.8 6.1 to 14.2	Quintana-Belmares et al. (2018)
	DnBP					$PM_{2.5}$: 21.5–229.7 1.8–23.9	
Volatile organic compounds (VOCs or BTEX)	Benzene	Argentina	Outdoor levels (μg/m^3)	–	13.42	–	Massolo et al. (2010)
	Toluene				18.9		
	Ethylbenzene				1.8		
	o-xylene				2.3		
VOCs	Benzene	Brazil	Outdoor levels (μg/m^3)	–	–	0.58–3.0	Godoi et al. (2013)
	Toluene					2.8–5.9	
	Ethylbenzene					0.2–1.6	
	o-xylene					0.26–13	
VOCs	Benzene	Mexico	Outdoor levels (μg/m^3)	–	5.9	–	Serrano-Trespalacios et al. (2004)
	Toluene				37.9		
	Ethylbenzene				5.0		
	o-xylene				5.9		
	Benzene						

[a] GRULAC: Group of Latin America and Caribbean countries.
[b] INP and SONP: Itatiaia and Serra dos Orgaos National Parks (Brazil).

(0.228–4187 mg/kg) and lanthanum (0.103–197.6 mg/kg). Usually, these RREs are the most abundant in nature. The REE levels in soils can vary according to the geographical origin, the source rocks composition, and the weathering conditions. Under natural conditions, Ce is a very abundant element in the Earth's crust, with similar levels to those of zinc and copper. In benchmark soil, La levels are between 0.15 and 0.25 mg/kg. In general, soil contains the highest REEs levels, and the excessive use them in agriculture increases significantly the concentration of these chemical elements in this environmental matrix. The knowledge regarding the background levels of REEs is essential to establish reference values for quality monitoring and prevent environmental and human health risks. Moreover, the natural values of REEs in soil samples allow the identification of contaminated locations (Turra et al., 2015; Paye et al., 2016). Although Brazil has the second-largest reserve of REEs, data regarding background levels of these chemical elements and their distributions in soils is still scarce.

Table 4
Levels of legacy and emerging pollutants in food samples from Latin American countries.

Classification	Emerging pollutants	Country	Sample	n	Median	Min–max	Reference
Additives	ClO^{4-}	Chile	Fruit	12	0.91	0.1–3.24	Calderón et al. (2020)
			Vegetable (ng/g)	42	3.25	0.1–107	
Additives	ClO^{4-}	Brazil	Vegetable (ng/g)	–	9.86	5.73–21.32	Leotério et al. (2017)
Additives	BrO_3^-	Chile	Fruit	12	–	<LLOD–0.91	Calderón et al. (2019)
			Vegetable (ng/g)	42	9.52	–	
PAHs	Σ-10PAHs	Brazil	Lettuce	–	13.53	–	Camargo and Toledo (2003)
			Tomato		9.50		
			Cabbage		8.86		
			Apple		4.05		
			Grape		3.77		
			Pear		3.87		
PAHs	Σ-10PAHs	Brazil	Roasted Coffee (μg/kg)	24	–	1.00–11.29	Pissinatti et al. (2015)
Phthalates	DEP	Mexico	Fruit	–	10.2	–	García-Fabila et al. (2020)
			Vegetable		18.7		
	DnBP		(μg/kg)		87.5		
					2.31		
	DEHP				10.82		
					94.7		
Pesticides	Dithiocarbamate residue	Brazil	Apple	406	0.309	–	Caldas et al. (2006)
			Tomato	603	0.202		
			Papaya	323	0.198		
			Lettuce	297	0.361		
			Strawberry	482	0.154		
			Banana	267	0.099		
			Orange	541	0.065		
			Carrot	435	0.040		
			Potato	396	0.052		
			Bens	32	0.052		
			Rice	39	0.050		
Pesticides	Acephate	Colombia	Tomato	400	0.07	0.04–0.45	Arias et al. (2014)
	Azoxystrobin		(mg/kg)		0.02	0.02–0.03	
	Benadryl				0.02	0.01–0.05	
	Carbendazim				0.05	0.01–0.74	
	Carbofuran				0.02	0.02–0.05	
	Chlorfenapyr				0.50	–	
	Cymoxanil				0.60	–	
	Difenoconazole				0.02	0.01–0.03	
	Dimethoate				0.02	–	
	Dimethomorph				0.02	0.01–0.12	
	Imazalil				0.04	–	
	Imidacloprid				0.30	–	
	Indoxacarb				0.04	0.02–0.08	
	Metalaxyl				0.01	0.01–0.03	
	Methomyl				0.03	–	
	Methoxyfenozide				0.03	–	
	Pyrimethanil				0.11	0.01–0.30	
	Spinosad				0.10	–	
	Tebuconazole				0.11	0.10–0.17	
	Thiocyclam				0.15	0.15–0.17	
Pesticides	Acephate	Colombia	Open-field and	32	–	–	Arias et al. (2021)
			greenhouse tomatoes		0.02	0.015–0.03	
	Azoxystrobin		(mg/kg)		0.01	0.003–0.01	
					0.03	0.03–0.04	
	Carbendazim				0.21	019–0.23	
					–	–	
	Carbofuran				0.05	0.052–0.053	
					–	–	
	Difenocozanole				0.51	0.45–0.59	
					–	–	
	Dimethomorph				0.03	0.02–0.05	
					–	–	
	Indoxacarb				–	–	
					0.47	0.33–0.71	
	Metalaxyl				–	–	
					0.01	0.008–0.01	
	Methomyl				0.06	0.05–0.06	
					–	–	
	Spinosad				–	–	
					0.05	0 03–0.05	
	Thiocylam				–	–	
					0.43	0.105–0.79	

Table 4 (*continued*)

Classification	Emerging pollutants	Country	Sample	n	Median	Min–max	Reference
Pesticides	Difenoconazole	Colombia	Passion fruit (mg/kg)	–	0.01	–	Juraske et al. (2012)
	Thiacloprid				0.37		
	Mancozeb				0.09		
Pesticides	Chlorpyrifos	Argentina	Lettuce (μg/kg)	28	–	<LOQ–1524.5	Mac Loughlin et al. (2018)
	Malathion					33.1–105.4	
	Lambda-cyhalothrin					1.3–155.3	
	Cypermethrin					3229.7	
	Permethrin					20.6–105.2	
	Bifenthrin					91.2	
	Endosulfan					5.2–211	
	Methoxychlor					15.3	
	DDT					4.5	
	DDE					10.6–20.2	
	Epoxiconazole					5.6–29.6	
	Tebuconazole					16.0	
Pesticides	Atrazine	Argentina	Orange (μg/kg)	41	–	34.7–63.7	Mac Loughlin et al. (2018)
	Acetochlor					129.6	
	Chlorpyrifos					<LOQ–76.8	
	Diazinon					84.4–304.3	
	Malathion					37.5	
	Finorpil					<LOQ–37.4	
	Lambda-cyhalothrin					23.2–184	
	Cypermethrin					<LOQ–698.8	
	Endosulfan					4.4–473.1	
	Methoxychlor					11.8–17.4	
	DDT					3.6	
	DDE					21.4	
	Heptachlor					12–21.4	
	Epoxiconazole					9.1–122.5	
	Tebuconazole					7.1–7821.5	
Pesticides	Acetochlor	Argentina	Pepper (μg/kg)	23	–	166.0	Mac Loughlin et al. (2018)
	Chlorpyrifos					5.2–168	
	Diazinon					32.7	
	Finorpil					10.8	
	Lambda-cyhalothrin					2.4–181	
	Cypermethrin					5.2–1024.3	
	Endosulfan					5.6–166.3	
	DDE					8.2	
	Epoxiconazole					9–116.1	
	Tebuconazole					40.9–210.1	
	Azoxystrobin					37.9–85.4	
Pesticides	Chlorpyrifos	Argentina	Tomato (μg/kg)	10	–	9–12.7	Mac Loughlin et al. (2018)
	Malathion					30–47.9	
	Permethrin					41.4–89.4	
	Bifenthrin					8.7	
	Methoxychlor					10.2–16.2	
	Azoxystrobin					18.9	
Pesticides	Trifluralin	Argentina	Carrots (μg/kg)	33	–	<LOQ–92.9	Mac Loughlin et al. (2018)
	Pendimethalin					<LOQ–19.2	
	Chlorpyrifos					4–231.2	
	Lambda-cyhalothrin					19.2–95.7	
	Cypermethrin					8.7–449.9	
	Permethrin					<LOQ–1658.7	
	Endosulfan					4.4–288.2	
	DDT					5.3–5.3	
	Epoxiconazole					18.7–138.8	
	Tebuconazole					143.2	
	Azoxystrobin					<LOQ–208.2	
REEs	La	Brazil	Orange (mg/kg)	12-	–	0.01–1.17	Turra et al. (2015)
	Ce					<0.0004–0.44	
	Sc					<0.0004–0.003	
REEs	La	Brazil	Citrus (mg/kg)	–	–	0.034–1.40	Turra et al. (2013)
	Ce					<0.045–0.58	
	Sc					<0.0004–0.036	
Dioxins and dioxin-like compounds	PCDD/Fs	Chile (2014)	Bovine	165	2.80 pg/g fat	0.83–32.5	Martin et al. (2016)
			Pork	186	1.03	0.62–2.65	
			Ovine	–	0.96	0.65–1.77	
			Chicken	129	2.61	0.83–11.9	
			Turkey	–	1.76	1.01–5.28	
	dl-PCBs		Bovine	165	91.1 pg/g fat	29.4–202	
			Pork	186	65.1	21.2–307	
			Ovine	–	96.5	41.9–300.8	
			Chicken	129	171	31.46–617	
			Turkey	–	138	34.1–369	
Dioxins	PCDD/Fs	Brazil	cow milk	34	24.39	8.15–74.48	Rocha et al. (2016)

(continued on next page)

Table 4 (*continued*)

Classification	Emerging pollutants	Country	Sample	n	Median	Min–max	Reference
Dioxins and dioxin-like compounds	Σ PCDD/Fs	Colombia	Shrimp	–	44.80	–	Pemberthy et al. (2016)
	Σdl-PCBs		(pg/g dw)		193.50		
Chemical Elements	Ce	Brazil	Honey	10	0.23	–	Oliveira et al. (2017)
REE	Dy		(μg/kg)		0.31		
	Er				0.21		
	Eu				0.14		
	Gd				0.65		
	Ho				0.08		
	La				0.85		
	Lu				<LOD		
	Nd				1.70		
	Pr				0.46		
	Sc				<LOD		
	Sm				0.46		
	Tm				<LOD		
	Y				2.02		
	Yb				0.04		
Chemical Elements	Th	Brazil	Muscle of Crabs	20	0.011	–	Bosco-Santos et al. (2017)
REE	U		(mg/kg)		0.02		
	La				0.12		
	Ce				0.18		
	Pr				0.02		
	Nd				0.07		
	Sm				0.01		
	Eu				0.003		
	Gd				0.01		
	Tb				0.005		
	Dy				0.005		
	Ho				<0.005		
	Er				0.004		
	Tm				<0.006		
	Yb				0.003		
	Lu				<0.003		
Flame retardants	BDE-47	Brazil	Eggs	40	0.62	–	Souza et al. (2019)
(FRs)	ΣPBDEs		(ng/g lp)		2.29	0.92–4.85	
FRs	BDE-47	Brazil	Fish	20	0.38	0.19–0.81	Souza et al. (2021)
	ΣPBDEs				1.98	1.23–3.04	
			Seafood	20	0.40	0.19–0.91	
					1.91	1.23–3.12	
			Milk	40	2.25	–	
			(ng/g ww)		4.42	1.26–8.42	
FRs	PCBs	Brazil	Fish	61	–	2.29–27.6	Lavandier et al. (2013)
			Muscle				
			Liver			3.41–34.22	
			(ng/g lw)				
FRs	PCBs	Brazil	Dolphin	13	–	3.26–174.7	Lavandier et al. (2015)
			Muscle			1.52–353.2	
	PBDEs		Liver			0.031–0.71	
			(μg/g lw)			0.065–1.29	
FRs	PCBs	Brazil	Threatened dolphin Liver	9	–	208–5543	Lavandier et al. (2016)
	PBDEs		(ng/g lw)			13.84–36.94	
FR	PBDEs	Brazil	Franciscana dolphin	FMA* III: 73	–	7.9–65.5	Leonel et al. (2014)
			(ng/g lw)	1994–2004			
				FMA II: 41		67.8–763.7	
				2002–2005			
FRs	PBDEs	Brazil	Cetaceans	51		3–5960	Dorneles et al. (2010)
			(Aquatic mammals)			(ng/g lw)	
	Methoxylated-PBDEs					>250	
						(μg/g lw)	
FRs	PBDEs	Brazil	*Stenella frontalis*	20	770	–	Yogui et al. (2011)
			Steno bredanensis	(ng/g lw)	475		
			Sotalia guianensis		65.6		
			Tursiops truncatus		64.2		
			Pontoporia blainvillei		60.3		
FRs	Brominated FRs	Brazil	Honey	16	5.19	0.46–25.2	Mohr et al. (2014)
	(BFRs)		(pg/g fw)				
FRs	PCBs	Chile	Salmon	12	28.04 ng/g ww	25.5–78	Montory et al. (2010)
	PBDEs				390 pg/g ww	272–1046	
FRs/organochloride pesticides	ΣPCBs	Brazil	Crabs	–	–	222–923	Magalhães et al. (2012)
	ΣPBDEs		(ng/g lw)			24.1	
	OCPs: ΣDDT					154–410	
	ΣHCH					10.3–30.9	
	Mirex					7.6–41.6	
	HCB					5.83–16.9	
FRs/organochloride pesticides	ΣPCBs	Brazil	Fish	–	–	8.98–12.61	Magalhães et al. (2017)
			Liver			3.32–9.87	

Table 4 (*continued*)

Classification	Emerging pollutants	Country	Sample	n	Median	Min–max	Reference
	BDE-47		Muscle (ng/g ww)		1.07 2.97	–	
	BDE-99				2.50 1.25	–	
	OCPs: ΣDDT				–	<DL–6.27	
	ΣHCH				–	<DL–0.91	
	Mirex				–	<DL–1.56	
	HCB				–	<DL–2.98	
FRs	PBDEs HBCDs	Mexico	Fish (ng/g)	28	–	ND–244.9 ND–509.4	Valenzuela-Sánchez et al. (2019)
FR	PBDEs	Brazil	Fish (ng/g ww)	29	–	<DL–72.7	Cipro et al. (2013)
Microplastics		Mexico	Fish	87	67 MP 100 μm	White-transparent: 43 % Blue: 36 % Brown: 18 % Black: 3 %	Jonathan et al. (2021)
Microplastics	Fibers Fragments	Argentina	*Mytilus chilensis*	10	8.6 items/individual	77.91 % 742.3 μm 17.44 % 1944.8 μm^2	Pérez et al. (2020)
Microplastics	–	Brazil	Fish	965	13.9 % 210 particles/134 individuals	5–25.8 % occurrence	Neto et al. (2019)
Microplastics	Fibers Fragments	Ecuador	Milk Honey	10 14	134–444 MP 300–954 MP	34–254 fibers/L 100–284 fragments/L 20–178 fibers/L 300–954 fragments/L	Diaz-Basantes et al. (2020)
Microplastics	Fibers Fragments Pellets	Mexico	Fish	240	138 items MP 154 24	–	Borges-Ramírez et al. (2020)
Plastics	Plastic particles (PP)	Brazil	Fish	68	201PP Gastrointestinal tract 182 PP gills	3 particles/individual 2.7particles/individual	Ribeiro-Brasil et al. (2020)
PAHs	Σ-16PAHs Σ-PAHs	Brazil	Brown mussels (ng/g dw)	180	–	38.96–243.59 432.69–848.78	Ramos et al. (2017)
PAHs	Σ-16PAHs Fluorene Phenanthrene Anthracene Fluoranthene Pyrene Benzo[*a*]anthracene Chrysene Benzo[*a*]pyrene	Brazil	Bivalve Mollusk (ng/g dw)	Six group sizes (mm)	–	41.4–52.5 1.1–5.7 4.7–17.4 1.6–2.1 5.5–8.4 2.0–8.0 0.6–1.8 2.5–2.8 0.2–3.3	Maioli et al. (2010)
PAHs	Σ-18PAHs	Brazil	Fish (μg/kg ww)	Species: Croaker/meagre	–	1.32–5.41 2.66–18	Oliveira et al. (2020)
PAHs	Σ-PAHs	Colombia	Fish (ng/g)	23	53.24	–	Burgos-Núñez et al. (2017)
PAHs	Σ-17PAHs	Argentina	Fish (ng/g ww)	514	–	11.27–52.80	Recabarren-Villalón et al. (2019)
PAHs	Σ-17PAHs	Argentina	Mussels Fish (ng/g dw)	4 sites	– 1095	348–1597 –	Arias et al. (2009)
Pesticides/FRs	PCBs DDT Mirex Chlordanes HCHs HCB	Brazil	Blubber marine Tucuxi dolphins (μg/g lp wt)	9	–	0.2–9.22 0.541–125 0.014–0.312 0.001–0.047 <0.003–0.044 n.d.–0.024	Yogui et al. (2003)
Pesticides/FRs	Σ-PCB Σ-DDT Σ-HCH HCB Mirex	Argentina	Dolphins (μg/g lp) *Delphinus delphis* *Lagenodelphis hosei*	12 3	5.92 3.68 3.58 4.98 0.03 0.03 0.18 0.17 0.12 0.35	–	Durante et al. (2016)
Pesticides	Chlorpyrifos Profenofos DDT HCB Gama-HCH Febitrothion	Colombia	Honey (% detection)	61	36.1 16.4 6.6 4.9 4.9 1.6	–	López et al. (2004)

(continued on next page)

Table 4 (*continued*)

Classification	Emerging pollutants	Country	Sample	n	Median	Min–max	Reference
Pesticides	Thiamethoxan	Chile	Honey	68	< 0.01	–	Balsebre et al. (2018)
	Fipronil		(μg/g)		< 0.02	–	
	Diazinon				<0.015	–	
	Chlorpyrifos				–	<0.017–0.067	
	Coumaphos				< 0.03	–	
Pesticides/FRs	PCBs	Brazil	small	5	8.08	–	Yogui et al. (2010)
	DDT		cetaceans		15.9		
	Mirex		(μg/g lp)		0.149		
	HCB				0.051		
	CHLs				0.008		
	HCHs				0.007		
Pesticides	Pesticides residues	Uruguay	Fish (μg/kg)	149	–	<1–194	Ernst et al. (2018)
Pesticides/FRs	OCPs	Argentina	Whales	35	22.6	–	Torres et al. (2015)
	PCB		(ng/g ww)		7.5		
Pesticides	Σ-HCH	Brazil	Fish	240	–	0.04–0.12	Botaro et al. (2011)
	HCB					<0.01	
	Σ-DDT					0.03–0.78	
	Heptachlor					0.01–0.04	
	Aldrin/Dieldrin					0.02–0.11	
	Endrin					0.01–0.04	
	Endosulfan					0.01–0.20	
	Mirex					0.01–0.06	
Phthalates	DEP	Mexico	Eggs	–	1.9	–	García-Fabila et al. (2020)
	DnBP		(μg/kg)		1.6		
	DEHP				101		
			Chicken		3.68		
					23		
					710		
			Beef		1.6		
					260.8		
					198.4		
			Pork		1.21		
					7.14		
					279.4		
			Seafood		3.2		
					24.98		
					250.2		
			Milk		1.75		
					15.36		
					225.8		
Pharmaceuticals/illicit drugs	Cafeine	Argentina	Fish	30	–	1.2–13.0	Ondarza et al. (2019)
	Antibiotics		(μg/kg ww)			1.3–13.4	
	Antidepressants					1.1–9.1	
	Illicit drugs (BE)					0.42–1.6	
Pharmaceuticals	Atenolol	Uruguay	Fish	27	0.088	–	Rojo et al. (2019)
	Carazolol		(Muscle)		0.054		
	Metoprolol		μg/kg wwt		0.370		
	Nadolol				0.059		
	Propranolol				0.190		
	Sotalol				0.020		
	Carbamazepine				0.190		
	Diazepam				0.048		
	10,11-EpoxyCBZ				0.053		
	2-HydroxyCBZ				0.440		
	Lorazepam				0.210		
	Venlafaxine				0.210		
	Clopidogrel				0.066		
	Salbutamol				0.082		
	Codeine				0.130		
	Hydrochlorothiazide				0.310		
Dioxins	Σ PCDD/Fs	Colombia	Soybean oil 1	–	4.71	–	Pemberthy et al. (2016)
	Σdl-PCBs		(pg/g fat)		109.5		
			Soybean oil 2		13.20		
					127.0		
			Olive Oil		2.87		
					112.9		
			Fish Oil 1		7.72		
					5493.4		
			Fish Oil 2		8.00		
					6828.6		
			Butter		12.90		
					92.30		
Microplastic	Fibers	Ecuador	Beer	15	70–976 microplastic	12–98 fibers/L	Diaz-Basantes et al. (2020)
	Fragments					50–920 fragments/L	
			Soft-drink	14	68–494 MP	10–144 fibers/L	

Table 4 (*continued*)

Classification	Emerging pollutants	Country	Sample	n	Median	Min–max	Reference
						58–350 fragments/L	
PAHs	Σ-PAHs	Brazil	Cold-pressed	13	–	<LOQ–9	Silva et al. (2017)
	Benzo(*a*)anthracene		Vegetable oils			ND–2.94	
	Benzo(*a*)pyrene		(μg/kg)			ND–1.01	
	Benzo(*b*) fluoranthene					ND–1.44	
	Chrysene					ND–4.30	
PAHs	Σ-PAHs	Brazil	Soybean oil	112	–	10–316	Camargo et al. (2012)
			Crude				
			Deodorized			3–69	
			(μg/kg)				
PAHs	Σ-13PAHs	Brazil	Canola oil	70	–	ND–31.70	Molle et al. (2017)
			Sunflower			0.65–17.88	
			Corn			2.61–38.23	
			(μg/kg)				
Phthalates	DEP	Mexico	Bottled water	–	0.01	–	García-Fabila et al. (2020)
	DnBP		(μg/kg)		0.47		
	DEHP				4.22		
			Bread		5.2		
					41.9		
					318		
			Butter		14.8		
					603.7		
					1299		
			Yogurt		0.45		
					1.7		
					47.16		
			Ice cream		0.35		
					0.72		
					309.4		

3.2.3. Sediments

Aquatic environments are not only one of the most fragile ecosystems, but they are also considered significant receptors of wastewater discharges. Once in the water, pollutants reach the sediments, considered the main sink of anthropogenic chemicals in aquatic ecosystems, mainly those pollutants with lipophilic characteristics. Over the years, estuaries have been impacted by industry and human activities, increasing the number of pollutants accumulated in sediments. A fraction of these chemical compounds can be reintroduced into the water column through resuspension and transferred and bioaccumulated in the aquatic biota. Given their high production rates and environmental persistence, environmental pollutants may mean an important risk to aquatic organisms. The effect of bioaccumulation and biomagnification of the legacy pollutants in the aquatic food chain is very relevant (Barón et al., 2013; Cesar et al., 2014). According to data shown in Table 2, the list of legacy and EPs detected in sediment samples from Latin America included: PAHs (20 %), pesticides (20 %), flame retardants (17 %), REEs (14 %), and microplastics (14 %), among others. However, sediments from only 3 countries (Brazil, Mexico, and Colombia) have been analyzed. In addition to the absence of data on these pollutants levels in sediments of the LA region, there is a lack of information regarding the biological effects of these sediment-bound toxicants.

The levels of ΣPAHs (sum of 16 PAHs) were between 7 and 41 ng/g dw in Colombia (Burgos-Núñez et al., 2017) and 37.5 to 380.5 ng/g dw in Argentina (Recabarren-Villalón et al., 2019), while a prolonged decrease of PAH concentrations over the years has been reported in Brazil. Leite et al. (2008) showed a range of concentrations for ΣPAHs of 143–1713 ng/g dw, while Maciel et al. (2015) and Rodrigues et al. (2018) reported levels ranging <LOD–497.6 ng/g dw, and 22.2–158.9 ng/g dw, respectively. In 2004, the Stockholm Convention, managed by the United Nations Environment Program (UNEP), required to remotion of some chemicals in the marketplace. That initiative resulted in a decrease in the environmental levels of legacy pollutants and other EPs in recent years (Souza et al., 2021). PAH concentrations in samples from Colombia (7–41 ng/g dw) were lower than those reported in Argentina (37.5–380.5 ng/g dw) and Brazil (22.2–158.9 ng/g dw) (Burgos-Núñez et al., 2017; Rodrigues et al., 2018; Recabarren-Villalón et al., 2019). Since PAH levels are higher in urban environments, being mainly influenced by vehicular emissions, the levels of these chemicals in Colombia are lower due to their lower industrial development in comparison to other LA countries (Burgos-Núñez et al., 2017; Rodrigues et al., 2018; Recabarren-Villalón et al., 2019; Caballero-Gallardo et al., 2021; Souza et al., 2022).

The studies with REEs in sediment samples were performed in Brazil, Mexico, and Colombia (Table 2). REEs levels were higher in Brazil than those found in Colombia, probably because Brazil owns the second-largest stock of REEs in the world. In Colombia, Palacio-Torres et al. (2020) reported levels of 15.7 mg/kg for La and 30.4 mg/kg for Ce, while in sediments from Brazil, Bosco-Santos et al. (2017) reported mean concentrations of 141 and 318 mg/kg for La and Ce, respectively.

Over the years, global plastic production has dramatically increased worldwide, thus making the microplastic presence an emerging environmental issue and a threat to marine life and human health. MPs are present in the environment in a heterogeneous array of shapes, sizes, and colors. Moreover, they can be carriers of other pollutants that are adhered to their surfaces. MPs are ubiquitous in marine and freshwater sediments, as well as in the water column and marine organisms, including their digestive systems and tissues. The density of the plastic material will determine its presence in sediments. Usually, high-density plastics can sink into sediments. However, some turbulence conditions can cause their resuspension and redistribution in the water (Neto et al., 2019; Barbosa et al., 2020; Yao et al., 2019). Nowadays, there is a high concern in the scientific community on the potential effects of MPs on the environment and human health. However, little attention has been still given to its determination in sediments, mainly in Latin America. Studies available in the literature show in Brazil MPs amounts of 0–38 particles/sample (Neto et al., 2019), 20.74–166.5 items/kg (Castro et al., 2020), and 2.4–30.4 particles/m^2 (Maynard et al., 2021). On the other hand, Ramirez et al. (2019) reported 1392 items/m^2 of MPs in the coastal sediments of Mexico. An increasing interest in this topic is expected in the close future, not only in the LA regions but also worldwide (Kutralam-Muniasamy et al., 2020).

Chaves et al. (2020) determined the caffeine concentrations in surface sediments from Brazil, with values between 6 and 20 ng/g. These concentrations were lower than those observed in water samples, demonstrating

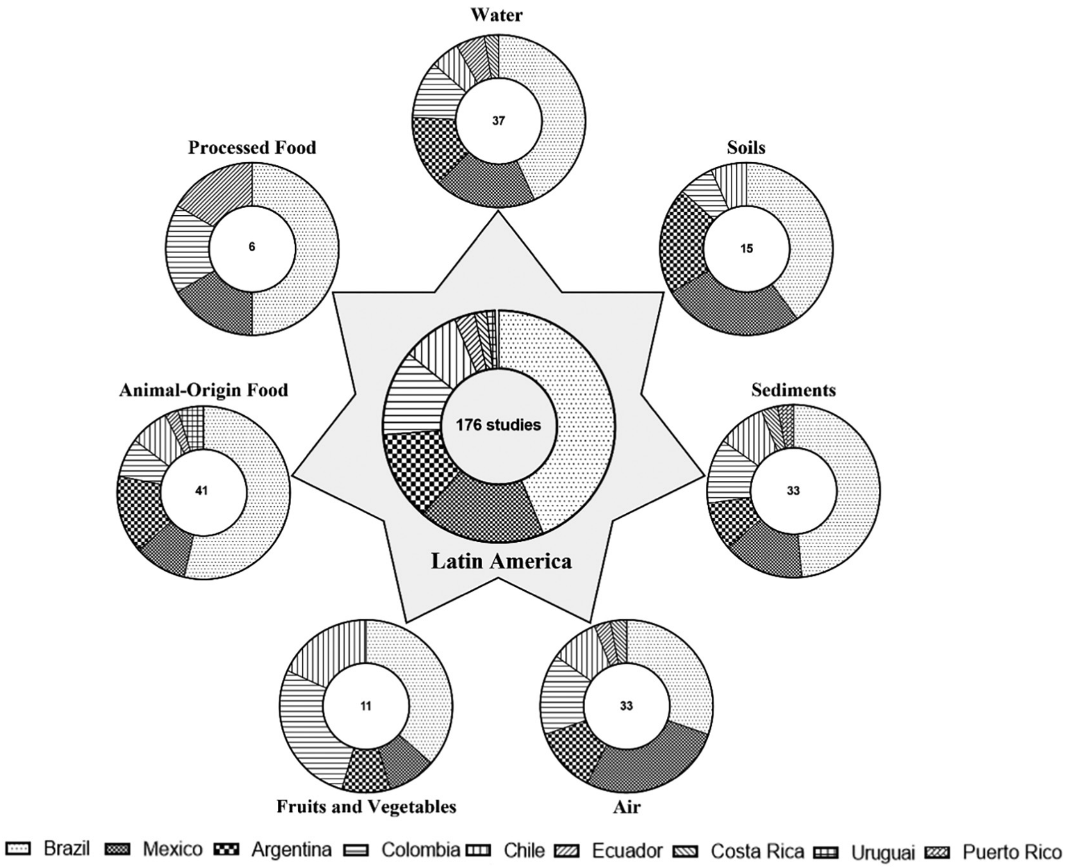

Fig. 2. Distribution of all matrices of this review in Latin American countries.

a more significant affinity of caffeine to water. Péres et al. (2021) determined glyphosate levels and their metabolite (AMPA), as well as other pesticides in water, soils, and sediments samples from Argentine. Levels in sediments ranged from 1.5 to 32 μg/kg, and from 3 to 17.5 μg/kg, for glyphosate and AMPA, respectively. Glyphosate is widely used, being the best-selling herbicide in the world. Thus, it can be suggested that it is ubiquitous in the environment since its disposal is constant. AMPA, the primary metabolite of glyphosate, is formed by microbial biodegradation in soils, sediments, and water. In addition, the phosphonic groups of glyphosate form covalent bonds with the iron oxides and hydroxides present in soils and sediments, being then absorbed. However, due to its high polarity, higher concentrations are usually found in water samples (Péres et al., 2021). Another class of pesticide that deserves attention in sediment samples is the organophosphate chlorpyrifos. Geographically speaking,

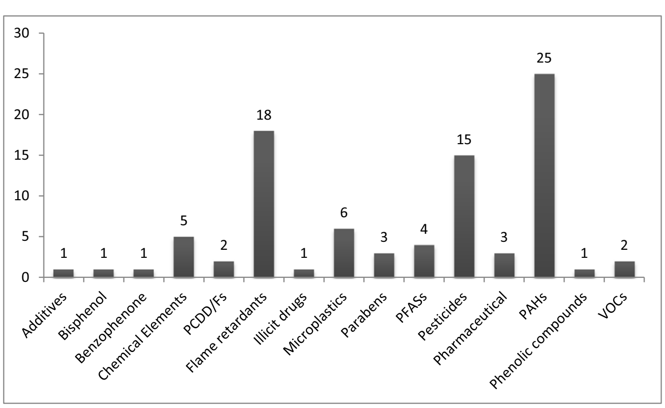

Fig. 3. Distribution of the legacy and EPs in Brazil. On the Y-axis is the number of studies.

chlorpyrifos showed higher concentrations in sediments of Costa Rica (10 μg/kg) than in those of Argentina (4.2 μg/kg) (Péres et al., 2021; Ramírez-Morales et al., 2021).

Some flame retardants such as PBDEs and PCBs, are lipophilic compounds that show higher affinity to sediments and aquatic organisms when compared to water compartments. Although the use and commercialization of PCBs have been banned for decades, due to their high environmental persistence, they are still detected at relatively high concentrations in complex matrices. Souza et al. (2018) determined PCBs in Brazilian sediments, with levels between <LOD and 190.7 ng/g, while in Argentina, Tombesi et al. (2017) reported PCB concentrations within a range of 0.61–17.6 ng/g. PCB levels in Puerto Rico were higher than those found in other LA countries (from 0.42 to 1232 ng/g) (Alegria et al., 2016). PBDEs are also toxic compounds with high environmental persistence but are usually found at lower levels than PCBs. Studies reporting PCB concentrations have been conducted in Mexico (Macías-Zamora et al., 2016) and Argentina (Tombesi et al., 2017), with levels ranging from 0.02 to 5.9 ng/g and 0.16–2.02 ng/g, respectively. Since there is not yet specific legislation regarding the use of these compounds in most LA countries, the environmental release of these flame retardants continues to be relevant (Alegria et al., 2016; Annunciação et al., 2018).

3.2.4. Air compartments

Passive air sampling is a practical methodology for atmospheric monitoring in urban regions (Rauert et al., 2018). PMs_{10} are atmospheric particulate matter with an aerodynamic diameter < 10 μm, which is mainly identified in the air of developing urban areas and considered a severe risk factor for human health (Rovira et al., 2018). Long-term air monitoring of EPs, but mainly legacy pollutants, is especially useful to evaluate the effectiveness of global regulatory measures (Rauert et al., 2018). Similar to other environmental samples, Brazil concentrates the largest number of studies on air samples (31 %), followed by Mexico (28 %). Most legacy pollutants investigations (23 % of the total) focused on PAHs and pesticides. In addition, the determination of VOCs was also remarkable, with 17 % of the scientific papers (Table 3).

PCDD/Fs are environmental contaminants whose monitoring in passive air should be routine in industrial and developed urban areas (Nadal et al., 2009). Cappelleti et al. (2016) reported a mean PCDD/Fs concentration of 362 fg/m^3 in the urban air of Argentina. In turn, Schuster et al. (2015) reported the PCDD/Fs concentrations in different countries, with the highest concentrations found in Argentina (1680 fg/m^3), Brazil (1580 fg/m^3), and Mexico (1310 fg/m^3). In 2001, the Stockholm Convention included PCDD/Fs in the first list of chemicals whose emissions and/or production must be eliminated.

Over the years, climate change has attracted interest in its potential to alter the environmental distribution, mainly semi-volatile organic chemicals like PAHs. Many mechanisms can influence the distribution of legacy pollutants in the atmosphere. Temperature, wind speed, and precipitation are environmental variables that affect the fate and transport of legacy pollutants through the different environmental compartments (Nadal et al., 2015).

The difference in temperature between seasons of the year, mainly winter and summer, interferes considerably with PAH concentrations. High ambient temperature and wind speed contribute to decreasing the atmospheric PAH concentrations (Lopez-Ayala et al., 2019; Meire et al., 2019). Lopez-Ayala et al. (2019) found that the ΣPAH levels in suspended particulate from Mexico were higher in winter (32–116 ng/m^3) when compared to those observed in spring (1.0–5.9 ng/m^3). Moreover, ΣPAH levels were higher in atmospheric samples from Chile (30–230 ng/m^3) than in Colombia (25–66 ng/m^3) and Brazil (0.17–90 ng/m^3).

3.3. Food samples

Food products constitute an important exposure source for both legacy and emerging pollutants in humans (González et al., 2018). However, the perception of the risk through food consumption is, in fact, still neglected/ignored in many countries worldwide. Considering that some of these compounds show high lipophilicity, human exposure to these chemicals is associated with the dietary intake of foods rich in lipids. In addition, the ability of legacy pollutants to bioaccumulate in the environment increases the concentrations of these substances in the aquatic food chain (Souza et al., 2021). Legacy and EPs levels in different food matrices, including fruit and vegetables, animal-origin food samples, and processed food samples collected in several LA countries are shown in Table 4.

3.3.1. Fruits and vegetables

Pollutants in vegetables and fruits can originate mainly from the deposition on their surfaces of contaminated air particulates, or also through contamination from soils and irrigation water. Most studies on EPs (up to 60 %) involved the determination of pesticides in food. In addition to their occurrence, some investigations have also focused on risk assessment, which should be mandatory in terms of public health prevention (Lopes-Ferreira et al., 2022).

Chlorpyrifos is a common pesticide routinely applied in citrus. Among the citrus, orange (*Citrus sinensis*) is the most important fruit, with around 89 million tons worldwide in 2019. Considering that citrus consumption is relatively high in LA countries, it is considered an important source of dietary pesticides (Chen et al., 2021; García-Valcárcel et al., 2019; Li et al., 2020; Acoglu and Omeroglu, 2021; Noorizadeh et al., 2022). Mac Loughlin et al. (2018) determined chlorpyrifos in 41 orange samples from Argentina, reporting levels ranging from <LOQ to 76.8 μg/kg. Other pesticides also showed relatively high concentrations in orange samples, including atrazine (34.7–63.7 μg/g), acetochlor (129.6 μg/kg), diazinon (84.4–304.3 μg/kg), malathion (37.5 μg/kg), lambda-cyhalothrin (23.2–184 μg/kg), cypermethrin (<LOQ–698.8 μg/kg), endosulfan (4.4–473.1 μg/kg) and tebuconazole (7.1–7821.5 μg/kg) (Mac Loughlin et al., 2018).

Since it is the most prevalent pesticide in water, atrazine, a systemic herbicide like glyphosate, was banned in the European Union in 2004. However, given its low price, atrazine has become one of the major pesticides in LA countries and the USA (Gupta, 2011; Holt, 2013; Mahmood et al., 2014). Considering the reported harmful effects of pesticides on humans, various countries and regions have enacted laws and regulations to minimize pesticides in agriculture, with the USA and the EU as leaders of these regulatory initiatives. In 2001, the Program for Analysis of Residues of Pesticides in Food (PARA), coordinated by the Brazilian National Health Surveillance System (SNVS), was created to continuously evaluate the levels of pesticide residues in plant-based foods. The regulatory agencies are responsible for setting up tolerance limits for pesticides in foods, being these tolerances are often called maximum residual limits (MRL). The MRL is a parameter related to food safety and corresponds to the higher levels of pesticide residues that are legally permissible on these matrices, as well as on animal feed. MRL constitutes one of the components for calculating exposure and assessing dietary risks before registering a pesticide or authorizing the inclusion of new crops.

Mac Loughlin et al. (2018) found maximum concentrations of cypermethrin (0.69 mg/kg) and tebuconazole (7.82 mg/kg) in orange crops above the MRL established by PARA (2017–2018) at 0.3 and 5 mg/kg, respectively. In contrast, the levels of other pesticides were below the respective MRL. Mac Loughlin et al. (2018) also determined the pesticide levels in lettuce samples from Argentina. It was found that chlorpyrifos (<LOQ–1524.5 μg/kg), cypermethrin (3229.7 μg/kg) and epoxiconazole (5.6–29.6 μg/kg) exceeded their respective MRLs (zero, 0.07 mg/kg and zero, respectively). Acephate, chlorpyrifos, and methomyl were the pesticides with the highest number of irregular detection in different crops in Brazil (PARA, 2017–2018).

Tomato is a delicate fruit and sensitive to pest infestation. It is one of the crops with more intense use of pesticides to maintain the quality of the plants, eventually causing a notable concern about the potential contamination of the final product (Juraske et al., 2007). In Colombia, the levels of pesticides in tomato crops were measured in two consecutive surveys by Arias et al. (2014, 2021), who observed a reduction in the levels of acephate (0.04–0.45 mg/kg vs. 0.015–0.03 mg/kg) and carbendazim (0.01–0.74 mg/kg vs. 0.19–0.23 mg/kg) with time. In contrast, difenoconazole levels increased (from 0.01 to 0.03 mg/kg to 0.45–0.59 mg/kg), while methomyl could be only quantified in the second study, at levels ranging 0.05–0.06 mg/kg. In turn, Mac Loughlin et al. (2018) reported levels of other pesticides in tomato crops from Argentina. The concentrations of chlorpyrifos and malathion, both organophosphate pesticides, ranged from 9 to 12.7 μg/kg and 30–47.9 μg/kg, respectively, while traces of other pyrethroids, permethrin, and bifenthrin, could be also found.

Concerning the presence of REEs in plants, the levels of these chemical elements vary according to the environmental contents, mainly those in soil samples and among different plant species. Besides, due to their higher soil mobility, REEs are easily absorbed by plants. However, the capacity of crops to accumulate REE depends on the species (Turra et al., 2013; Ramos et al., 2016). Fertilizers are extensively used in citrus production, being Brazil the biggest producer of oranges worldwide. Turra et al. (2015) determined the levels of three REEs in orange samples from Brazil. The concentrations of Ce (<0.049–0.44 mg/kg), La (0.01–1.17 mg/kg), and Sc (<0.0004–0.003 mg/kg) in oranges, mainly in the peel samples, could be attributed to superficial contamination from soils after application of fertilizers. Nevertheless, Sc concentrations were in the range considered normal for plants. The same researchers had previously found higher concentrations for La (0.034–1.4 mg/kg) and Ce (<0.045–0.58 mg/kg) in citrus samples from the same area. Sc values were also considered normal levels (Turra et al., 2013). The quantification of REE in the citrus production system is still very little studied around the world. Thus, no safety intake limits have been established yet for humans.

3.3.2. Animal-origin foods

Animal-origin foods present a high percentage of lipids in tissues, showing a high affinity for lipophilic pollutants (González et al., 2020a, 2020b).

Legacy pollutants in these foods have been largely studied in LA countries (Table 4). Most studies focused on flame retardants (36 % of the total), with Brazil being the country with the highest number of publications (up to 88 %). Other EPs that are also receiving attention are pesticides (19 % of the studies) and microplastics (14 % of the articles).

PCBs are used as insulating fluid in transformers and capacitors. Due to their high thermal and chemical stability, PCBs are classified as legacy pollutants, being their use and commercialization are currently prohibited. Regulatory actions that removed PCBs from the marketplace have notably decreased environmental levels worldwide. However, even after being banned, PCBs are still found in the environment, especially in aquatic animals, since they show high environmental persistence, while some PCB equipment is still in operation. In Brazil, Lavandier et al. (2013) determined PCBs in fish (2.29–27.6 ng/g) and Magalhães et al. (2017) in crabs (222–923 ng/g). In Chile, the range concentration of PCB in salmon was found to be 25.5–78 ng/g (Montory et al., 2010).

Due to their low cost, PBDEs are the most used flame retardants. In Brazil, Souza et al. (2019, 2021) determined ΣPBDEs in different animal origin foods, including eggs (0.92–4.85 ng/g lp), fish (1.23–3.04 ng/g), and seafood (1.23–3.12 ng/g), and milk (1.26–8.42 ng/g). In Chile, Montory et al. (2010) reported a range of 0.27–1.05 ng/g for PBDEs in salmon. Flame retardants may enter the environment through the leaching process and improperly dispose of materials containing these substances. Therefore, soils can be considered a potential source of flame-retardant contamination in animals. Moreover, samples from urban and industrialized areas usually present higher concentrations than those from rural areas (Camargo and Toledo, 2003; Souza et al., 2021).

In the LA region, PCDD/Fs concentrations were determined in shrimp samples from Colombia, with values of 44.80 pg/g fat for PCDD/Fs and 193.50 pg/g fat for dl-PCBs (Pemberthy et al., 2016). In Brazil, Rocha et al. (2016) quantified PCDD/Fs in cow milk (24.39 pg/g fat), while Martin et al. (2016) analyzed meat samples from different animals (bovine, pork, ovine, chicken, and turkey), reporting concentrations ranges of 0.96–2.80 pg/g fat for PCDD/Fs, and 65.1–171 pg/g fat for dl-PCBs.

Regarding PAHs, fish samples from Brazil (Oliveira et al., 2020), Colombia (Burgos-Núñez et al., 2017), and Argentina (Recabarren-Villalón et al., 2019) have been analyzed. The highest concentration was observed in Colombia, with a median value of 53.14 ng/g dw. In Brazil, Ramos et al. (2017) and Maioli et al. (2010) determined the concentrations of PAHs in seafood samples, with values ranging from 38.96 to 243.59 ng/g dw in mussels, and 41.4–52.5 ng/g dw in other mollusks.

The inadequate disposal of pharmaceutical products and the precariousness of the sewage treatment system contaminate the water column and sediments with these substances, eventually favoring their accumulations in the tissues of aquatic animals. This contamination is a threat to global human and environmental health since it occurs continuously due to the high consumption of these pharmaceuticals in continuous administration to treat chronic diseases. Rojo et al. (2019) determined a variety of pharmaceuticals in fish samples from Uruguay, being the results summarized in Table 4. In turn, Ondarza et al. (2019) quantified caffeine (1.2–13 μg/kg), antibiotics (1.3–13.4 μg/kg), antidepressants (1.1–9.1 μg/kg), and illicit drugs (0.42–1.6 μg/kg) in fish samples from Argentina.

3.3.3. Processed food

Some food-safety incidents have been associated with food processing and packaging materials of foods, including vacuum and canned packaging (García-Fabila et al., 2020; Souza et al., 2021). However, the exact source has not been determined. Moreover, industrial processing can also add EPs to foods. It is extremely relevant to compare the human toxicity in acute exposure to chemicals with the potential occurrence of chronic toxicity by compounds that are frequently identified in the packaging materials (Camargo and Toledo, 2003; Souza et al., 2019; García-Fabila et al., 2020; Souza et al., 2021). Very few studies have assessed the presence of EPs in packaging and processed foods in Latin America. Phthalate esters are used as plasticizers in many products, and the DEHP shows high human toxicity. In Mexico, García-Fabila et al. (2020) quantified phthalate esters, including the DEHP (bis(2-Ethylhexyl) phthalate), in different processed food samples. Plastic production has increased significantly over the years worldwide. Microplastics can carry a range of pollutants (Barbosa et al., 2020). In Ecuador, Diaz-Basantes et al. (2020) determined fibers and fragments of microplastics in beer (70–976 fragments/L).

4. General overview

It must be noticed that most of the studies here included were concentrated in a few LA countries, namely Brazil, Mexico, Costa Rica, Chile, Colombia, Argentina, Uruguay, Ecuador, and Puerto Rico. Brazil (45 %) is the country with the highest number of published articles, followed by Mexico (18 %), Argentina (13 %), Colombia (12 %), and Chile (8 %). Most reported papers in LA countries were on water compartments, mainly in surface water (38 %) and wastewater (19 %) samples. Pesticides and pharmaceutical compounds are the prevalent EPs in water samples. The distribution of legacy and emerging pollutants in Brazilian papers is depicted in Fig. 3. Brazil is an extensive country with a territorial extension >8 million km^2, with >208 million inhabitants, formed by five regions, and a total of 26 states and the Federal District. However, as observed in the present review, the published studies are concentrated in the Southeast region, mainly in the State of São Paulo. The economy of the State of São Paulo is the most developed among the Brazilian states, with the greatest investments in research. PAHs were the major group of anthropogenic environmental pollutants studied in Brazil, followed by flame retardants, including PCBs and PBDEs.

On the other hand, pesticides were the most studied EPs in Mexico, Argentina, and Colombia. Interestingly, the levels of some pollutants were higher in LA matrices than those reported in European countries and the United States. Souza et al. (2021) found PBDE levels in Brazilian eggs (2.29 ng/g fat) higher than those of Belgium (1.41 ng/g fat), and Spain (0.53 ng/g fat) (Bocio et al., 2003; Covaci et al., 2009). PBDEs in Brazilian cow's milk samples (4.42 ng/g ww) were also higher than those found in Italy (3.70 ng/g ww) (Martellini et al., 2016). This could be a result of the lack of legislation in LA, in contrast to several restrictions on the use of many of these compounds, both in the USA and in Europe.

Few studies have been reported in LA on processed foods, fruits and/or vegetables, and soil samples. Bisphenol, phthalates, parabens, and benzophenones are endocrine disruptors that can cause deleterious effects on humans and the environment. However, few studies have determined the concentrations of these EDCs in environmental and food matrices, which are considered important sources of exposure for the general population. In turn, pharmaceutical products are compounds of high consumption worldwide, being environmental contamination a real and ongoing possibility. The high levels of EDCs in the water columns, soil, sediments, and aquatic biota, suggest a precarity and malfunction of the water treatment system in these emerging economies. Only two studies reported the presence of illicit drugs in environmental matrices. Furthermore, there are still many gaps in the occurrence of PFASs in LA countries.

The Stockholm Convention on Persistent Organic Pollutants was adopted in 2001 and globally came into effect in 2004. This agreement is a global treaty, signed by many LA countries, whose purpose is to safeguard human health and the environment from highly harmful chemicals, which persist in the environment and affect the well-being of humans, as well as wildlife. This Convention listed some pesticides, industrial chemicals, and unintentional production (UNEP, 2019). Concerns about the harm of legacy pollutants to ecosystems and human health, most of these identified pollutants are banned or restricted around the world by Stockholm Convention. However, even long-banned pollutants remain in the environment. It is important to mention the identification of OCPs and PCBs in several studies, although their use and commercialization have been banned for decades. Other legacy pollutants are still in use in Latin America, with very limited information on their levels in environmental samples (Lavandier et al., 2016; Magalhães et al., 2017; Oliveira et al., 2020; Souza et al., 2021).

Table 5
General overview and description of the knowledge gaps and the next step in Latin American (LA) Science.

Knowledge gaps	Next steps in LA science
The disparity in the spread of studies within LA; Brazil contributes a significant 45 % of the total articles published on the subject area while no information is available in some LA countries.	The incentive for the international cooperation between research groups in LA countries and/or other geographic regions (Europe and the USA) would help generate more data on legacy and emerging pollutants in the region.
Most papers are concentered in water compartments (surface water and wastewater)	Improvements in the investments in research related to environmental monitoring of EPs in Latin America.
Few studies on processed foods, fruits/vegetables, and soil samples. Many gaps in the occurrence of bisphenol, phthalates, parabens, benzophenones, illicit drugs, and PFASs in food and environmental matrices Few records of official programs that are focused on legacy and emerging pollutants. Few laboratories are equipped with appropriate analytical capacity.	Due to the massive agricultural and industrialization expansion in the coming years, establishing regular monitoring programs for legacy and emerging pollutants should be on the top priority list of regulatory agencies in Latin America.

The pollutants from e-waste are an emerging threat in urban areas. The international project hosted by the UN Industrial Development Organization (UNIDO) and the Global Environment Facility is aimed at establishing national e-waste management strategies, like the correct disposal of e-waste, and recycling and reuse standards. This project involves some countries, including Argentina, Bolivia, Chile, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Nicaragua, Panama, Peru, Uruguay, and Venezuela (Stockholm Convention, 2019; UNIDO, 2020). Since 1989, the Basel Convention is responsible for controlling transboundary movements of hazardous wastes and their disposal, to stop the export of hazardous wastes to countries in the developing world, like Latin America (Basel Convention, 2011). The Rotterdam Convention is an action to the protection of the environment and human health through the responsible trade and use of hazardous chemicals. This convention was adopted by most countries in Latin America to prevent the environmental impacts caused by hazardous pesticides (Rotterdam Convention, 2022).

The Global Atmospheric Passive Sampling (GAPS) Network is a program, initiated in December 2004, for producing comparable global-scale data for legacy pollutants. In 2012, the GAPS Network provided the opportunity to evaluate time trends of the legacy POPs monitoring in a Group of Latin America and Caribbean countries (GRULAC), which covered seven countries, including Mexico, Costa Rica, Colombia, Brazil, Bolivia, Argentina, and Chile (Rauert et al., 2018). Rauert et al. (2018) reported the levels of PCBs in passive air from GRULAC, with concentrations in the range of 0.08 to 128 pg/m^3. Pesticides levels were also determined in passive air from GRULAC, including hexachlorobutadiene (<20–120 pg/m^3), pentachloroanisole (<1–8.5 pg/m^3), dichlorobenzophenone (<0.9–4.6 pg/m^3), hexachlorobenzene (8.8–108 pg/m^3), chlordane (<1.6–7.1 pg/m^3), heptachlor (<0.5–3.1 pg/m^3), endosulfan (<1.0–868 pg/m^3), dieldrin (17–112 pg/m^3), DDT (<0.7–8.3 pg/m^3) and DDE (<0.4–2.5 pg/m^3).

Over the last 50 years, the LA agricultural surface area increased considerably. Agriculture is the most widespread activity causing soil pollution in Brazil, Argentina, and Colombia, which is mainly due to the excessive use of pesticides and fertilizers, as well as crop irrigation with untreated wastewater and/or polluted surface water (Rousis et al., 2016; Kim et al., 2017; Kalliora et al., 2018). The United Nations Environment Programme (UNEP) is controlling the use, disposal, and management of highly toxic pesticides in LA. The main purpose of this program is to minimize the adverse effects of chemicals on human health and the environment over the years. UNEP works with governments, some industries, and civil society organizations around the world. It is expected that, over the years, the environmental impact due to contamination by chemicals will be significantly reduced and minimized, mostly because of both global and local legislative measures.

The increasing national capacities to reduce releases of legacy pollutants, and control their levels in breast milk and air, were implemented between 2016 and 2019. Notwithstanding, the residues of some pollutants in soil represent a great problem in LA (Rauert et al., 2018). According to the Inter-American Development Bank (IDB), wastewater treatment plants are one of the major environmental problems in Latin America. In this region, a considerable fraction of industrial wastewater is not treated before its discharge into the environment. In South America, most wastewater without treatment is discharged into the water bodies (IDB, 2018).

In Brazil, there are some programs to control legacy and emerging pollutants in environmental and food samples. The National Council for the Environment (CONAMA) provides criteria and guiding values for soil quality regarding the presence of some chemical substances, including chemical elements, VOCs, PAHs, phthalates, organochlorine pesticides, and other chlorinated substances. The Program for Analysis of Residues of Pesticides in Food (PARA) was created in 2001 to continuously evaluate the levels of pesticide residues in foods of plant origin, being responsible for setting up tolerance limits for pesticides in foods (MRL). VIGISOLO is a component of Environmental Health Surveillance focused on assessing the risk of various diseases resulting from soil contamination by chemical substances. This program is aimed at identifying populations exposed -or at risk of exposure- to chemical contaminants and soil contaminated with mercury, asbestos, lead, benzene, and pesticides (VIGISOLO, 2014). On the other hand, the VIGIAR program has the general objective of promoting the population's health exposed to atmospheric pollutants. Priority is given to regions where economic or social activities generate atmospheric pollution, and thus, characterize potential risk factors for the exposed populations. However, the last two programs are mainly aimed at integrated prevention, promotion, and health care actions for exposed populations (VIGIAR, 2022).

Legislation and regulatory actions are essential to assess whether the pollutant concentrations in the different matrices follow the established and/or maximum allowed limits. Nevertheless, in LA, there are only a few records of official programs that are focused on legacy and emerging pollutants.

However, discussions in different sectors of public health have increased in recent years and academic research has contributed significantly to stimulating government decisions (Kim et al., 2017; Kalliora et al., 2018; Lopes-Ferreira et al., 2022). The regional characteristics of LA, such as the economy and land characteristics, request attention for specific classes of pollutants, which makes the process of prioritization more complex. This specific attention has been already applied by the United States Environmental Protection Agency (USEPA) in the US. In the European Union, some regulatory actions were initiated in 1999 to select the priority pollutants to be legislated.

In the current review, almost all identified studies were conducted in very few types of samples and very specific groups of compounds. To assist regulatory agencies, studies should be carried out with different classes of pollutants and different exposure sources. However, the advances in research related to legacy and EPs determination are also related to the technological advancement of analytical instrumentation facilities. Thus, a major challenge is to obtain analytical tools capable of measuring concentrations below which the adverse effects caused by the presence of these contaminants are observed (Rocha et al., 2016; Kim et al., 2017; Kalliora et al., 2018; Lopes-Ferreira et al., 2022).

In general terms, the determination of legacy and EPs in complex solid matrixes such as soils, sediments, and food samples, among others, requires specific and efficient sample preparation methods before their analysis (Rocha et al., 2016, 2017, 2018; Souza et al., 2019, 2021). For many routine laboratories, the cost-effectiveness and high sample throughput are too complex, and difficult to develop reliable analytical methods. Environmental monitoring studies are usually very expensive, requiring financial investments and specialized trained personnel to obtain reliable results. The most common analytical instrumentations for the quantification of legacy and emerging pollutants are the equipment of high cost, including liquid chromatography coupled to mass spectrometry (LC-MS/MS), gas chromatography coupled to mass spectrometry (GC–MS), and inductively coupled plasma mass spectrometry (ICP-MS). To obtain results that are representative of a particular country or region, it is necessary to conduct studies with a high number of samples. In LA, only a few laboratories are equipped with appropriate analytical capacity, most of them concentrated in only two or three countries. It considerably limits many countries to get data on this issue. The general overview of the knowledge gaps and the next step to be taken in Latin American science are summarized in Table 5.

5. Future trends and perspectives

In recent years, the LA scenario has advanced in research related to legacy and emerging pollutants in different environmental matrices. However, it must be highlighted that there are still few studies in the literature about this. It is essential to assess some questions, including what kind of research and scientific studies must be developed in LA countries to fill data gaps. Based on these facts, new public policies in the LA region should boost research development to minimize and prevent the discharge of legacy and EPs into environmental compartments.

Pharmaceutical products, caffeine, estrogens, and other EDCs synthetics, like bisphenol and phthalates, are groups of EPs that should be further studied in environmental samples in LA. These EPs are highly consumed worldwide and environmental contamination is more than a real possibility. Water and food are important sources of exposure for the population to these compounds, which cause potential deleterious effects even at low concentrations. On the other hand, pesticides mean an important concern in LA. The indiscriminate use and approval of new formulations in an uncontrolled way, increase considerably their levels in the environment, increasing the risks of human exposure. Due to the tendency of a massive agricultural expansion in coming years, associated with high consumption of pesticides and fertilizers in the region, establishing regular monitoring programs for these EPs should be on the top priority list of local/regional/national environmental agencies.

Another topic of interest is the presence of microplastics/nanoplastics in the environmental samples from the LA region. This is a relatively new globally issue, which is gaining already attention in some LA countries, such as Brazil, Mexico, Argentina, and Ecuador (Neto et al., 2019; Ramirez et al., 2019; Borges-Ramírez et al., 2020; Castro et al., 2020; Diaz-Basantes et al., 2020; Pérez et al., 2020; Ribeiro-Brasil et al., 2020; Álvarez-Lopeztello et al., 2021; Jonathan et al., 2021; Maynard et al., 2021). However, considerable improvements in the investments in research related to environmental monitoring of EPs are mandatory in the region. Furthermore, the cooperation between research groups in LA countries, and/or between LA countries and other geographic regions, must be stimulated. It would help generate much more data on legacy and EPs in the region and would create better conditions for regulatory actions/decisions.

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Data availability

Data will be made available on request.

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

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